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Fuzzy Logic in Decision Support: Methods, Applications and Future Trends

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Abstract

During the last decades, the art and science of fuzzy logic have witnessed significant developments and have found applications in many active areas, such as pattern recognition, classification, control systems, etc. A lot of research has demonstrated the ability of fuzzy logic in dealing with vague and uncertain linguistic information. For the purpose of representing human perception, fuzzy logic has been employed as an effective tool in intelligent decision making. Due to the emergence of various studies on fuzzy logic-based decision-making methods, it is necessary to make a comprehensive overview of published papers in this field and their applications. This paper covers a wide range of both theoretical and practical applications of fuzzy logic in decision making. It has been grouped into five parts: to explain the role of fuzzy logic in decision making, we first present some basic ideas underlying different types of fuzzy logic and the structure of the fuzzy logic system. Then, we make a review of evaluation methods, prediction methods, decision support algorithms, group decision-making methods based on fuzzy logic. Applications of these methods are further reviewed. Finally, some challenges and future trends are given from different perspectives. This paper illustrates that the combination of fuzzy logic and decision making method has an extensive research prospect. It can help researchers to identify the frontiers of fuzzy logic in the field of decision making.

Keywords: fuzzy logic, intelligent decision making, cognitive complex information.

1 Introduction

The rapid development of social economy and technology brings complexity and difficulty in modern decision making. In the era of big data, the immense volume of data with complex structures poses a challenge to decision-makers (DMs). Intelligent decision-making, which supplies active decision support through proper integration of artificial intelligence techniques, has growing influence in many fields, such as logistics outsourcing [45], manufacturing [12], health care [94], negotiation pricing [29], etc. The application of intelligent decision making realizes a high level of human-machine cooperation in problem solving, which uses machines to mimics human thought processes.

Most of the conventional approaches to knowledge representation were based on bivalent logic that is the foundation of logic in intelligent decision making and software development. However, in realistic problems, DMs must make critical decisions with vague and imprecise information that are not fully reliable, it is difficult to represent such uncertain information in the form of numerical values. As bivalent logic is intolerant of imprecision and partial truth, human perception is unreasonable to be expressed by bivalent logic or some complicated computer programs. To overcome this limitation, fuzzy set [132] was proposed to depict the vagueness in the decision making process and has been widely applied in areas including decision support systems [54], machine learning [116], pattern recognition [112], etc. The original fuzzy set (called type-1 fuzzy set) determines the membership of an element by numbers in the range [0,1]. Considering situations where the membership grade is also uncertain, the type-2 fuzzy set was introduced to represent uncertainty by a membership function [49].

Since DMs prefer to express their assessments with natural language, linguistic variables that contain a lot of words and sentences were introduced as a flexible way to model subjective information. For example, the value of the variable Age is taken from the label set: very young, young, not young, old, etc., rather than the numerical values 20, 25, 30, 40, etc. The linguistic characterizations play the same role as the numerical ones in the decision making process. Although the former is generally less specific than the latter [135], the linguistic variables are more in accordance with people's descriptive conventions. As the proper processing of linguistic information is vital for making intelligent, informative, and reasonable decisions, fuzzy logic that offers better capabilities to handle linguistic uncertainty was put forward [133, 134, 135]. It employs fuzzy sets to model the uncertainties associated with the information described in natural language. As an extension of classical logical systems, fuzzy logic provides a conceptual framework for knowledge representation under uncertainty and imprecision. It is not a replacement for conventional methods of numerically-based computing, but an additional tool that can significantly enhance the ability of decision-making methods to deal with real-world problems. Developments in other theories such as possibility theory [24], evidence theory [48] further reveal the advantages of methods based on fuzzy logic. Moreover, in terms of computing speed and related accuracy, machine computing based on fuzzy logic has a competitive advantage over linear algebra-based methods. Since introduced by Zadeh, there have been a large number of contributions focusing on the application of fuzzy logic in various areas. For example, a series of research [3, 22, 27, 66, 92] gives power engineers a sight into how the concept of fuzzy logic can be applied to solve some long-standing power system problems.

With the rapid development of information technology, intelligent decision making requires support relying on computational algorithms that can realize brain-like computing. During the last decade, there has been an explosion of interest and a significant growth of applications of fuzzy logic in decision-making. This paper aims to offer a systematic review of fuzzy logic and its applications in decision support during the period from 2010 to 2020. To do so, we start our presentation by introducing the original definition of fuzzy logic. Different types of fuzzy logic systems are further reviewed. Combined with fuzzy logic, decision-making methods are summarized from four angles, i.e., evaluation methods, prediction methods, decision support algorithms, and group decision making methods. In these four categories, a lot of methods with their primary ideas are overviewed. After that, real-world applications are discussed in relevant areas, including performance evaluation, healthcare management, etc. Finally, the current challenges with fuzzy logic applications in decision support are outlined, and based on this, the future trends are presented to guide the development of decision-making methods based on fuzzy logic.

This paper is organized as follows: Section 2 reviews some preparatory knowledge of fuzzy logic.

Section 3 focuses on the basic structure of the fuzzy logic system in the decision making process. In Section 4, fuzzy logic-based methods are presented in detail. The applications to decision making with fuzzy logic-based methods are summarized in Section 5. Some discussions about current challenges and future directions are provided in Section 6. This paper ends up with some conclusions in Section 7.

2 What is fuzzy logic?

Most semantics of classical logic are bivalent, which means that all possible propositional representations are classified as true or false. In reality, human decision making includes a range of possibilities between true or false, such as certainly true, possibly true, possibly false, certainly false, etc. As classical logic cannot deal with ambiguous information expressed in natural language, fuzzy logic was proposed to model such imprecise modes of reasoning. It is reasonable to describe the truth of any statement as a matter of degree in realistic decision making. For example, when evaluating a product, we might say that the price of this product is expensive. The variable, 'expensive', maps to ranges of values. Then, fuzzy logic lays a foundation for approximate reasoning in which the 'truth' values and the rules of inference are fuzzy rather than precise [12, 26], using techniques from fuzzy set theory. Over the past decade, most research in decision-making has emphasized the use of fuzzy logic. In what follows, we present some basic ideas underlying different types of fuzzy logic.

2.1 Linguistic variable

Fuzzy logic treats truth as a linguistic variable that is formally defined as a 5-tuple (H, $T(H)$, U, G, M) [131] in which

- H denotes the name of the variables,
- $T(H)$ denotes a finite term set of linguistic values of H,
- U is a universe of discourse,
- G is a syntactic rule for generating the terms in $T(H)$ and
- M is a semantic rule to map terms in $T(H)$, $M(X)$ represents a fuzzy subset of U.

Figure 1 shows an example of the linguistic variable 'Price' [38], whose linguistic term set is $T(Price) = VeryLow, Low, Medium, Expensive, VeryExpensive$. It is clear to see how the semantic rule associates the linguistic terms to a fuzzy subset $M(X)$.

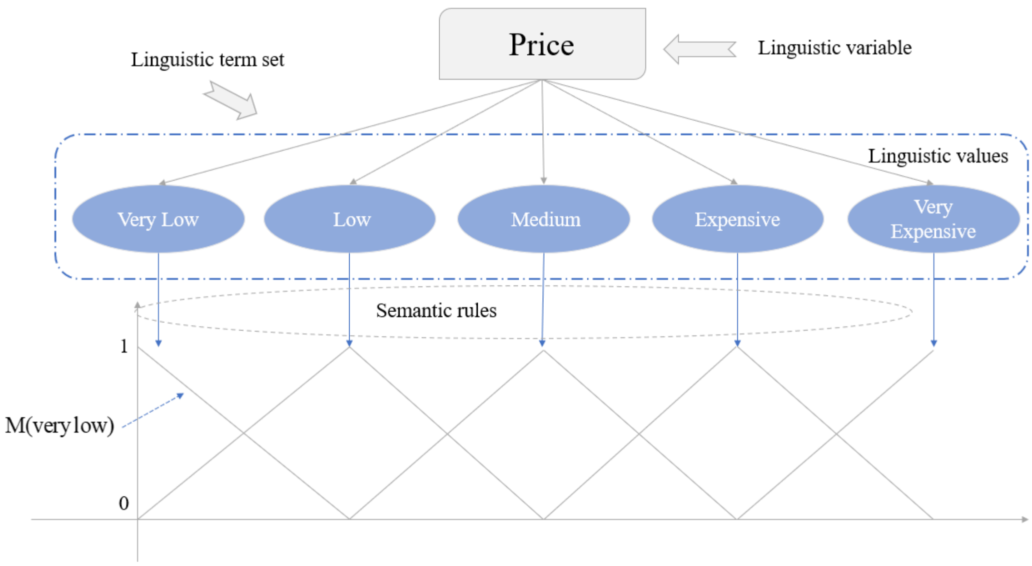


Figure 1: The linguistic variable "Price"

The tight relationship between linguistic variables and fuzzy set theory has been intensively investigated [71, 110, 111, 133, 134, 135]. There is also a large volume of published studies describing the role of linguistic variables in intelligent decision making [85, 86, 121]. In cooperation with clinic experts, the knowledge base of the decision support system was described in terms of linguistic variables, linguistic values, and membership functions [44]. A decision-making system utilized linguistic variables to express evaluations of alternatives [80]. The fuzzy inputs and outputs in a decision support system for variable rate irrigation were defined as linguistic variables [98]. In a word, as a significant and useful tool to manage uncertainty, linguistic variables provide a direct way to model quantitative information in the decision making process.

2.2 Type-1 fuzzy logic

The type-1 fuzzy set was introduced by Zadeh [135], the membership function of which takes a value in the interval [0, 1]. It can be described as a set of ordered pairs of elements and the membership degrees of elements to the set. The mathematical form for type-1 fuzzy set in the universe X was defined as:

$$A = \{(x, \mu_A(x))|x \in X\} \tag{1}$$

where $\mu_A(x)$ is the membership function and satisfies $\mu_A(x) : X \to [0, 1]$. The type-1 fuzzy set is used to calculate intermediate values between the crisp values associated with completely true or completely false [70]. Type-1 fuzzy logic is to study the validity of fuzzy reasoning based on the type-1 fuzzy set. Figure 2 illustrates the general structure of the type-1 fuzzy logic system [70].

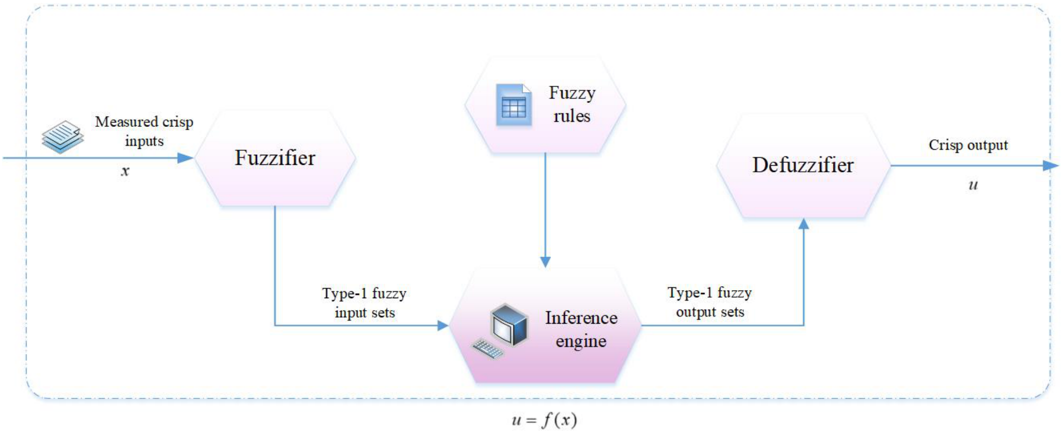


Figure 2: The structure of the type-1 fuzzy logic system

A great deal of research on type-1 fuzzy logic has been carried out in various fields. For example, by using genetic algorithms as an unsupervised learning method, an intelligent fuzzy logic controller was constructed. The optimal rules of this fuzzy logic controller can be designed without human operators' knowledge [43]. Combining the idea from type-1 fuzzy logic with the neural network structure, a general decision network for medical diagnosis was automatically developed according to learning some training examples [61]. Taking the cross-layer parameters' dispersion as inference system inputs, a fuzzy logic-based routing algorithm was put forward to get the most balanced performance in the next hop relay node selection [57]. During the past decades, type-1 fuzzy logic has found a variety of applications because bringing type-1 fuzzy logic to classical methods can provide more promising approaches.

2.3 Type-2 fuzzy logic

Although type-1 fuzzy logic has laid a foundation for approximate reasoning, it is unreasonable to utilize an accurate membership function in some cases [60]. Thus, the type-2 fuzzy set was proposed and discussed, which can provide better capabilities to deal with the uncertainty and ambiguity of linguistic information [13]. Based on Zadeh's ideas, the mathematical form of the type-2 fuzzy set was defined as follows [70]:

$$\widetilde{A} = ((x, u), \mu_{\widetilde{A}})|\forall x \in X, \forall u \in J_x \subseteq [0, 1] \tag{2}$$

where $\mu_{\widetilde{A}}(x,u)$ is a type-1 fuzzy set and satisfies $0 \leq \mu_{\widetilde{A}}(x,u) \leq 1$. In addition, J_x represents the primary membership degree of x and $\mu_{\widetilde{A}}(x,u)$ denotes the secondary membership degree. It can be seen that the primary membership degree of a type-2 fuzzy set can be any subset in [0, 1]. Corresponding to each primary membership degree, there is a secondary membership degree that indicates the possibility for the primary membership degree can also be in [0, 1]. When $\mu_{\widetilde{A}}(x,u) = 1, \forall u \in J_x \subseteq [0,1]$, the membership functions of interval type-2 fuzzy set can be derived [33], which were denoted as $\bar{\mu}_{\widetilde{A}}$ and $\underline{\mu}_{\widetilde{A}}$. Especially, $\bar{\mu}_{\widetilde{A}}$ represents the upper membership function and $\underline{\mu}_{\widetilde{A}}$ represents the lower membership function. The uncertainty is described by a region (as shown in Figure 3).

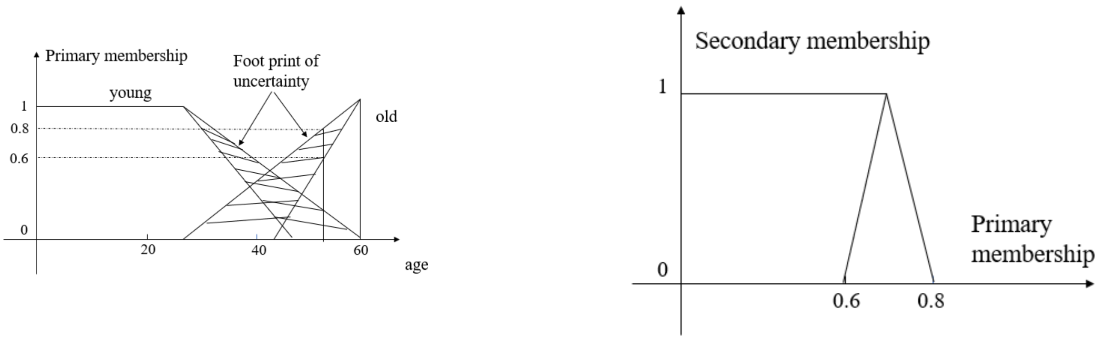


Figure 3: Type-2 fuzzy set

The interval type-2 fuzzy set assumes a constant secondary membership degree, which can effectively avoid evaluating multiple values. Most of the type-2 fuzzy sets have been currently implemented as interval type-2 fuzzy sets, which are more comprehensible and have lower computational complexity. In dealing with fuzzy information, the type-2 fuzzy set provides a significant improvement on the type-1 fuzzy set. When the degree of uncertainty increases, type-2 fuzzy logic can solve complex problems that cannot be solved by type-1 fuzzy logic. The relationship between uncertainty degree, information, and fuzzy techniques is presented in Figure 4.

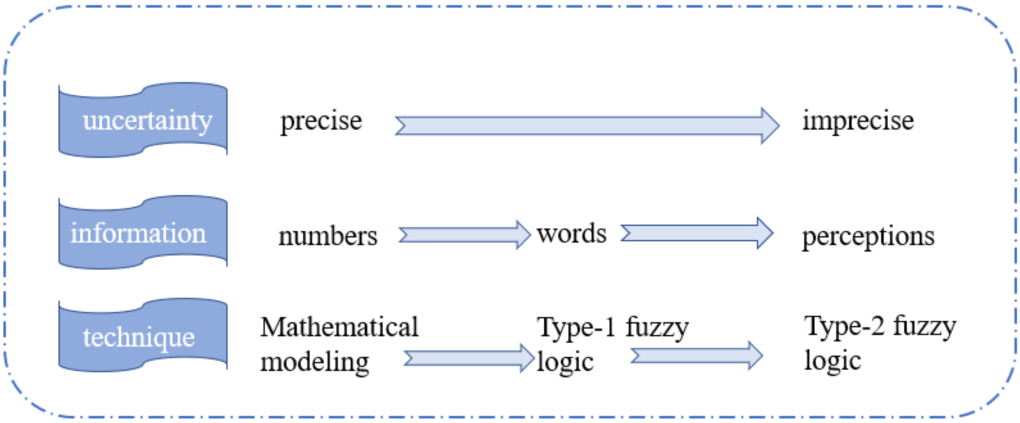


Figure 4: Relationships between the degree of uncertainty, information and fuzzy techniques [30]

The general structure of the type-2 fuzzy logic system is presented in Figure 5.

In the last 10 years, there has been an increasing amount of literature on the applications of type-2 fuzzy logic. The use of type-2 fuzzy logic is extensive in intelligent control, such as airplane flight control [15], control system for multimachine power systems [1], trajectory control of an autonomous tractor [52], etc. Besides, numerous studies have attempted to apply type-2 fuzzy logic to various fields. The proposal of type-2 fuzzy logic takes one more step towards the goal of representing human perception by machine.

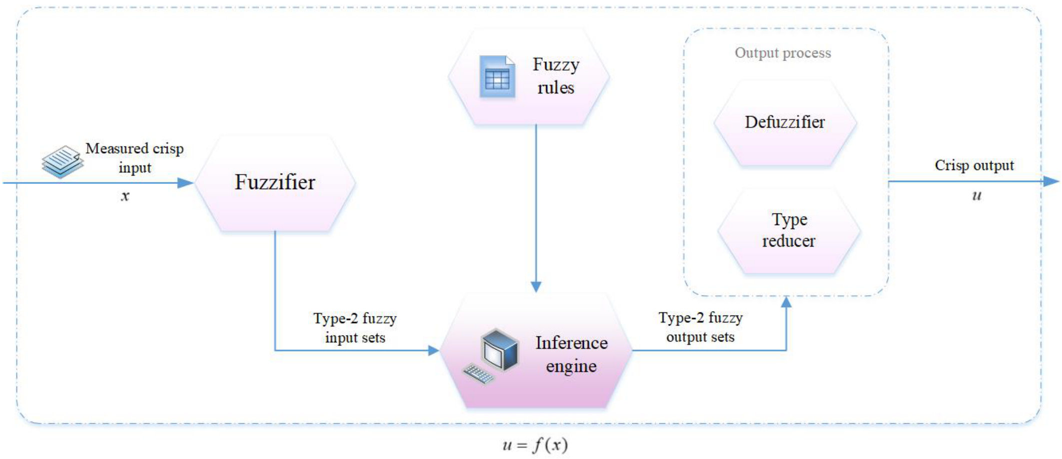


Figure 5: The structure of the type-2 fuzzy logic system

3 Basic structure of the fuzzy logic system in decision support

Fuzzy logic provides a specific view on the analysis of knowledge, which plays an important role in the process of making rational decisions under an uncertain environment. Combined with fuzzy logic, the reliability and flexibility of traditional decision making methods are significantly enhanced. In this section, we explain the structure of the fuzzy logic system and the workflow for the modules in intelligent decision making.

The fuzzy logic system traditionally consists of four components: 1) a fuzzification interface, 2) a fuzzy rule base, 3) an inference engine, 4) a defuzzification interface [125]. At first, the source data, which are linguistic inputs, need to be transformed into fuzzy numbers by using fuzzification methods. According to the needs of special issues, the fuzzy rule base provides some fuzzy IF-THEN rules. Then, the inference engine, as the key of a fuzzy logic system, executes the reasoning process base on fuzzy logic rules. Finally, the fuzzy results of the inference are converted into linguistic outputs by the defuzzification interface. A complete framework of this four-steps procedure can be clearly illustrated in Figure 6.

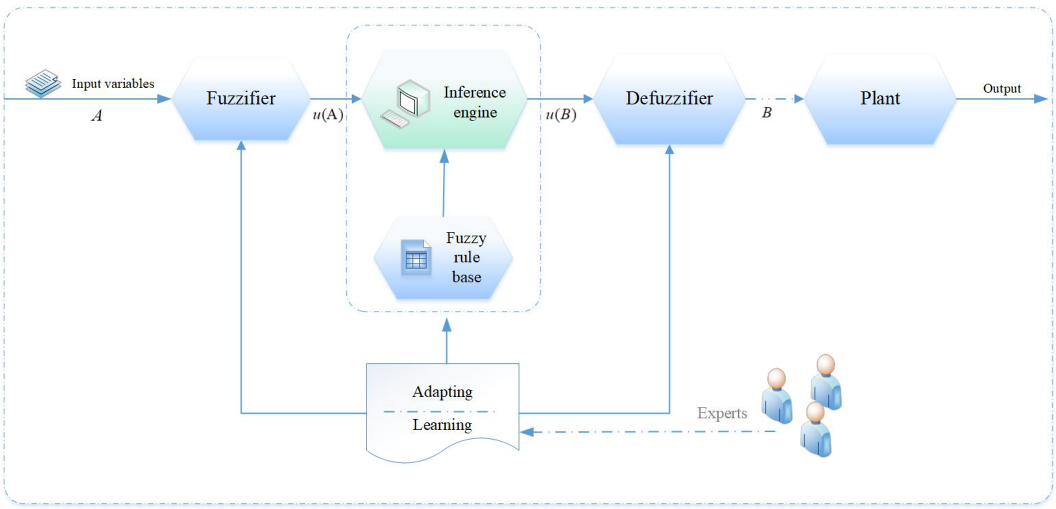


Figure 6: The framework of fuzzy logic system in decision support

For clarity, each step is presented in detail as follows:

(1) *Fuzzification*. The purpose of fuzzification is to map linguistic inputs to fuzzy numbers according to a set of membership functions [125]. To achieve this, the number of linguistic variables and the corresponding mapping values for each linguistic variable need to be defined in this process. Following the definition in Subsection 2.1, the input vector *inp* and the output vector *outp* can be presented as:

$$inp = A_i, U_i, (T^1_{A_i}, T^2_{A_i}, \cdots, T^{k_i}_{A_i}), (\mu_(A_i)^1, \mu_(A_i)^2, \cdots, \mu_(A_i)^{k_i})|i = 1, \cdots, n \quad (3)$$

$$outp = B_i, U_i, (T^1_{B_i}, T^2_{B_i}, \cdots, T^{z_i}_{B_i}), (\mu_(B_i)^1, \mu_(B_i)^2, \cdots, \mu_(B_i)^{z_i})|i = 1, \cdots, m \quad (4)$$

where A denotes the name of linguistic variables, U is a continuous universe, T is the term set of A, M is the membership function of linguistic values, n and m represent the number of linguistic variables in *inp* and *outp* respectively, k and z represent the number of linguistic values for each linguistic variable in *inp* and *outp* respectively. For a linguistic variable A_i, it is mapped to the fuzzy set T^1_A with the membership degree μ^1_A, and to the fuzzy set T^2_A with the membership degree μ^2_A, etc.

Considering computational efficiency, membership functions are formed by straight lines. The most common types of membership functions are listed below:

• Triangular membership function

The expression of a triangular membership function is given by:

$$\mu(x, a, b, c) = \max\left\{\min\left(\frac{x-a}{b-a}, \frac{c-x}{c-b}\right), 0\right\} \quad (5)$$

where a and c determine the "feet" of the triangle, b determines the "peak".

• Trapezoidal membership function

A trapezoidal membership function depends on four parameters a, b, c and d as given by:

$$\mu(x, a, b, c, d) = \max\left\{\min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right), 0\right\} \quad (6)$$

where a and d determine the "feet" of the trapezoid, b and c determine the "shoulder" of the trapezoid. In particular, a trapezoidal membership function may have narrow "shoulders" or wide "shoulders".

• Gaussian membership function

A Gaussian membership function is defined as:

$$\mu_G(x, \sigma, c) = e^{-[x-c]^2/2\sigma^2} \quad (7)$$

where c denotes the center of the fuzzy set and σ parameterizes the width of the fuzzy set. It is noted that the Gaussian membership function is a non-zero membership function. The $\alpha - cut$ of a fuzzy set contains all the elements in the universe set X whose membership degrees are equal to or greater than α, where $0 \leq \alpha \leq 1$. Then, the width of the fuzzy set ω_α can be determined by

$$\omega_\alpha = \sqrt[2]{(-\ln \alpha)(2\sigma^2)} \quad (8)$$

Gaussian membership function has better performance in processing data on probability and statistics [4].

• Generalized bell membership function

A generalized bell membership function is described by three parameters, the definition of the membership function is presented as follows:

$$\mu(x, a, b, c) = \frac{1}{1 + |\frac{x-c}{a}|^{2b}} \quad (9)$$

where the parameter c determines the center of the curve and the parameter indicates the width of the curve. It should be noted that the value of the parameter b is always positive.

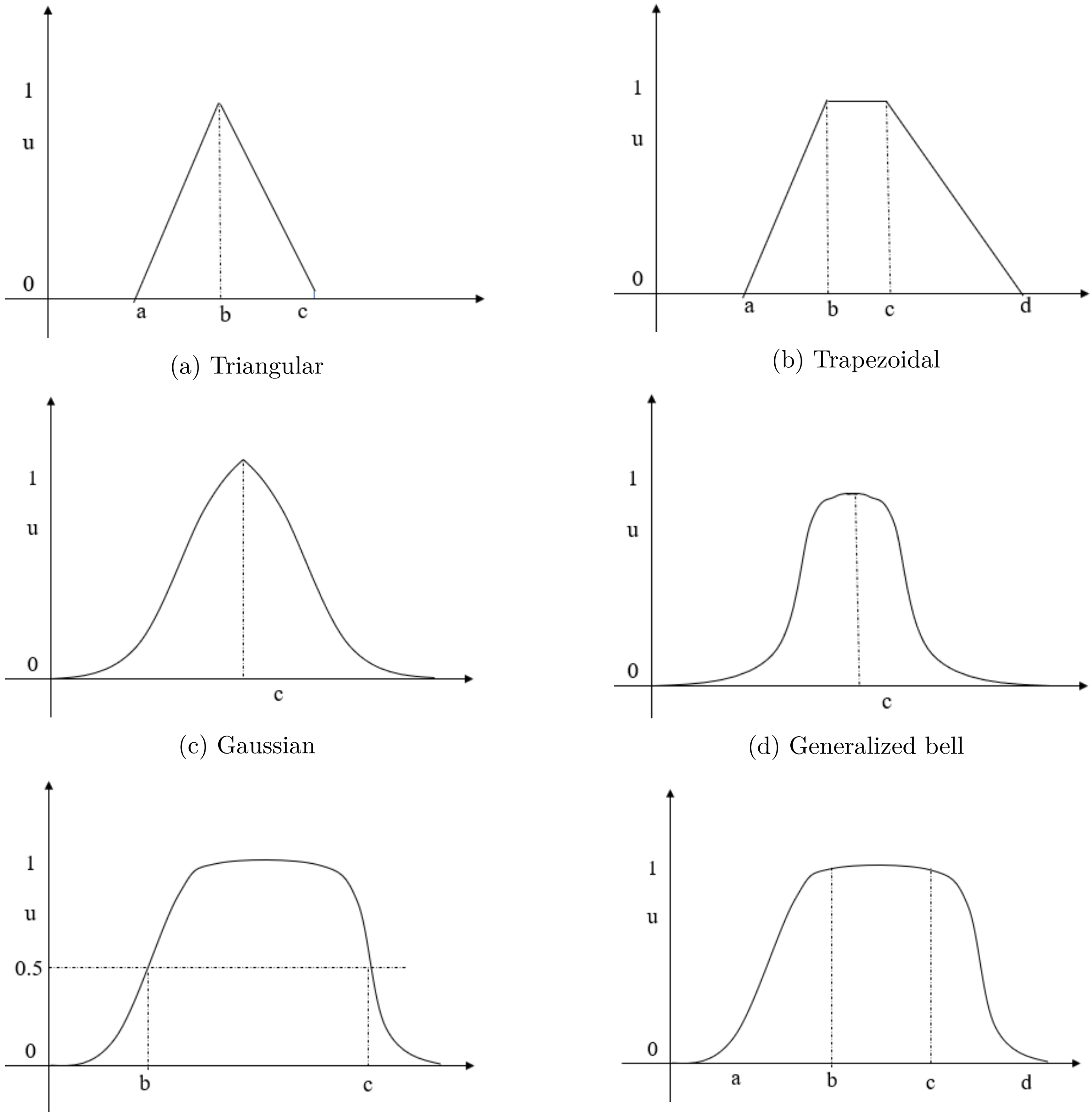
• Sigmoidal membership function

A Sigmoidal membership function can be generally expressed as:

$$\mu(x, a, b) = \frac{1}{1 + e^{-a(x-b)}} \quad (10)$$

where b indicates the distance from the origin and a determines the steepness of the function.

• π-Shaped Membership Function



(a) Triangular (b) Trapezoidal (c) Gaussian (d) Generalized bell (e) Sigmoidal (f) π-Shaped

Figure 7: Different types of membership functions

A π-Shaped membership function is zero at both ends and can be seen a rise in the middle [137]. It is given by the expression:

$$y = \mu(x, [a, b, c, d]) \tag{11}$$

The shape of this membership function may be symmetric or asymmetric. The curves of different membership functions are illustrated in Figure 7.

Particularly, when a set of parameters are defined to determine the proper meaning of the membership function, any type of continuous probability distribution function can be used as a membership function for specific applications [4].

(2) *Fuzzy rule base.* This is a database storing a large number of linguistic statements and a set of fuzzy logic rules [61, 125]. Then, the fuzzy rule base assists the fuzzy logic system to make rational decisions about input classification and output control. Practical experience shows that these fuzzy logic rules can provide a convenient framework for integrating human knowledge [82]. In the fuzzy reasoning process, the relationship between input variables and output variables is usually described by using the IF-THEN scheme. For example, if the fuzzy rule set is denoted as R, then for a multi-input

and multi-output (MIMO) system [61], we have

$$R = \{R^1_{MIMO}, R^2_{MIMO}, \cdots, R^n_{MIMO}\} \tag{12}$$

where n is the number of fuzzy rules and the $i-$th rule can be described as:

$$\begin{aligned} R^i_{MIMO}: \quad & \text{IF} \quad (A_1 \quad \text{is} \quad T_{A_1} \quad \text{and} \ldots \text{and} \quad A_p \quad \text{is} \quad T_{A_p}) \\ & \text{Then} \quad (B_1 \quad \text{is} \quad T_{B_1} \quad \text{and} \ldots \text{and} \quad B_q \quad \text{is} \quad T_{B_q}) \end{aligned} \tag{13}$$

Since the consequence of R^i_{MIMO} is the union of q independent outputs, this fuzzy logic rule can be denoted as a fuzzy implication [61]:

$$R^i_{MIMO}: (T_{A_1} \times \ldots \times T_{A_p}) \to (T_{B_1} + \cdots + T_{B_q}) \tag{14}$$

where the symbol "+" indicates the union of independent output variables. It should be noted that there are generally two or three input variables for one output variable for reducing the number of fuzzy rules. For sure, a lot of researchers investigating fuzzy logic systems have proposed various membership functions and developed the corresponding fuzzy logic rules from human knowledge. For example, on the basis of closely-reasoned scientific proofs, some basic operational laws and fuzzy rules of intuitionistic fuzzy logic were put forward. For an intuitionistic fuzzy logic proposition (IFLP) formula $a(\mu_a, v_a)$, we have [124]:
a) $a(\mu_a, v_a)$ is strong true (ST) if and only if $\mu_a > 0.5$ and $v_a < 0.5$;
b) $a(\mu_a, v_a)$ is strong false (SF) if and only if $\mu_a < 0.5$ and $v_a > 0.5$;
c) $a(\mu_a, v_a)$ is weaken true (WT) if and only if $\mu_a < 0.5$, $v_a < 0.5$ and $\mu_a > v_a$;
d) $a(\mu_a, v_a)$ is weaken false (WF) if and only if $\mu_a < 0.5$, $v_a < 0.5$ and $\mu_a < v_a$;

Then, three characteristics were concluded as: 1) the intuitionistic disjunction symbol "∧" obeys true principle, which indicates that the type of operation result is the same as the IFLP with high priority; 2) the intuitionistic conjunction symbol "∨" obeys false principle, which indicates that the type of operation result is the same as the IFLP with low priority; 3) the intuitionistic implication symbol "→" may lead to two possible operation results, WT or WF. After that, the corresponding reasoning process was established including direct proof method, additional premise proof method and reduction to absurdity method [124].

(3) *Inference engine.* Fuzzy reasoning aims to acquire new knowledge based on the existing knowledge by fuzzy logic. The task of the inference engine is to derive outputs from input variables based on a set of fuzzy logic rules that are extracted from the fuzzy rule base. For example, for a single output variable, we assume that there are two rules [61]:

$$\begin{aligned} R1: \quad & \text{IF} \quad A_1 \quad \text{is} \quad T^1_{A_1}, \quad \text{and} \quad A_2 \quad \text{is} \quad T^1_{A_2}, \quad \text{Then} \quad B \quad \text{is} \quad T^1_B. \\ R2: \quad & \text{IF} \quad A_1 \quad \text{is} \quad T^2_{A_1}, \quad \text{and} \quad A_2 \quad \text{is} \quad T^2_{A_2}, \quad \text{Then} \quad B \quad \text{is} \quad T^2_B. \end{aligned} \tag{15}$$

Subsequently, the firing strengths of the above two rules (denoted as $\alpha_i, i = 1, 2$) can be defined as:

$$\alpha_i = \mu^i_{A_1}(A_1) \wedge \mu^i_{A_2}(A_2)$$

where the symbol "∧" is the AND operation in fuzzy logic. Considering that algebraic product and intersection are the most commonly used AND operation, α_i can be represented by

$$\alpha_i = \mu^i_{A_1}(A_1) \wedge \mu^i_{A_2}(A_2) = \begin{cases} \min\left((\mu^i_{A_1}(A_1), \mu^i_{A_2}(A_2)\right) \\ \text{or} \\ \mu^i_{A_1}(A_1)\mu^i_{A_2}(A_2) \end{cases} \tag{16}$$

After the fuzzy reasoning based on the two rules, the membership function for the output linguistic variable (denoted as $\hat{\mu}^i_B(x), i = 1, 2$) are defined as:

$$\hat{\mu}^i_B(x) = \alpha_i \wedge \mu^i_B(x) = \begin{cases} \min\left(\alpha_i, \mu^i_B(x)\right) \\ \text{or} \\ \alpha_i\mu^i_B(x) \end{cases} \tag{17}$$

where x indicates the variable that denotes the support values of the membership function. Finally, the output with the membership functions can be obtained:

$$\hat{\mu}_B(x) = \hat{\mu}_B^1(x) \vee \hat{\mu}_B^2(x) \tag{18}$$

where the symbol "$\vee$" is the OR operation in fuzzy logic. Similarly, as union and bounded sum are the most commonly used OR operation, $\hat{\mu}_B(x)$ can be represented by

$$\hat{\mu}_B(x) = \hat{\mu}_B^1(x) \vee \hat{\mu}_B^2(x) = \begin{cases} \max\left(\hat{\mu}_B^1(x), \hat{\mu}_B^2(x)\right) \\ \text{or} \\ \min\left(1, \left(\hat{\mu}_B^1(x) + \hat{\mu}_B^2(x)\right)\right) \end{cases} \tag{19}$$

It can be found that the final result is a membership function curve. This example just presents the standard function operations in traditional fuzzy logic, which means there also exist other *AND* operations, *OR* operations, and reasoning operations in fuzzy logic.

According to the type of fuzzy inference and the fuzzy rules adopted, most fuzzy inferences can be divided into two types: the Mamdani's fuzzy inference method [68] and the Takagi–Sugeno fuzzy inference method [106]. Mamdani's fuzzy inference method is one of the earliest fuzzy inference methods, which applied a set of fuzzy rules generated by experienced operators [82]. The most difference between these two methods is that both the antecedent and the consequence of the former are fuzzy set, while in the latter, the output membership function is linear or constant (as shown in Figure 8) [14, 125]. Also, the linguistic structure used by the Takagi–Sugeno fuzzy inference method is arranged in a causal relationship format (the IF-THEN rules), which can promote human understanding and interpretation [17]. In summary, the capability to understand each part of complex models makes these two fuzzy inference methods widely applied in different fields.

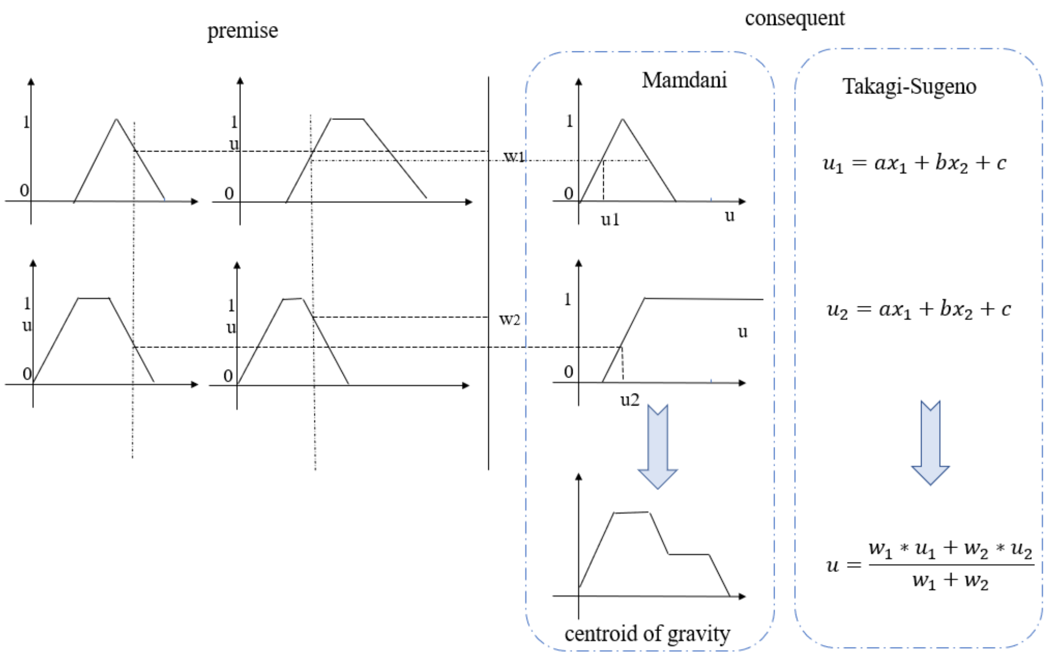


Figure 8: Two types of inference engines

(4) *Defuzzification.* This step is to obtain the output variable by aggregating the qualified results. There are some traditional defuzzification techniques, such as the mean of maximum [130], the Bisector of Area [130], and the Center of Gravity [114]. For the example mentioned in (3), the output result can be derived by the Center of Gravity method as follows:

$$B = \frac{\sum_j \hat{\mu}_B^j(x_j)x_j}{\sum_j \hat{\mu}_B^j(x_j)} \tag{20}$$

Table 1: Some fuzzy logic systems

References	Fuzzy set	Membership function	Inference engine	Defuzzification
[6]	Type-1	Triangular	Mamdani	Centroid of Gravity
[118]	Type-1	Triangular or Trapezoidal	/	Euclidean distance
[119]	Type-1	Triangular	/	Euclidean distance
[121]	Type-1	Fuzzy logic toolbox	Mamdani	Fuzzy logic toolbox
[20]	Type-1	Four types membership functions	Mamdani	Centroid of Gravity
[125]	Type-1	Gaussian	Mamdani	Centroid of Gravity
[104]	Type-1	Triangular	Sugeno	Sugeno membership function
[14]	Type-1	Triangular	Sugeno	Sugeno membership function
[17]	Type-1	Triangular	Sugeno	/
[67]	Type-1	Triangular Trapezoid	Mamdani	Centroid of Gravity
[93]	Type-1	Triangular	Mamdani	Centroid of Gravity
[19]	Type-2	Gaussian	Mamdani	Centroid of Gravity
[42]	Type-2	Triangular	Mamdani& Takagi-Sugeno	Nie-Tan method [64]
[122]	Type-2	Zadeh's Extension Principle	Mamdani	Centroid of Gravity
[38]	Type-2	Gaussian	Mamdani	Centroid of Gravity
[95]	Type-2	Complex fuzzy membership function	Mamdani	Trapezoidal rule
[41]	Type-2	Gaussian	Mamdani	Center type reduction
[76]	Type-2	Gaussian	Takagi-Sugeno-Kang	GCCD
[75]	Type-2	Triangular	/	/
[56]	Type-2	Gaussian	Takagi-Sugeno-Kang	Karnik-Mendel method [84]
[55]	Type-2	Gaussian	Takagi-Sugeno-Kang	Karnik-Mendel method [84]

By taking the total output distribution into account, the Center of Gravity method exhibits its superiority in many studies [11]. Meanwhile, some literature points out that the Center of Gravity methods may lead to systematic errors, which makes the training process of the fuzzy logic system more complicated [114]. The Bisector of Area method calculates the abscissa of the vertical line that divides the area of the membership function of output results into two equal areas by [130]:

$$B = \left| \sum_{j=1}^{t} \hat{\mu}_B^j(x_j) - \sum_{j=t+1}^{j_{max}} \hat{\mu}_B^j(x_j) \right|, j < t < j_{max} \tag{21}$$

where j_{max} is the indicator of the largest abscissa. However, the high computational complexity limits the application of this method [130]. As another commonly used method, the formula of the mean of maximum method is presented as [130]:

$$B = \frac{\sum_{j \in J} x_j}{|J|}, J = \left\{ j | \hat{\mu}_B^j(x_j) = \mu_{max} \right\} \tag{22}$$

where J represents the set of the indices j and $|J|$ denotes the cardinality of J. In order to overcome the shortcomings of those methods, a large number of scholars have studied the improvement of those traditional models of defuzzification including introducing novel definitions for the defuzzification of generalized fuzzy numbers [89], developing defuzzification methods on the root mean square value [16] and the continuity focused choice of maxima [115], and extending the traditional Center of Gravity method [64], etc. For type-2 fuzzy logic system, there are some effective defuzzification strategies including the Greenfield–Chiclana Collapsing Defuzzifier (GCCD) algorithm [35], the Nie–Tan method [77], the KMIP (in the form of EIASC [126]), the Wu–Mendel approximation [127], etc.

Some methods are summarized in Table 1 for visually showing their distinct characteristics. From Table 1, we can see that the Triangular membership function is the most commonly used membership in type-1 fuzzy logic-based methods, while the Gaussian membership function is more popular in type-2 fuzzy logic-based methods. This is because the Gaussian membership function is suitable for solving problems that require continuously differentiable curves and smooth transitions between levels.

4 Fuzzy logic-based decision making methods

Fuzzy logic-based decision making methods help to establish the structure of the problem from different perspectives. We have given a detailed introduction to the fuzzy logic system above. In this section, we first summarize some statistical results of published papers in this field to present the development of decision-making methods with fuzzy logic in the last decade. Then, we further explain the role of fuzzy logic in intelligent decision making and provide a concise description of some fuzzy logic-based decision making methods.

4.1 How fuzzy logic developed in decision making during the last decade?

Fuzzy logic in decision making is a growing research topic. When the search topic was set as "fuzzy logic" and "decision making" in the Web of Science Core Collection, a large number of published papers were selected. Figure 9 manifests the growth in the number of academic papers from 2010 to 2020.

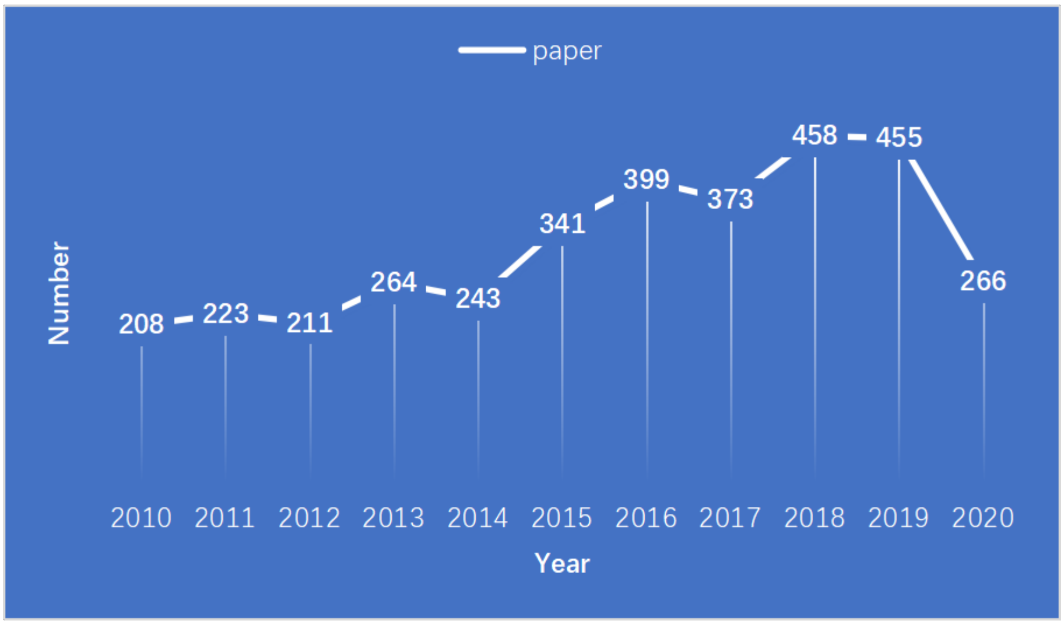


Figure 9: The number of published papers from 2010 to 2020

As can be seen in Figure 9, there was a substantial growth during the 10-year period, rising from 208 in 2010 to 455 in 2019. Despite some initial fluctuation, the number of published papers increases steadily. It is worth noting that there was a significant increase in 2015. This is to mean, the application of fuzzy logic in decision making has attracted much more attention from researchers in this year. In 2020, the number of published papers in this field has reached 266 and will continue to grow, which indicates that fuzzy logic theory provides effective tools for realistic decision making and has broad application prospects. In what follows, some fuzzy logic-based decision making methods are summarized from four angles: evaluation methods, prediction methods, decision support algorithms, and group decision making methods.

4.2 Evaluation methods

Due to the great flexibility and reliability, the idea of applying fuzzy logic in evaluation methods has been investigated extensively. With the aim of processing linguistic information more naturally and conveniently, Ma and Xu developed a fuzzy logical algebras-based virtual linguistic model. General strictly increasing functions were adopted to match the membership functions with existing linguistic terms and some novel operational laws and measures were further defined, including distance measures, similarity measures, and entropy measures. Based on the proposed linguistic aggregation operators, a multi-attribute decision-making model was constructed to select the propulsion/maneuvering system for reducing travel time in highly congested maritime traffic [63]. To describe DMs' risk attitude, prospect theory was applied to behavioral three-way decision making under interval type-2 fuzzy environment. With the 2-additive Choquet integral, a non-additivity fusion method was introduced to handle interactions between multiple attributes. Then, the proposed behavioral three-way decision model was utilized to solve a decision-making problem of distinctive street identification of Chengdu [59]. Benefited from fuzzy logic techniques, a fuzzy expert system was constructed for evaluating the academic performance of students [129]. It was observed that the proposed method was more suitable in the academic environment compared to the classical fuzzy logic. As a highly intuitive tool for analyzing natural language, intuitionistic fuzzy logic was employed for proposing fuzzy evaluation methods. Due to the capacity of the Bonferroni mean (BM) to capture the inter relationship among input arguments, Xu [128] proposed an intuitionistic fuzzy BM for multi-criteria decision making problems. For the credit risk assessment of potential strategic partners, a new distance measure between intuitionistic fuzzy sets was introduced, based on which an extended TOPSIS approach was also developed to derive the final ranking [97]. Furthermore, on the basis of the hesitant fuzzy membership, Zhou and Xu [138] proposed the extended intuitionistic fuzzy set, which not only comprehensively mined decision information, but also avoided the logical difficulty of providing membership degree and non-membership degree in the same time. Then, the proposed concepts and approaches were applied to assist in risk preference investment problems. In order to measure social sustainability performance, a conceptual model based on fuzzy logic was developed and applied to identify proposals for the improvement of social sustainability performance [85]. In addition, a unified decision framework was introduced by integrating fuzzy logic, the TOPSIS method, and the DEA-AHP method, which can better capture the subjectivity among evaluators [37]. To achieve the application of lean manufacturing, a fuzzy logic-based method was proposed to handle the multidimensional concept, showcasing great advantages in dealing with the vagueness of DMs' subjective assessments [105]. A comprehensive evaluation method, which was based on fuzzy logic and energy analysis, was established to evaluate the health of agricultural land utilizing geographic information system [58].

4.3 Prediction methods

In order to effectively make use of fuzzy logic for a prediction problem, an automated approach was carried out to generate the weighted fuzzy rules [6]. According to the frequency of the attribute category and the attribute weights, fuzzy rules in the proposed decision support system can be automatically generated from the classified dataset. These rules consist of IF and THEN parts, where the IF part assigned the numeric variables and the THEN part assigned the class label. Then, the designed fuzzy inference system that contained m input variables and a single output variable was developed. Due to the capability to predict highly complicated problems based on a small number of rules, a fuzzy logic-based approach for stock trading forecasting was introduced [17]. The combination with the Takagi–Sugeno fuzzy model enabled the stable dynamic identification of the complexity of the stock forecasting system. Based on the adaptive neuro-fuzzy inference system, Yadollahpour etc. presented a medical decision support system to predict the timeframe for renal failure [131]. For the triage classification and management, the rule-based reasoning and the fuzzy logic classifier approaches were employed to predict patients' triage level, which is proved helpful for users as guidelines when they made decisions [100]. The prediction model combining multiple linear regression, artificial neural network, and adaptive network-based fuzzy inference systems were constructed, trained, and tested [53]. The outcomes from this model exhibited high reliability and provided useful suggestions that can be adopted in selecting appropriate concrete mix designs.

4.4 Decision support algorithms

Various fuzzy logic-based decision support systems have been developed to assist users in organizing decision making activities. Walia et al. introduced a systematic approach to the construction of an expert system [121]. The fuzzy rule base was updated by dynamic rules that were generated by adopting experts' knowledge and experience. Then, the Mamdani's max-min fuzzy inference engine was employed to infer input data from fuzzy logic rules, and appropriate decision results can be finally obtained. This proposed algorithm made the expert system easy to store amounts of information and the fuzzy rules generation process helped to clarify the logic in the decision making process. In the decision support system proposed by Perera et al. [20], four types of membership functions were employed to handle the input variables. For the output variables, the course change membership functions and the speed change membership functions were formulated. This work demonstrated that different types of membership functions can enhance the processing ability of different input variables.

To deal with complicated relationship between input information, the theory and technology of IFLP reasoning was developed to lay a foundation for the construction of expert system [124]. This work offered a sound structure for intuitionistic fuzzy logic and improved the efficiency of logic programming. A fuzzy logic-based dynamic decision-making system was established for intelligent navigation strategy selection, which was achieved from the perspective of perception-anticipation-inference-strategy [125]. Considering that the input variables of this system included speed and distance whose membership degrees should increase sharply, the Gaussian membership function was introduced for the fuzzification process. Cosenza described the implementation of fuzzy techniques in the development of a hierarchical fuzzy system including three subsystems [20]. Particularly, the first subsystem utilized the Mamdani inference method while the third subsystem adopted the Sugeno inference method. This is because the Mamdani inference method is more intuitive and well suited to human input, and output membership functions of the Sugeno inference method are either linear or constant. Moreover, the fuzzy logic was applied to a mobile decision support system so that the input information can be simplified [104]. In this work, the Sugeno inference method, in the form of IF-THEN, was proven to have high accuracy in the calculation process. Cavallaro also proposed an application of the Sugeno fuzzy inference to establish an index to evaluate the sustainability of biomass production for energy purposes [14]. This work attempted to illustrate that fuzzy sets are suitable for uncertain approximate reasoning. Besides, it is feasible to use estimated values to make decisions when the original information is incomplete [14]. With a fuzzy rule-based system, a decision support system was developed to assist physicians in making more accurate and faster medical diagnosis [67]. Driven by fuzzy logic, a web-based decision support system was explored to improve the accuracy and efficiency of the diagnosis of typhoid fever [93]. To assist in the depression diagnosis, which was complex due to the conflicting, overlapping, and chaotic nature of multiple symptoms, an intelligent decision support system was proposed by combining with the adaptive neuro-fuzzy inference system [28]. Some programming models were also developed to deal with fuzzy numbers [102, 103].

4.5 Group decision-making methods

Many decision-making activities are carried out within the group framework, which works as a mechanism for integrating views of DMs according to some rules. As for the group decision-making problems, fuzzy logic techniques have been employed as a formal tool to help DMs deal with uncertainty.

Based on experts' opinions and preferences, a fuzzy logic multi-criteria group decision making system was established, which adopted the interval type-2 fuzzy logic to handle vagueness [75]. The interval type-2 fuzzy values were extended into intuitionistic values, which not only dealt with linguistic uncertainty by type-2 membership function but also derived the hesitation degree from the intuitionistic evaluations. This method can resolve conflicts in decision-making by integrating various factors judged by multiple users [75]. Also, an interval type-2 fuzzy weighted arithmetic averaging operator was applied to aggregate decision matrices from DMs [123]. Under intuitionistic fuzzy environment, an automatic ranking approach for multi-criteria group decision making was proposed to achieve group opinion satisfaction, which extended the ELECTRE III method as group decision techniques [96]. Based on the ranking-value matrices, some optimization models were developed to obtain the attribute weights. Through the intuitionistic fuzzy logic, Mousavi et al. introduced a group decision-making model for construction project selection [31]. In this model, the evaluation information was expressed by linguistic terms, which were transformed into intuitionistic fuzzy sets. With fuzzy logical operators, a multi-granular fuzzy rough set model was constructed to solve multi-attribute group decision-making problems [136]. This work took advantage of fuzzy logic to implement approximate reasoning, in which the imprecise knowledge of DMs can be stated in formal terms. Combined with the fuzzy logic and analytic hierarchy process (AHP), a fuzzy AHP was proposed to derive weights of evaluation criteria [136]. In the context of intelligent systems, a fuzzy majority model for group decision making was developed through fuzzy logic and ordered weighted averaging operators [10].

5 Application fields of fuzzy logic-based decision making method

In this section, we review recent decision applications regarding fuzzy logic-based method (as shown in Table 2), since it has become extremely important to present this science along with some applications. As fuzzy logic-based decision making methods have been widely applied, the application papers can be organized as the following areas:

5.1 Performance evaluation

Decision analysis based on fuzzy logic has been widely used in the evaluation process, which can effectively increase the reliability of the evaluation and reduce the subjectivity and uncertainty in decision making. Many fuzzy logic-based methods have been carried out to deal with real performance evaluation problems. In recent years, fuzzy logic has been employed in education systems for evaluating the academic performance of students [117]. For example, a novel fuzzy inference system was introduced for multi-input variables, in which the Triangular membership function, the Trapezoidal membership function, and the Gaussian membership function were adopted to derive the satisfaction degrees of students [86]. With a fuzzy logic system, a neuro-fuzzy approach was proposed to classify students and predict the final period grade of each student [90]. As students may consider various courses, fuzzy logic was applied to evaluate students' academic performance so as to provide useful suggestions for students to choose suitable research fields in the future [2]. In addition, different decision making models equipped with fuzzy logic have been applied to various evaluation and selection processes, such as project evaluation and selection [23, 79, 125], material selection [36], supplier selection [18, 78], etc.

5.2 Healthcare management

Fuzzy logic has received a great deal of attention in healthcare management, which is the most popular application areas among these references. With the gradual development of artificial intelligence in healthcare management, fuzzy logic-based clinical decision making methods have been successfully developed in different medical fields [44]. To deal with linguistic statements of patients, generalized triangular fuzzy numbers were used to describe these input variables in medical decision making [25]. The fuzzy inference system was applied to the construction of clinical decision support systems for breast cancer classification [39], medical diagnosis [21, 34], medical data analysis [7], etc. Combined with data mining technology, fuzzy logic was adopted as a tool for automatic drug delivery in a two-level computer decision system [72]. Moreover, based on a multi-agent system and intuitionistic fuzzy logic, a practical decision support system framework was provided to realize mart healthcare [47].

5.3 Other applications

Due to inherent uncertainties in management, fuzzy logic has been used in enterprise management to solve decision making problems in the risk environment [109]. Based on different data sources, the fuzzy logic-based decision making methods were also proposed for enterprises' activities analysis [109], supply chain management [5, 81, 107], human resources management [46], customer management [30], product development [62], etc. Furthermore, fuzzy logic algorithms were developed to optimize the investment decisions within companies [9, 91]. As for applications in other fields, the fuzzy logic system has proven useful in groundwater quality evaluation [113], energy management [101], city management [83], sustainable development [8], internet-based services [33, 74], tourism management [139], etc.

In order to clearly illustrate the application status of those methods, Figure 10 is provided to manifest the application areas in Table 2 and their corresponding proportions.

From Table 2 and Figure 10, we can see that 41 papers which applied fuzzy logic-based methods in various fields were reviewed, with the application in healthcare management having the largest proportion at 20%, compared to only 3% in several other areas, such as city management, product development, tourism management, etc. In other application fields, academic performance evaluation has a relatively higher percentage (10%), followed by supply chain (8%), project selection (8%), and enterprise management (8%).

Table 2: Application fields of fuzzy logic-based methods in recent years

Reference	application	year
[86]	Performance evaluation	2020
[90]	Performance evaluation	2018
[2]	Performance evaluation	2019
[117]	Performance evaluation	2019
[79]	Project selection	2016
[125]	Projects selection	2020
[113]	Water resources management	2016
[65]	Energy management	2017
[36]	Material selection	2018
[78]	Supplier selection	2018
[18]	Supplier selection	2019
[23]	Projects selection	2016
[9]	Investment	2019
[91]	Investment	2019
[99]	Water resources management	2019
[83]	City management	2019
[109]	Enterprises management	2018
[51]	Enterprise management	2018
[108]	Enterprise management	2019
[5]	Supply chain	2019
[81]	Supply chain	2019
[107]	Supply chain	2020
[39]	Healthcare management	2019
[21]	Healthcare management	2016
[7]	Healthcare management	2020
[32]	Healthcare management	2018
[34]	Healthcare management	2018
[72]	Healthcare management	2018
[25]	Healthcare management	2018
[47]	Healthcare management	2019
[30]	Customer management	2018
[46]	Human resources management	2018
[84]	Robot design	2018
[8]	Sustainable development	2018
[101]	Energy management	2018
[74]	Cloud infrastructure services	2019
[33]	Web-resources management	2018
[62]	Product development	2018
[139]	Tourism management	2019
[73]	Smart watering system	2019

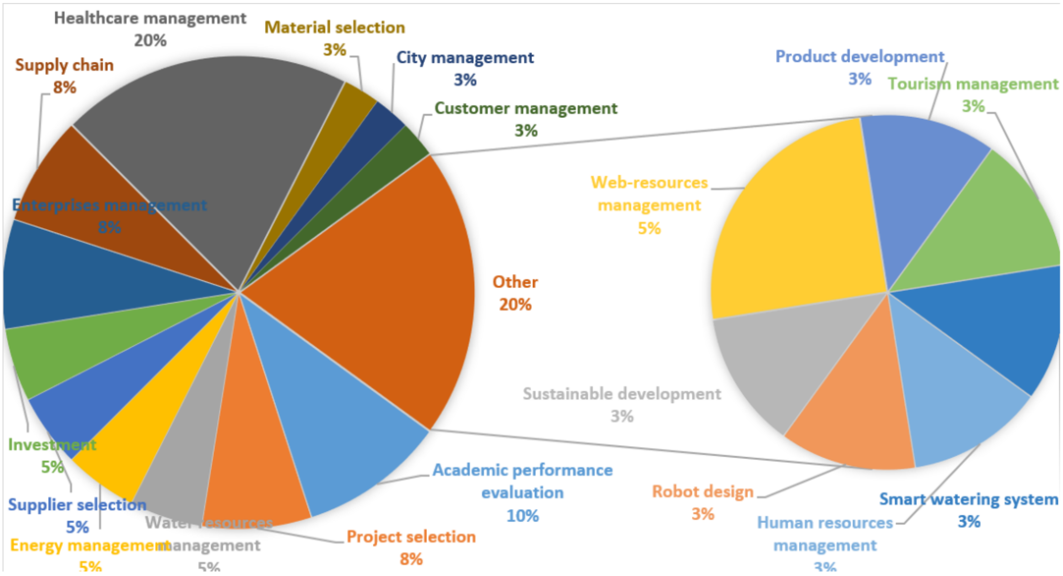


Figure 10: The proportions of applications

6 Challenges and trends for the future

The rapid development of social economy and technology has made actual decision making more complicated, leading to difficulties in the management of uncertain and vague information. In such an environment, fuzzy logic has been successfully employed to model linguistic expressions. However, as the process of natural human reasoning is very complex, more attention and further research are needed for the application of fuzzy logic in intelligent decision making. Here we raise some problems and open questions that are worth solving and answering. Also, some corresponding possible future trends that can be envisioned based on the review of this field are presented.

6.1 Improvement of the fuzzy logic system in decision making

(1) Although fuzzy logic has offered an appropriate modeling approach to deal with uncertainty in decision making information, realistic decision making problems will become more complicated and need to manage higher volumes of vague information. In addition, it is unrealistic to use only several techniques to solve various decision making problems because different criteria, attributes, etc. suit to different types of modeling [69]. Therefore, the development of different types of fuzzy logic is worthy to be investigated to achieve better results for intelligent decision making. For example, as mentioned in Subsection 2.3, most of the research on type-2 fuzzy logic currently focuses on the interval type-2 fuzzy logic. For reducing the computational overhead, the interval type-2 fuzzy logic is adopted as a simplified form of generalized type-2 fuzzy logic. Theoretically speaking, using generalized type-2 fuzzy logic can deal with a higher degree of uncertainty, which can obtain better decision results. Thus, it is necessary to develop effective algorithms for the generalized type-2 fuzzy logic.

(2) Fuzzy logic-based methods have shown the outperformance in intelligent decision making. With the help of fuzzy logic, the use of linguistic modeling improves the interpretability of decision-making methods. Nevertheless, this usually reduces the accuracy of the original information. Membership functions play an important role in the fuzzification process since the shape of them has an impact on specific problems. For the purpose of increasing the accuracy of these methods, different types of membership functions should be improved to obtain a better representation of input linguistic variables.

(3) Fuzzy inference methods have been widely used to model experts' behavior, which constructs mapping based on human knowledge and learning algorithms in the form of IF-THEN rules. However, fuzzy inference methods lack standard procedures for quantitative analysis and optimization process to transform experts' experience and knowledge [120]. Moreover, most of these methods are weak in self-learning and generalization of rules. Thus, with the development of artificial intelligence, fuzzy

inference systems can be combined with mining techniques to better generate fuzzy logic rules.

(4) The previous research has proven that outcomes derived from the decision-making methods based on fuzzy logic are understandable and accurate. However, due to the structure of linguistic variables, the outcomes obtained through the defuzzification are still very inflexible. Thus, the current challenge is to increase the linguistic operators and improve the flexibility and operability of the defuzzification process. Meanwhile, it is also an important issue to keep the simplicity of defuzzification methods.

6.2 Development of fuzzy logic-based decision-making methods

The overview of fuzzy logic-based methods in this paper illustrates that the depth and breadth of the application of fuzzy logic in decision making can be further enhanced.

(1) As linguistic information provides a richer environment to solve complicated problems, many evaluation methods have adopted linguistic expressions to describe decision information [40]. And the aim of using fuzzy logic techniques in evaluation methods is to improve the flexibility and reliability of the existing methods by providing effective information for DMs. It is beneficial to employ fuzzy logic as a tool for transforming human knowledge in the evaluation process. Future studies could dedicate to investigating fuzzy logic-based evaluation methods that allow experts' knowledge to be added when experts' knowledge is available.

(2) Consensus reaching is a crucial topic in the group decision making field, which is a mechanism for integrating views of DMs according to some rules. It is quite natural that DMs may have different opinions on the same issues. Thus, designing appropriate rules to regulate conflicts in a group is a topic that still needs to be studied. With advantages in process uncertain linguistic information, fuzzy logic has application prospects in the feedback mechanism of consensus reaching process.

(3) The limitation of time and space, the difficulty of evaluating alternatives, and the necessity of making reasonable decisions in an uncertain environment make the application of intelligent decision support systems indispensable to solve complicated decision-making problems. There is still an urgent need to develop kinds of decision support systems for different issues to assist DMs. Besides, it has been acknowledged that problems with high complexity are a certain case of decision support systems. Thus, the application of fuzzy logic-based methods to the construction of the decision support system requires further research. For example, it is needed to adapt existing decision support systems to linguistic environments and develop the corresponding algorithms to flexibly modeling uncertainty.

6.3 Application prospects

It is obvious that healthcare management is currently the hottest application field of fuzzy logic-based decision making methods. With the improvement of people's living standards, healthcare management will catch more and more attention. Although a lot of decision support systems for medical diagnosis have been constructed, it is necessary to develop intelligent decision support algorithms to assist in other complex medical management affairs, such as patient classification, medical data analysis, etc. Moreover, considering there always exist difficulties and uncertainties in the selection processes of many fields, fuzzy logic-based decision making methods can be applied to industry, agriculture, manufacturing, resource management, voting systems, etc.

7 Conclusions

As decision making becomes more difficult when faced with vague linguistic information, intelligent decision making has received a great deal of attention in recent years. Fuzzy logic techniques provide a solid foundation and a set of rich methodologies in processing natural language, which makes it of significant importance to intelligent decision making both from theoretical and practical points of view.

In this paper, we have attempted to provide a comprehensive review of fuzzy logic and its applications in decision support. Firstly, we reviewed some basic concepts of fuzzy logic, including type-1 fuzzy set, type-2 fuzzy set, and linguistic variables. The comparative analysis of different types of fuzzy logic was conducted. In order to clarify the process of fuzzy logic system, four components of the system were introduced. After that, some statistical results of published papers regarding fuzzy logic and decision making were presented. We saw a steady increase in the number of academic papers in this field. As to this fact, more investors have their sights on the fuzzy logic-based decision making methods in recent years. Then, a comprehensive overview of different decision making methods based on fuzzy logic was provided. After discussing the theoretical knowledge, practical applications were also summarized. Finally, we discussed some challenges and future trends of the fuzzy logic-based decision making methods.

To sum up, this paper has summarized the current research status and applications of fuzzy logic-based decision making methods. Furthermore, it illustrates the extensive research prospect of fuzzy logic in decision making and has guiding significance for the latter research on this topic.

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Author contributions

The authors contributed equally to this work.

Conflict of interest

The authors declare no conflict of interest.

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