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ORIGINAL ARTICLE

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A study on fault diagnosis and maintenance of CNC-WEDM based on binary relational analysis and expert system

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Abstract The paper presents a binary relational analysis and expert system base module for maintenance and fault diagnosis of CNC wire EDM. The module proposes a framework of integrated maintenance and fault diagnosis system. The study explores the binary coded matrix system, which plays an important role in prediction and diagnosis of wire electrical discharge machining (WEDM) faults on the spot by expert guidance. In this study, 15 inputs were considered to observe eight probable causes with the help of the forward and backward propagation algorithms. Inputs and output matrices were considered in the form of a square matrix. To explain the fault diagnosis and to realize the importance of maintenance through advice, the detection of faults is investigated through forward and back propagation of matrix transformation on the spot. It is an integrated backup that can be individually focused when input and output parameter do not match. It is a time saving, knowledge acquisition, easy to maintain, and capable of self-learning system. To verify the developed framework, 120 data sets were generated for proper analyzing of acquired output through graphical representation. The paper also presents some of the important features of maintenance schedule and probable causes of wire breakage with remedial actions in tabular form. The developed system can help the operators, trainees, and manufacturing engineers in achieving trouble free machining through quick detection of faults and proper maintenance of machines in actual practice.

Keywords Binary relations · Expert system (ES) · Fault diagnosis · Wire breakage

1 Introduction

To explore the advanced technologies for machining of hard wear resistance and high strength to weight ratio, temperature resistance materials together with the scope of macro and micro domain application in modern industry for achieving enhanced productivity and the quality characteristics feature of part or product requires fault diagnosis and maintenance schedule study on the non traditional machining process. One of the non-traditional machining processes, which have gained momentum for its practical applicability in current manufacturing scenario, has been the wire electrical discharge machining (WEDM) process. This is comparatively new concept in the electrical discharge machining (EDM) where the workpiece configuration is generated by a traveling wire electrode whose movements are often controlled by NC or CNC sub system [1]. The suitability of the WEDM process is greatly exhibited while generating complicated jobs in contours, making through holes, producing straight tapered jobs and so on [2]. WEDM system setup can also be aided with computer numerical control (CNC) features to facilitate the machining programming known as part program so that the same can be easily stored and called as and when required. The WEDM process may provide a high degree of flexibility and consistency as regard to the machining of diverse shape and sizes. WEDM has been found to be the most potential electro thermal process among the other non-traditional machining processes owing to the capability of the process in meeting with requirements of the present day product manufacturing industry. Despite being successful in solving many manufacturing problems, fault occurrences during machining may still pose an important restriction in WEDM operations. Integration of an expert system and binary relational algorithm will reduce the time in constructing the fault diagnosis system. A conventional expert system was used for fault diagnosis in the hydraulic system [3]. To establish the importance of fault diagnosis an IF THEN rule based knowledge system was utilized for operator assistance in wire EDM [4]. An iterative generated classification code based on weighed property indices in machining was proposed for preliminary selection of the non-traditional machining process [5]. A decision support system for car fault diagnosis based on an expert system was presented for the inexperienced mechanic and driver [6]. System diagnosis is often performed by a human using fault diagnosis knowledge [7].

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The main objective of the paper is to establish the binary relational analysis and an expert system base module for maintenance and fault diagnosis of CNC wire EDM. The developed expert system on binary coded matrix plays an important role in prediction and diagnosis of WEDM faults on the spot by expert guidance in supporting CNC. It is an integrated backup that can be individually focused when input and output parameter doesn't match. The developed system can help the operator, trainees, and manufacturing engineers by explaining the fault diagnosis and advice against the fault. It may help to achieve trouble free and smooth machining through quick detection of faults.

2 Methodology

An expert system is a set of programs that represents and manipulates encoded knowledge to solve problems in a specialized domain [8]. The expert system uses knowledge base code or symbolic representation to control the solution process. Expert system knowledge is obtained from the expert sources in the form of coded value, which is suitable for the system to use in its interface. These systems are also capable for explaining how a particular conclusion was reached and why the requested information is needed during a consultation. The knowledge base expert system increases output flexibility, reduces downtime, improves quality, and consistency of output.

Knowledge of CNC machine intelligence is an important tool for understanding the causes of failure during manufacturing. The knowledge base operational software helps to identify the faults, which reduces dependability and improves the concept of emerging WEDM operation. However, manufacturing engineers need system base operational software for quick detection of CNC-WEDM faults that will effectively support to improve the shop floor manufacturing process through knowledge base resources. To develop such new tools, information models are necessary to support the software development and its integration with the fault occurrences in expert systems. The architecture of an expert system is shown in Fig. 1. It consists of a user interface, which interacts with the knowledge base rules, coded plans, and actual facts through the expertise knowledge acquisition. Figure 2 represents the configuration of a binary structure. The binary relational algorithm was developed considering three phases of matrices such as input, dummy, and output matrix.

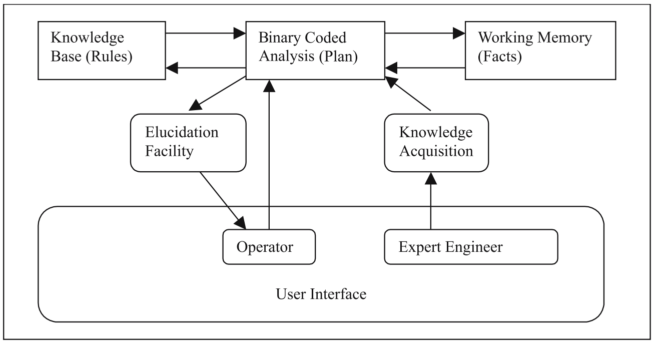


Fig. 1. Architecture of an expert system

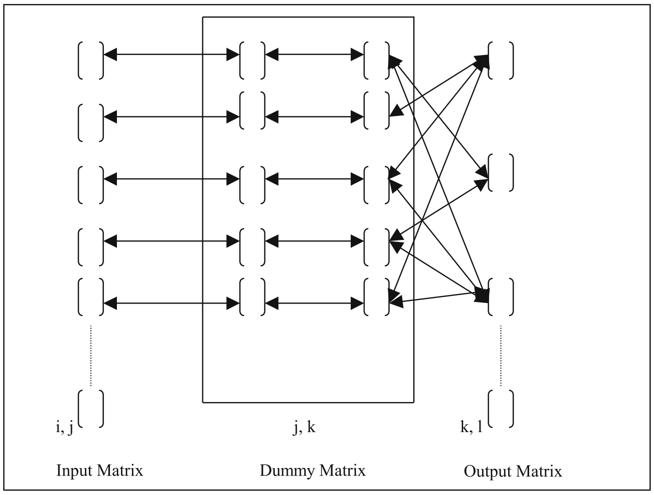


Fig. 2. Configuration of binary structure

In this study, 15 inputs were considered to observe eight probable causes with the help of the forward and backward propagation algorithms. Input and output matrices were considered in the form of a square matrix. In forward propagation the [15 × 15] matrix is transformed into the [8 × 8] matrix with the help of transformation algorithms and dummy matrix. Similarly, the output [8 × 8] matrix is transformed into the [15 × 15] matrix in back propagation. The weight fractions were calculated for each input in backward propagation and for each output in forward propagation using the developed algorithms. The calculated weight fraction helps to investigate and identify the most effective parameters for analyzing the causes of fault. To analyze the causes of fault and to assess 15 inputs, more than 120 different possible matrices were identified. In the case of forward propagation the output matrices indicate the probable causes with their weight fraction for the respective inputs. Similarly, for backward propagation the input matrices indicate the probable faults with their weight fractions. The binary coded knowledge-base system is used to convert the coded data into the relevant information. The system has been trained for probable 15 inputs and there possible eight causes. The developed philosophy can provide a solution for a system in which the output prediction is undetermined and the operator is in a dilemma to understand the causes. It also provides an efficient solution for the different causes of uncertainty in the platform of multi-input and multi-output parameters with non-uniform framework.

3 Maintenance schedule and fault diagnosis

Routine maintenance of machine tool parts improves the reliability of machine tool operations. Proper maintenance of Wire EDM decreases the fault occurrences. In view of that a maintenance and fault diagnosis of Wire EDM expert system (WEDMES) is developed. An architectural view of the

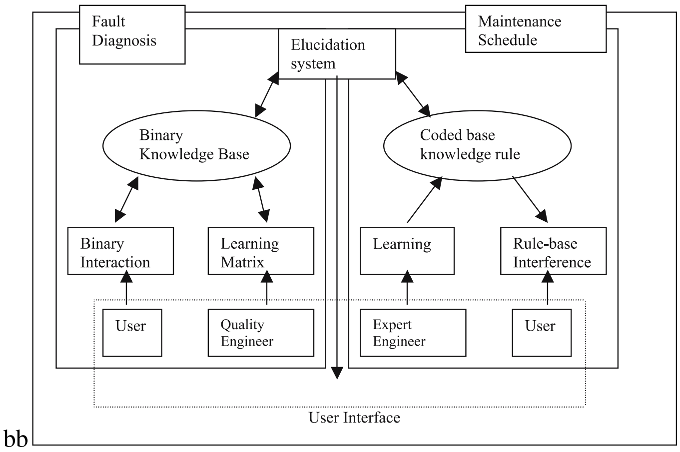


Fig. 3. An architectural illustration of WEDMES

developed WEDMES is shown in Fig. 3 for proper maintenance and fault diagnosis of wire-EDM. It describes the two independent modules viz. maintenance module and fault diagnosis module. The modules are constructed on the concept of expert system base knowledge in the form of logical clauses. The formulated logical clauses are used in the system that links with the knowledge base rule for generating decisions. The decision and explanation with coded information have been received in the form of the following setup:

IF <Antecedent>
THEN <Consequence>.

The antecedent typically contains clauses linked by logical connectives with weight fractions. The results consist of one or more expression that indicates the corresponding actions to be performed. It has two forms such as:

Structure I:
IF <Conditions>
THEN <Actions>
Structure II:
IF <Conditions>
THEN <Actions with significant weight fraction>.

The rules are scanned until the antecedent's matches with the assertions in the matrix system. Using the rules, relevant data is extracted from the available set of database. The system database consists of two groups, input and output database. The first group consists of various questions related to the particular class, subclass and objects. The second group includes the probable causes of the first group.

3.1 Module of maintenance schedule

In a non-conventional machining system, WEDM is a precision machine tool which requires preventive maintenance for long life and trouble free operations. The proper maintenance of such a machine can protect the deterioration of machining performance obtained from the machine over a long period. To achieve better machining accuracies, it is recommended that the machine is to be installed in a controlled atmosphere with room temperature of 20 ± 1 °C. The dielectric water temperature is also to be maintained within the span of 1 °C below the machine tool temperature by proper setting of the temperature controller of the dielectric cooling system. The room temperature, machine tool temperature, and job temperature must be stabilized by air conditioning before starting any job alignment or machining operation. Also the power switches of machine tool and dielectric cooling system should be "ON" at least half an hour before starting the machining operation. For trouble free operation, maintaining maximum cutting rate it is recommended that the guide nozzles of dielectric flushing should be closely contacted with both sides of the work surfaces (0.1 to 0.2 mm away from the workpiece), keeping the upper and lower flushing valves fully open. The upper flushing nozzle should be adjusted properly to achieve the require flow rate. The dielectric water should also be kept splashing on the job and especially in the work area. If the upper guide nozzles cannot be in close contact with the work surface, it is recommended to keep the lower flushing valve fully open and adjust the flow through the upper flushing valve. If both of the guide nozzles are not in a position to make close contact with the work surface, the low pressure flushing switch may be made operational, i.e., set Wp at '0' mode for dielectric flushing. Conductivity of water should be checked before starting the machine tool and must be monitored by checking it periodically during machining.

3.2 Module of fault diagnosis

The CNC-WEDM is a versatile as well as complicated machine that includes various mechanical and electrical systems and sub systems such as the power system, fluid system, CNC part programming system, voltage sub system, guide nozzle sub system, floppy drive sub system, etc. Manufacturers of WEDM provide an alarm with the machine tool, which gives a message through alert signals against any fault occurrences during machining. They also recommended some specific procedures to remove these faults during or post operation. However, sometime the alarm messages cannot help directly to detect the faults on wire electrode of WEDM during machining. There are several causes of fault occurrences. Wire breakage is one of the most important causes of fault occurrences during machining. It may occur due to the wrong parameter setting. It may also occur due to other reasons such as wire deflection, wire mechanical property, wire flexibility, spark gap width, excessive free length of wire in between workpiece and guide, etc. Hence, to find the relevant causes many factors are required to be analyzed step by step through the use of suitable algorithms. The location of pre failure symptoms on the wire and other systems of WEDM provide important clues to find the probable causes of a particular fault. Table 1 describes probable causes of wire breakage of WEDM with remedial actions, which may help in detection of fault during machining.

3.3 Binary relational base building and learning mechanism

The CNC-WED machine can be made more versatile by utilizing the facts given by the online operator or direct user on the spot for detection of fault without any waste of production time.

Table 1. Probable causes of wire breakage of WEDM with remedial actions

Parts/portion to be checked	Probable causes	Remedial/ recommended actions
If wire break at inlet side		
Wire tension and pressure rollers.	High wire tension damage the surface of the pressure roller or the movement of the tension roller is not smooth.	Reduce the wire tension slightly. Change the tension roller, if the wire gets trapped completely into the tension roller groove formed during machining. Check for any groove formed on the pressure roller.
If wire break at outlet side		
Wire drive mechanism and wire feed.	Disturbed wire feed produces vertical bands on the machined surface may cause of wire breakage. It may occur due to the deposition of copper or foreign particle stuck in the wire guide.	Clean the guide. Increase wire feed rate.
	The wire after sparking becomes weak due to wear.	Clean or change the guide.
	Uneven movement of lower roller.	Change the bearing of the roller.
	Feed spool brake over travels.	Feed spool brake set properly.
Checking machining condition (parametric setting values).	Setting value of Tp (peak current), T_{ON} (pulse on time), No load voltage etc are too high and cause of increasing in electrode wear.	Set proper values as per technology of cutting.
Lower flushing nozzle	Insufficient water column could not wrap the sides of the wire at the energizing current pickup may cause of wire breakage.	Clean the lower flushing nozzle.
If wire break inside the machining gap.		
Dielectric water	Due to excessive injection pressure the water dielectric may escape or mix with air and developing aerial discharge. Air will not be trapped if upper and lower flushing get balanced in the spark gap. The pressure of air in spark gap may cause of wire breakage.	Adjust flushing pressure of water dielectric water (Wp) by setting of Wp knob.
Conductivity	Low conductivity of water dielectric may cause of wire breakage.	Set the conductivity value at 20 and control it within 2 units.
Workpiece surface and clearance	Formation of stacks on the surface of the workpiece.	Avoid machining of stacked workpieces.
	Air may be trapped in between the clearance of stacked pieces or cracked formed at the workpiece surface and may cause of aerial discharge.	Perform grinding or any suitable machining operation to remove stacked pieces from the workpieces and subsequent heat treatment operation on the work material if required or otherwise change the workpiece.
Wire	Twisted or bent wire may develop discharge concentration that causes wire breakage.	Replace twist or bent wire.

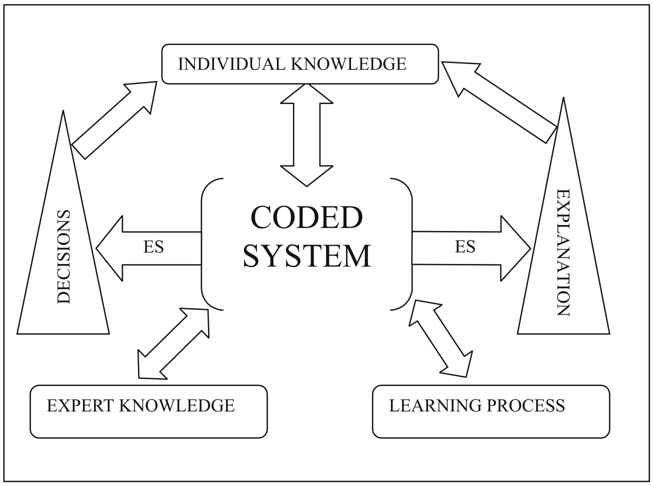


Fig. 4. Knowledge base binary coded system

Expert engineer's knowledge is considered for training the input based on the observation of pre fault occurrences. Figure 4 shows an architectural interaction of expert knowledge and individual knowledge through a coding system. The binary coding is used to generate the learning process which can contribute to the operator in diagnosis and understanding the faults. Education courses, training programs, and innovations of knowledge are essential for various sub-systems of the learning process to construct a respective learning matrix. A trained network of a learning matrix for individual training is described in Fig. 5. It highlights the dependency of eight causes on various input features represented by the alphabetic symbols as mentioned in Table 2. The machine tool operator put 'YES' or 'NO' in the

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1					1			1	1					1
2			2		2						2			
	3				3	3		3					3	
		4		4										
	5	5					5	5				5		
											6		6	
				7					7	7				
		8				8			8	8				8

Fig. 5. Learning matrix

Table 2. Probable input and output features for wire breakage

Symbol	Input features
A	Is breaking immediately after starting the machining?
B	Is breaking after sometime of starting the machining?
C	Whether the breaking occurred at upper guide?
D	Whether wire breaking occurred at workpiece?
E	Whether wire breaking occurred between lower guide and roller?
F	Did any unpleasant sound produced immediately after breaking?
G	Did the wire glued to the workpiece?
H	Are the electrode pin moved after a long time?
I	Is the machining being performed after a long time?
J	Is the operation is multi machining operation?
K	Whether the machining parameters table used?
L	Is the water dirty in the water tank?
M	Have the machine indicated any alarm signal before breaking?
N	Is the workpiece being used of a different height?
O	Is the electrical discharge frequency observed unstable?
Symbol	Output features
1	Setting of wrong machining parameters.
2	Either wire or workpiece is oxidized.
3	The conductivity of dielectric fluid is poor.
4	The wear and tear has occurred at wire guide.
5	Setting gap between nozzle and workpiece is improper.
6	Wear and tear has occurred at the roller bearing.
7	Wire feeding mechanism not working properly.
8	Clamping of workpiece is not proper.

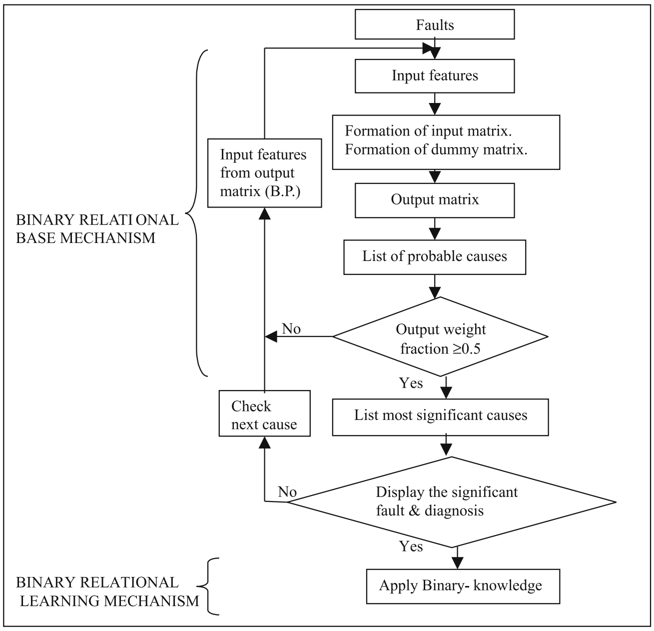
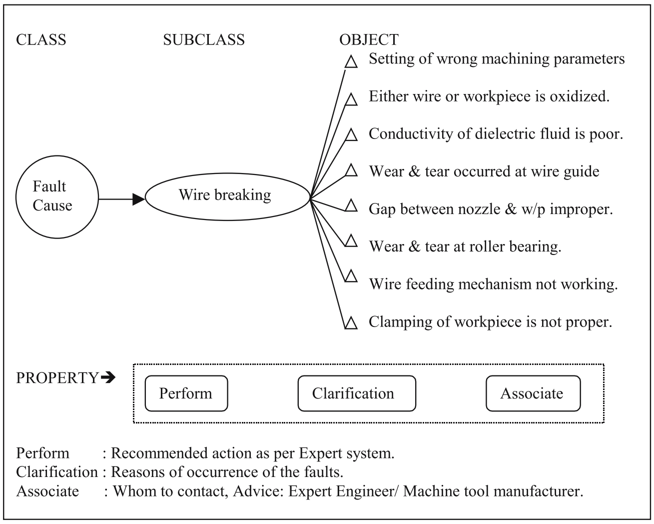


Fig. 6. Flow chart of the interacting matrix of fault-diagnosis module

form of ‘Y’ or ‘N’ against the formatted input features as a clue observed by the operator on the spot for detection of the most effective output features in the form of numerical symbols. The probable input and output features of wire breakages are also described in Table 2. The symbolic form of inputs and outputs are utilized to develop the WEDM expert system.

The knowledge base developed system consists of rules that can be divided into four groups of matrices. The first group includes the input matrix (i,j) that identifies the set of possible observations for the output matrix (k,l). The dimension of the input square matrix directly depends upon the number of input features. The second and third group includes the dummy matrices (j,k) that identifies the set of possible combination between the input and the output in two different steps of matrix multiplication. The dimension of the dummy matrix depends upon the number of input features and their relevant causes. The fourth group includes the output matrix that identifies the set of possible causes by the input matrix, which helps to understand and detect the causes of fault without much concern and waste of precious time. The dimension of the output square matrix directly depends upon the number of causes trained on coded inputs. The operator describes the observed clue in the symbolic form of ‘Y’ or ‘N’ as an input to develop the first group of rules. The second and third groups recognize the input matrix and rearrange the parameters to form the output matrix in the desired format.

Figure 6 shows the flow chart of the interacting matrix of the fault diagnosis module. The flowchart also describes how and when the binary knowledge is to be applied. The module activates after the occurrences of fault on WEDM. The faults are converted into input features through symbolic coding. The coding is processed with the help of dummy matrices to get the probable output matrix along with its weighted fraction. Hence, the most significant causes can be highlighted with its recommended action. From the data of output causes the most effective input feature is analyzed through back propagation. This input data is again processed to get final effective causes and its recommended actions. The fault may be analyzed under the head of class, subclass, and object. Figure 7 shows a relational example of class, subclass, and object for the most important fault of wire breakage during WEDM operation. Figure 7 also shows the properties like what to perform?, why to perform?, whom to contact? for better expertise and to interact with the probable objects for solving the causes occurring during machining in the form of a questionnaire.



Perform : Recommended action as per Expert system.
Clarification : Reasons of occurrence of the faults.
Associate : Whom to contact, Advice: Expert Engineer/ Machine tool manufacturer.

Fig. 7. Relation of class, subclass, object and properties of the causes of faults

3.4 Binary relational formulation mechanism

A binary coded matrix has been successfully applied to solve the problem after proper training. To solve the problem formulation of proper algorithm is essential at every stage of matrix formulation. The algorithm is developed considering the input matrix as,

$$\eta_{ij} = \begin{cases} \text{Y} & < \text{if input is yes} > \\ \text{N} & < \text{if input is no} > \end{cases}$$

$$\eta_{ij} = \begin{cases} 1 & < \text{if input is yes} > \ \text{positioned at } i = j \\ 0 & < \text{if input is no} > \end{cases}$$

These entries are then arranged in a diagonal form in which each value represents an input value. A binary bit pattern of 1s and 0s is used for formulation of the coding scheme. The coded scheme is generated for easy interaction with the formulated algorithm. The coded value carries important descriptive knowledge which is pre generated by the expert engineer. It makes it easy for the manufacturing engineer to exploit the philosophy of the formulated algorithm in the form of binary coded matrices. These algorithmic matrices are generated on the view of the knowledge of expertise engineers basically for searching for WEDM faults and their remedial actions. The algorithmic matrices are formulated in a sequential order of input, dummy, and output is expressed as the layer of the coded matrix. The layer of these coded matrices can be expressed mathematically as:

Forward propagation

i, j	Activity of input matrix
k, l	Activity of output matrix
α_{ij}	[Input square matrix, i.e, $i = j$],
β_{ik}	[First dummy matrix, i.e, $i > k$],
γ_{ki}	[Second dummy matrix, i.e, $i > k$],
δ_{kl}	[Output square matrix, i.e, $k = l$],
α_{ij}	[ith row ith column $= i$, jth row jth column $= j$ and other row $= 0$],
β_{ik}	[ith row $= 1$, jth row $= 1$ and other row $= 0$],
γ_{ki}	[ith row $= i$, jth row $= j$ and other row $= 0$],
δ_{kl}	[ith row ith column $= i$, jth row jth column $= j$ and other row $= 0$],
	The second dummy matrix is formulated as, $\gamma_{ki} = [\alpha]\{\beta\}$,
	The output matrix is further formulated as, $\delta_{kl} = \{\beta'\}\{\gamma\}$
	The output matrix can also be expressed as,
δ_{kl}	[ith row jth column $= i + j$, jth row ith column $= i + j$]
	Initial output matrix $= \delta_{o/p(0)} = \{\beta'\}\{\gamma\}/\sum i$
	Corresponding output matrix can be expressed as,
	$\delta_{o/p(m)} = \delta_{o/p(m-1)} - Q_m/m$
	Where,
m	No. of output corresponding to input i
Q_{kl}	[Output square matrix, i.e, $k = l$, learning matrix],
	Final output matrix $= \delta_{o/p} = \delta_{o/p(m)} - 1$

The diagonal of the [15 × 15] input square matrix 'α' represents the input parameters in the ith part. The first layer of the dummy matrix 'β' of [15 × 8] express the inputs of the above matrix 'α' in terms of ith digits at the ith rows of the 'β' matrix. The second layer of the dummy matrix 'γ' forms with the interaction of 'α' and 'β' matrix and has the same characteristics as that of the first layer. The digit of initial output layer defines as the sum of all the ith inputs entered by the operator in 'Y' or 'N' format. It is again simplified into a binary matrix of [8 × 8] order to obtain the desired final output. The final output matrix gives the appropriate intensity of output along the diagonal of $\delta_{o/p(m)}$ after interacting with the learning matrix format. Finally, the kth layer reflects the most significant output parameters for the given set of inputs.

Back propagation

δ_{ij}	[ith row ith column $= i$, jth row jth column $= j$ and other row $= 0$],
γ_{ik}	[ith row $= 1$, jth row $= 1$ and other row $= 0$],
β_{ki}	[ith row $= i$, jth row $= j$ and other row $= 0$],
α_{kl}	[ith row ith column $= i$, jth row jth column $= j$ and other row $= 0$],
	The second dummy matrix is formulated as , $\gamma_{ki} = [\delta]\{\gamma\}$,
	The input matrix is further formulated as , $\alpha_{kl} = \{\gamma'\}\{\beta\}$
	The input matrix can also be expressed as,
α_{kl}	[ith row jth column $= i + j$, jth row ith column $= i + j$]
	Initial input matrix $= \alpha_{i/p(0)} = \{\gamma'\}\{\beta\}/\sum i$
	Corresponding input matrix can be expressed as,
	$\alpha_{i/p(m)} = \alpha_{i/p(m-1)} - Q_m/m$
	Where,
m	No. of input corresponding to output i.
Q_{kl}	[Input square matrix, i.e., $k = l$, learning matrix],
	Final input matrix $= \delta_{i/p} = \delta_{i/p(m)} - 1$

Similarly, the diagonal of the [8 × 8] output square matrix 'δ' represents the output parameters in the ith part. The first layer of the dummy matrix 'γ' of [8 × 15] includes the confirmation of these outputs in terms of ith digits at the ith rows of the matrix. The second layer of the dummy matrix 'β' forms with the interaction of the 'δ' and 'γ' matrix and has the same characteristics as that of the first layer. The initial input layer includes the digit as the summation of all the ith input given by the operator in 'Y' or 'N' format. It is again simplified into a binary matrix of [15 × 15] order to obtain the desired final input. The final input matrix provides the values and intensity of the input along the diagonal after interacting with the learning matrix format. Finally, the kth layer reflects the most significant input parameters for the given set of outputs.

4 Results and discussion

The proposed binary relational analysis and expert system incorporate the probable input parameters which are appearing on the screen in the form of a relevant questionnaire for an online operator. The on line operator is required to put his observations in the form of Y or N against each of the sub classes displayed on the screen. Instantly after input the data against the sub class, objects

Table 3. Probable output after wire breakage

	Forward propagation
The probable causes in machine are	Setting of wrong machining parameters.⇒ 0.3333 Either wire or workpiece is oxidized ⇒ 0.5 Conductivity of dielectric fluid is poor ⇒ 0.1667
The most sensitive cause is	Either wire or workpiece is oxidized
The recommended action is	If fault is in electrode, change electrode wire. Otherwise, remove oxidized surface from the workpiece by any suitable surface finishing operation. Avoid machining of stacked workpieces.
Reason for the cause is	Due to excessive injection pressure the water dielectric may escape or mix with air and developing aerial discharge. Air will not be trapped if upper and lower flushing get balanced in the spark gap. The pressure of air in spark gap may cause of wire breakage. Twisted or bent wire may develop discharge concentration that causes wire breakage. This is probably due to the use of low conductivity of dielectric or concentration of electrical discharges on the stacked/ uneven surface of workpiece or wire itself.
	Backward propagation
The probable causes in machine are	Is breaking immediately after starting the machining?⇒ 0.334 Is breaking after sometime of starting the machining?⇒ 0.167 ——— Whether wire breaking occurred at workpiece?⇒ 0.167 ——— Did any unpleasant sound produced immediately after breaking?⇒ 0.5 Did the wire glued to the workpiece?⇒ 0.167 ——— Is the machining being performed after a long time?⇒ 0.334 Is the operation is multi machining operation?⇒ 0.167 ——— Is the water is dirty in the water tank?⇒ 0.167 ——— Is the workpiece being used is of different height?⇒ 0.167 Is the electrical discharge frequency observed unstable?⇒ 0.167
The Most input parameter is	Did any unpleasant sound produced immediately after breaking?
The probable causes in machine are	Setting of wrong machining parameters.⇒ 0.83 Conductivity of dielectric fluid is poor ⇒ 0.83 Gap between nozzle and workpiece is improper ⇒ 0.33 Wear and tear at the roller bearing ⇒ 0.33 Wire feeding mechanism not working ⇒ 0.16 Clamping of workpiece is not proper.⇒ 0.5
The most sensitive cause is	Setting of wrong machining parameters.⇒ 0.83 Conductivity of dielectric fluid is poor ⇒ 0.83
The recommended action is	**Action for setting of wrong machining parameters:** Check and reduce the pulse ON time (T_{ON}), Peak current (I_p), pulse peak voltage setting (V_p). Adjust setting value of pulse OFF time (T_{OFF}). Set wire tension between 1020 to 1140 gm. Set wire feed rate more than 6 m/min for working with higher pulse power. Set flushing pressure of water dielectric as per the pulse power supply and thickness of the workpiece. High input pressure of water dielectric is recommended for more than 30 mm of job thickness cutting. The selected pulse ON time, the machining gap voltage, peak current, servo feed should not be changed during machining. The spark gap setting should be done by spark gap set voltage and servo feed should be adjusted to get the optimal speed with stable gap voltage. For stable machining, it is recommended that servo feed setting should be set in such a way so that the average gap voltage is higher than the spark gap set voltage by at least 5 volts. Suggested setting value for general purpose machining: T_{ON}: 0.5 to 0.7 μsec, T_{OFF}: 9.5 to 15 μsec, I_p: 60 to 120 Amp, V_p: 100 volts, W_F: 5 to 7 m/min, W_T: 800 to 1200 gm (for ϕ250 μm brass wire), S_v: 20 to 30 volts. However, actual machining may differ from the recommended action, as the machining characteristics are different for different materials. Hence, it is suggested that the test cut should be performed on a trial piece to get the exact parametric setting value and set accordingly while machining the actual job. **Action against poor conductivity of dielectric fluid:** Change the dielectric fluid, check De-ionizer resin and change if required.
Reason for the Cause is	**Causes of wire breakage due to wrong setting of machining parameters:** Higher the setting value of T_{ON} , I_p, V_p higher is the pulse discharge energy that can break the wire frequently. Lower the T_{OFF} setting, larger is the number of discharges in a given time resulting in increase of sparking efficiency. As a result cutting rate is increased and may cause of wire breakage. Higher setting value of Wp with low wire tension may deflect the wire and it is a cause of wire breakage. **Causes of wire breakage against poor conductivity of dielectric fluid:** Lower the conductivity, lower is the gap between wire electrode and workpiece and lower is the over cut. Hence, wire runs closer to the work surface. The dielectric fluid flow along the machining gap is limited because of the narrow gap. As a result there is a difficulty in flushing which may cause wire breakage. Again use of very low dielectric conductivity during machining, the wire metal deposits on the workpiece that may cause of wire breakage. Even very high dielectric conductivity the water dielectric allows direct current to flow in the gap, hence sufficient discharge voltage can not built up, as a result machining becomes unstable

are displayed in the form of probable inputs. The final output matrix is obtained along with the weight fraction as per the generated algorithm of the relevant fault through the interaction of the fault input matrix. The acquired fault detection square matrix will have a binary output along its diagonal, which is converted to the useful signal for the operator working on the line.

Table 3 describes the probable causes and recommended actions with explanations of the fault against wire breakage, which has been found using the developed forward and backward propagation technique.

To verify the developed framework 120 sets of data were generated for proper analyzing of the acquired output. Each data set was characterized for the input, output, and the weight fraction in terms of a graphical binary signal between 0 and 1 as shown in Fig. 8. Figure 8a shows the influence of the coded value on the input parameters for a data set out of 120 collected data. It also shows the different shoot up position of input code at the different signal. If the operator defines the ith input as 'Y', $i = 1, 2, 4$, the shoot-up in the signal exists at input codes 1, 4, 6. In the same way the significant causes is highlighted by the bounce at the signal 2, where the output causes is stored. The negative part in the graph also depicts the significant weight of -3 at signal 2 as the most negative and critical weighted signal. Figure 8b shows the influence of the coded value on the input for another data set. From Fig. 8c it is observed that at a different position of the ith input signal, $i = 4, 9, 13$, the shoot-up is at the signal 5 which highlights the significant causes. The graph also shows that the most negative weighted signal (i.e., -5 weighted fractions) for the output code is at signal 5. Another important graph is generated to verify the developed framework considering a data set with ith input, $i = 1, 3, 5, 7, 9, 11, 13, 15$ as shown in Fig. 8c. The graph shows that the maximum negative weight fraction, i.e., -7 corresponding to the output signal point 8 for the respective input codes. The generated framework introduces a new methodology that can guide the operators and manufacturing engineers on spot for detection of probable causes against faults and provide their remedial actions in the form of suggestions to enable them to face new challenges in the CNC-WEDM operations.

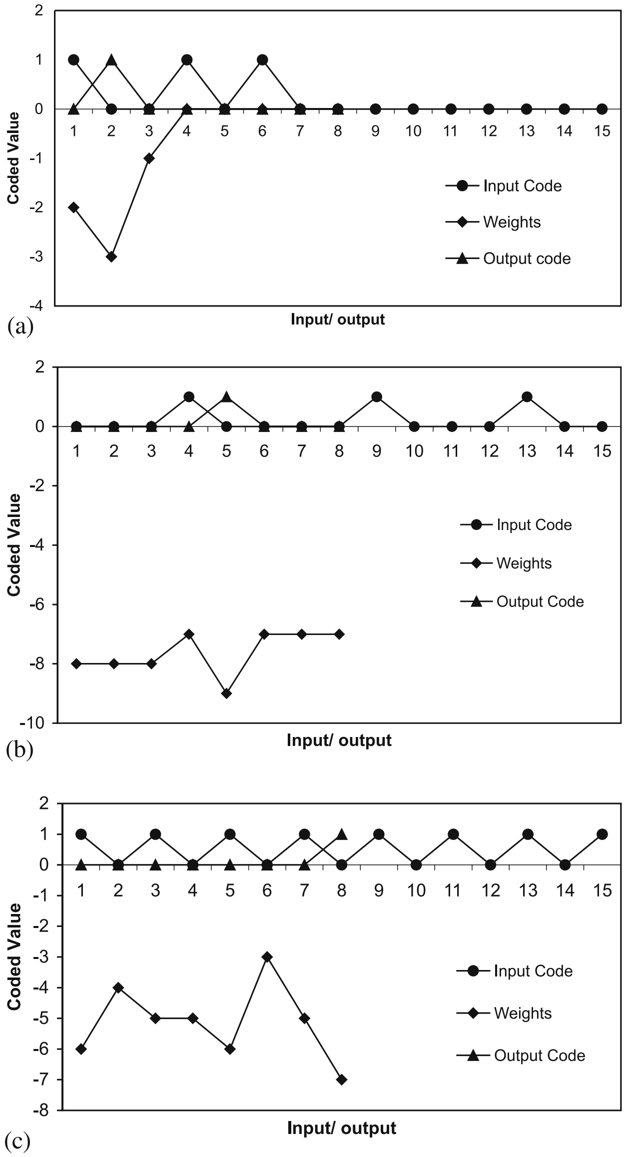


Fig. 8. Graphical relation between input, output and weight fraction

5 Conclusions

On the basis of a developed binary coded relational base expert system for fault diagnosis and maintenance of WEDM the following conclusions are drawn:

1. It is found that the binary data has a significant influence on the fault diagnosis and determination of appropriate weight fraction for each probable machine fault.
2. The developed new expert philosophy can meet the requirement of the manufacturing industry through fault findings on WEDM in a short cycle of time and enhance the productivity by reducing the lead time.
3. It is found that the developed approach can be used in both forward and backward propagation effectively. Results obtained from backward propagations are most significant and sensitive as compared to forward propagation. The most sensitive cause for forward propagation is crucial as compared to the backward propagation if the weight fraction value is more than 50% and vice-versa. To detect the fault and remedial action, application of backward propagation is recommended.
4. The develop system is time saving, easy to maintain, capable of self-learning and knowledge acquisition. This developed system can help and guide the operator and trainees through proper identification of actual faults of WEDM and suggest proper remedial actions against faults during WEDM operation.
5. This developed expert system can also be applied for fault diagnosis of other applications where the module of input and output are large and well defined.

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