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An integrated fuzzy approach for the selection of manufacturing technologies

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Abstract In this paper, an integrated decision support system is developed, which employs fuzzy techniques to assist decision-makers in choosing an optimal solution from alternative manufacturing options in an uncertain environment. The integrated approach incorporates different justification methods (e.g., strategic, economic, and analytic evaluations) for assessing tangible benefits, like cost, and intangible benefits, like quality, of different alternatives by a fuzzy multi-criteria decision-making method. As an illustrative example, selection of different advanced manufacturing technologies has been demonstrated by using the proposed methodology. The proposed concept will greatly reduce conflicts between tangible and intangible factors, and enhance the process of identification, interpretation, and diagnosis of the value of complex manufacturing and engineering systems.

Keywords Decision support system · Fuzzy multi-criteria decision-making · Justification tool · Technology selection

1 Introduction

In the current competitive business scenario, one of the key requirements on global as well as local firms is to provide their markets with products and services at lower costs, at a higher quality, with a shorter product development cycle, and with a shorter delivery time. In order to achieve these objectives, several important and critical decisions have to be taken at a tactical as well as a strategic level. Economic justification methods, such as return on investment, or analytic justification methods, such as linear programming, are frequently employed before making decisions involving significant investment decisions. It is important to note that irrespective of the kind of evaluation – economic or analytic – the information available for making the decision is generally vague and uncertain. It is very difficult to obtain exact data on attributes like investment cost, expenses, project lifetime, depreciation, etc. for making these decisions. Hence, these evaluation methods tend to be less effective in delivering required information in such an imprecise, or fuzzy, decision environment.

To tackle the problem mentioned above, fuzzy set theory can play a significant role. The approximate reasoning of fuzzy set theory can properly represent linguistic terms [1]. To deal quantitatively with imprecision and uncertainty, all of the assessment data can be specified as triangular fuzzy numbers [2, 3]. Subsequently, a fuzzy multi-criteria decision-making (MCDM) method can be applied to integrate various linguistic assessments and weights in order to determine the best selection. In contrast to traditional approaches, which tend to adopt only one specific evaluation technique, an integrative approach is proposed, combining strategic, economic, and analytic justification approaches.

Adopting advanced manufacturing technologies (AMTs) is believed to be the key to survival for many companies in the current highly volatile business environment [4]. If these technologies are properly selected and implemented, they can enhance operational efficiency of a company, thereby helping the company achieve an enhanced competitive position in the market. Some industrialists and economists believe that AMT can offer many tangible and intangible benefits. Some examples of the benefits are stated as follows: increased product and process flexibility [5, 6], reduced labor cost [7], improved product quality [8], and shortened time-to-market [9, 10]. However, some AMT acquisition proposals are rejected as a result of failing to satisfy financial justification measures. Since adoption of AMT involves a very high level of investment, its payback period is usually longer than that for traditional manufacturing technologies. Consequently, decision-makers tend to adopt a rather con-

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servative policy and hence refuse to consider AMT, even if it can potentially benefit the firm. In this connection, manufacturers generally hesitate from investing in AMT because of the existing difficulties in justification of the investment by means of traditional economic analysis alone. To overcome this dilemma, an adequate economic analysis and evaluation method, which can assist decision-makers in selecting a technology best suited to their operations and business objectives, needs to be employed. For example, Ordoobadi and Mulvaney [11] developed a process known as system-wide benefits value analysis that can be used to assist decision-makers with advanced technology decisions. A fuzzy expert system is the internal mechanism used to convert user inputs into crisp output values for each benefit category. Users of the tool first perform an economic analysis to see if the investment is economically justified. If it is not justified, the gap between the minimum desired economic return and the actual return amount is calculated. Users can follow a series of procedures to determine if the value of the system-wide benefits associated with the advanced technology is sufficient to justify this gap.

The objective of this paper is to present an approach that integrates different justification methods (i.e., strategic, economic, and analytic techniques) for selecting AMT alternatives. Firstly, a conceptual framework is established wherein the strategic manufacturing objectives, performance capabilities, and different programs (or projects) are explicitly linked to each other. Subsequently, the manufacturing strategy and critical areas for capability improvement in the manufacturing systems are identified. Finally, a set of integrated performance capability measures that capture both tangible and intangible aspects of manufacturing system capability is developed. There is a need for an operational methodology to evaluate the impact of different programs (i.e., upgrading alternatives) on manufacturing capability goals and to verify the interdependence amongst the selected technologies. The integrated methodology will greatly enhance the process of identification, measurement, analysis, interpretation, and diagnosis of the accountability and value of complex manufacturing systems. Furthermore, the information collected from these techniques will assist planning, control, and decision-making activities, and will provide insights into overall value improvement.

This paper is organized as follows: Sect. 1 provides an introduction to the background of this research. Section 2 presents a literature review of the work done in the domains of evaluation methods, decision-making under uncertainty, and fuzzy logic applications to technology selection. Section 3 describes the methodology of the proposed integrated method. During the design of the methodology, emphasis has been placed not only on the strategic/manufacturing strategy planning process, and company objectives, but also on its implications to information input/output requirements of the framework. In particular, assigning of performance variables and identification of different technologies available are described. Section 4 focuses on the most difficult problems that decision-makers encounter during the assessment process, such as the evaluation of subjective factors, the hierarchical relationship amongst the factors, the justification of financial factors, and the assessment of the impact of interactions amongst factors within the framework. Once the decision criterion has been established, fuzzy set theory is applied to represent the linguistic terms. Such a method enables decision-makers to tackle the ambiguities involved in the process of linguistic estimations. Section 5 summarizes recent related research and compares it with the proposed framework in this paper. Section 6 concludes this paper and recommends directions for future research.

2 Literature review

Due to intense global competition, AMT is considered a strategic resource for operational enhancement by securing an organization's competitive position within the international market. This competitive environment has renewed interest with regard to research on economic analysis and justification methods, which can be employed to assist companies in selecting appropriate technologies to fulfill their operational and business objectives. This section reviews various methods that have been widely adopted to assess the benefits of AMT.

The term "advanced manufacturing technology (AMT)" mainly refers to computer-aided technologies in design, manufacturing, transportation, and testing, etc. [12]. AMT affects the structure and organization of a supporting network. In other words, AMT changes the nature of tasks, the ways in which they are done, the interconnections, nature of physical and information flows, the skills required, management style and coordination, and the organizational structure.

Standard economic justification approaches can be used where the purpose is simply to replace old and worn-out equipment, even if some economic benefits usually considered are not available. For an integrated system, some level of flexibility, risk, and non-economic benefits are expected. When these intangible benefits are taken into consideration, analytic investment appraisal techniques are required. The analytic techniques are largely quantitative but more complex than the economic techniques, since they involve collecting more information and frequently consider uncertainty, multiple measures, and their effects. Finally, as systems approach seamless integration, clear competitive advantages and major increments in the firm's performance parameters are usually well-defined. In such cases, strategic approaches are needed to take these benefits into consideration, although tactical and economic benefits may arise as well. Strategic approaches tend to be less technical than the economic and analytic methods, but the former are frequently used in combination with the latter. The primary advantage of a strategic approach is its direct link to a firm's business goals and objectives.

Each of the above justification categories spans a number of approaches that can be broadly classified into three main categories; namely, economic justification approaches, analytic justification approaches, and strategic justification approaches, as summarized in Chan et al. [13]. In fact, AMT projects are usually capital-intensive and it is logical to assume that the ultimate decision or approval rests at the corporate level in the company. It is not surprising that these high-level managers are usually not well experienced in AMT, so inevitably, they are forced to make decisions based purely on a financial basis [14]. A survey of related literature [15–17] shows that there are uncertain features involved in the above economic evaluation methods, but they are mostly neglected by the decision-makers in order to reduce the complexity of the decision-making processes. Some research work reveals that conventional cost accounting cannot accurately measure the improvements in quality, flexibility, and other synergistic effects of AMT. They reflect the external reporting requirement rather than the reality of the AMT production environment [18, 19]. Indeed, if a company only applies traditional financial or economic justification to evaluate the AMT investment, some potential problems may arise, such as the following:

1. AMT induces a massive alteration to the operations of a company, which means the existing financial data are not sufficient to make an easy and rational decision.
2. Financial data may not be accurate and reliable so far as the current situation is concerned, since, in many circumstances, it can change very rapidly.
3. In handling multifaceted problems in investment, management requires far more sophisticated support than what could be provided by simple mathematical formulae.
4. There are many examples where the intangible benefits are extremely important and cannot be ignored.

In addition, many of the problems raised by the introduction of AMT are due to general ignorance about the strategic role of AMT. Excessive attention paid to technical development may not be enough for the adjustments needed in the organization to accommodate the technology. It is commonly claimed that investment in AMT can result in some strategic benefits. However, decision-makers always disregard this superiority because of the following reasons:

1. they sometimes consider such investments as operational or functional decisions rather than a strategic one [20],
2. they do believe that it is easier for monetary issues to generate an objective evaluation and that the situation becomes much more complicated when human resources or the personnel element is introduced in the analysis, and
3. strategic benefits are difficult to quantify in financial terms and the decision-making process requires a long-term perspective.

As a result, many new projects have been curtailed due to the fact that decision-makers came to their conclusion based solely on financial considerations [21]. Under these circumstances, an analytic evaluation method such as an analytic hierarchy process (AHP) could be applied to assess the non-financial (or intangible) aspects of AMT. The main reason for this is that AHP can capture more intangible information, and is also capable of handling other measures and effects. Through analytic evaluation, the company's situation can be reflected realistically, more factors and subjective judgements can be taken into account, and hence, the situation can be fully understood by knowledge managers or decision-makers [22]. The analytic hierarchy process [23] structures a complex decision into a hierarchy of elements. It then establishes shares of influence, or relative weights, among the elements through a sequential process of pair-wise comparisons. The pair-wise comparisons are based on judgments about relative differences among comparable elements. Consequently, the relative weights are combined in order to derive a single overall rating for each decision alternative. The advantages of using hierarchies are as follows: (i) they can describe how changes in priority at upper levels affect the priority of elements in lower levels; (ii) they provide more detailed information on the structure and activity of a system in the lower levels, and give an overview of the actors and their purposes in the upper levels; and (iii) natural decision-making systems assembled hierarchically, i.e., through modular construction and final assembly of modules, evolve much more efficiently than those assembled as a whole [24]. However, AHP also has several shortcomings. The major criticisms being: (i) the lack of a theoretical framework to model decision problems into a hierarchy; (ii) the use of subjective judgments in making pair-wise comparisons; (iii) the use of the eigenvector method for estimating relative weights, and (iv) the lack of formal treatment of risk [25].

Recent studies show that the manufacturing strategic map [26] can be used to simplify the strategic analysis. It is a set of plans and policies from which the manufacturing industry seeks to provide six kinds of manufacturing dimensions (i.e., cost, performance, quality, delivery, flexibility, and innovation) at target levels, to the rest of the organization. Thus, appropriate plans and policies are designed for some or all of the decision areas (i.e., production capacity, facilities, process technology, supplier relations, planning and control, measurement, work force, and quality and structure policies) within manufacturing. It shows precisely what the manufacturing function will provide (specific outputs at specific levels) to the rest of the organization and indicates how the manufacturing functions provide such outputs. For example, Persentili and Alptekin [27] proposed a manufacturing planning and control strategy based on a product flexibility measure. Efstathiadesa et al. [28] developed a framework by incorporating all of the planning procedures and implementation parameters to be followed, in order to ensure successful AMT adoption and implementation. Details of the manufacturing strategic map can be found in Sect. 3.2.

The theory of fuzzy sets is appropriate for dealing with sources of uncertainty or imprecision that is non-statistical in nature. Determining proper membership functions and choosing suitable set operators are often the key factors for successful application of fuzzy set models. When dealing with uncertainty, decision-makers may be provided with information characterized by vague language, such as high risk, low profit, and a significant degree of investment. By using such vague language, people are usually attempting to quantify uncertain events or objects [29, 30].

Many attempts have been made to apply the idea of fuzzy theory to the capital budgeting problem. Leung [31] studied project selection with fuzzy procedures. He constructed a criterion function, which has components of worth, cost, and risk in the function, and he assumed these three components to be linguistic variables. Values of the criterion function imply which alternative project is the most suitable for all required specifications. Ward [32] introduced fuzzy discounted cash flow analysis by computing deterministic or crisp values for cash flows and then transforming the results into symmetric triangular fuzzy numbers (TFN). Consequently, a fuzzy present worth and fuzzy internal rate of return is found. Buckley [33] studied fuzzy present value and fuzzy future value by assuming a cash amount, interest rate, and period of time to be fuzzy. He also discussed methods of comparing fuzzy net cash flows in order to rank fuzzy investment alternatives from the best to the worst. Chui and Chan [17] proposed models where cash flow and discount rate for each year are specified as triangular fuzzy numbers.

In order to overcome the difficulties associated with technology selection and justification, in this research work, a unified framework of AMT planning and justification is presented using the concepts of hierarchical structure analysis and fuzzy set theory. The framework takes an integrated approach, in which the AMT acquisition is modeled as an essential element in a process of building key manufacturing capabilities for a firm's long-term competitive positioning. Intangible benefits associated with AMT acquisition are explicitly considered and modeled as a set of manufacturing capability measures. Through the identification of strategic capability objectives, the most appropriate alternative technologies can be determined. The procedures of technology selection and justification are described in Sect. 3.

3 Methodology

3.1 Structure of the conceptual framework

Step 1. Form a committee of decision-makers, who come from different levels of the company –, a team of experts as well as stakeholders – to identify the manufacturing strategies and company objectives. The committee collects relevant internal and external information from diverse sources. This information can be an expressed need for automation to enhance performance or a manager's recommendation of an automation technology; or data from vendors about different technologies and the technologies adopted by competitors. All of this information can be treated as a means to determine whether or not the proposed investment is capable of assisting the organization to attain its goals. With the aid of a strategic evaluation tool called the "manufacturing strategic map" [26], the committee identifies various available technologies under each of the decision criteria. The details of strategic analysis are discussed in Sect. 3.2.

Step 2. Explode criteria hierarchically and classify them into subjective and objective criteria. Subjective criteria are those criteria characterized by linguistic assessments. Examples are flexibility, productivity, quality, etc. These linguistic assessments should be convertible into triangular fuzzy numbers through a rating scale. With regard to objective criteria such as economic factors, these are evaluated in monetary terms. These may include investment cost, operating expenses, etc., and are calculated using a fuzzy cash flow model. After the fuzzy cash flow is calculated, the fuzzy net present value of each technology can be determined. It should be mentioned that all financial data are specified as triangular fuzzy numbers, which represent "the most likely value," "the most pessimistic value," and "the most optimistic value." The calculated fuzzy net present value is then used to provide financial data for further analysis. Criteria evaluation is discussed in detail in Sect. 4.2.

Step 3. The weighting of each criterion can be obtained by either directly assigning a weight in triangular fuzzy numbers or indirectly using pair-wise comparisons. In this research work, it is suggested that the decision-makers should employ a proper linguistic scale (say "High," "Medium," and "Low") to evaluate the importance of criterion. The weightings can be assessed by requesting each decision-maker to weigh the criteria through a designed rating scale. Then, fuzzy reciprocal matrices of various criteria as well as subcriteria are constructed. The geometric row mean of each fuzzy reciprocal matrix is calculated. Then, the normalization of geometric row mean is obtained in order to indicate the importance, in terms of weighting, of each criterion, as well as each subcriterion and the appropriateness of technologies. All details are presented in Sect. 4.2 through a numerical example.

Step 4. Aggregate the weightings of criteria and fuzzy ratings of alternatives versus criteria with respect to all criteria. The fuzzy appropriate index of each technology can be obtained by standard arithmetic methods. The details of the calculation of the fuzzy appropriate index are discussed in Sect. 4.4.

Step 5. After calculating the fuzzy appropriate index, the next step is to determine the ranking value associated with each technology's fuzzy appropriate index. Details are shown in Sect. 4.5.

Step 6. Based on the ranking, the committee can easily make the preference selection. This is determined by the maximum or minimum of the ranking value. In addition, the decision-makers can include current technology in the evaluation process described. If the ranking values of new alternatives are not better than the ranking value of the present selection, new alternatives should not be selected. This is a simple "go" or "no-go" decision.

3.2 Strategic analysis

Manufacturing strategy is well-known and developed [34, 35]. It is a set of plans and policies from which manufacturing industry seeks to provide six types of manufacturing dimensions (i.e., cost, performance, quality, delivery, flexibility, and innovation) at a target level to the rest of the organization. The definition of each manufacturing dimension is shown in Table 1. All of these manufacturing dimensions can help the company build a suitable manufacturing strategy and hence a competitive advantage. They form crucial decision criterion

Table 1. Manufacturing dimensions and corresponding criteria

Manufacturing dimension	Definition	Criteria of each Manufacturing dimension
Cost of product	The labor cost, material cost, and other costs of producing a product.	- Product cost - Maintenance cost - High rate of return - Labor cost - Material cost
Product performance	Whether the product's design permits it to do more or better things than other products.	- Compatibility with existing machine - Worker morale - Productivity - Utilization - Machine breakdown - Human integration
Quality	Whether the materials and workmanship enhance the product value and increase its durability and reliability.	- Scrapped value - Rework - Conformance - Consistency
Delivery time and delivery time reliability	The time between order taking and delivery to the customer, and how close actual delivery is to any quoted or anticipated delivery date.	- Transportation - Customer services - Time scheduling - Delivery time - Inventory/work in process - Lead time
Flexibility	The manufacturer's ability to quickly change production volumes or product mix in response to the needs of customers.	- Design change accommodation - Change in product mix - Market responsiveness - Capacity growth - Routing and scheduling flexibility
Innovativeness	The capability to effectively introduce new products or product variations.	- Research and development - Introduce product variation

with regard to the selection of a suitable AMT. For this reason, a manufacturing strategic map is employed to determine the consistency between the proposed technology and the manufacturing strategy. Furthermore, it can also be applied to reveal the ability of an organization to exploit the new technology. With the assistance of this map, ambiguity at the strategic level can be effectively removed. After the decision-makers have considered the manufacturing dimensions and the decision areas in depth, these are combined to give a manufacturing strategic map as shown in Fig. 1. Each row of the manufacturing strategic map shows precisely what the manufacturing function will provide to the rest of the organization. Each column of the map indicates how the manufacturing function will provide these outputs. That is, decisions are made across a number of manufacturing decision areas.

When the company objectives and the six manufacturing dimensions have been identified using the manufacturing strategic map, it is necessary to decide the weighting factors of these six manufacturing dimensions with regard to the company's objectives. Each of the manufacturing dimensions is a composite criterion consisting of attributes, and this is illustrated in Table 1. However, companies' objectives vary in individual cases. For instance, one company may be highly concerned with research and development while another may emphasize the effect of an increase in product quality and manufacturing flexibility. Consequently, whenever a company plans to invest in a new technology, it has to determine its specific requirements for the new system.

4 Assessment of influencing factors and selection of appropriate technology

In order to demonstrate the proposed integrated approach, an example of AMT selection is presented. Tangible and intangible factors have been used in the example to show how this decision-making methodology can be employed effectively.

4.1 Identify available technologies and decision criteria (Step 1)

As mentioned in Sect. 3.2, the manufacturing strategies and different decision factors are clearly identified by the manufacturing strategy map. The factors are then exploded hierarchically and classified into subjective and objective criteria. A committee of decision-makers is responsible for assessing the suitability

Manufacturing dimensions		**Decision Areas**							
Current Level	12 Month Target	Capacity	Facilities	Process Technology	Suppliers	Control, Planning and Measurement	Labour Force Policies	Quality Policies	Organisational Structure
Cost									
Performance - feature									
Quality - warranty - rework									
Delivery time and delivery time reliability									
Flexibility - product range narrow - volume change									
Innovativeness									

Fig. 1. Manufacturing strategy map

of m alternatives $(A_1, A_2, \dots A_m)$ under each of the k criteria $(C_1, C_2, \dots C_k)$, and the importance of each criterion. Subjective criteria, such as quality and flexibility, are characterized by linguistic assessments. Objective criterion, however, are evaluated in monetary terms. For instance, investment cost, operating expenses etc., are calculated using a fuzzy cash flow model. Current technology can be assigned A_0 as a reference for comparison. It is assumed that a company needs to select an AMT to fulfill the company objectives. After the strategic planning phase, three alternative technologies A_1, A_2, and A_3 are left for further evaluation. A committee of decision-makers is formed to determine the most suitable technology. For the purposes of the example, a simplified assessment process is considered consisting of three selection criteria: flexibility (C_1), quality (C_2), and economy (C_3).

4.2 Criteria evaluation (Step 2)

4.2.1 Subjective criteria evaluation

Multi-criteria decision-making, particularly for technology selection, involves several subjective judgements by decision-makers or experts. Therefore, the concept of linguistic variables is very useful in dealing with situations that are too complex to be reasonably described in conventional quantitative expressions [1]. A linguistic variable is a variable whose values are words or sentences in natural or artificial language. Vague, fuzzy information may frequently be expressed in a linguistic (term) expression. Linguistic terms are mathematically inoperable. In order to cope with that difficulty, each linguistic term is associated with a fuzzy set or a composition of fuzzy sets, which represents the meaning of that linguistic term. The verbal terms used in our scales are in the universe $U = \{\text{Very high, High, Medium, Low, Very low}\}$. This universe of verbal terms may be appropriate to describe the reliability of a machine but certainly is not suitable for describing the distance of two places or two objects. Fortunately, our system does not confine itself to that universe. Rather, the universe can be adjusted to fit the nature of attributes used in a decision problem. For instance, if price is one of the attributes, the possible universe will be {Very expensive, Expensive, Fair priced, Cheap, Very cheap}. If size is one of the attributes, the possible universe will be {Very small, Small, Medium, Large, Very large}. Ultimately, the proposed standard scale system is capable of converting linguistic terms into fuzzy numbers in a systematic manner. These characteristics guarantee consistent translation of linguistic terms into fuzzy numbers. Furthermore, it should be noted that the linguistic values are utilized to assess the linguistic ratings given by decision-makers as well as the linguistic weights assigned to various selection criteria.

The weighting of each criterion can be obtained by either assigning weight directly or indirectly, using pair-wise comparisons. In this paper, it is suggested that the decision-makers employ a weighting set $W = \{\text{VL, L, M, H, VH}\}$, where VL = Very low, L = Low, M = Medium, H = High, VH = Very high, to evaluate the importance of the subjective criteria and subcriteria. The membership functions of the linguistic values in the weighting set W are then fixed, and the linguistic expressions will then be transformed into fuzzy numbers, attribute by attribute through a designed rating scale, as indicated in Table 2. The process is continued until all linguistic terms under every attribute have been converted to fuzzy numbers. The criteria, as stated in Sect. 4.1, are then classified into subjective criteria (i.e., flexibility and quality) and objective criteria (i.e., economic). The decision-makers employ a linguistic weighting set $W = \{\text{VL, L, M, H, VH}\}$, where VL = Very low, L = Low, M = Medium, H = High, VH = Very high, to evaluate the importance of the subjective criteria and subcriteria.

Table 2. Triangle fuzzy conversion scale

Verbal term	Linguistic scale	Triangle fuzzy scale
Very high	VH	$(3, 5, 5)$
High	H	$(1, 3, 5)$
Medium	M	$(\frac{1}{3}, 1, 3)$
Exactly equal	EQ	$(1, 1, 1)$
Low	L	$(\frac{1}{5}, \frac{1}{3}, 1)$
Very low	VL	$(\frac{1}{5}, \frac{1}{5}, \frac{1}{3})$

4.2.2 Objective criteria evaluation

In an engineering economic analysis, most decision problems involve the uncertainty feature of cash flow modeling. If sufficient objective data are available, probability theory is commonly used in modeling cash flows and performing decision analysis. However, a committee of decision-makers rarely has enough information to perform decision analysis, such that probabilities can never be known with certainty and the economic decision is attributable to many uncertain derivations. In this situation, most decision-makers rely on expert knowledge in the modeling of cash flows [17].

Expert knowledge is a collection of information and techniques that may be obtained from an expert's past experience in a specific problem domain. Along with the financial expert's knowledge, subjective probability distributions are extensively employed in estimating future cash flows. However, in an uncertain economic decision environment, an expert's knowledge about the cash flow information usually consists of a lot of vagueness instead of randomness. For instance, to describe the profit associated with a specific product, this may be implicitly forecasted from past incomplete information and the typical linguistic description "around one million" is often used. In order to deal with vague, imprecise, and uncertain financial data, cash flows are modeled using fuzzy numbers rather than crisp numbers. All data are specified as triangular fuzzy numbers such as "the most pessimistic value," "the most likely value," and "the most optimistic value." For example, an expert or decision-makers might give the most pessimistic, most likely, and most optimistic values of depreciation as \$90 000, \$100 000, \$110 000 respectively. Consequently, the depreciation cost can be represented by a triangular fuzzy number such as (\$90 000, \$100 000,

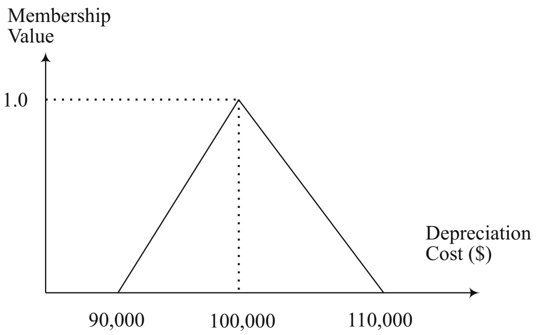

Fig. 2. A triangular fuzzy number of depreciation cost

\$110 000). In the same manner, other determining factors in the cash flows can also be modeled as a triangular fuzzy number (TFN). Figure 2 is an example of a triangular fuzzy number for the depreciation amount of technology m in year j. In many instances, the most pessimistic, most likely, and the most optimistic values of a triangular fuzzy number come from historical data.

4.2.2.1 Fuzzy cash flow analysis. As mentioned previously, the total cash flow model is usually applied in a capital investment project. However, when faced with uncertain or vague data, the use of a deterministic cash flow model is not necessarily a good method to assist decision-makers with day-to-day capital budgeting decisions. One alternative is to use a probabilistic cash flow model. However, it typically requires a great amount of time and effort with regard to gathering data to obtain representative means, variances, and distributions. Therefore, a fuzzy cash flow model is presented in this section by using fuzzy set theory to cope with uncertain data. The equation for the total cash flow model is stated below:

$$X_{mj} = (G_{mj} - C_{mj}) - (G_{mj} - C_{mj} - D_{mj})T_m - K_m + L_{mj} + V_{mj} \quad (1)$$

where X_{mj} is the net total cash flow of technology m at the end of year j, G_{mj} is the revenue of technology m at the end of year j, C_{mj} is the operating expenses of technology m at the end of year j, D_{mj} is the depreciation amount of technology m in year j, T_m is the tax rate of technology m, K_m is the investment cost of technology m, L_{mj} is the salvage value received in year j, and V_{mj} is the incremental tax credit of technology m in year j.

After the fuzzy cash flow is calculated, the net present value of technology m can be determined by the following equation:

$$\text{NPV}_m = \sum_{n=0}^{j} \frac{X_{mj}}{(1+i)^n} \quad (2)$$

where NPV_m is the net present value of technology m, i is the discount rate, and j is the life of a project.

4.2.2.2 Fuzzy weightings determination of objective criteria. In order to ensure compatibility between the fuzzy total cost of objective criteria and linguistic ratings of subjective criteria, the fuzzy total cost must be converted into dimensionless indices. The alternative technologies with the maximum NPV should have the maximum rating. Based on the principle stated previously, the fuzzy weightings of alternative technology m versus objective criterion can be determined by normalizing their values.

To evaluate the objective criterion in our example, the decision-makers of the committee assess the fuzzy cash flow associated with alternative technologies A_1, A_2, and A_3 in order to calculate the fuzzy net present value. Before building the models for fuzzy total cash flow analysis, two key assumptions are stated:

1. The depreciation amount of technology m in year j (D_{mj}) is calculated by a straight-line method.
2. The salvage value of technology m is assumed to be zero.

Equation 1 will be used to compute fuzzy yearly cash flows of the project and can be rewritten as below:

$$X_{mj} = (1-T_m)G_{mj} - (1-T_m)C_{mj} + D_{mj}T_m - K_m + L_{mj} + V_{mj} \quad (3)$$

For ease of calculation, each term in Eq. 3, $(1-T_m)G_{mj}$, $(1-T_m)C_{mj}$, $D_{mj}T_m$, K_m, L_{mj}, and V_{mj} will be calculated first using fuzzy operations and eventually combined to obtain fuzzy yearly cash flows. Going back to the example, the calculation of annual cash flows for technology A_1 is shown below.

At the end of Year 0,
$G_{10} = (0, 0, 0) \quad \Rightarrow \quad (1-T_1)G_{10} = (0, 0, 0)$
$C_{10} = (0, 0, 0) \quad \Rightarrow \quad (1-T_1)C_{10} = (0, 0, 0)$
$D_{10} = (0, 0, 0) \quad \Rightarrow \quad D_{10}T_1 = (0, 0, 0)$
If $K_{10} = (57\,000, 60\,000, 63\,000)$, by Eq. 3,
$X_{10} = (-63\,000, -60\,000, -57\,000)$.

At the end of Year 1,
$G_{11} = (47\,500, 50\,000, 52\,500)$
$C_{11} = (14\,250, 15\,000, 15\,750)$
$D_{11} = (19\,000, 20\,000, 21\,000)$
$K_{11} = (0, 0, 0)$
By Eq. 3,
$$X_{11} = (47\,500, 50\,000, 52\,500)(1-0.4) - (14\,250, 15\,000, 15\,750)(1-0.4) + (19\,000, 20\,000, 21\,000)(0.4)$$
$X_{11} = (26\,650, 29\,000, 31\,350)$.

The cash flow of Year 2 and Year 3 will be the same as Year 1. By using similar techniques, the cash flow for technologies A_2 and A_3 can be calculated as well. Using Eq. 2, the fuzzy net present value of technology A_1 can be determined as:

$$\begin{aligned}\text{NPV}_{A1} &= (-63\,000, -60\,000, -57\,000) \\ &\quad + \frac{(26\,650, 29\,000, 31\,350)}{(1.12, 1.12, 1.12)^1} \\ &\quad + \frac{(26\,650, 29\,000, 31\,350)}{(1.12, 1.12, 1.12)^2} \\ &\quad + \frac{(26\,650, 29\,000, 31\,350)}{(1.12, 1.12, 1.12)^3} \\ &= (1008.8, 9653.11, 18\,297.41)\end{aligned}$$

After the fuzzy net present value of each alternative technology is obtained, the fuzzy weightings are determined by normalizing their values. It should be stressed here that the fuzzy weightings of subjective or objective criteria are used to calculate the fuzzy appropriate indices for further determination of the ranking order of technologies.

4.3 Fuzzy reciprocal matrices and geometric row means (Step 3)

When a given decision-making group evaluates the set of alternative technologies $(A_1, A_2, \ldots A_m)$ against the set of criteria $(C_1, C_2, \ldots C_k)$, a rating matrix can be constructed with alternatives along one axis and factors on the other. Thereafter, a fuzzy reciprocal matrix of different criteria as well as subcriteria is formed. The elements of the fuzzy reciprocal matrix are such that products of each upper triangle element with its corresponding lower triangle element should be approximately equal to one. Table 3a is an example to show the fuzzy reciprocal matrix of relative importance of various criteria C_1, C_2, C_3 in our AMT selection example.

Subsequently, the normalization of the geometric row mean is obtained in order to indicate the importance in terms of weighting of each criterion, as well as the subcriterion and appropriateness of technologies. Let W_{mk} be the weight of technology A_m versus criterion C_k, W_k be the weight of criterion C_k, and a_{ij} be the element of fuzzy reciprocal matrix. Geometric row mean is given by Eq. 4:

$$r_i = (a_{i1} \otimes a_{i2} \otimes a_{i3} \otimes \ldots \otimes a_{ik})^{\frac{1}{k}} \tag{4}$$

The normalized geometric row mean is determined using Eq. 5:

$$W_k = r_i \varphi(r_1 \oplus r_2 \oplus r_3 \oplus \ldots \oplus r_k) \tag{5}$$

Using Eqs. 4 and 5, the geometric row means of fuzzy reciprocal matrices are normalized, thus allowing the fuzzy weightings for to allow decision-makers to determine their opinion. An example illustrating the calculation of the geometric row means of C_1, C_2, and C_3 and the corresponding weightings W_1, W_2, and W_3 is shown in Tables 3b and c. All other factors can be followed by adopting the same method. In other words, the fuzzy weightings of various criteria and subcriteria can be determined.

4.4 Fuzzy appropriate index (Step 4)

As described in Sects. 4.1 to 4.3, the weights of the criteria and the weights of the alternative with respect to each criterion are computed using pair-wise comparisons. Let W_{mk} be the weight of technology A_m versus criterion C_k, and W_k be the weight of criterion C_k. Aggregate the hierarchy by the corresponding products W_{mk} and W_k over all the criteria. The fuzzy appropriate index FAI_m of the mth alternative technology can be obtained by the standard arithmetic method, as follows:

$$\mathrm{FAI}_m = \left(\frac{1}{k}\right) \otimes [(W_{m1} \otimes W_1) \oplus (W_{m2} \otimes W_2) \oplus \ldots \oplus (W_{mk} \otimes W_k)] \tag{6}$$

Table 3. Calculations of geometric row means of C_1, C_2, and C_3, and fuzzy weightings of W_1, W_2, and W_3

	C_1	C_2	C_3
C_1	(1, 1, 1)	$\left(\frac{1}{5}, \frac{1}{3}, 1\right)$	(1, 3, 5)
C_2	(1, 3, 5)	(1, 1, 1)	(3, 5, 5)
C_3	$\left(\frac{1}{5}, \frac{1}{3}, 1\right)$	$\left(\frac{1}{5}, \frac{1}{5}, \frac{1}{3}\right)$	(1, 1, 1)

(**a**) Fuzzy reciprocal matrix of relative importance of various criteria C_1, C_2, and C_3

	C_1	C_2	C_3
C_1	(1, 1, 1)	$\left(\frac{1}{5}, \frac{1}{3}, 1\right)$	(1, 3, 5)
Geometric row mean, r_1	$\left\{\left(1 \times \frac{1}{5} \times 1\right)^{\frac{1}{3}}, \left(1 \times \frac{1}{3} \times 3\right)^{\frac{1}{3}}, (1 \times 1 \times 5)^{\frac{1}{3}}\right\} = (0.59, 1.00, 1.71)$		
C_2	(1, 3, 5)	(1, 1, 1)	(3, 5, 5)
Geometric row mean, r_2	$\left\{(1 \times 1 \times 3)^{\frac{1}{3}}, (3 \times 1 \times 5)^{\frac{1}{3}}, (5 \times 1 \times 5)^{\frac{1}{3}}\right\} = (1.44, 2.47, 2.92)$		
C_3	$\left(\frac{1}{5}, \frac{1}{3}, 1\right)$	$\left(\frac{1}{5}, \frac{1}{5}, \frac{1}{3}\right)$	(1, 1, 1)
Geometric row mean, r_3	$\left\{\left(\frac{1}{5} \times \frac{1}{5} \times 1\right)^{\frac{1}{3}}, \left(\frac{1}{3} \times \frac{1}{5} \times 1\right)^{\frac{1}{3}}, \left(1 \times \frac{1}{3} \times 1\right)^{\frac{1}{3}}\right\} = (0.34, 0.41, 0.69)$		
$r_1 \oplus r_2 \oplus r_3 = (2.37, 3.88, 5.32)$			

(**b**) Calculations of geometric row means of C_1, C_2, and C_3

Fuzzy weighting of each criterion, W_k	$W_k = r_i \varnothing (r_1 \oplus r_2 \oplus r_3 \oplus \ldots \oplus r_k)$
W_1	$\left(\frac{0.59}{5.32}, \frac{1.00}{3.88}, \frac{1.71}{2.37}\right) = (0.11, 0.26, 0.72)$
W_2	$\left(\frac{1.44}{5.32}, \frac{2.47}{3.88}, \frac{2.92}{2.37}\right) = (0.27, 0.64, 1.23)$
W_3	$\left(\frac{0.34}{5.32}, \frac{0.41}{3.88}, \frac{0.69}{2.37}\right) = (0.06, 0.11, 0.29)$

(**c**) Calculations of factors W_1, W_2, and W_3

When the fuzzy appropriate index of the mth alternative technology is computed, the next step is to rank these index values to determine the most appropriate alternative technology.

4.5 Ranking the final ratings (Step 5)

Traditionally, MCDM solution methods assume all decision data are crisp numbers, with the performance ratings being aggregated into a final rating score. As a result, the alternative with the highest score is typically the preferred choice by the decision-makers.

In reality, the alternative performance rating can be crisp, fuzzy, and/or linguistic. When fuzzy data are incorporated into the MCDM problem, the final ratings are no longer crisp numbers; they are fuzzy numbers. Since a fuzzy number represents many possible real numbers that have different membership values, it is not easy to compare the final ratings to determine preferred alternatives. In other words, fuzzy numbers do not always yield a totally ordered set as real numbers do. When the final ratings are fuzzy, it is very difficult to distinguish the best possible course of action from the mediocre ones, or even the worst one.

For ease of implementation in problem-solving, Chui and Chan's [17] method, or Kaufmann and Gupta's [36] method can be used to rank the final ratings. In fact, other ranking methods can be employed, but these two are used here in order to show how to finalize the decision. The fuzzy appropriate indices of the m alternatives, which are described in Sect. 4.4, are represented by triangular fuzzy numbers (X, Y, Z).

4.5.1 Chui and Chan's method

Chui and Chan [17] suggest the ranking method using Eq. 7:

$$\text{Ranking value} = \frac{(X+Y+Z)}{3} + wY \tag{7}$$

The alternative with the largest ranking value is the most preferred value. They also suggested that the weight w should be between 0.1 and 0.3 depending upon whether or not the "most possible value" of fuzzy appropriate index, Y, is considered to be very important. If the "most possible value" is very important, 0.3 is suggested, and 0.1 is suggested if it is not.

4.5.2 Kaufmann and Gupta's method

Kaufmann and Gupta [36] recommended three criterions in determining the best preference alternative as follows:

- Compare the ranking values:

$$\text{Ranking value} = \frac{(X+2Y+Z)}{4} \tag{8}$$

- Compare the most probable value Y.
- Compare the range $X-Z$.

Fuzzy appropriate indices are first compared by the ranking values. The largest ranking value means the best alternative technology. However, if there are two fuzzy appropriate indices having the same ranking value, the value of Y will be used as the second criterion. A larger Y indicates a better alternative. Finally, if the ranking value and the most probable value (Y) are the same again, the last criterion will be used by comparing the range $X-Z$. The project with the largest $X-Z$ is preferred.

4.6 Selection of alternatives (Step 6)

After determination of the fuzzy appropriate index, the alternative technologies are ranked using the methods described in Sect. 4.5. The one with the highest or lowest value (depending on which ranking method is used) is the best choice among the alternatives. However, it should be further compared with the existing technology approach in order to decide whether this alternative choice is preferred. In other words, this step acts as a "go" or "no-go" gauge.

One point should be noted here. Since no control experiment can be set from past research, the proposed method can only be demonstrated as above. There is no comparison with other methods available. However, the benefits of the proposed method, which is to integrate various justification methods, can be shown through the above AMT selection example.

5 Recent related works

Traditional financial justification methods are major decision tools to justify investments of AMT selection. Sohal et al. [37] conducted a survey to examine planning and implementation activities relating to AMT investment in South Africa. Results indicated that this payback evaluation technique was more frequently used for investment selection and evaluation. Another survey that was conducted by Orr [38] also concluded that US respondents were found to predominantly utilize financial evaluation techniques in planning and implementing AMT. As mentioned previously, the evaluation of AMT investment is a MCDM problem involving both tangible and intangible attributes. This proposition can be verified by another survey that was conducted by Saleh et al. [39]. They concluded from the findings of their survey that "a quantitative, systematic multi-criteria decision process that incorporates both tangible and intangible attributes can be used to evaluate competing alternatives."

Although intangible factors play a vital role in the AMT selection process, not all reported research in this area has taken intangible factors into consideration. For example, Verter and Dasci [40] presented an integrated mixed integer nonlinear programming model to identify the minimum cost for facility location, capacity acquisition, and technology selection decisions. Although this model integrated different aspects of technology selection, all factors were represented by cost. The implications are that only those factors that can be quantified as costs were considered. Bokhorst et al. [41] also employed a mixed integer programming model to determine the optimal investment sequence and timing of investments in new CNC machine tools. The assessment is solely based on maximization of NPV. The authors concluded that intangible factors need to be considered into the final decision.

Real option valuation technique is another financial tool that was employed in evaluating AMT investment [50]. Real option terminology is borrowed from the financial options model. The value of a real option is derived from the present value of the cash flows of the optional or contingent project, less the present value of the investment required to exercise the option. The real option valuation technique is better than a purely financial technique like payback period analysis because the former takes strategic options into considerations. However, MacDougall and Pike [42] argue that the real option valuation technique is often only vaguely defined at the adoption stage and frequently manifests itself during implementation of AMT. They determined through a case study approach that option value was lost during implementation of AMT due to the occurrence of misalignments and the adaptations of managers and plant floor workers.

The authors stressed that selection and implementation of AMT needs to be thoughtfully planned, and implementation should be carefully managed, with the benefits tending to be intangible and hard to quantify.

When strategic factors (most of them intangible in nature) are taken into consideration, the decision model becomes complex since quantification of such intangible factors is not easy. AHP is a popular analytical tool to solve problems that involve intangible factors. Yusuff et al. [43] studied the potential use of AHP to help organizations in planning the AMT implementation process. They concluded that the ability of AHP to model multi-attribute problems is appropriate for the AMT implementation process, despite the limitation of AHP with regard to subjection priority and evaluation weightings. Mohanty and Deshmukh [44] proposed a framework that utilizing AHP for analyzing a firm's justification problem in AMT investment, and validated the framework in a case example.

Data envelope analysis (DEA) is another analytical tool that can help decision makers consider intangible factors in AMT selection problems. DEA is a mathematical programming technique that evaluates the relative efficiencies of a homogeneous set of decision-making units in the presence of multiple inputs and outputs. Talluri et al. [45] made use of DEA and nonparametric statistical procedures for the selection of flexible manufacturing systems (FMS). Talluri and Yoon [46] applied a modified version of DEA – namely, cone-ratio DEA – in analyzing the AMT selection process. Their research has taken intangible factors into consideration in the proposed model.

AHP and DEA are techniques that could be adopted for the selection of AMT technology with consideration of intangible factors. However, these analytical tools overlook the importance of tangible factors. Therefore, there is a need to integrate both intangible and tangible factors together in the decision-making process. Punniyamoorthy and Ragavan [47] used AHP to measure the subjective factors in the justification of AMT selection and used effective cost, which involves those costs the organization would like to maximize, such as profits and revenues, to measure objective factors. Chiadamrong and O'Brien [48] proposed a decision support tool that has been designed to use an integrated approach to assist decision makers in choosing the best alternative manufacturing and production systems in a given situation. It can be seen that an integrative approach to solve AMT selection problems is more appropriate since both tangible and intangible factors can be considered together. To make the decision process more realistic, uncertain or imprecise information should be taken into account as well. Fuzzy logic is a tool to deal with problems that involve vagueness. Karsak [49] developed a distance-based fuzzy MCDM framework for the selection of FMS from a set of alternatives. Triangular fuzzy numbers are employed to represent vague information. However, the author ignores cash flow in the model developed.

This summary of related research indicates that past research in the selection of AMT is polarized into two extremes: one of them is to consider financial factors only and the other is to consider intangible factors by utilizing analytical models like AHP and DEA to come up with a decision. Although some researchers have attempted to develop an integrated model to consider both tangible and intangible factors, they do not take uncertainty or vague information into account. This is the motivation of this research, which is to suggest a model that can integrate both tangible and intangible factors and, at the same time, take into account uncertainty and ambiguity in the AMT investment decision through the application of fuzzy theory.

6 Conclusions and recommendations for future research

In many real-world problems, not all of the decision data can be precisely assessed. When information is easily measurable or accessible, the information should be coded in crisp (real) numbers. For those data that cannot be precisely obtained or is too costly to assess, fuzzy numbers are used to denote them. Fuzzy set theory makes it possible to incorporate unquantifiable information, incomplete information, non-obtainable information, and partially ignorant facts into the decision model.

This paper proposes a systematic and an integrated approach to the technology selection and justification problem by using the concepts of fuzzy set theory and hierarchical structure analysis. An analytic hierarchy process (AHP) is employed to classify the technology selection criteria into two categories (i.e., subjective and objective) and to identify the relative weights among these aspects through a sequential process of pair-wise comparisons.

To evaluate subjective criteria, vague or uncertain information is expressed in a linguistic expression. Subsequently, all of the linguistic expressions are transformed into fuzzy numbers, attribute by attribute, under the designed conversion scale. The process continues until all linguistic terms under every attribute have been converted into fuzzy numbers, with fuzzy cash flow analysis being applied to justify the objective (e.g., economic) criterion. All the imprecise financial data are modeled as fuzzy numbers, which represent "the most pessimistic value," "the most likely value," and "the most optimistic value." After the subjective and objective criteria are evaluated, the fuzzy weightings of each criterion are calculated and the alternative technologies are ranked.

The advantages of this new approach over the existing ones are as follows:

1. Traditional capital budgeting analysis is not capable of solving the financial data, which consists of vague, imprecise, and uncertain features. The proposed approach in this study can alleviate such difficulties.
2. In technology selection, the usual assessment of alternative technologies with regard to criteria and their associated weighting are expressed in linguistic terms. Conventional approaches, both deterministic and stochastic, tend to be less effective in conveying the imprecision or vagueness of the linguistic assessment. By using the concepts of fuzzy numbers and linguistic variables, the objective and subjective factors are evaluated in such a manner that the viewpoints of an

entire decision-making body can be expressed with minimal constraints.

3. The proposed approach allows multiple criteria decision-making problems to take data in the form of linguistic terms, fuzzy numbers, and/or crisp numbers. This facilitates more realistic decision models compared to those generated using existing methods to be created.
4. Triangular fuzzy numbers are mathematically easy to implement in comparison to trapezoidal fuzzy numbers and the mathematical computations are reduced. The easy-to-use and easy-to-understand characteristics of this new approach provide a valuable evaluation tool for management and system analysts.

Some research areas that require special attention in the future have been identified. In a decision process, conflict, uncertainty, fuzziness, imprecision, and randomness simultaneously exist. Due to its complex nature, research on searching and solving stochastic fuzzy mathematical programming and multiple criteria decision-making problems is suggested. Secondly, since the proposed area is generic enough for other decision-making processes, applications of the proposed algorithm to other business or engineering problems are encouraged. Finally, ranking approaches are very important to solve fuzzy or imprecise attributes and constraints. It is worth noting that even though most of the existing ranking methods are not perfect, they have shown the process of human efforts to find ways of solving problems. There are always some benefits produced by each method. Recognizing and continuing the effort in improving these methods is necessary. Flawless ranking methods may possibly be obtained by combining some of the good points of each of these methods into one algorithm. In this connection, searching for better ranking methods is urgently needed to solve fuzzy or imprecise constraints and other problems.

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