Management of the Power Distribution Network Reconstruction Process Using Fuzzy Logic

Mirza Saric and Jasna Hivziefendic

Abstract This paper presents a fuzzy system for management of the power distribution network reconstruction process. The proposed system is based on Mamdani type fuzzy inference which is used to model reconstruction criteria. The system considers number of customers, rate of failure and age of distribution lines as input variables and provides output values used as criteria in a decision making process. The decision making process is based on the Bellman-Zadeh method in which decision making is performed by the intersection of fuzzy goals and constraints. In this paper, fuzzy logic is introduced as a system planning tool in order to account for weaknesses and imprecision of the traditional planning methods. The proposed model is presented as a logical decision making framework which can be used to evaluate and rank power distribution network reconstruction projects according to their ability to deliver long term benefits, both to the utility and customers.

1 Introduction

The power system is a complex and very capital intensive system which requires substantial investments in order to maintain predetermined quality standards and meet future energy and capacity needs. It is estimated that 30–40 % of total investments in the electricity sector is allocated to distribution systems [1]. The cost of electricity distribution constitutes a significant portion of the overall electricity cost [2]. The electricity distribution planning process requires that a large number of decisions be made within predetermined time and budget. Considering its strategic importance and the fact that the power system is very cost intensive, it is crucial to make the right decisions regarding planning management. Mistakes made during

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such processes can be very costly for decision makers and customers. Utilities make long term, ambitious investment plans which are evaluated by traditional planning techniques, based on load flow analysis [3]. However, network planning and project evaluation is a preference based decision making process which involves an assessment of a complex criteria [4]. Traditional approach neglects numerous planning criteria, which might result in misallocation of resources. Numerous judgments based on experience or expert opinion are crucial in decision making. Unfortunately, it is almost impossible to capture them all within the formulations of conventional optimizing models [5].

2 Power Distribution Network Planning Process

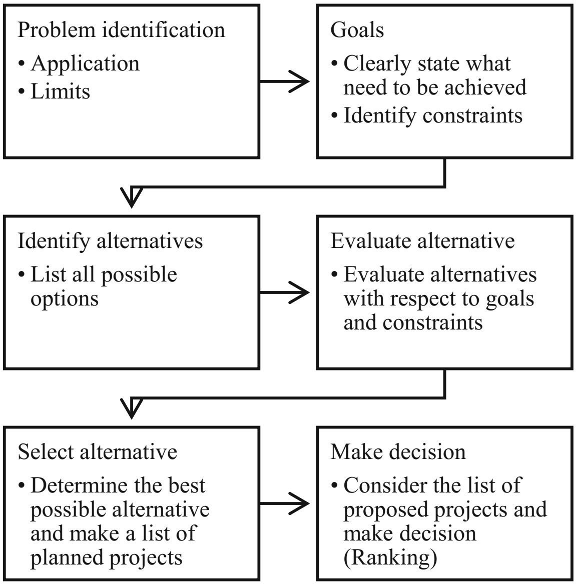
Certain managerial preferences are trade-offs, not hard constraints and need to be taken into considerations in order to make a balanced plan or decision [5]. Power distribution network planning requires analysis and management of large amount of data which need to be collected, processed and interpreted in a structured and systematic manner. The planning process requires that data be grouped to appropriate sets and subsets based on their attributes and characteristics. It is therefore justified to use advanced methods and tools to create a logical framework which will be used to determine a set of single valued criteria used for evaluation of electricity distribution network planning process. Such framework should include relative importance factors for each criteria which would be used to create a clear decision making algorithm. Their inclusion is not straightforward and it requires to use techniques designed for evaluation of qualitative aspects and vagueness or uncertainty [6] and multiple decision making criteria [3]. Fuzzy sets can be regarded as a tool which can be used to translate qualitative information into quantitative, crisp output [7].

Reference [8] shows that the main objectives of the planning process is the reduction of energy losses, voltage profile improvements, and the increase of reliability levels. Distribution planning process can be divided in two functional groups [9], namely exploitation (working) and construction and reinforcement planning. Reference [10] shows that distribution network process can be subdivided into following stages:

- problem identification which clearly defines applications and limits
- goals that need to be achieved
- identification of alternatives
- evaluations of alternatives
- selection of the best alternative
- make the final decision.

Figure 1 represents a simple illustration of the power distribution network planning process as described above. It shows various planning stages and their interaction.

Fig. 1 Simple illustration of the electrical power network planning process



Review of research problems as well as models related to the planning of the power distribution network is provided in [2]. More recently, a comprehensive review of modern power distribution planning has been provided in [11] and it includes overview of modern models, methods and future research trends.

Decision making process relevant to network planning requires a logical, well-structured and easy to follow framework which can be used to categorize features of particular set and subset. Such framework is necessary in order to perform data interpretation and alternative raking. This kind of framework can hardly be defined within limits of classical set theory. Aristotelian binary logics does not offer an adequate framework required to model a wide range of practical engineering problems because a particular element x, either belongs to a set A ($\chi_A = 1$) or it does not belong to a set A ($\chi_A = 0$). Such a sharp (hard) approach to membership and boundary definition between two sets is not suitable for modelling various physical processes because it reduces real and natural process to discrete ones. Substantial number of authors highlight obvious advantages of fuzzy set models over the deterministic model for power system planning purposes. There is also enough evidence to argue that probabilistic approach is difficult to apply to planning problem because of the lack of significant data and because uncertainty is not random. Reference [12] observed that classical mathematical programming is not sufficient in many applications. This fact is especially true in the area of long term planning and strategy problems since the nature of these problems considers multiple objectives on one hand and uncertainly on another [12]. In traditional planning methods, many coefficients are modelled as crisp values and such crisp conditions can result in solutions which are not realistic [2].

Fuzzy approach appears to be appropriate to address these issues because it can provide significant information in a single fuzzy model, while traditional deterministic models need to include a large number of scenarios in order to produce the same result. Certain level of deviations or violations might be tolerated and might lead to substantial savings [2]. It is therefore justified to adopt a fuzzy approach and design a new framework capable to address these issues. Such framework should include relative importance factors for each criterion which would be used to create a straightforward decision making algorithm. It is expected that modern planning includes a number of other factors such as environmental issues, distributed generation, asset management, and quality of supply [3]. The power distribution network planning process also requires modelling of system attributes as network development criteria. Rigorous application of classical set theory to modelling of attributes and criteria leads to similar problems of artificial reduction to discrete values. This is not optimal because the given physical processes are continuous. In practice, these issues are overcome by the application of expert knowledge because the human mind has a remarkable capability to make decisions based on incomplete and approximate information.

3 Fuzzy Sets Operations and Properties

In a classical set theory, belonging or membership of an object to a set is precisely defined quantity. The object either belongs to a set or it does not belong to a set, which means that membership function can either take a value of 1 (an object belongs to a set) or 0 (an object does not belong to a set). If for example we define two sets A = {x|x is weekday} and B = x {x|x is weekend} and if we were constrained to the framework of classical Aristotelian logic, we would agree that Monday, Tuesday, Wednesday, Thursday and Friday belong to set A, while Saturday and Sunday belong to set B. The world is therefore either white or black. This binary description of membership can be represented mathematically with the following function [13]:

$$\chi_A(x) = \begin{cases} 1, & \text{for } x \in A \\ 0, & \text{for } x \notin A \end{cases} \tag{1}$$

$$\chi_B(x) = \begin{cases} 1, & \text{for } x \in B \\ 0, & \text{for } x \notin B \end{cases} \tag{2}$$

However, human perception is quite different as it adopts a softer approach to boundary conditions. Fuzzy logic, as a mathematical tool, recognizes such approach to membership concept. It considers the values of graded (partial) membership, which can assume values between 0 and 1 and can, therefore, be used to model human perception. Fuzzy set, therefore, can be described as an extension of classical set theory with softer transition from one membership function to another.

Similarly, classical sets can be defined as a special case of a fuzzy set where all membership grades equal to 1. Friday, in this case, is still a working day, but only until the end of business hours. The weekend starts on Friday afternoon and therefore, in fuzzy terms, we could define Friday as an element of fuzzy set, described by membership function having a value of 0.66 in set A, and 0.33 in set B. Similarly, we can define Sunday with a membership of 0.66 in set B and 0.33 in set A. If we consider a classical set A of the universe U, a fuzzy set A is defined by a set or ordered pairs, a binary relation as [14]:

$$A = \{(x, \mu_A(x)) | x \in A, \mu_A(x) \in [0, 1]\} \tag{3}$$

In this case, $\mu_A(x)$ is a function called membership function and it specifies the grade or degree to which any element x in A belongs to the fuzzy set A. This definition associates, with each element x in A, a real number $\mu_A(x)$ in the [0, 1] interval, which is assigned to x. The mapping of a fuzzy set to a universe of membership values is performed using a function-theoretic form [13]. If universal set X is a finite set $X = \{x_1, x_2, \ldots, x_n\}$ and μ_i is a membership function of x_i in A, then a fuzzy set A can be represented as [14]:

$$A = \frac{\mu_1}{x_1} + \frac{\mu_2}{x_2} + \cdots + \frac{\mu_n}{x_n} = \sum_{i=1}^{n} \frac{\mu_i}{x_i} \tag{4}$$

Members $\frac{\mu_i}{X_i}$, $i = 1, 2, \ldots, n$ represent degree of membership μ_i of the element x_i to a fuzzy set A. If X is an infinite and continuous set, rather than discrete, with elements x (X, then fuzzy set A can be represented as [14]:

$$A = \int_{x \in X} \frac{\mu(x)}{x} \tag{5}$$

Let us define two fuzzy sets A and B on the universe X as shown in Fig. 2. The basic fuzzy set operations can be defined as:

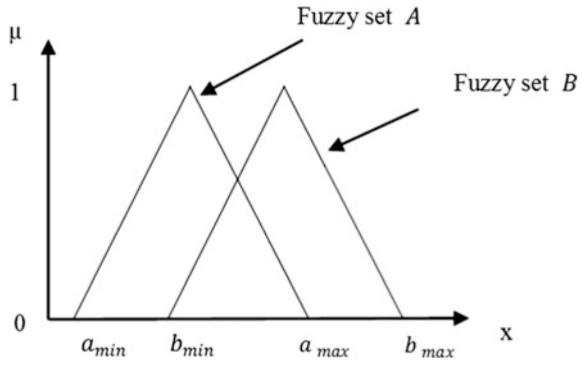


Fig. 2 Graphical representation of fuzzy sets A and B

- Union:

$$\mu_{A\cup B}(x) = \mu_A(x) \vee \mu_B(x) \tag{6}$$

Graphical representation of union of fuzzy sets A and B is shown in Fig. 3. In the Eq. 6 the sign ∨ represents the maximum operator, which means that union can be represented as:

$$\mu_{A\cup B}(x) = \mu_A(x) \vee \mu_B(x) = \max\{\mu_A(x), \mu_B(x)\} \tag{7}$$

- Intersection

$$\mu_{A\cup B}(x) = \mu_A(x) \wedge \mu_B(x) \tag{8}$$

Graphical representation of the intersection of fuzzy sets A and B is shown in Fig. 4. In the Eq. 8 the sign ∧ represents the minimum operator which means that intersection can be represented as:

$$\mu_{A\cup B}(x) = \mu_A(x) \wedge \mu_B(x) = \min\{\mu_A(x), \mu_B(x)\} \tag{9}$$

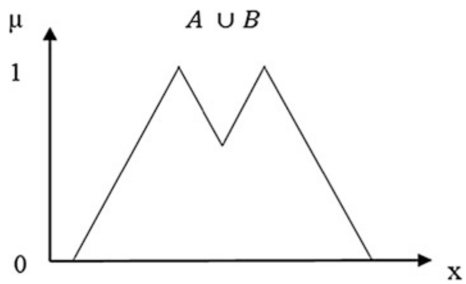


Fig. 3 Graphical representation of the union of fuzzy sets A and B

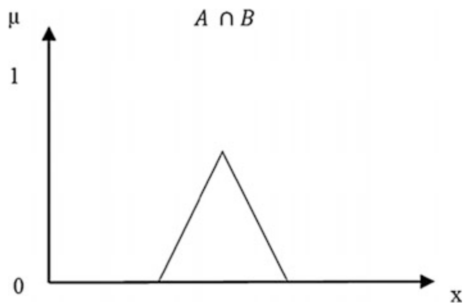


Fig. 4 Graphical representation of the intersection of fuzzy sets A and B

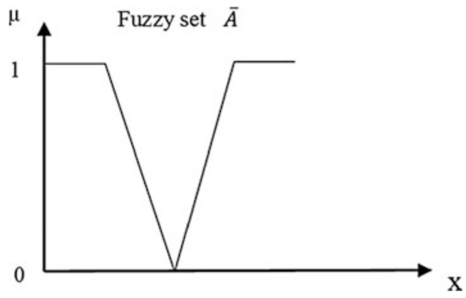


Fig. 5 Graphical representation of fuzzy set $\bar{A}$ (complement of A)

- Complement:

$$\mu_{\bar{A}}(x) = 1 - \mu_A(x) \tag{10}$$

Graphical representation of the complement of fuzzy set A is shown in Fig. 5.

All operations on classical sets are also true for fuzzy sets, apart from the excluded middle axioms. This property in the case of classical sets can be represented as $A \cup \bar{A} = X$ and it represents the fundamental difference between fuzzy and classical sets because a fuzzy set and its complement can overlap. Therefore, in the case of a fuzzy set, it can be written that:

$$A \cap \bar{A} \neq 0 \quad \text{and} \quad A \cap \bar{A} \neq X \tag{11}$$

Fuzzy sets display the same properties of crisp sets. Some of the most common properties are [13]:

- Commutativity

$$A \cup B = B \cup A \tag{12}$$

$$A \cap B = B \cap A \tag{13}$$

- Associativity

$$A \cup B(B \cup C) = (A \cup B) \cup C \tag{14}$$

$$A \cap (B \cap C) = (A \cap B) \cap C \tag{15}$$

- Distributivity

$$A \cup (B \cap C) = (A \cap B) \cap (A \cup C) \tag{16}$$

$$A \cap (B \cup C) = (A \cap B) \cup (A \cap C) \tag{17}$$

- Idempotency

$$A \cup A = A \quad \text{and} \quad A \cap X = A \tag{18}$$

- Identity

$$A \cap 0 = 0 \quad \text{and} \quad A \cap X = X \tag{19}$$

- Transitivity

$$\text{If} \quad A \subseteq B \quad \text{and} \quad B \subseteq C \quad \text{then} \quad A \subseteq C \tag{20}$$

- Involution

$$\overline{\overline{A}} = A \tag{21}$$

4 Fuzzy Models and Methods for Electrical Distribution Network Planning

Fuzzy apporach has been extensively used in distribution system planning [15], reconfiguration [8] and DG allocation problems [16]. Reference [17] develops a robust possibilistic mixed-integer programming method for planning applied to municipal electric power systems considering the uncertatitny. Fuzzy models for decision making behave more like expert systems than fuzzy control algorithms because they are modelled by human expert knowledge and can only be confirmed by testing their outcomes. Fuzzy models for decision making are implemented as control algorithms. Using crisp values as inputs and outputs of fuzzy rule based models in decision-making, significantly limits their ability to support decision-making [18]. Reference [5] found that there are three main reasons for incorporating expert systems in the planning process. First is the guidance of the decision making procedure by the knowledge and experience built up over many years by system planning engineer. Secondly, expert systems can be exploited to make the models more viable. Finally an extension and innovation is carried out within the expert system.

Reference [19] reports specification of fuzzy logic based knowledge modelling for development of decision support system which would be used to assist utility engineers in medium term outage planning. Reference [5] describes a long range power system expansion planning program which is an optimizing program and uses dynamic programming for tracking an optimal expansion strategy, a rule based decision making mechanism to incorporate engineering and fuzzy set theory has which is used to define decision making procedure. Reference [17] proposes a fuzzy multi-criteria group decision-making method for power distribution system planning evaluation. It considers technology, economy, society and environment as evaluation aspects with 8 evaluation criteria. This contribution determined that the engineering practice is more complex since quantitative values of criteria are often difficult to determine. Additional criteria need to be determined and modelled. There is therefore a considerable gap between existing model and what is required in order to represent other important aspects of modern distribution system planning and create practical and robust expert system which can be extensively used in practice. Reference [20] presents a computational system used to assist decision makers in the process of the power distribution network planning and designs a single objective optimization model with technical and economic considerations, a multi-objective model which considers various aspects and, finally, a fuzzy mathematical programming model which takes into consideration fuzzy goals and constraints. Reference [21] develops a fuzzy method used to improve operational planning efficiency of the distribution network, based on indices of economic feasibility and service quality. Reference [22] presents a fuzzy knowledge-based approach for reliability planning purposes as it makes the assessment of circuit configuration and hazards and assigns each section and feeder a relative risk index by expressing the configuration variables mathematically using fuzzy logic. Reference [23] defines mathematical operations by the extension principle and proposes the way to model the partial correlation between variables and that fuzzy numbers provide a good way to include non-statistical uncertainties in the decision making process.

Reference [3] describes a method for the power distribution network planning which considers load growth, distributed generation, asset management, quality of supply and environmental issues by using a number of discrete evaluation criteria within a multi criteria decision making (MCDM) environment to examine and assess the trade-offs between alternative solutions. Reference [3] demonstrates suitability of MCDM techniques to the distribution planning problem and highlight how evaluating all planning problems simultaneously can provide substantial benefits to a distribution company. Reference [24] introduces comprehensive evaluation hierarchy which includes system security, reliability, economic profit, supply capability and derivative capability. The proposed model is based on fuzzy sets, introduced in order to account for the lack of suitable quantitative evaluation method to the connection model. Evaluation includes indices such as maximum short circuit current, maximum voltage drop, voltage shift, ASAI and SAIDI which are described by fuzzy sets. This paper shows that it is possible to identify key elements influencing network planning and evaluate connection modes quantitatively.

Fuzzy approach has been used in a few closely related fields such as power system stability and control, load forecasting, monitoring, diagnosis and market design [25]. A fuzzy reasoning approach is also used in numerous papers written on the topic of the service restoration, which is a multiple-objective problem with some objectives contradictory to each other [26]. Reference [27] discusses a new expert model for decision making process in electrical outage management while [28] shows a fuzzy expert system for the integrated fault diagnosis. Reference [29] designed a fuzzy model which can be used in the management of the water supply system planning process. Reference [30] develops a decision-making fuzzy control model for small and medium enterprise, which can be used in an ambiguous environments to train company's strengths and develop long term strategy. Reference [31] presents the improvements of the fuzzy load models with the application of fuzzy clustering techniques for the distribution networks planning.

5 Model Development

Figure 6 shows a simplified structure of the proposed systems and interaction of its major components while Fig. 7 show a simple graphical representation of Mamdani type inference. Three major attributes, namely the number of customers, rate of failure and age of distribution line, are evaluated in two separate, Mamdani type inference models. In the first model, reconstruction criteria is evaluated according to

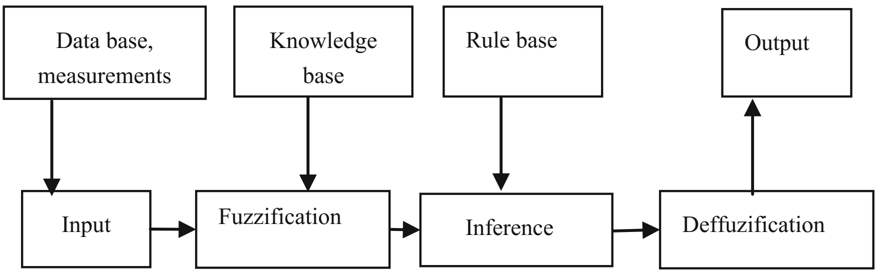


Fig. 6 Simple graphical representation of the proposed fuzzy systems

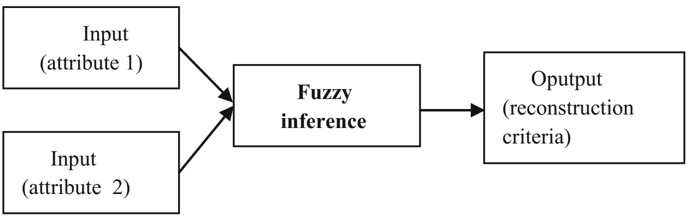


Fig. 7 Graphical representation of Mamdani type fuzzy inference

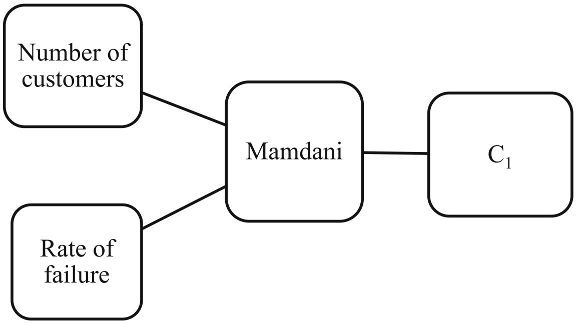


Fig. 8 Model 1-criteria based on number of customers and failure rate

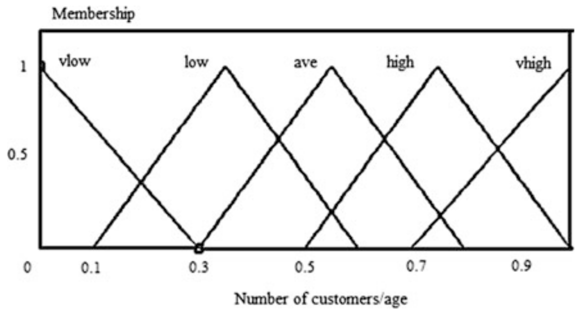


Fig. 9 Fuzzy set representation of number of customers and age

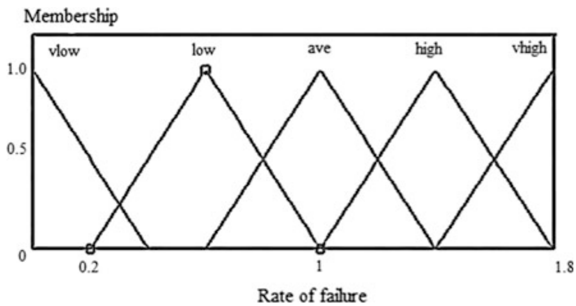


Fig. 10 Fuzzy set representation of failure rates

the logics shown in Fig. 8. The number of customer data (first input variable) and quantitative measure of failure rates (second input variables) are both represented by fuzzy sets, as shown in Figs. 9 and 10. The output value of the first Mamdani type model represents the value of the first planning criteria C1. In the second Mamdani type inference model, the input attributes are age of distribution power line and respective failure rates. These two attributes are combined according to the logic shown in Fig. 12 and provide the output variables of fuzzy system which is used to estimate the condition of the line in question. This output variable represents the second reconstruction criteria, C2.

Electricity outages are unwelcome and unpleasant events which, apart from inconvenience, might cause serious damages. Number of customers served by network section (power line) is a quantitative criteria which considerably influences the risk for utility in the case of service interruptions. If a power line serves large number of customers and if its failure rate is high, then risk faced by utility is high. This type of infrastructure should be given priority considerations during the service restoration and reconstruction planning process. This system attribute is fuzzified as shown in Fig. 9. In proposed model, customer number values are normalized into 0–1 range, where 1 is maximum, corresponding to 1000 customers and 0 is minimum, corresponding to 0 customers. This attribute is combined with rate of failure value, in order to obtain C1. This attribute is represented by fuzzy set as follows:

$$\mathrm{NC} = \{\mathrm{A}_1, \mathrm{B}_1, \mathrm{C}_1, \mathrm{D}_1, \mathrm{E}_1\} \tag{22}$$

$$\mathrm{NC} = \{\text{very low, low, average, high, very high}\} \tag{23}$$

The second attribute used as input in this model is rate of failure, given by λ. Conductor aging and deterioration is a physical and chemical process which causes irreversible alterations of conductor mechanical and electrical properties. Major factors which determine the speed of such deteriorations are temperature, pollution, quality of storage and installation and finally, loading conditions which considerably contribute to conductor heating. System security depends on security and performance of its individual components. Reliability considerations are important part of planning and development process. In proposed model, the probability of an event is represented by rate (intensity) of failure defined as [32]:

$$\lambda = \frac{\text{number of failures}}{\text{number of components} \times \text{number of years}} \tag{24}$$

It was shown in [32] that the average and maximum sustained failure rates for cables and overhead lines are (0.93/100 km, year) and (1.81/100 km, year) respectively. Values for overhead lines are used in model, represented by set (shown in Fig. 10):

$$\mathrm{RF} = \{\mathrm{A}_2, \mathrm{B}_2, \mathrm{C}_2, \mathrm{D}_2, \mathrm{E}_2\} \tag{25}$$

$$\mathrm{RF} = \{\text{very low, low, average, high, very high}\} \tag{26}$$

Third attribute is modelled according to the same logic, with 1 being the maximum value corresponding to 60 years of age. It is shown in Fig. 9 and can be represented by a fuzzy set in following way:

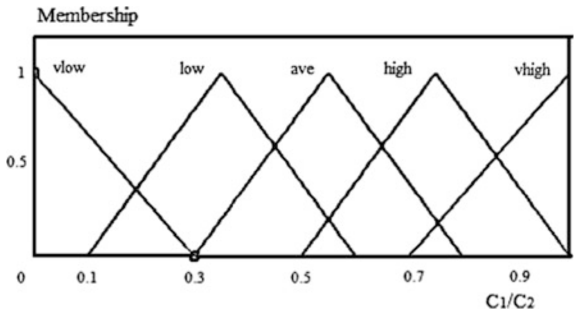


Fig. 11 Fuzzy set representation of the output variables

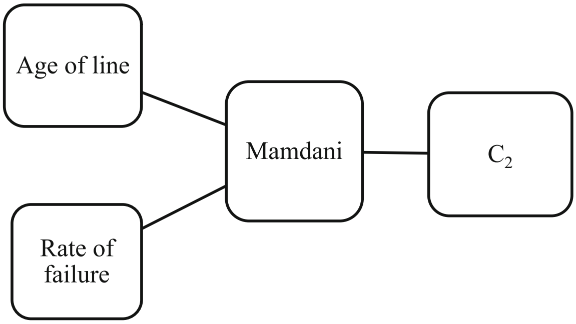


Fig. 12 Model 2-criteria based on the distribution line condition

Table 1 Fuzzy rules for models 1 and 2

Rate of failure	Number of customers/age				
	Vlow	Low	Ave	High	Vhigh
Very low	VL	VL	L	L	L
Low	VL	L	A	H	VH
Average	L	A	H	H	VH
High	L	A	H	H	VH
Very high	L	A	H	VH	VH

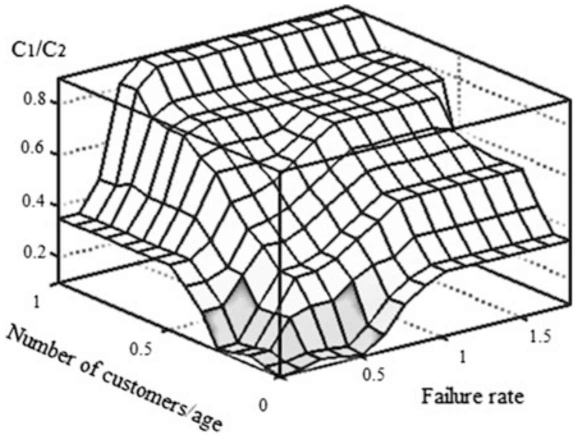
$$AGE = \{A_3, B_3, C_3, D_3, E_3\} \tag{27}$$

$$AGE = \{\text{very low, low, average, high, very high}\} \tag{28}$$

Finally, output variables, C_1 and C_2 as shown in Fig. 11 are used as criteria in power network reconstruction process and are represented by following fuzzy sets (Fig. 12):

$$C_1 = \{A_4, B_4, C_4, D_4, E_4\} \tag{29}$$

Fig. 13 Surface viewer



$$C_1 = \{\text{very low, low, average, high, very high}\} \quad (30)$$

$$C_2 = \{A_5, B_5, C_5, D_5, E_5\} \quad (31)$$

$$C_2 = \{\text{very low, low, average, high, very high}\} \quad (32)$$

Table 1 shows n x m IF…AND…THEN rules, where n and m are the numbers of elements of input variable sets, giving a total of 25 rules. These rules are used to obtain the output variable described by the sets C_1 and C_2. Rules are the same in both models. Final simulation results can be summarized in surface viewer shown in Fig. 13 which, for a given value of number of customers (or age) and rate of failure, returns the value C_1 and C_2 respectively.

Control output value are used to grade entire network according to these criteria, thus providing a model for project selection and priority ranking. This method is particularly useful in applications such as distribution network planning, where large amount of data need to be processed.

6 Application Example

Figure 14 shows a single line diagram of a simple power distribution system. The values relevant for application demonstration are listed in Table 2. It can be seen that crisp values are obtained as criteria for ranking distribution system reconstruction project. Proposed system can be used as a business analysis/intelligence tools and decision making support tool. The list of possible criteria is obviously not exhausted by the attributes proposed in this model. It is possible to extend the existing model to include any other criteria required by decision maker. One of the characteristics associated with planning problem is the trade of between different

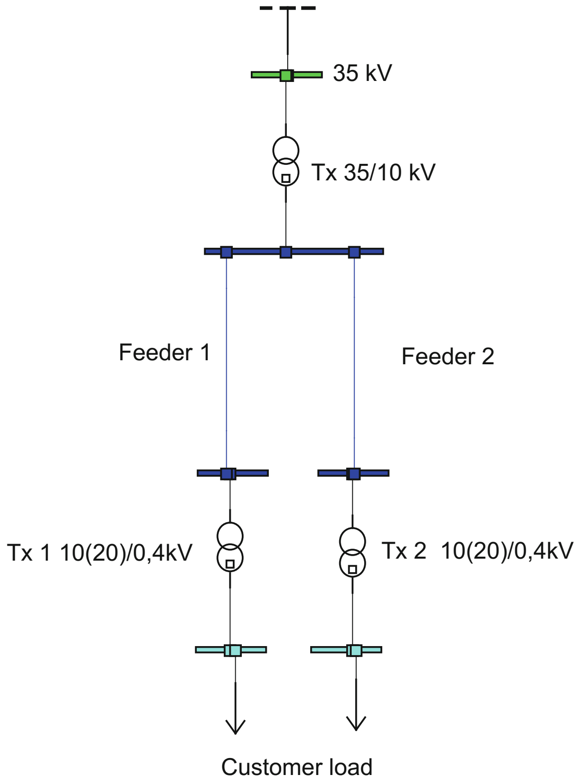


Fig. 14 Single line diagram of simple power distribution network

Table 2 Model application results

Line name	Number of customers	Failure rate (km, year)	Age of the line (years)	Criteria 1	Criteria 2
Feeder 1	481	1.2	18	0.71	0.55
Feeder 2	111	0.8	48	0.28	0.75

planning criteria. One possible way to resolve the conflict between criteria is use of fuzzy MCDM. In order to make decision it is necessary to construct a decision making matrix M where each column represents a particular alternative and each row corresponds to a particular criteria.

More formally, each element of a decision making matrix M represents a ranking of an alternative X_i with respect to a criteria C_j. For the case of m criteria (C_1, C_2, …, C_m) an n alternatives (X_1, X_2,…, X_n), decision matrix M is [29]:

$$M = \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_m \end{array} \begin{array}{c} \begin{array}{cccc} X_1 & X_2 & \dots & X_n \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \end{array} \tag{33}$$

For fuzzy set of goals G_g, where r is the number of goals, it can be written that:

$$G_g = \sum_{i=1}^{n} \frac{\mu_{Gg}(x_{gi})}{X_i} \Bigg|_{g=1}^{g=r} \tag{34}$$

Similarly for constraints fuzzy sets C_c, where h is the number of constraints, it can be written that:

$$C_c = \sum_{i=1}^{n} \frac{\mu_{Cc}(x_{r+c,i})}{X_i} \Bigg|_{c=1}^{c=h} \tag{35}$$

Decision set is given by the intersection of fuzzy goals and fuzzy constraints and can be represented as follows [29]:

$$D = G_g \cap C_c = \sum_{i=1}^{n} \frac{\mu_{Gg}(x_{gi})}{X_i} \Bigg|_{g=1}^{g=r} \bigcap \sum_{i=1}^{n} \frac{\mu_{Cc}(x_{r+c,i})}{X_i} \Bigg|_{c=1}^{c=h} \tag{36}$$

Fuzzy sets intersection is defined according to [29]:

$$D = G_g \cap C_c = \min \left(\min_{g=1,r} \left(\mu_{Gg}(x_{ij}) \right), \min_{c=1,h} \left(\mu_{Cc}(x_{ij}) \right) \right) \tag{37}$$

7 Conclusion

Fuzzy logic control and MCDM have developed rapidly since 1970 and have been a very vibrant field of research. This is a mature field and there are still numerous areas where fuzzy logic could be applied. Availability of fuzzy criteria is necessary for application of fuzzy MCDM. Including uncertainty in the process of decision making optimizes the social cost of network expansion and is therefore beneficial for electricity customers and society. This paper presented a simple fuzzy system used for management of the power distribution network reconstruction process. The proposed model considers set of the criteria based on the number of customers served by the line, rate of failure and age. The decision making process is based on the Bellman-Zadeh method in which decision making is accomplished by the intersection of fuzzy goals and constraints. Output values of the proposed fuzzy system are used inputs to decision making matrix (criteria). It is argued that this paper makes a contribution toward more effective management of power distribution network planning process and that there is an opportunity to further investigate the application of fuzzy control in the process of power distribution network planning.

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