International Journal of
INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING
ISSN:2147-6799 www.ijisae.org Original Research Paper

Fuzzy Rule-Based System to Predict the Sustainability in Machining Process

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Submitted: 23/10/2023 **Revised:** 10/12/2023 **Accepted:** 18/12/2023

Abstract: Industry 5.0 is the highly widespread version at present, with a time- and energy-efficient functioning procedure. Industry 5.0 focuses an immense value on augmented intelligence (AuI), which indicates both artificial and human intelligence are integrated in this industrial version. Industry 5.0 can promote environmentally friendly targets like durability, socio-environmental reliability, and human-centricity, extending outside the profit-centered effectiveness of Industry 4.0. For any industry to be worthwhile, the machine's sustainability remains the top priority. This research article delivers a fuzzy rule-based strategy for Industry 5.0 which is a human-robot collaboration. The primary justification for adopting this fuzzy rule-based strategy in this machine sustainability forecast mechanism is that it is an If-Then rule-based reasoning method. This will offer an extremely precise and familiar prediction of sustainability in machining, enhancing industrial wealth while minimizing expenditure. The Augmented Intelligence (AuI) has turned popular recently in the industries given that when contrasted with industry 4.0, it is noticeable that industry 5.0 is persistently profitable, dependable, and offers greatest outcomes at a suitable hour. Any business will save time and money due to the manufacturing process rarely yields a significant level of waste and employs a sufficient quantity of input equipment. Consequently, this industrial 5.0 can deliver positive results without any losses thanks to its fuzzy rule-based method.

Keywords: *Industry 5.0, Augmented Intelligence, Fuzzy rule based method, save time and money*

1. Introduction

The overall objective of Industry 5.0 is to boost resilience in all spheres—economic, environmental, and social. The production process that looks like to be human-centric is the primary concern of Industry 5.0. Social smart factories' technological developments must advance an individual's quality of life. The key component of the Industry 5.0 model is a collaboration between humans and robots within a "smart business ecosystem" that puts a priority on an environmentally friendly economy and efficient extraction of resources. The scope of Industry 5.0, in accordance, is made up of an assortment of organizations, consisting of production, medical treatment, renewable energy, and agriculture [1]. Hence, coordination between mankind and artificial intelligence will enhance the economy, natural, and social atmosphere. The future and ecosystem will be enhanced by avoiding the excessive garbage generated by the industries. Although industrial wastes such as physical, urban, process, and social wastes remain industry 5.0 will discover an easier way to eradicate and sustain better machining and environmental conditions when a fuzzy rule-based approach is adopted. Industries need to boost their resilience, which necessitates them to generate new business models, comprehend talent, and classify strategies [2]. Fuzzy logic (FL) is a form of reasoning that replicates the human mind. The FL strategy comprises possibilities between digital yes and no values and adopts human judgment into account. A machine that can precisely comprehend input and manufacture an apparent outcome that signals whether a subject is true or false—akin to a person's choice of yes or no—is said to have a classic logic circuit. The FL researcher said a few factors involve how individuals make alternate choices. It covers areas that could be between yes and no, like maybe yes, really yes, maybe no, no, and cannot say [3].

In accordance with unbiased facts, fuzzy theory could convey or customize data and information that carries unpredictability. Additionally, the fuzzy theory presents formal instruments to deal with the natural fuzziness of decision-making issues and has been meticulously established for conveying inconsistency and vagueness. Fuzzy theory alleges that inconsistency and misunderstandings can be caused via conceptualization. Representing fuzzy data is the primary accomplishment of a fuzzy theory. The fuzzy theory has been utilized heavily in instances where addressing indeterminacy and uncertain values, such as risk governance, is mandatory. Fuzzy logic can be utilized for determining the probability of participation in a data set and ambiguous circumstances. Therefore call for a reaction that can't be identified with perfect clarity ("yes" or "no"). The initial step is to fully understand fuzzy infrastructure, which necessitates a grasp of fuzzy variables, fuzzy sets, discussion universes, and genres. The fuzzy logic model that is displayed beneath in Figure 1.1 will offer an easily understood summary of the method that it goes through.

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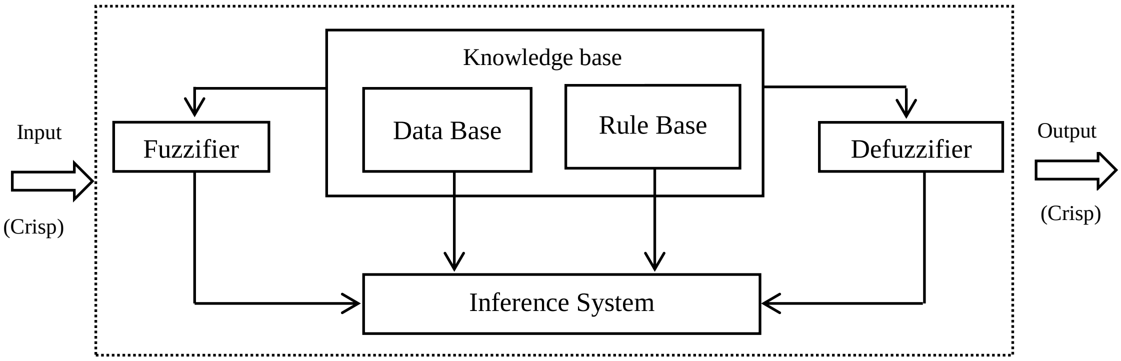

Fig. 1.1. Diagram for fuzzy logic

The three primary tactics in a fuzzy procedure are swirling, rule scrutiny, and defuzzification. Fuzzification is the procedure of shifting the three risk factors—severity, incidence, and detection—into fuzzy expressions implementing linguistic variables. Determining an appropriate level of involvement in each group demands explanations and linguistic circumstances, followed by an easy scale grading of the three criteria.Expert knowledge regarding error pattern interactions and their implications have been incorporated into rule formulation in the form of fuzzy "if-then" constraints. When compared to mathematical regulations that are these guidelines are straightforward to put together in language rules.The technique of sorting fuzzy Risk Priority Numbers (RPNs) to denote an error mode's urgency ranking is known as defuzzification. The centroids think about is employed in the defuzzification operation. A fuzzy set produced by composing fuzzy rules serves as the process's input from users, while a number occurring inside of the fuzzy set's domain behaves as its final result. This suggests that it must be possible to take a specific crisp integer if allowed a fuzzy set inside a defined range [4].

The subsequent paper offers a brief overview of each subsection of this academic function. In Section 2, the study's concentration on relevant previous research has been rendered explicit. Section 3 describes the unique features of the recommended fuzzy logic building construction, particularly its statistical investigation, system scheme, subconscious conceptual framework, and graph-based strategy aspects. The fuzzy rule-based technique for protecting the long-term viability of the machining procedure is examined in this third section. An assortment of distinct graphs and photographs addressing fuzzy logic in industry 5.0 are provided in Section 4. The final verdict on the fuzzy logic-based approach employed by industries is included in Section 5.

2. Related works

Lau, H. C., Hui, I. K. et. al [5] Automatically, fuzzy rules applicable to imprecise classifications. They propose a technique for tackling difficult situations with fuzzy thoughts. Rules are more flexible, clarified, and understandable when depicting lengthy procedures whose individual elements are challenging to the group because they tolerate fuzzy boundaries compared to crunchy ones. Fuzzification is an algorithm for selecting any specific idea and transforming it from a separate, precise version to a smooth one.

Ali, F., Kim et. al [6] Fuzzy logic and traditional semantics have become becoming ever more prevalent within research teams in the last few years. However, linguistic and probability difficulties develop when merging a fuzzy logic controller with a typical ontology for automated machinery, especially when dealing with harmful scenarios. Type-2 fuzzy reasoning is an appropriate method to solve these ambiguities as an option.

Coşkun, G. T., &Yalçıner, A. Y.et. al [7] The aim is to add an extensive instance to the main body of research to increase awareness of the LPP technique in cost valuing and buying practices. It was additionally designed to show that, these techniques and innovative techniques may be employed to tackle pricing challenges as opposed to focusing solely on traditional mathematical frameworks. Fuzzy logic was implemented to confirm the truthfulness of the deposit boxes witnessed in the case for the reason that the findings of the research fit the fuzzy logic method.

Samanta, B. et. al [8] The decision-making process of fuzzy membership functions (MFs), by amount and category, generating the rule base that imitates the decision-making procedure, and opting for the range of scaling factors to be applied during the various stages of fuzzification and defuzzification are the primary difficulties faced when applying FL, or fuzzy inference system (FIS). In most cases, these settings and the frameworks are determined using an amalgamation of specialized information and multiple tests.

Arghavani, J., Derenneet. al [9] The acclaimed researcher crafted the methodology's industrial application through a remarkable study on the implementation of the fuzzy set concept for controlling systems and making decisions. Some authors describe their findings on a fuzzy technique for picking the cutting parameters for a machining operation and performing decisions. Fuzzy-Flou, a fuzzy logic tool, was developed based on the fuzzy logic theory of a widely recognized paper.

MOHAMMADI, M. T., Salehiet. al [10] Moreover, fuzzy reasoning is flexible, accepting of flawed input, and straightforward to grasp mentally. Every system undergoing investigation might have its intricate non-linear behavior simulated by leveraging that approach. There are three kinds of fuzzy logic modeling strategies: Tagaki, Sueno, and Kang (T-S-K), Linguistic, and Structural formula. The methodology employed for calculating the social effects of norms indicates where these approaches deviate most. Since the T-S-K strategy is effective for simulating non-linear dynamic systems, it is implemented here

Deveci, M. et. al [11] The researcher investigated a fuzzy LMAW framework for analyzing decisions in the backdrop of the sustainable economy when constructing smart transportation networks. Fuzzy MCDM-based models were additionally employed to solve decision-making issues. The unsteady fuzzy Aczel-Alsina parameters of the equations utilized to figure out the proportions of the standards facilitate the consideration of intricate and dubious data. Eventually, the model permits logical inquiry considering the interconnections among judgment variables.

3. Methods and Materials

3.1 Fuzzy interference system for machine balance

Random MTF parameters will be supplied to each system. There will be an assortment of variables from 0 to 50 units. As seen in Figure 3.1, the triangle association function captures these parameters. Where the outermost value for the acceptable membership role is $(D_{+b}, D_{+c}), (D_{-b}, D_{-c})$ *and* $(D_{jb}, D_{jc}), (j = 0,1,\ldots,4)$.In cases where the information being provided is fuzzy, a collection of fuzzy sets gets produced. {NB,NM,NS,Z,PS,PM,PB} has been employed to denote it, where NB corresponds to negative big, NM to negative middle, NS to negative small, Z to zero, PS to positive small, PM for positive middle, and PB for positive big. As a result of every fuzzy set, the fuzzy membership function g is illustrated as in (1), (2), and (3) proceeds.

$$g_{NB} = \begin{cases} 1 & if\ y < D_{-b} \\ \frac{D_{-c}-y}{D_{-c}-D_{-b}} & if\ D_{-b} \le y \le D_{-c} \\ 0 & if\ y > D_{-c} \end{cases} \quad (1)$$

$$gj,\Delta = \begin{cases} 0 & if\ y < D_{jb} \\ 2\frac{y-D_{jb}}{D_{jc}-D_{jb}} & if\ D_{jb} \le y \le \frac{D_{jb}+D_{jc}}{2} \\ 2\frac{D_{jc}-y}{D_{jc}-D_{jb}} & if\ \frac{D_{jc}+D_{jb}}{2} \le y \le D_{jc} \\ 0 & if\ y > D_{jc} \end{cases} \quad (2)$$

$$g_{PB} = \begin{cases} 0 & if\ y < D_{+b} \\ \frac{y-D_{+c}}{D_{+c}-D_{+b}} & if\ D_{+b} \le y \le D_{+c} \\ 1 & if\ y > D_{+c} \end{cases} \quad (3)$$

A single collection of integers supplied by the predecessor is utilized as the inference technique's information, and a fuzzy set functions as the final result. The Matlab Fuzzy Logic Toolbox, which trims the outcome of fuzzy sets, includes the built-in fuzzy logic approaches that we implemented.

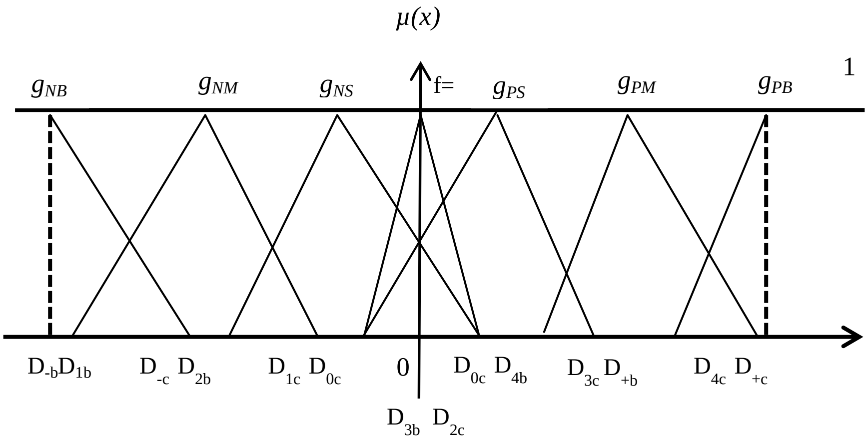

Fig. 3.1. Membership Functions

The structure of the fuzzy rules are present in the below format

if$<$ *antecendent, related to the MTF* $>$ then $<$ *consequent, the machine reliability* $>$

FL based rules are available as follows

If (MTF is very low) then (machine reliability is very low)

If (MTF is low) then (machine reliability is low)

If (MTF is medium) then (machine reliability if standard)

If (MTF is high) then (machine reliability is high)

If (MTF is very high) then (machine reliability is very high)

Each FL legislation faces scrutiny preceding an assessment is taken on it. Employing all of the guidelines simultaneously is crucial for making judgments. The procedure of merging the fuzzy sets that independently symbolize an output's outcomes into only one fuzzy set is called aggregation. The collection of decreased production variables that the implication process for each rule reverted is the input parameter of the collection method. One fuzzy collection per output parameter is the end product of the amalgamation function.

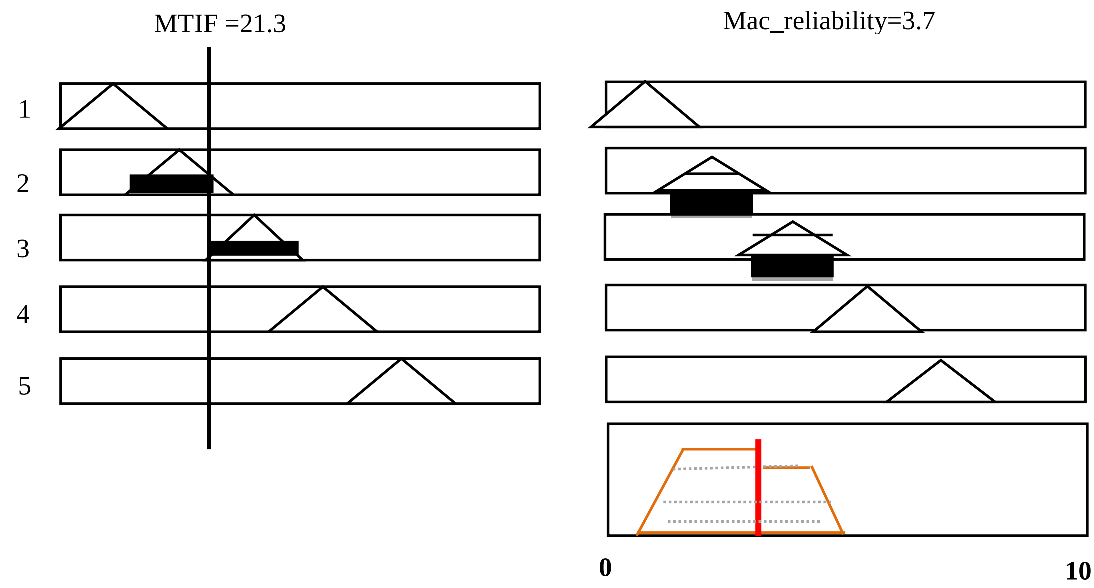

Fig. 3.2. Sample of the input-output of the fuzzy inference system

Defuzzifying the entire final fuzzy set is the ultimate stage. This stage produces just one value as the result. The index of reliability is the result of this research. Figure 3.2 illustrates a demonstration of the stuff that FL generates the actual application of the entered parameter in the guidelines is displayed in the first paragraph. The value of the input variable, MTF= 21.3, can be seen at the highest level. The placement of the resultant parameter, or machine reliability (mac_reliability), in the procedure, is highlighted in the supplementary column. One principle is portrayed by each row of plots. The input data column's five plots, frequently referred to as the triangle-shaped plots, reveal the membership categories that each rule's antecedent, or if associated with it, relates to. Charts in the second column illustrate the membership functions for every rule-based, or then, portion suggestion. The MTF frequency is demonstrated by the darkened input plots; 21.3 is a component of the A2 and A3 membership functions. The consequence of this process is shown in the truncated output charts. To precisely the same proportion as the predecessor, it has been abbreviated. The outcome of the cumulative plot is exhibited in the final product column's lower plot. The stream of data that travels through the collection of fuzzy sets represents the defuzzified output number. In this particular instance, the machine trustworthiness index is 3.7 if the MTF is 21.3. The defuzzification result of the FL is the ranking which ranges between 0 and 10. If mathematical data doesn't exist, FL can be customized to accommodate fuzzy or linguistic data (such as "low"). A certain advantage of using FL for planning connectivity with machine power is it.

3.2 The Process and its Sustainability Measures

In this article, the production technique that most represents the environmentally friendly assessment methodology is milling. In the reductive production method of milling, the material is gradually eliminated from a component's surface in the form of chips to sculpt the item into the desired form. Machining is, quite legitimately, the most commonly employed production method worldwide owing to its merits in terms of geometric reliability, surface texture, contour adaptability, and an assortment of plausible resources.

Whilst translating natural raw materials into GDP renders milling an immediate boost to the national economy, it additionally results in a detrimental impact on the environment. The technology is recognized to harm the surroundings in plenty of ways, which include the leverage of electrical energy, which creates additional energy and greenhouse gas pollution, the generation of processing garbage that demands to be cleaned, reused, and deposited in a landfill, the exhaustion of natural supplies in the shape of unusual metals used to make trimming tools, and the infection of land and water from the disposal of cutting fluids. The machining sector was examined in terms of performance measures, which included economy-oriented metrics including tool life, material removal rate, process cost, dimensional accuracy, and work surface quality, before the adoption of the sustainability criteria and rules. The list of "performance measures" has been replaced by "sustainability measures" following the global acceptance of the sustainability norms. Additional parameters like cutting energy, slag generation, private security, and many more are covered in the latter.

Presented the current importance that the three dimensions of sustainability are getting concerning the production sector, it makes sense to allocate the economy, environment, and society weights of 45%, 45%, and 10%, respectively, in the sustainability score (SS) estimation. Statistically speaking, societal indicators like hours of labor, wellness, security, and many more are approximately half as significant as ecological or financial factors. Additionally, contrasted to other present manufacturing methods, the governing features of most of them—which comprises machining—have less of an impact on societal gauges. Thus, the aforementioned is the basic expression (4) for the sustainability score about a machining process:

$$SS = 0.4(SS_{eco} + SS_{env}) + 0.2SS_{soc} \quad (4)$$

where the appropriate sustainably scores for the economy, environment, and society are symbolized by the characters SS_{eco}, SS_{env}, and SS_{soc}.

It progresses without mentioning that the weightages' numbers can be modified to accommodate any specific inclination. The statistical methodology persists consistently regardless of the variances in these statistics. It passes without mentioning that this could impact the sustainability score, which would enhance the quantification final result given the implications of that preference. According to the debate in this work, a sustainability score is the proximity of how effectively a procedure functions in the perspective of sustainability. Industrial decisions about whether to preserve an operation or alter it to boost sustainability (or any of its attributes) do not necessitate extremely precise sustainability score computation.

4. Implementation and Results

A milling process's sustainability parameters can be categorized into sections depending on the different elements of sustainability that they target. A summary of the indicators classified beneath each of the three indicators of sustainability is displayed in Table 1, alongside the related percentage shares for each dimension. The financial section lists six measures. The cost of buying the tools needed is calculated by the tool procurement economy. The glaze, geometric dimensions, and tooling substance all affect its value. This measure's worth diminishes alongside rising buying costs. The volume of work product withdrawn by a specific instrument instantly before the tool renewal circumstance has been fulfilled is referred to as tool lifespan. The most frequently employed indicator is the widening of the flank wear land's breadth exceeding a given barrier. For financial viability, the more prolonged the instrument's life, the greater the benefit. The two sustainability efforts described above are incompatible with one another. Put another way, a machining tool that demonstrates a high gaining finances is supposed to yield a comparatively brief tool life.

Table 1. Machining sustainability measures under three dimensions

Economy		Environment		Society	
Measure	**Share**	**Measure**	**Share**	**Measure**	**Share**
Toll acquisition economy	26%	Specific energy saving	35%	Health	35%
Toll life	21%	Swarf avoidance	35%	Safely	45%
Productivity	26%	Landfill avoidance(tool)	15%	Working hours normality	20%
Fluid consumption economy	12%	Landfill avoidance(work)	15%	-	
Surface quality	11%	-		-	
Electricity conservation	4%	-		-	

Yield is defined as the volume of output generated for each unit of resource utilized. The asset in terms of manufacturing procedures might include the quantity of energy or substance used or the volume of the working period (machine hours or man hours). For a subtractive production procedure, the quantity of work material eliminated per unit of time is an exceptionally important profitability variable. The metric is referred to as material removal rate (MRR) in the machining sector and is represented in mm3/s. The goal of financial durability is to raise this metric's significance. The expenditure of delivering a cutting fluid to offer lubrication and cooling effects during the cutting operation is termed a fluid consumption economy. This metric unit has the greatest value when removed via a dry technique.

Expensive fluids, like cryogenic coolants, on the other hand, bring back low numbers. Surface cleanliness is an additional financial measure of viability. When it comes to machining, the dimension dictates whether a piece is allowed for the next level of manufacturing or necessitates to be destroyed or reworked. A demolished portion symbolizes the lowest level of economic sustainability as the arrangement induces wastages of the work substances as well as the energy utilized. Rework mindsets are superior but not perfect because they sustain the work outcome but not the resources consumed. The price of the main source of energy usage per unit volume of the work material eradicated is a framework for the calculation of electrical energy conservation. The measure's value decreases as a certain energy consumption boosts.

Under their proportional contribution to the overall expense of machining observed in the present machining industry, the proportional shares awarded to the indicators of financial viability are listed below (Table 1).

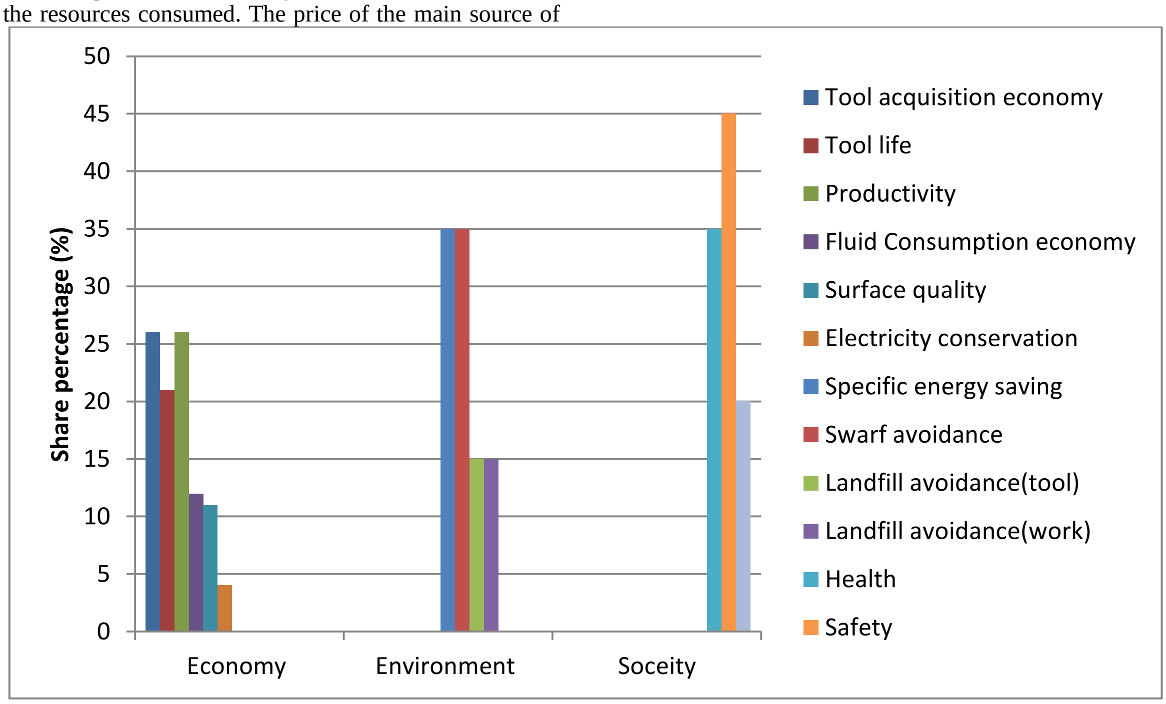

Fig. 4.1. Graph for Sustainability measures in various dimensions in industry 5.0

The inverse of specific consumption of energy is specific energy conservation, which is an assessment of environmental sustainability. Its substantial worth (supportive of environmental benignity) signifies that for any particular volume of work, stuff eliminated with very little energy is used.The graph Figure 4.1 above delivers an excellent justification of the sustainability metric with its multiple factors.

The term "swarf elimination" describes chip formation purity. The elevated amount demonstrates that the chips are oil/emulsion free and easily acquired, which eliminates the need for pieces to be cleaned before the recycling procedure should start, which involves a lot of materials as well as energy. The expressions "landfill avoidance" and "workpiece" indicate metrics that evaluate the total quantity of material extracted from a tool and a workpiece ahead of when they are disposed of as garbage. A large number for the former implies a long tool longevity, while an elevated amount for the latter illustrates a well-machined surface that minimizes non-compliance with the quality specification and the components that follow scrapping. The matched and somewhat approximate contribution to the environment generates the appropriate proportion of funding allotted for each of the four metrics under the area of environmental sustainability. Health and safety are evident when it comes to the societal metrics of sustainability. Table 1 demonstrates that protection from harm is assigned a little higher weight than the other two societal regulations. The third measure, working hours, is correlated with productivity. It makes rational sense that a higher MRR would motivate machine operators to invest less time in their job zone opposing an assigned production goal.

4.1 The Criterions of Control

It is essential to demonstrate how the primary machining control factors influence the long-term viability indicators that have already been addressed to analyze machining sustainability. The authentic shapes of the machining forecasters on the different behaviors have been demonstrated by a vast body of scholarship that is dependent on empirical observations. To figure out the overall impact of the control settings on sustainability metrics, the outcomes of the published research can be aggregated. The seven categories that follow indicate the primary machining parameters traced in this function: Turning, milling, drilling, and drilling are examples of machining types. Work materials include carbon steel, alloy steel, and titanium alloy. Surface hardness is an example of a mechanical property of the material. High-speed steel, carbide, coated carbide, and polycrystalline cubic boron nitride are instances of tool products. Tool layout encompasses rake angles, helix angles, and drill diameters. Cutting lubricants comprise a dry, fluid, a limited amount of lubrication, air, liquid nitrogen, or condensed carbon dioxide. At last, cutting parameters include cutting speed, rate of feed, and depth of cut. Whereas the remainder of the criteria are classified, the factors classified beneath (c), (e), and (g) are mathematical.

To estimate the extended impacts of the test outcomes on the 13 indicators mentioned in Table 1, the consequences of the previously discussed machining attributes on the sustainability evaluation were compiled, organized, linked together, and reviewed from over 115 documents, dissertations, and chapters from novels. Despite the "generalized impacts" being evidently not precise estimations of the "effects," they are notwithstanding adequate to provide a structure for calculating a vague metric, like sustainability. The procedure for merging the overall effects of the process factors to build an entire framework for durability forecast is outlined clearly [12].

4.2 Fuzzy modeling and prediction

The least RMSE value was utilized as an indication to select the most optimal model across the tested fuzzy parameter groupings. Initially, the fuzzy inference system (fis) deployed was the Mamdani. Second, three participation functions—the Gaussian (gausmf), triangular (trimf), and generalized bell (gbellmf)—were picked to be mixed. Thirdly, it was selected to merge the defuzzification strategies. The centroid, bisector, largest of maximum (lom), smallest of maximum (SoM), mean of maximum (mom), and bisector are defuzzification methods. The RMSE figures were then examined by matriciding the data samples. A single program's RMSE and Fj are evaluated using the equation (5).

$$F_j = \sqrt{\frac{1}{o}\sum_{k-1}^{o}\left(Q_{(jk)} - U_k\right)^2} \quad (5)$$

Where U_k is the target quantity for sample case k and $Q_{(jk)}$ is the value that, out of o specimen cases, the particular program j forecasted for test case k. $U_k = F_j = 0$ and $Q_{(jk)} = U_k$ for a flawless match. Hence, the optimum value of the $F_j$variable is 0, while the spectrum from 0 to infinite is symbolized by 0. After that, the RMSE figures generated by the mathematical equations were collated as mentioned in Table 2.

Table 2. Summary of RMSE for several collective representations

FIS Type	Membership Function	Defuzzification Method	RMSE
mamdani	**trimf**	centroid	1.7486
		bisector	1.7170
		mom	1.7879
		lom	1.8937
		som	1.7910
	gbellmf	centroid	1.9659
		bisector	1.8573
		mom	1.8710
		lom	3.7283
		som	2.4860
	gaussmf	centroid	2.1941
		bisector	1.8786
		mom	1.7636
		lom	2.5145
		som	1.9127

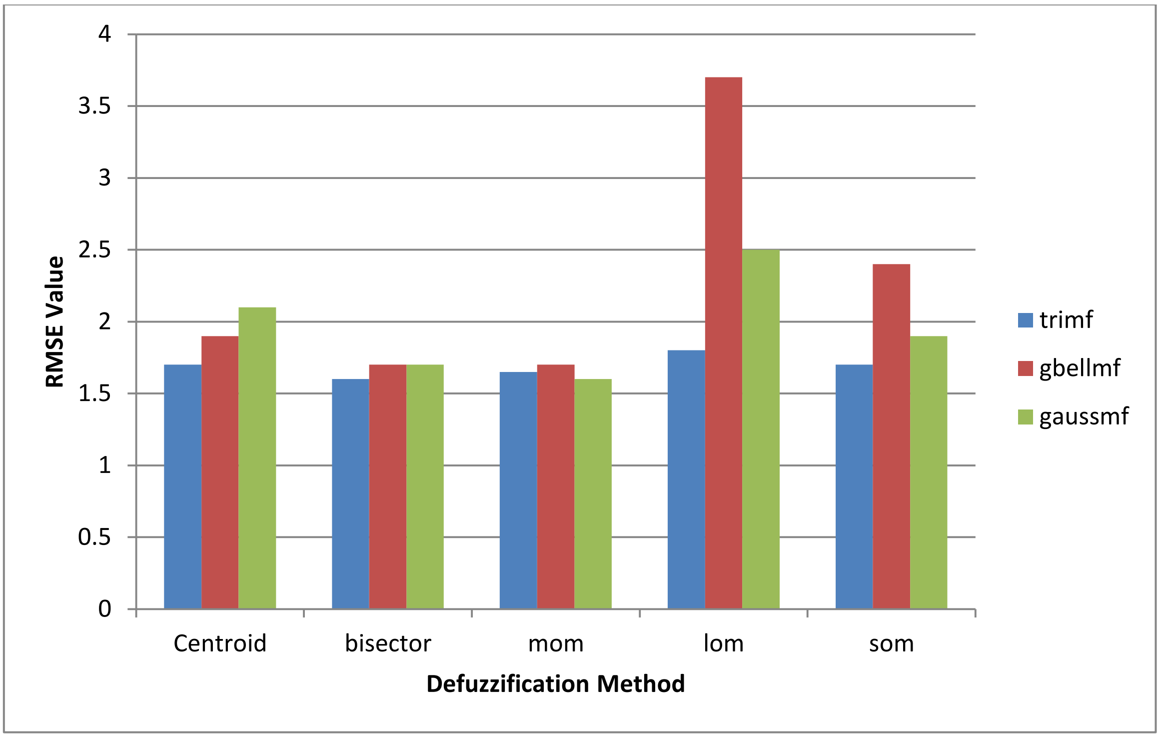

Fig. 4.2. RMSE for each united fuzzy Models

The design parameters were subsequently displayed in histograms to enhance awareness of the characterization of the defuzzification tackle depending on various kinds of membership functions. The bisector defuzzification approach with triangle characteristic function provides the lowest RMSE, as revealed by the RMSE values gathered according to the combos in Figure 4.2. As a result, the framework was further validated by implementing a prediction precision examination with percentage error, where it was utilized to verify the forecasting endurance [13].

5. Conclusion

To safeguard machining sustainability, a fuzzy rule-based model built around the utility concept has been developed through this investigation. The suggested techniques are straightforward to implement and successful in building a dependable, versatile, and dynamic manufacturing process. It is not essential to allocate various response weights in the models suggested. In any manufacturing or production setting, this technique can be suggested for ongoing quality improvement and offline quality control of a method or product. Each produced model's RMSE value was investigated and modified to yield the lowest amount achievable, revealing the model's strength. Each framework that has been developed suggests that blunders are inevitable while generating new models. As stated before, Industry 5.0 attempts to maximize resource use in the form of the application of technology. Industry 5.0 provides real-time energy consumption tracking and management practicable by utilizing smart sensors, networked devices, and sophisticated data analytics. This decreases waste and boosts energy utilization for the industries. The decline in resource usage contributes to maintaining sustainability during machining. The determination of the sustainability qualities of industrial operations is a current susceptible that the essay explores. Longevity is often thought of to be a phenomenon of quality that is tough to gauge due to the fact it involves numerous variables. Plenty of the control indicators are inaccurate and contradictory from a manufacturing point of view, which renders it tougher to accurately assess sustainability. In the final analysis, this fresh approach delivers an accurate method to analyze the machining process, which will cut down on time and finally yield excellent earnings.

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