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Fuzzy-based Intelligent Approach for Enhancing Stakeholder Engagement and Strategic Decision-Making in Nuclear Programs

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Abstract

This study presents a fuzzy-based intelligent model to improve stakeholder engagement in nuclear power program by strategic and data-driven decisions to manage the uncertainty, complexity, and subjectivity involved. The model considered four key factors as input: stakeholder trust (ST), risk perception (RP), communication quality (CQ), and engagement effectiveness (EE), collected from various stakeholders. Input factors influence two key outcomes: (i) Strategic decision alignment (SDA), which describes how well decisions align with stakeholder needs and organizational goals, & (ii) stakeholder satisfaction (SS), which describes how satisfied stakeholders are with the decision-making process. A Fuzzy Inference System (FIS) is applied to handle uncertainties in stakeholder dynamics and communication which also enables decision-makers to identify potential misalignments and areas for improvement for specific targeted groups. To evaluate the conditions of all stakeholders, the distinct fuzzy outputs for every group are incorporated into an integrated system to easily identify specific interventions towards specific stakeholders in order to facilitate trust, enhance communication and achieve more coordinated decision-making. This flexible approach allows adapting engagement strategies based on dynamic stakeholder views and external factors.

Keywords: Stakeholder engagement, Nuclear power, SDA, Fuzzy inference system, and Risk perception.

1. Introduction

Although nuclear energy has the capability of providing the society with reliable low-carbon energy, its popularity and popularity among the population remains a significant challenge, particularly among the developing countries. Concerns about managing radioactive waste, high capital expenditure costs, and anxieties related to previous nuclear accidents like the ones at Three Mile Island (TMI), the Chernobyl Nuclear Power Plant, and the Fukushima Daiichi Nuclear Power Plant are frequently the main factors influencing stakeholder viewpoints. The fact that radiation is undetectable adds to these worries by making people feel more anxious and vulnerable. All newcomer countries should overcome these challenges by improving knowledge sharing regarding the advan-

tages of nuclear power and, at the same time, overcome the myths and minimize the fear of the population of the effects of radiations and nuclear accidents. The negative perception of stakeholders in the past has proven that the perception may be a major impediment or even a barrier to nuclear power projects, which translates into the long-term economic and strategic loss to the country. For example, Austria completed the construction of its nuclear power plant but never brought it into operation for electricity generation following a public referendum (Kirchhof, 2020). And Poland faced great challenge in 1990 to construct their first nuclear power plant "Żarnowiec Nuclear Power Plant" due to its strong opposition from the environmental activists and other mix reasons like profitability, financing issues and government ended the project that time (Szulecka & Szulecki, 2017). It became extremely hard to restart the construction of nuclear power plants in Japan after the 2011 calamity that struck the Fukushima Daiichi Nuclear Power Plant due to the introduction of stringent precautionary steps post the economic disaster and the protracted of regulatory inspections. Several future nuclear developments were postponed as a result of both rising compliance costs and the heightened scrutiny of the Nuclear Regulation Authority and the need to restore confidence in the community (Japan Atomic Industrial Forum, 2023; Ebrahimifard *et al*., 2024).

According to a study of Japanese public perception polls conducted over a 30-year period, opposition to nuclear power generation (NPG), which was formerly steady at 20–30%, increased to 70% in the four to six months following Fukushima, which coincided with increased popularity of renewable energy. Although 60 percent perceived NPG as essential and confirmed its usefulness in the case of power shortage anxieties, post-accident panic, mistrust, and risk aversion were increased, and little was known about NPG reduction trade-offs or willingness to accept renewable-induced electricity price increases (Kitada, 2016). The nuclear power initiative should be committed in ensuring the awareness and support of the technology and science to serve the interest of the population. The perceptions of local communities and key stakeholders must be carefully addressed, regardless of whether those perceptions are technically justified or not.

Numerous parties with various responsibilities and functions are involved in a nuclear power program. Broadly, the government initiates the program, which is implemented by the nuclear power operating organization and overseen by the nuclear regulatory body. In addition, numerous other entities-including environmental agencies, security forces and intelligence agencies, fire services, Universities, NGOs, local governments and municipalities, hospitals and medical sectors, and, most importantly, the local community - play key roles (IAEA, 2011). To achieve maximum support and commitment, all stakeholders must work and engaged simultaneously in their respective roles, coordinating effectively to ensure the safety and security of the plant. A nuclear power project's progress can be hampered by any change in enthusiasm, ignorance of technical or scientific concerns, or nervousness among stakeholders. These factors can also affect public opinion. To effectively engage all stakeholders, different organizations should take proactive initiatives to ensure the highest level of commitment, coordination, and motivation. This study uses fuzzy logic based intelligent system to design and improve the stakeholder participation in nuclear power initiatives. By using opinion-based findings gathered from organized surveys, interviews, and recorded documents, the suggested structure unifies various stakeholder groups. The statistical variables that are generated from these data and utilized as inputs to the fuzzy inference system (FIS) are stakeholder trust (ST), risk perception (RP), communication quality (CQ), and engagement effectiveness (EE). The model evaluates stakeholder satisfaction and strategic decision coherence by examining these inputs, pointing out areas that require consideration in the engagement procedure.

The results of the model can be implemented through timely and targeted interventions targeted at specific stakeholder groups. To resolve the ambiguities in the perception and communication process of the stakeholders, the fuzzy inference system (FIS) systematically maps the input parameters to the helpful decision-support outputs. The study results for each stakeholder group may be combined to evaluate stakeholder satisfaction and the overall alignment of strategic choices. Targeted corrective action can then

be implemented when the stakeholder groups that need improvements have been identified.

2. Review of Literature

The nuclear sector presents a difficult situation in making decisions because of the presence of various stakeholders, high safety standards, long duration of nuclear projects, and high degree of uncertainty that comes with nuclear power development. Successful decision making thus goes beyond technical and financial aspects to cover the perception of the stake holders, risk communication, regulatory limitations, and wider socio-political elements. Nevertheless, the classical sharp decision-making models are not always able to reflect the ambiguity and subjectivity of such complex and multidimensional scenarios.

In an attempt to overcome such limitations, fuzzy logic has proved to be an effective strategy modeling uncertainty and making informed choices concerning strategies. Fuzzy logic offers a mathematical frame- work to deal with linguistically expressed and imprecise data in that it can be a member of a set partially as opposed to a binary classification (Zadeh, 1965). This property renders it especially appropriate in decision settings that are typically characterized by human judgment, expert opinion and qualitative evaluations. In the nuclear sector, several investing- ations have used fuzzy-based decision-making models in the selection of sites, technology and also safety issues. As an example, fuzzy multi-criteria decision- making (MCDM) models have been employed to evaluate the appropriateness of nuclear power plant (NPP) locations by considering environ- mental effects, seismic risk, economic viability and social acceptance aspects (Abdullah *et al.*, 2023).

Fuzzy logic in such studies also helps decision- makers to overcome uncertainties in expert ratings and stakeholder interests than the deterministic methods. On the same note, hybrid fuzzy systems have been suggested that integrate approaches like Fuzzy VIKOR and Fuzzy Analytic Hierarchy Process (FAHP) to rank among the alternative nuclear sites and technologies thus enhancing the strength of the strategic planning process in face of uncertainty (Das, Kumar, & Dutta, 2024). In addition to technical planning, the stake holder engagement has also been incorporated into risk-informed decision-making frameworks. Branko *et al.* (Branko *et al.*, 2022) illustrated the use of a structured framework where risk assessment is integrated with engaging stake- holders using case studies of naturally occurring radioactive material (NORM) and nuclear legacy sites. Their framework is effective in helping to have participative and transparent decision making, but is mostly qualitative and lacks quantitative representations of stakeholder preferences and uncertainties. This shortcoming identifies a research gap on the development of advanced decision-support frame- works like fuzzy logic-based or multi-criteria frame- works that can be able to systematically capture stakeholder uncertainty and build robust risk-based decision-making.

The management of nuclear as well as radiological emergencies also requires transparency and an effective stakeholder engagement. Perko *et al*. (Perko, Martell, & Turcanu, 2020) also analyzed the concept of transparency, information sharing, and stakeholder participation in emergency management and revealed that all these factors greatly contribute to increased trust and quality of choices when faced with a nuclear or radiological emergency. Nevertheless, they are mainly interested in qualitative and governance approaches and do not include formal risk-informed or quantitative decision-support systems. These also provide support to the necessity of integrated frame- works that combine stakeholder engagement with powerful and quantitative decision-making methodo- logies in nuclear and radiological settings. The system based on fuzzy logic can also be applied in the evaluation of a chemical hazard assessment and avert the hazard in various industries sector.

The Aziz, A *et al.* (Aziz *et al.*, 2025) research sug- gested a fuzzy logic-based system to assess the risk and estimate the degree of precaution when handling explosive, flammable, and toxic chemicals The suggested system can properly address uncertainty in the severity of hazards, the nature of exposure, and human judgement, and it can be considered a strong way to use fuzzy logic in making decisions that are safety-related. Nonetheless, the framework is mainly concerned with the technical analysis of risks and the estimation of precautions and lacks the consideration of the involvement of stakeholders, regulatory views,

and social-political aspects of the decision-making process.

The paper could not collect the real-world data from the chemical factories as there is lack of ability to measure the risk parameters in country like Bangladesh. There could be a research opportunity to develop a more robust model for measuring the intensities of the hazardous properties. The integration of stakeholder judgment with fuzzy logic was examined by Kraidi *et al.* (Kraidi *et al.*, 2020). Their research shows the fuzzy logic is a practical approach that can integrate expert and stakeholder views in determining the risk factor on complex and uncertain factor, which will improve the credibility of the infrastructure risk assessment. Relative to this work, the authors formulated a Computer-Based Risk Analysis Model (CBRAM) that is based on the theory of fuzzy logic in order to analyze the factors that affect risk systematically. The findings of the CBRAM have determined the most essential risk factors, especially those that were closely linked with the stakeholder judgment and the problems of data scarcity.

Moon *et al.* (Moon *et al.*, 2024) applies the fuzzy-Analytic Hierarchy Process (AHP) method to prioritize structural and human-related risks in dismantling radioactive concrete structures, identifying collision, jamming, and falling objects as critical hazards. Stakeholder engagement and more comprehensive risk-informed strategic decision- making are not included in the approach, which primarily concentrates on operational risk assessment even though it successfully supports task-level safety prioritization. This brings out the necessity of integrated fuzzy-based systems incorporating technical risk evaluation with stakeholder-oriented governance in nuclear programs.

The above literature shows that fuzzy logic is efficient in providing the uncertainty modeling and technical risk assessment (Hossain *et al.*, 2018) in the nuclear and other safety-related industries whereas independent research emphasizes the significance of stakeholder involvement and disclosure. Nevertheless, there are still isolated strategies, and few are using quantitative fuzzy models and formal involvement of stakeholders. Thus, there is a research gap in the development of a holistic fuzzy logic framework that will integrate the element of risk-informed analysis and stakeholder involvement in strategic decision-making in nuclear programs.

3. Methodology

Overall System Architecture

This proposed model is designed to evaluate strategic decision alignment (SDA) and stakeholders' satisfaction (SS) by gathering the concerns from all stakeholder groups of a new build nuclear power plant, taking into consideration the input variables Stakeholder's Trust (ST), Risk Perception (RP), Communication Quality (CQ), and Engagement Efficiency (EE). These input variables are the information that may be collected from the stakeholders' part. Accumulated data can then be processed by different methods like distribution analysis, mean approach, or weighted center to identify the input values for fuzzification. These discrete values of input are then converted to linguistic variables via a fuzzification interface with predetermined membership functions. **Fig. 1** represents the proposed model that was studied in the research.

$$SDA/SS = (ST, RP, CQ, EE) \quad (1)$$

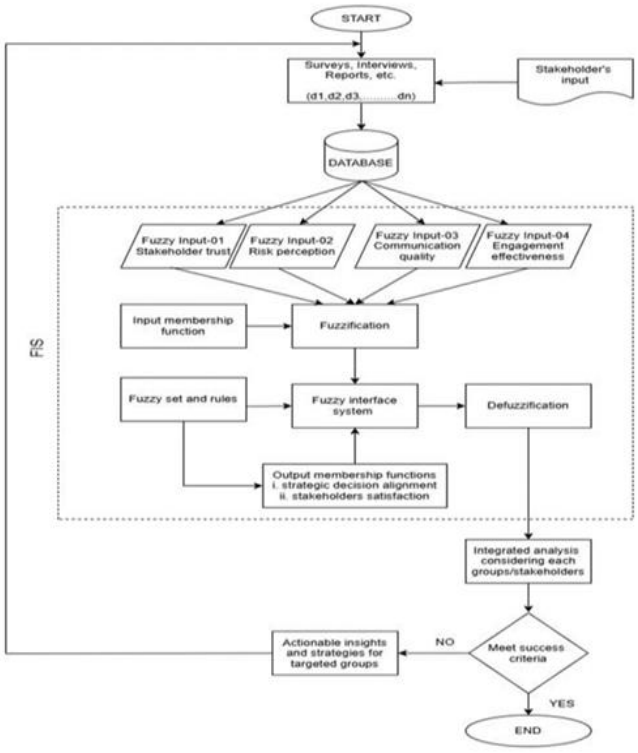

Fig. 1: Flow chart of the Fuzzy Logic-Based Framework for nuclear stakeholder engagement and decision-making approach.

A rule-based inference engine that is built on the principles of the expert knowledge evaluation and interaction with stakeholders is used to assess the interaction between the input variables. The results of the fuzzy inference are then pooled and transformed to crisp outputs to Strategic Decision Alignment (SDA) and Stakeholder Satisfaction (SS) through a defuzzification strategy. Equation (1) is applicable to evaluate SDA and SS. The last step in the process is the analysis of the outputs at the individual stakeholder-group and integrated system levels in order to detect misalignments and implement specific, evidence-based engagement strategies.

Implementation of Fuzzy Inference System (FIS)

This assessment model uses a Mamdani type fuzzy interface system. To implement this FIS model to establish stakeholder engagement enhancement, the dataset made from taking inputs from the stakeholders used for input of this model. These four input variables (ST, RP, CQ & EE) are taken as input for fuzzification process. By fuzzification process, all the non-fuzzy inputs (crisp values) convert into fuzzy inputs in the fuzzy inference system. It is a fundamental component in the implementation of the fuzzy system, as it allows the necessary information to be provided that the interference engine needs in order to make a decision. In a typical fuzzy system based on fuzzy logic, crisp inputs are converted into a fuzzy set by the use of a membership function. In this research, the membership function maps the input into a range from 0 to 10, representing how well the input maps into a specific fuzzy category. This allows the fuzzy system to deal with the inherent uncertainty in the inputs in a much more effective way, leading to a smoother, more adaptive, and more human-like decision-making process. For input and output parameters, three possible linguistic variables "Low", "Medium" and "High" were used. If more input variables have been used for interface rules, the system would become more complex and vice versa. To use fuzzification, several ways are there like triangular, trapezoidal, and Gaussian membership functions. The categories of language were modeled into trapezoidal membership functions to represent the type of "Low" and "High" and triangular membership functions were considered to represent the category of Medium to the input variables due to the simplicity of these functions, modeling efficiency and the appropriateness of the functions in getting the system representation. A similar way has been adopted for membership function selection of output variables. In this study, the Mamdani method of max–min inference and the centroid method of center of gravity defuzzification were used, as they offer smooth and continuous interpolation between the output values of the two rules. The FIS rule editor was then used to optimize and modify the rule base, as necessary. The system is designed with four input variables (ST, RP, CQ & EE) and two outputs (CQ & SS) resulting from the 'IF' and 'THEN' rules which relate the input and outputs. A number of 81 fuzzy interface rules are applied to the system based on expert knowledge to gain the results. The rue editor used in the FIS model is shown in Fig. 3 a general fuzzy "IF–THEN" rule can be expressed as follows (Equation 2):

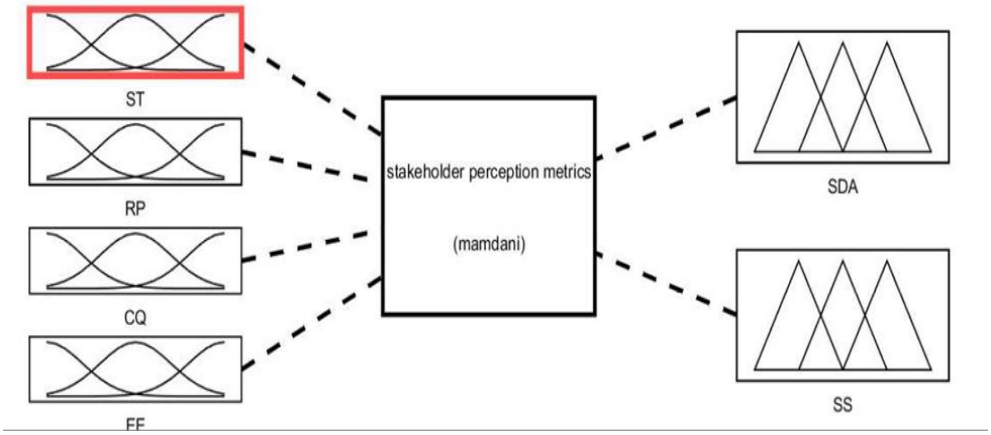

Fig. 2: FIS for Stakeholder perception metrics.

Fig. 2 displays the FIS for Stakeholder perception metrics in the case of four inputs and two outputs.

IF ST is….. **AND** RP is ….. **AND** CQ is ….. **AND** EE is ….. **THEN** CQ is ….. **AND** SS is…….. (2)

To demonstrated fuzzification process, linguistic expression for trapezoidal and triangular membership functions are described by the following equations (3) and (4).

$$\mu_{triangular}(x;\ c_1, c_2, c_3) = \begin{cases} 0; & x \leq\ c_1 \\ \frac{x-c_1}{c_2-c_1}; & c_1 \leq x \leq\ c_2 \\ \frac{c_3-x}{c_3-c_2}; & c_2 \leq\ i_1 \leq\ c_3 \\ 0; & x \geq 4.5 \end{cases} \quad (3)$$

$$\mu_{trapezoidal}(x;\ c_1, c_2, c_3, c_4) = \begin{cases} 0; & x \leq\ c_1 \\ \frac{x-c_1}{c_2-c_1}; & c_1 \leq x \leq\ c_2 \\ 1; & c_2 \leq\ x \leq c_3 \\ \frac{c_4-x}{c_4-c_3}; & c_3 \leq\ x \leq c_4 \\ 0; & x \geq\ c_4 \end{cases} \quad (4)$$

Where, x is the input and output variables and c_1, c_2, c_3, c_4 are the coefficients of membership functions. Linguistic expressions and their membership functions (MFs) for the four inputs (ST, RP, CQ & EE) and two outputs (SDA, SS) in equation form are defined in Equations 5(a, b, c), 6(a, b, c), 7(a, b, c), 8(a, b, c), 9(a, b, c) and 10(a, b, c) respectively.

Domains of all inputs are taken to be [0, 10]. These equations are well distributed in the sense that it is an existing fuzzy set with overlapping sets that cover the domain [0,10] without the sharp jumps.

Stakeholder Trust (ST)

- Low (L): trapezoidal

$\mu_{ST,\ low}(x) = \mu(x; 0,0,2.5,4)$ (5a)

- Medium (M): triangular

$\mu_{ST,\ medium}(x) = \mu(x; 2.5,5,7.5)$ (5b)

- High (H): trapezoidal

$\mu_{ST,\ high}(x) = \mu(x; 6,7.5,10,10)$ (5c)

Risk Perception (RP)

- Low (L): trapezoidal

$\mu_{RP,\ low}(x) = \mu(x; 0,0,2.5,4)$ (6a)

- Medium (M): triangular

$\mu_{RP,\ medium}(x) = \mu(x; 2.5,5,7.5)$ (6b)

- High (H): trapezoidal

$\mu_{RP,\ high}(x) = \mu(x; 6,7.5,10,10)$ (6c)

Communication Quality (CQ)

- Low (L): trapezoidal

$\mu_{CQ,\ low}(x) = \mu(x; 0,0,2.5,4)$ (7a)

- Medium (M): triangular

$\mu_{CQ,\ medium}(x) = \mu(x; 2.5,5,7.5)$ (7b)

- High (H): trapezoidal

$\mu_{CQ\ high}(x) = \mu(x; 6,7.5,10,10)$ (7c)

Engagement Effectiveness (EE)

- Low (L): trapezoidal

$\mu_{EE,\ low}(x) = \mu(x; 0,0,2.5,4)$ (8a)

- Medium (M): triangular

$\mu_{EE,\ medium}(x) = \mu(x; 2.5,5,7.5)$ (8b)

- High (H): trapezoidal

$$\mu_{EE,\ high}(x) = \mu(x; 6,7.5,10,10) \quad (8c)$$

Strategic Decision Alignment (SDA) - $y \in [0,10]$

Low (L) – trapezoidal (x; 0,0,2.5,4.5)

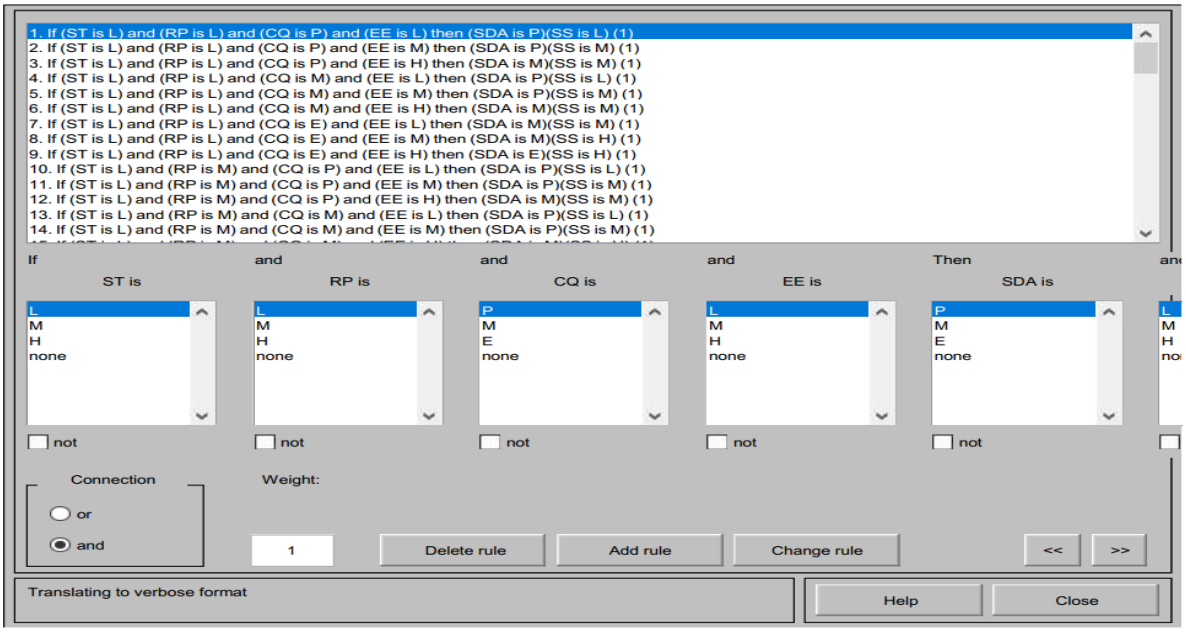

Fig. 3: Rule editor of FIS system.

$$\mu_{SDA,low}(x) = \begin{cases} 0; & x \leq 0 \\ 1, & 0 \leq x \leq 2.5 \\ \frac{4.5-x}{2}, & 2.5 \leq x \leq 4.5 \\ 0, & x \geq 4.5 \end{cases}$$

(9a)

Medium– triangular (x; 4.0, 5.6, 7.0)

$$\mu_{SDA,Medium}(x) = \begin{cases} 0, & x \leq 4.0 \text{ or } x \geq 7.2 \\ \frac{x-4.0}{1.6}, & 4.0 \leq x \leq 5.6 \\ \frac{7.2-x}{1.6}, & 5.6 \leq x \leq 7.2 \end{cases}$$

(9b)

High - trapezoidal (x; 7.5, 9, 10, 10)

$$\mu_{SDA,high}(x) = \begin{cases} 0; & x \leq 7.5 \\ \frac{x-7.5}{1.5}, & 7.5 \leq x \leq 9.0 \\ 1, & 9.0 \leq x \leq 10.0 \\ 0, & x \geq 10 \end{cases}$$

(9c)

Stakeholder Satisfaction (SS) - $y \in [0,10]$

Low – trapezoidal (y; 0,0,2.0,4.5)

$$\mu_{SS,\ low}(y) = \begin{cases} 0; & x \leq 0 \\ 1, & 0 \leq x \leq 2.0 \\ \frac{4.5-x}{2.5}, & 2.0 \leq x \leq 4.5 \\ 0, & x \geq 4.5 \end{cases} \quad (10a)$$

Medium – triangular (y; 4.1, 5.6, 7.6)

$$\mu_{SS,\ Medium}(x) = \begin{cases} 0, & x \leq 4.1 \text{ or } x \geq 7.6 \\ \frac{x-4.1}{1.6}, & 4.1 \leq x \leq 5.7 \\ \frac{7.6-x}{1.9}, & 5.7 \leq x \leq 7.6 \end{cases}$$

(10b)

High - trapezoidal (x; 7.0, 8.6, 10, 10)

$$\mu_{SS,\ High}(x) = \begin{cases} 0; & x \leq 7.0 \\ \frac{x-7.0}{1.6}, & 7.0 \leq x \leq 8.6 \\ 1, & 8.6 \leq x \leq 10.0 \\ 0, & x \geq 10 \end{cases}$$

(10c)

The input variables (ST, RP, CQ & EE), their fuzzy set, linguistic value & meaning are represented in **Table 1** and output variables are described in **Table 2**. The membership functions of four input variables are shown in **Fig. 4** to **Fig. 7** and **Fig. 8** and **Fig. 9** represent the membership functions for output results SDA and SS, respectively.

Table 1: Input variables (ST, RP, CQ & EE), their fuzzy set, linguistic term & meaning.

1) Stakeholder Trust (ST)		
Fuzzy sets	**Linguistic Term**	**Meaning**
Low	L	Stakeholders doubt the program's intent/competence; assume information is selective; low willingness to grant benefit of the doubt.
Medium	M	Mixed/conditional trust; willing to listen, but need reassurance and proof; trust varies by topic or spokesperson.
High	H	Strong confidence in motives, competence, and fairness; stakeholders expect issues to be handled well.
2) Risk Perception (RP)		
Low	L	Hazards seen as understood/controlled; low dread/uncertainty.
Medium	M	Balanced concern; accept risk if benefits/controls are credible; want ongoing evidence.
High	H	Strong concern about likelihood/severity or unknowns; low tolerance for ambiguity.
3) Communication Quality (CQ)		
Low	L	Infrequent, late, jargon-heavy, one-way; key info missing or inconsistent across channels.
Medium	M	Mostly timely and accurate; some gaps in clarity, accessibility, or responsiveness.
High	H	Timely, clear, two-way, tailored to audience; consistent across channels; issues tracked to closure.
4) Engagement Effectiveness (EE)		
Low	L	Tokenistic or late involvement; stakeholders feel decisions are predetermined.
Medium	M	Participation occurs at key milestones; inputs considered, but limited influence on outcomes.
High	H	Co-creation/partnership; stakeholder input measurably shapes choices; shared ownership.

Table 2: Output variables (SDA & SS), their fuzzy set, linguistic term & meaning.

1) Strategic Decision Alignment (SDA)		
Fuzzy sets	**Linguistic Term**	**Meaning**
Low	L	Decisions diverge from stakeholder needs or organizational goals; frequent rework/conflict.
Medium	M	Decisions broadly consistent with goals and acceptable to most individuals; some trade-offs unresolved.
High	H	Decisions strongly reflect needs and constraints, high robustness, and legitimacy.
2) Stakeholder Satisfaction (SS)		
Low	L	Dissatisfied with process/fairness; feel unheard or misled.
Medium	M	Mixed but acceptable; recognize effort and some influence; request improvements.
High	H	Positive experience; feel respected, informed, and influential.

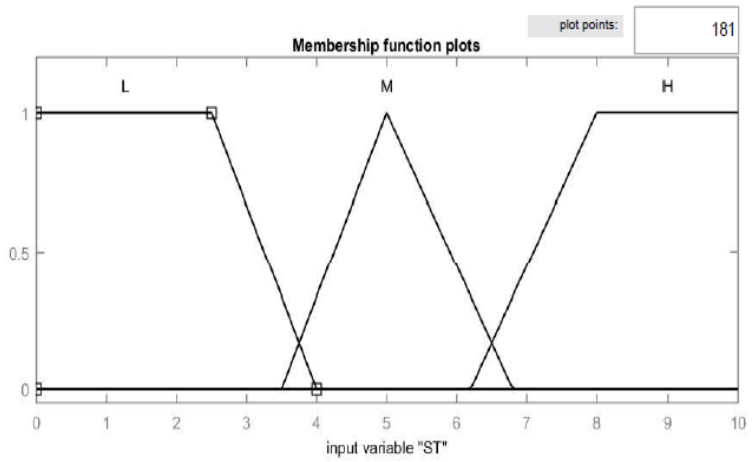

Fig. 4: Input Membership function of Stakeholder's Trust (ST).

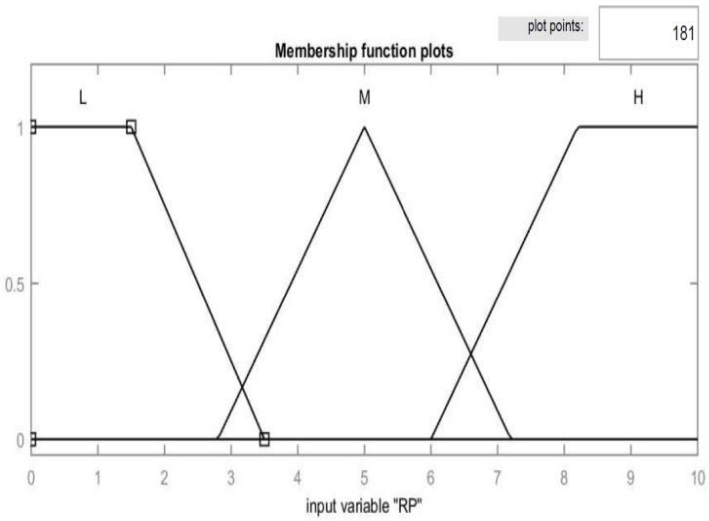

Fig. 5: Input Membership function of Risk Perception (RP).

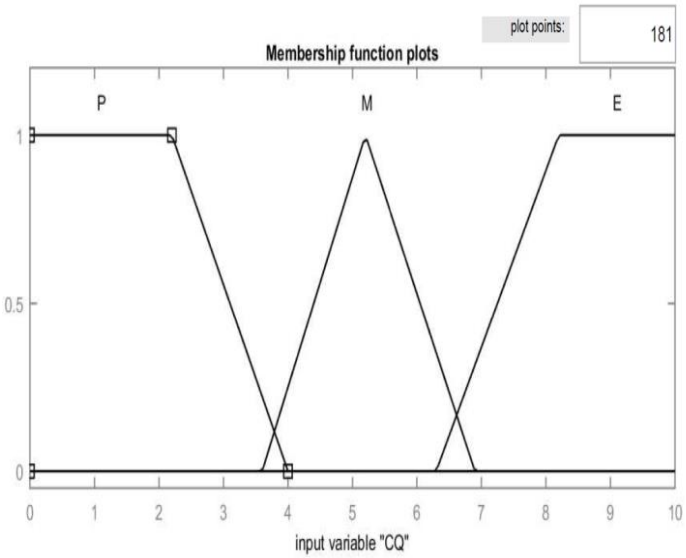

Fig. 6: Input Membership function of Communication Quality (CQ).

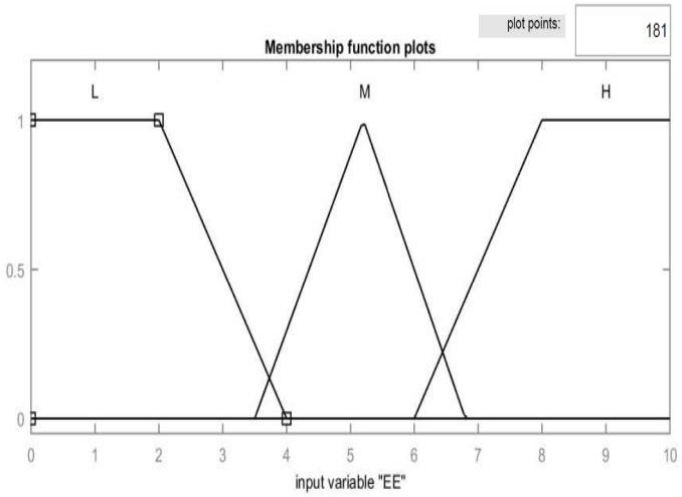

Fig. 7: Input Membership function of Engagement Effectiveness (EE).

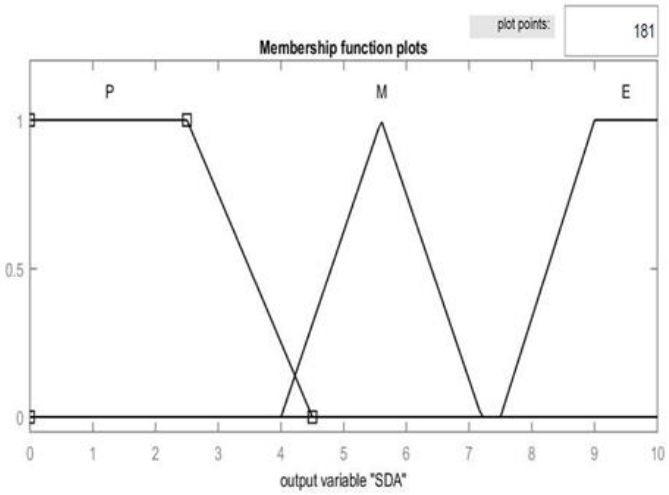

Fig. 8: Output Membership function of SDA.

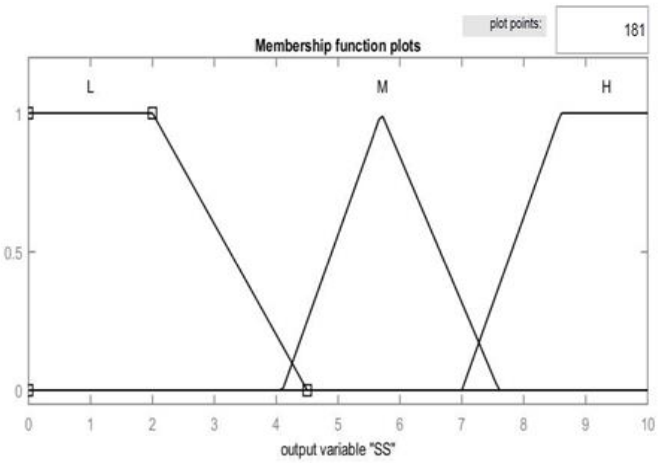

Fig 9: Output Membership function of SS.

4. Results and Discussion

The proposed fuzzy logic–based framework for enhancing stakeholder engagement in nuclear programs is developed using four key input parameters: ST, RP, CQ and EE. These inputs will be derived from stakeholders' perceptions collected through structured assessment methods. This process constitutes a vital component of the proposed model, as it requires significant effort to collect a comprehensive dataset from all relevant stakeholders involved in the nuclear power program. The data collection process itself is time-consuming and demands careful planning, coordination, and systematic survey design to ensure reliability and representativeness. Since stakeholders possess varying levels of technical knowledge, perception, and involvement, the dataset must capture diverse viewpoints to reflect realistic conditions.

Furthermore, the data processing methodology is crucial for generating appropriate input values for the fuzzy model. Proper validation, normalization, and categorization of the collected data are necessary to minimize bias and uncertainty before converting them into fuzzy linguistic variables. In this study, however, crisp input values are considered randomly to evaluate and demonstrate the functionality and structural behavior of the proposed fuzzy model. Future work will incorporate real stakeholder survey data to enhance the model's practical applicability and robustness. Within the proposed framework, the input data are processed through a FIS model to support strategic decision- making for nuclear programs at specific sites. The outcomes of the developed FIS model are evaluated using the rule viewer and surface

viewer, which provide insights into the influence of each of the stakeholder-related factors on strategic decision alignment and stakeholder satisfaction. These two are described below in sections. After evaluation using the FIS, the results obtained for each stakeholder group can be integrated to construct a comprehensive mapping of overall stakeholder motivation and satisfaction toward nuclear power development. This integrated modeling approach enables a holistic understanding of stakeholder dynamics of the complex nuclear power program. The development of such a comprehensive mass framework is considered a direction for future work, where advanced integration techniques may be applied to enhance the robustness and scalability of the proposed model.

Rule Viewer

Rule viewer is a graphical depiction of all the variables in FIS systems which show the output results after defuzzification based on the rules. One of the results as an example of the operation is shown in **Fig. 10**. In this example, the conditions are assumed at a specific point where Stakeholder Trust (ST) is 31% which is low (L) in linguistic term, reflecting doubts about the program's intent or competence. Risk Perception (RP) is 32% which is also low (L), indicating that potential hazards are viewed as well-understood and controlled, with minimal uncertainty. Communication Quality (CQ) is 51% which is moderate (M), meaning that information is generally timely and accurate, although some gaps remain in clarity, accessibility, or responsiveness. Engagement Effectiveness (EE) is 52% which is also moderate (M), demonstrating co-creation and partnership, where stakeholder input has limited influence on outcomes. This situation can easily come if the communication strategy & effectiveness of the department is good enough; however, the stakeholders hold a strong negative belief about the nuclear program. Trust and perception cannot easily build with the engagement programs within the stakeholders, then result of this model showing, SDA is estimated as 21% which is LOW and SS is estimated as 58% which is MODERATE, aligns with the situation where stakeholders' belief is strongly dominating the environment. Results obtained from the study shows a good performance from this model and that is strategic decisions need a modification according to the stakeholder's trust & perceptions. Satisfaction is mixed which also aligns with the situation can be improved along with the first two variables change. However, the ranking of input variables depends on the developed FIS model for obtaining the final result. Moreover, this model can be improved with higher precision by including more variables and rules.

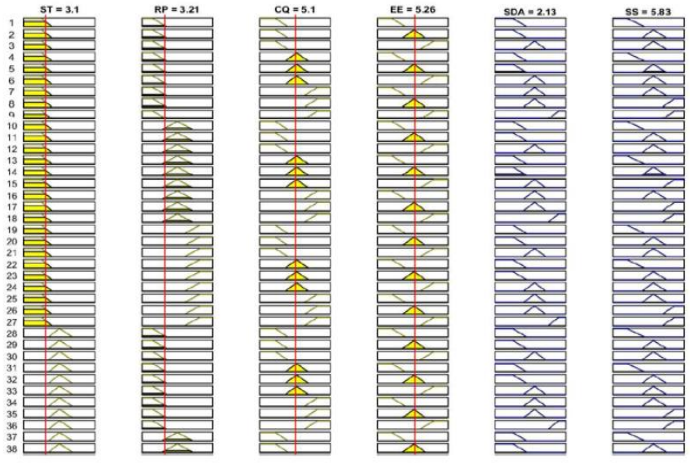

Fig. 10: Rule viewer.

Surface Viewer

Fuzzy control surfaces for two different output variables were developed using the MATLAB Fuzzy logic tool. These graphs are actually the visual representation of how the FIS operates dynamically over time. These mesh plots are showing the relationships between four input variables (ST, RP, CQ & EE) with each output variable for the example stated above. Graphs in **Fig. 11** & **12** are showing the relationship between SDA & SS with four input

variables respectively. To verify the applied rules and membership functions or required modifications for improvement, these plots can be used. After developing the model, it becomes possible to predict the level of stakeholder satisfaction and the degree of strategic decision alignment for specific stakeholder groups, thereby supporting the achievement of the effective engagement objectives in a nuclear power program. Due to the multidimensional nature of the proposed FIS, surface plots were generated by varying two input variables at a time while fixing the remaining inputs at representative levels (low, medium, and high).

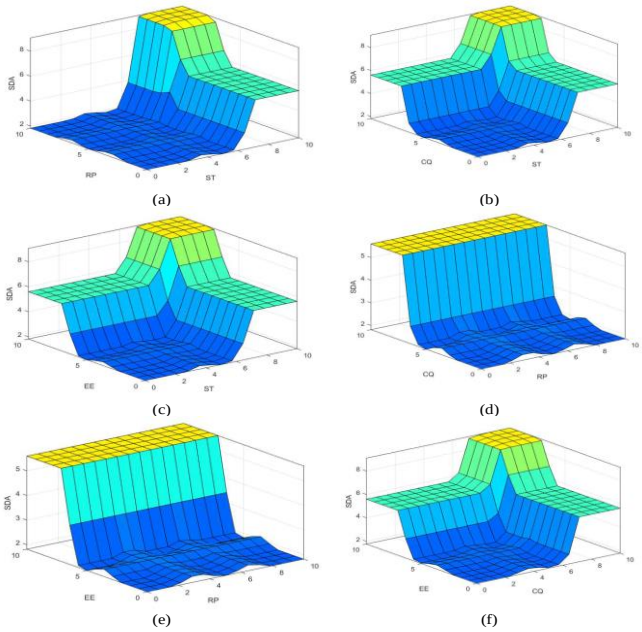

Fig. 11: Surface viewer for (a) SDA vs inputs (RP & ST); (b) SDA vs inputs (CQ & ST); (c) SDA vs inputs (EE & ST); (d) SDA vs inputs (RP & CQ); (e) SDA vs inputs (RP & EE); (f) SDA vs inputs (EE & CQ).

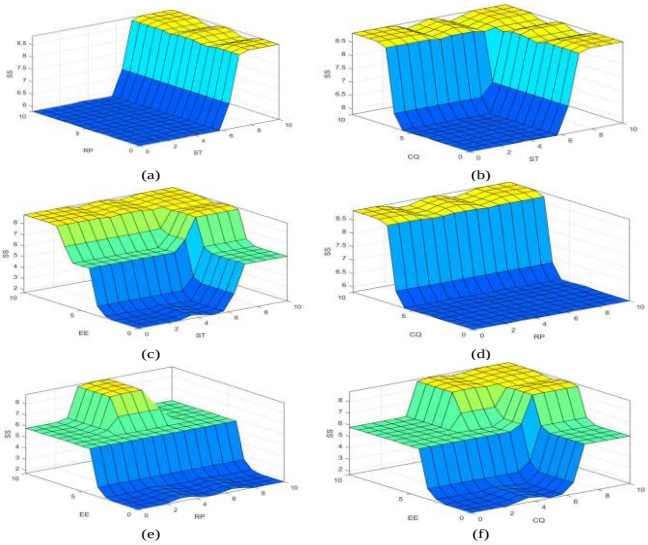

Fig. 12: Surface viewer for (a) SS vs inputs (RP & ST); (b) SS vs inputs (CQ & ST); (c) SS vs inputs (EE & ST); (d) SS vs inputs (RP & CQ); (e) SS vs inputs (RP & EE); (f) SS vs inputs (EE & CQ).

5. Conclusion

The aim of this study is to enhance stakeholder engagement in establishing a nuclear power program by using a fuzzy logic-based decision-making approach. A prediction model was developed using a Fuzzy Inference System (FIS), supported by a database

generated from direct input of the stakeholders. This approach allows the model to be highly interactive and effective, helping to identify deviations in engagement and improve the overall quality of the engagement program. The key conclusions of this work are as follows: The proposed FIS model demonstrates strong performance in critical situations, allowing stakeholders' deviations to be analyzed and understood. This enables state authorities to take targeted measures for specific stakeholder groups, reducing perceived risks and improving overall engagement outcomes. For the given input scenario (ST = 31%, RP = 32%, CQ = 51%, EE = 58%), the fuzzy model predicts a strategic decision alignment (SDA) of 21% and stakeholder satisfaction (SS) of 58%. The low SDA reflects insufficient trust and persistent risk concerns, which negatively affect alignment with strategic objectives. In contrast, the comparatively higher SS suggests that acceptable communication quality and engagement effectiveness contribute positively to stakeholders' overall perception of the decision-making process. These findings highlight the sensitivity of the model to variations in stakeholder perception parameters and demonstrate its effectiveness in identifying areas requiring strategic intervention. The results suggest that this method is both reliable and suitable as an innovative tool for enhancing stakeholder engagement through data- driven, strategic decision- making. The model can be further validated with real-world scenarios to assess its practical effectiveness. Additionally, optimizing fuzzy membership functions and exploring alternative shapes can improve the model's predictive accuracy and reliability.

6. Author Contributions

M.S.S.K.: contributed to the conceptualization of the study, methodology development, fuzzy inference system design, and overall review of the manuscript. M.N.H.: contributed to the methodology, model implementation, data interpretation, literature review, manuscript writing, editing, and corresponding author responsibilities. M.T.H.: contributed to the development of the fuzzy logic framework, rule-base preparation, validation of the model structure, and technical review of the manuscript. K.M.R.A.H.: contributed to the analysis of stakeholder engagement parameters, preparation of figures and tables, data organization, and manuscript formatting. M.A.H.: supervised the research work, technical guidance on fuzzy-based risk and decision-making approaches, critical revision of the manuscript, and final approval of the submitted version.

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8. Conflicts of interest

The authors declare that there are no conflicts of interest to publish it.

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