A NOVEL AMFMEA APPROACH TO IDENTIFY MOST CRITICAL COMPONENT AND DECISION MAKING APPROACH FOR COMBINING NDTS FOR SCREW COMPRESSOR

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Abstract:

To ensure higher reliability, it is necessary to identify the most prominent cause of failure. It was observed in multiple works that most of the researchers used failure mode and effect analysis (FMEA) and failure mode and effect criticality analysis (FMECA) but these approaches contain lots of hindrances. Alternatively, the MATRIX FMEA approach applied to identify the most prominent cause of failure and critical sub-component prone to that particular failure. The matrix FMEA developed for design engineers so that they can identify the potential cause of failures and design-out them in new product design. The central idea of this research is to apply this approach to maintenance, since the potential failure mode and the affected components were known. In most research, a single component such as a cylinder or turbocharger is used for analysis, but this research targets an entire machine. Multiple researchers also highlighted that the combination of non-destructive testing (NDT) provides better results instead of single NDT. Multiple researchers also highlighted the suitability of the analytical hierarchy process (AHP) and preference ranking organization method for enrichment evaluation (PROMETHEE) for decision making (DM). Therefore, this work covered firstly, a novel AMFMEA (AHP-Matrix FMEA) to identify the most critical component of particular machinery located in a heavy industrial setup and secondly, DM approach for combining NDTs. It was observed that the incorporation of AHP in Matrix-FMEA improved its analytical ability and reduced overall computation time. This work also provided the guideline with a detailed procedure for combining NDTs.

1 Introduction

The matrix FMEA is developed for design engineers to use during the earliest stages of the design process so that they can identify the potential cause of failures and design-out them in new product design. The Matrix-FMEA approach focuses on the interrelation between function, component, and failure. The ultimate goal is to find the relation between the function of component and potential failure mode and then, identification of components that are prone to these potential defects. The central idea of present research work is to use this approach for maintenance as the potential failure mode and the components affected were known and it can aid the engineer in

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reducing or eliminating the unplanned failures equipment might experience. While typical FMEA approaches also include severity and detectability data, but this work applied only the occurrence data and the inherent statistical knowledge it holds. Although the Matrix-FMEA approach replaces the RPN but it lacks in the analysis part, therefore, it is a standard practice to apply Matrix-FMEA on the single component like cylinder or turbocharger. This research work targeted a complete machine i.e. compressor which contains several components, therefore, to enhance the analytical capability of Matrix-FMEA, AHP was incorporated with it. For early detection of defects, non-destructive testing techniques are usually preferred because the component under test does not have to be destroyed. There are several different NDT techniques are available for different-2 applications. Multiple research work highlighted the fact that various non-destructive testing techniques have several benefits, while there are some hindrances too.

Therefore, a single NDT technique cannot give highly reliable fault detection. For early detection of defects, non-destructive testing techniques are usually preferred because the component under test does not have to be destroyed. The organization of this research paper is as follows: In section 2, the review part of failure criticality analysis covered. In section 3, the methodology part covered. In section 4, problem analysis covered. In section 5, the result and discussion part covered and then, conclusions are drawn in the last section. This analysis is not only helpful for maintenance personnel for preparing pin-pointed maintenance plans but also the design engineers can use these findings to improve the design of components by taking into consideration the functions and select appropriate analyses to eliminate or design out the potential failure modes.

2 Literature Review

This section discussed the hindrances of FMECA and the role of matrix FMEA to identify the prominent cause of failure in components prone to those failures. As per Lolli F.et al.[1] FMEA consists of a bottom-up approach in which a system is subsequently broken down into its constituent parts, whose failures are correlated to potential effects to assess a risk priority number (RPN) for each failure *i* by the following product:

$$RPN_i = O_i.\ D_i.\ S_i \tag{1}$$

Whereby, O_i, D_i and S_i is score given to the occurrence likeness, to the detectability and the severity of the failure. These values usually vary from 1-10. Here failure ranked in descending order of RPN for criticality assessment.
As per Lipol et al. [2], Sachdeva A. et al. [3] and Arunajadai S.G. et al. [4] besides the advantages of FMECA, there are some significant hindrances which are as follows -

- As per in risk-based analysis the multiplication of the severity, occurrence and detection rankings may result in rank reversals. For instance, a ranking of *2* may not be twice as bad as a ranking of *1* but multiplication treats them as though they are. A severity of *1*, occurrence of *8*, and detection of *8* have the same RPN value as the severity of *8*, the occurrence of *4*, and detection of *2*. It means that it is not a wise decision to blindly rely on the outcomes of FMECA.
- This technique considers only some kinds of failure i.e. likelihood of failure, non-revealing, and severity, where many other important factors are not considered.
- Lack of detailed taxonomy to record the information

As per Roberts R. et al. [5], a function-failure method is an efficient tool for detecting a failure in rotorcraft components. Once the relation of failure modes in critical aerospace applications with the functionality of components identified, then the designer can draw suggestions to improve an existing design or complete change in its design. If necessary corrections implemented in the early design stage then, the components can be made less susceptible to the failure mode. In some cases, the faulty component may be replaced with another fault-free component that performs similar functions but not affected by the identified failure mode.
Generally, the MATRIX FMEA approach is commonly used for identifying the most prominent cause of failure and critical sub-component [1] prone to that particular failure. Domagała [6] applied matrix-FMEA in the failure analysis of turbocharger. Roberts R. et al. [5] applied matrix-FMEA in failure analysis of the rotorcraft component.

Domagała [7] applied matrix-FMEA in the failure analysis of a hydraulic cylinder. Lolli F. et al. [1] applied matrix-FMEA in failure analysis of the blow molding process.

The function-component (EC) matrix [4] consists of its column and row, the components and functions respectively. Similarly, the component-failure (CF) matrix consists of its column and row as failure modes and components respectively. The CF matrix is based on the information obtained either from failure reports or from an FMEA rather than from reliability testing, therefore, the function-failure method is a tool for re-design as an aid for reliability engineering. The entries in the rows and columns of EC matrix indicates the number of times that a component was used for a function across the range of products examined. Similarly, the entries in the rows and columns of the CF matrix indicate the number of times a component experienced a particular failure. NDT combination gives better reliability in fault detection/assessment of defects in industrial equipment/components in multiple applications. Each technique [8] has some hindrances; therefore, making combination helps in countering these hindrances. To make an appropriate combination, it is necessary to consider attributes.

3 Methodology

This section explained the basic steps of AMFMEA and then the steps of AHP and PROMETHEE required to make the most appropriate decision regarding a critical component and then an appropriate combination of NDT for that component. This section is divided into a series of subsections to make it easy to understand.

3.1. AMFMEA (AHP-Matrix FMEA) Procedure

The AMFMEA (Figure 1) procedure consists of two parts viz., part A covered the Matrix FMEA and part B covered the decision making.

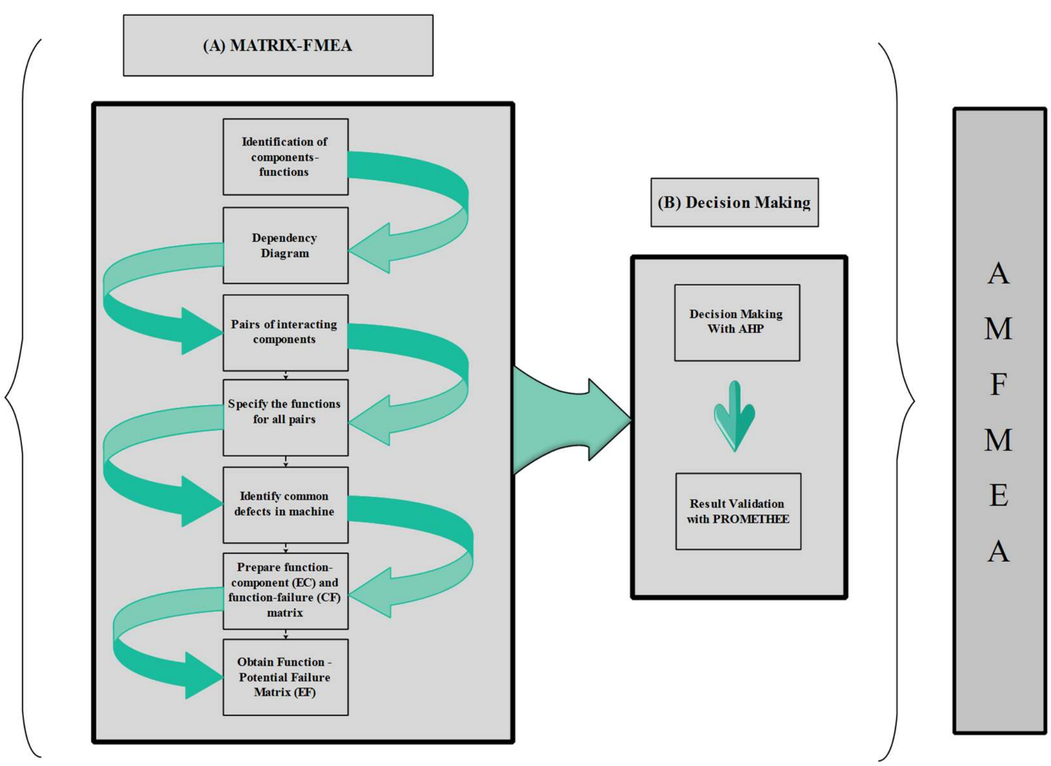

Figure 1. AMFMEA Procedure.

Part A. Matrix FMEA
Step 1. Identify components and their functions
Step 2. Prepare Dependency Diagram
Step 3. Prepare pairs of interacting components
Step 4. Specify the functions for all pairs
Step 5. Identify common defects in the machine
Step 6. Prepare function-component (EC) and function-failure (CF) matrix
Step 7. Obtain Function – Potential Failure Matrix (EF)

$$(EC)\ (CF) = EF \tag{2}$$

Part B. Decision Making
Step 1. Perform AHP procedure on the result obtained in step 7 of part A to find a critical component in critical equipment.
Step 2. Result validation with the PROMETHEE procedure.

3.2. Analytical Hierarchy Process (AHP)

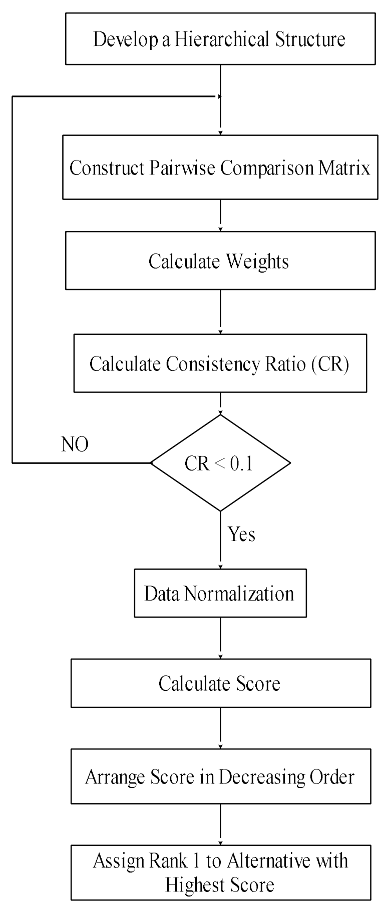

Figure 2. Flow Chart of AHP.

As basic steps of AHP are in a standard form [9] but this research work also incorporated the elaboration of each individual step [10-13] to make it more graspable.

The steps are as follows-
Step 1: Break the entire problem into three levels to prepare a hierarchical structure: goal or objective at the top level, judgment criteria or simply criteria or attributes at the second level and alternatives at the third level.
Step 2: To evaluate the weights of each attribute, simply construct a pair-wise comparison matrix **A1** using a scale of relative importance. This scale varies from 1 to 9 (Table 1).

Table 1. Scale of Relative Importance.

Value	Significance	Explanation	Importance*
1	Equal importance	Two activities contribute evenly to the aim.	A has the same significance as B
3	Moderate Importance	Experience and judgment vaguely favor one activity over another	A is more significant than B
5	Strong Importance	Experience and judgment robustly favor one activity over another	A is much more significant than B
7	Very Important	An activity is sturdily favored and its dominance demonstrated in practice.	A is very significant than B
9	Absolute Important	The evidence favoring one activity over another is of the utmost possible order of affirmation.	A is extremely significant than B
2, 4, 6, 8	in-between the two adjacent judgments	When there is a need for negotiation.	Intermediate
Reciprocal of above numbers	If activity *i* has one of the above (non-zero) numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value	------------	------------

**Assuming that two criteria's as A and B*

- The below square matrix is named A_1 which shows quantified judgment prepared with the help of Table 1 on a pair of criteria.

$$
\begin{array}{c} \\ K_1 \\ K_2 \\ K_3 \\ - \\ K_M \end{array}
\begin{array}{c} \begin{array}{cccccc} K_1 & K_2 & K_3 & - & - & K_M \end{array} \\
\begin{bmatrix} 1 & k_{12} & k_{13} & - & - & k_{1M} \\ k_{21} & 1 & k_{23} & - & - & k_{2M} \\ k_{31} & k_{32} & 1 & - & - & k_{3M} \\ - & - & - & - & - & - \\ k_{M1} & k_{M2} & k_{M3} & - & - & 1 \end{bmatrix} \end{array}
$$

- Where the k_{ij} (always $k_{ij} > 0$) is the relative importance of K_1 over $K_1, K_2 \ldots K_M$ and so on. There are two conditions arises –
  1. $k_{ij} = k_{ji} = 1$; for $i = j$ (equal relative importance), $i, j = 1,2,3\ldots, M$;
  2. $k_{ij} = 1/k_{ji}$; for $i \neq j$

- If all the comparisons are perfectly consistent, then the below relation should always be true for any combination of comparisons taken from the judgment matrix

$$k_{ik} = k_{ij}\, k_{jk}$$

- Find the geometric mean of each row and add all the geometric means

$$GM_i = \sqrt[M]{[\prod_{i=1}^{M} k_{ij}]} \quad (3)$$

$$w_j = GM_i / \sum_{i=1}^{M} GM_i \quad (4)$$

- The consistency checked for the pair-wise comparison matrix and the weights of different criteria also calculated. Make A_2 with the help of w_j values.

$$A_2 = \begin{bmatrix} w_1 \\ w_2 \\ - \\ - \\ w_j \end{bmatrix} \quad (5)$$

$$A_3 = A_1 * A_2 \text{ and } A_4 = A_3 / A_2$$

- Evaluate the maximum Eigenvalue λ_{max} that is the average of the matrix A_4. The closer λ_{max} is to Eigenvalues, the more consistent it is with the comparison matrix A1 or the more coherent will be the judgments provided.
- The consistency index (CI) is used as a measurement of the consistency of the judgments. Calculate the CI = (λ_{max} - M) / (M - 1), where M is the order of matrix A_1 which is also equal to the number of defined criteria. Therefore, the CI represents an average of the Eigenvalues.
- Use the table of Random index (Table 2) to evaluate the consistency ratio (CR= CI/RI)

Table 2. Random Index.

Attributes	3	4	5	6	7
RI	0.52	0.89	1.11	1.25	1.35

If the consistency ratio (CR) value is less than 0.10 than the weights calculated are correct or considerable with a maximum 10 % of error. To state the relative significance of diverse criteria, the weighting coefficients (weights w_j) introduced.

These weights have no clear economic meaning, but their use allows modeling the actual decision making.

Step 3: A normalized matrix prepared from the comparison matrix.

Step 4: Use the weights evaluated in step 2 to find the score of an alternative as-

$$P_i = \sum_{j=1}^{M} w_j n_{ij} \tag{6}$$

Where,
w_j = weight of each attribute
n_{ij} = normalized value of alternative regarding each attribute
P_i = overall or a composite score of the alternative
The alternatives which have the highest value of P_i are considered as the best alternative. Now, give the ranking to the alternative in the decreasing order of score calculated.

3.3. PROMETHEE Method

These [11, 14-16] tools are mostly used for the ranking and selection of a fixed set of alternative actions among often conflicting criteria. In this method, there is a comparison of alternatives with other alternatives during making the matrix for a particular attribute.
The steps are:
Step 1: Use AHP to calculate the weights of the criteria.
Step 2: The dominant alternative (*a*) like equipment, shop, technique, etc. with respect to other assigns the value 1 and 0 for non-dominating alternatives with respect to others. The no. of matrix and the no. of the attribute (*A*) are equal. Now use the weights assigned to each attribute to prepare an overall matrix.
Let the decision-maker have specified a preference function P_i and weight w_i for each criterion c_i *(i = 1, 2. . . M)* of the problem.
The multiple criteria preference index Π_{a1a2} is:

$$\Pi_{a1a2} = \sum_{i=1}^{M} w_i P_{i,a1a2} \tag{7}$$

Π_{a1a2} represents the intensity of preference of the decision-maker of alternative *a1* over alternative *a2*, Its value ranges from 0 to 1. This preference index determines a valued outranking relation on the set of actions.
Step 3: Evaluate the sum of every, row and column of the overall matrix. The difference between the corresponding row and column or net domination gives the score for the alternatives. The following equations defined an alternative ***a*** belonging to a set of attributes *A*:

$$\varphi^{+}(a) = \sum_{x \varepsilon A} \Pi_{xa} \tag{8}$$

$$\varphi^{-}(a) = \sum_{x \varepsilon A} \Pi_{ax} \tag{9}$$

$$\varphi(a) = \varphi^{+}(a) - \varphi^{-}(a) \tag{10}$$

$\varphi^{+}(a)$ is the leaving flow which is the measure of the outranking character of *a*, $\varphi^{-}(a)$ is the entering flow which is the outranked character of *a* (i.e. degree to which all other alternatives dominates alternative *a*) and $\varphi(a)$ is the net flow which represents a value function, whereby a higher value reflects a higher attractiveness of alternative *a*. The net flow values used to indicate the outranking relationship between the alternatives.
Step 4: Arrange the score in the descending order and accordingly gives the ranking to the alternatives.

4 Problem analysis

This section will cover the analysis part of this industrial problem. The first step includes the use of matrix-FMEA for identification of the list of components more critical as compared to other and then, most critical one among these using AHP and PROMETHEE, subsequently identification of the most suitable combination of NDT that can be applied on this critical component.

4.1. Analysis with Matrix FMEA

This sub-section shows part A of AMFMEA. The steps are as follows:
Step 1. Identify components and their functions - The methodology involves the formation of a function-failure matrix that can be used as a knowledge base to identify and analyze potential failures for new designs and redesign.

- The problems [17] associated with the use of natural language often lead to ambiguity, or uncertainty when conducting failure analysis.
- This problem is amplified when other researchers viewed these results or after time has passed.
- Therefore, this research work used taxonomy mentioned in the research work of James L. Greer et al. [18] and Michael E. Stock et al. [17] for giving standard names to components (See Table 3).

Step 2. Prepare Dependency Diagram

- As the name suggests, this diagram [8] (see Figure 3) shows the inter-dependency of various components of the equipment.

Step 3. Prepare pairs of interacting components

- Using decomposition of the screw compressor and the relationship graph a 17 pairs of interacting components have been identified.
- These are: P_1 (C_1-C_8), P_2 (C_1-C_9), P_3 (C_1-C_{23}), P_4 (C_2-C_3), P_5 (C_2-C_{10}), P_6 (C_3-C_{11}), P_7 (C_3-C_{12}), P_8 (C_3-C_{13}), P_9 (C_4-C_8), P_{10} (C_4-C_{14}), P_{11} (C_4-C_{15}), P_{12} (C_5-C_{16}), P_{13} (C_5-C_{17}), P_{14} (C_5-C_{18}), P_{15} (C_6-C_{20}), P_{16} (C_7-C_{21}), P_{17} (C_7-C_{22}) and P_{18} (C_7-C_{23}).
- The relation occurring between the interacting components of the screw compressor helped to obtain a relationship between a set of the screw compressor components (C) and a set of interacting pairs (P).

Step 4. Specify the functions for all pairs

- As mentioned in step 1, To avoid ambiguity, or uncertainty this work used the taxonomy of Julie Hirtz et al. [20] for standardizing functions
- For all pairs (P) the functions (e) have been specified, which are as follows-
- ✓ **Branch or Separate** (e_1) – To separate flow (material, energy, time) into distinct components. This includes the components whose function is either refine as in C_{10} & C_{17} and filter as in C_{21} & C_4
- ✓ **Channel or Export** (e_2) – To send a flow (material, energy, time) outside the system boundary. This includes the components whose function is to eject as in C_{15}, C_{16} & C_{19}
- ✓ **Control or Regulate** (e_3) – To alter or govern the size or amplitude of a flow (material, energy, time). This includes the components whose function is to control as in C_7, C_{22}, C_{12}, C_8, C_9, C_{20}, C_{23}& C_{18}, to maintain as in C_6 & C_{14} and to compress C_1
- ✓ **Convert** (e_4) – To convert one form to another form. This includes the components whose function is to condense as in C_5
- ✓ **Provision or Store** (e_5) – To accumulate a flow. This includes the components whose function is to accumulate as in C_2, C_3 & C_{11}
- ✓ **Signal or indicate** (e_6) – To provide information on material, energy or signal flow as an output signal. This includes the components whose function is to show as in C_{13}.

Table 3. List of Components and Their Functions.

Component	Abbr.	Component Code	Function
Compressor Element	**E**	**C_1**	The compressor chamber consists of this which compresses the air.
Air Receiver	**AR**	**C_2**	The compressed air and oil flow into AR through **the** check valve (CV).
Oil Tank	**OT**	**C_3**	The oil collects in the lower part of AR which serves as an oil tank.
Oil Filter	**OF**	**C_4**	It cleans the oil coming from the oil cooler and after cleaning supply this oil to the element through Oil Stop Valve (VS).
Condenser	**Cd**	**C_5**	To condense liquid from compressed air
Water Cooler	**Cw**	**C_6**	In water-cooled compressor **(C#5)**, the water flows through the inlet pipe, the coolers, and the outlet pipe.
Inlet Valve	**IV**	**C_7**	Through this air enters to compressor chamber.
Oil Stop Valve	**VS**	**C_8**	Air pressure forces the oil from AR through OF & VS to E and its lubrication points.
Check Valve	**CV**	**C_9**	Prevents blowback of compressed air when the compressor is stopped.
Table 3 contd…			
Oil Separator	**OS**	**C_{10}**	In AR most of the oil is removed from air/oil mixture centrifugally. The oil separator (OS) removed the rest.
Oil Filter Plug	**FC**	**C_{11}**	To depressurize the compressor by unscrewing FC just one turn to permit any pressure in the system to escape. This is also the inlet for oil filling, just remove it for filling and then refit it.
By Pass Valve	**BV**	**C_{12}**	When the oil temperature is below a certain value the BV shuts-off the supply from oil cooler (CO). BV starts opening the supply from CO when the oil temperature has increased to the set point.
Oil Level Indicator	**OI**	**C_{13}**	Shows the level of oil in the oil tank.
Oil Cooler	**CO**	**C_{14}**	To cool the oil before supply it to E
Drain Valve	**Dm**	**C_{15}**	To drain the oil from the oil tank
Moisture Trap	**MT**	**C_{17}**	To remove moisture from compressed air
Outlet Valve	**AV**	**C_{18}**	The air is discharged through it via. Minimum Pressure Valve (VP)
Drain	**D**	**C_{16}, C_{19}**	Drainage
Minimum Pressure Valve	**VP**	**C_{20}**	Prevents the receiver pressure from dropping below minimum pressure.
Air Filter	**AF**	**C_{21}**	Air drawn from air filter.
Solenoid Valve	**Y1**	**C_{22}**	Controls opening and closing of the inlet valve.
Safety Valve	**SV**	**C_{23}**	Release the excess pressure

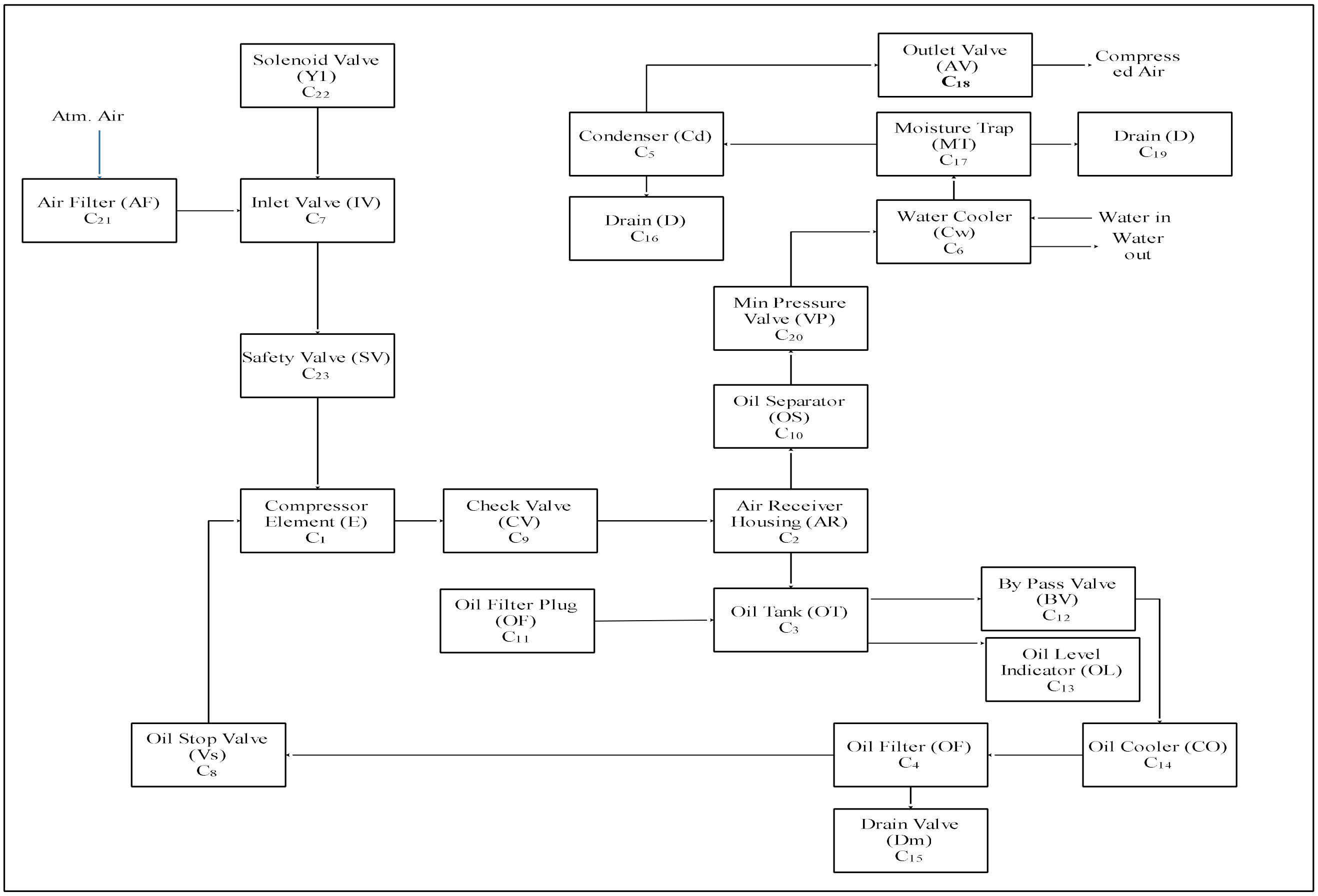

Figure 3. Dependency Diagram.

Step 5. Identify common defects in the machine

- This research work is concentrated on the maintenance of the machine instead of re-designing of a component. In this part a failure taxonomy of Irem Y. Tumer et al. [19] used. The commonly occurred defects in machine components are considered, viz. Insufficient Inlet air (f_1), High element outlet temperature (f_2), Seizure (f_3), Improper unload of a compressor (f_4), Oil in discharge line (f_5), Insufficient Pressure (f_6).
- A list of common-mode and cause of failures also prepared (Table 4).

Table 4. List of common mode and cause of failures.

Potential Failure Mode	Potential Cause of Failure	Recommended Action
Insufficient Inlet air (f_1)	Inlet valve leakage (C7)	Replace defective parts
	Solenoid valve jammed (C22)	Replace defective parts
	Minimum pressure valve (C20) leaking	Check valve
High element outlet temperature (f_2)	Oil level (C3, C11 & C13) too low	Check & correct
	Cooling water flow too low (C6, C16)	Increase flow
	Restriction in cooling water flow (C6)	Repair it
	Oil cooler clogged (C14)	Clean cooler
	By-pass valve (C12) malfunctioning	Check & repair valve
Seizure(f_3)	Drive Shaft Damaged (C1)	Repair or Change it
	Compressor element out of order (C1)	Repair/change it
	Air Receiver (C2) element defective	Check & replace if necessary.
	Condensate (C5) is not discharged	Check & Correct
	Inlet valve (C7) stuck in a closed position	Check valve
	Safety valve blows (C23)	Change it
	Outlet Valve (C18) clogged	Check & replace if necessary.
Improper unload of the compressor (f_4)	Inlet valve (C7) does not close	Check valve
	safety valve (C23) out of order	Replace valve
	Check Valve (C9) out of order	Replace valve
	Compressor element (C1) out of order	Repair it
	Oil separator clogged (C10, C4)	Replace its element
Oil in the discharge line (f_5)	Oil level (C13, C15) too high	Check for overfilling, release pressure & drain oil to correct level
	Impure oil (C11) causing foam	Change to correct oil
	Oil separator element defective (C10, C8)	Every time separator element is renewed, examine the discharge pipe & inside of the separator vessel, If excessive then deposits must be removed
Insufficient Pressure (f_6)	Choked air filter element (C21)	Replace filter element
	Solenoid valve (C22) malfunctioning	Replace valve
	Inlet valve (C7) does not fully open	Check valve
	Oil separator (C10, C17) clogged	Replace its element
	Safety valve (C23) leaking	Replace valve
	Compressor element (C1) out of order	Repair it

Step 6. Prepare function-component (EC) and function-failure (CF) matrix

Table 5. Function-Component Matrix (EC).

		Analyzed Components																						
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	C_{19}	C_{20}	C_{21}	C_{22}	C_{23}
Functions	**e_1**	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	1	0	0
	e_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0
	e_3	1	0	0	0	0	1	1	1	1	0	0	1	0	1	0	0	0	1	0	1	0	1	1
	e_4	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	e_5	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	e_6	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

Table 6. Component-Failure Matrix (CF).

		Potential Failures					
		f_1	**f_2**	**f_3**	**f_4**	**f_5**	**f_6**
Analyzed Components	C_1	0	0	1	1	0	1
	C_2	0	0	1	0	0	0
	C_3	0	1	0	0	0	0
	C_4	0	0	0	1	0	0
	C_5	0	0	1	0	0	0
	C_6	0	1	0	0	0	0
	C_7	1	0	1	1	0	1
	C_8	0	0	0	0	1	0
	C_9	0	0	0	1	0	0
	C_{10}	0	0	0	1	1	1
	C_{11}	0	1	0	0	1	0
	C_{12}	0	1	0	0	0	0
	C_{13}	0	1	0	0	1	0
	C_{14}	0	1	0	0	0	0
	C_{15}	0	0	0	0	1	0
	C_{16}	0	1	0	0	0	0
	C_{17}	0	0	0	0	0	1
	C_{18}	0	0	1	0	0	0
	C_{19}	0	0	0	0	0	0
	C_{20}	1	0	0	0	0	0
	C_{21}	0	0	0	0	0	1
	C_{22}	1	0	0	0	0	1
	C_{23}	0	0	1	1	0	1

Step 7. Use Equation (2) to get the matrix Function – Potential Failure Matrix (EF)**.** In this step check valve, inlet valve, compressor element, safety valve, solenoid valve, and outlet valve found as the most critical one (details are discussed in the result and discussion section.)

4.2. Decision Making

This sub-section covers the part B decision making part of AMFMEA. The attributes selected for this study are based on two principal factors, viz. internal procedures deficiency and plant maintenance priorities. The attributes are as follows-

- Total Number of Failures per unit Time (In Numbers) - Shows how many times failures occurred in FY 2015-16
- Quantity of Spares (In Numbers) -Shows the number of spares mechanical maintenance department issued in FY 2015-16
- Spare Part Cost (INR) - Spare part cost in Indian Rupees

4.2.1. AHP

To make a hierarchy diagram as presented in Figure 4, each shop has been assigned with unique IDs (Table 7). The industrial data of one complete year were collected for all the attributes (Table 7) including a total number of failures, the number of spares and spare part cost for the corresponding component.

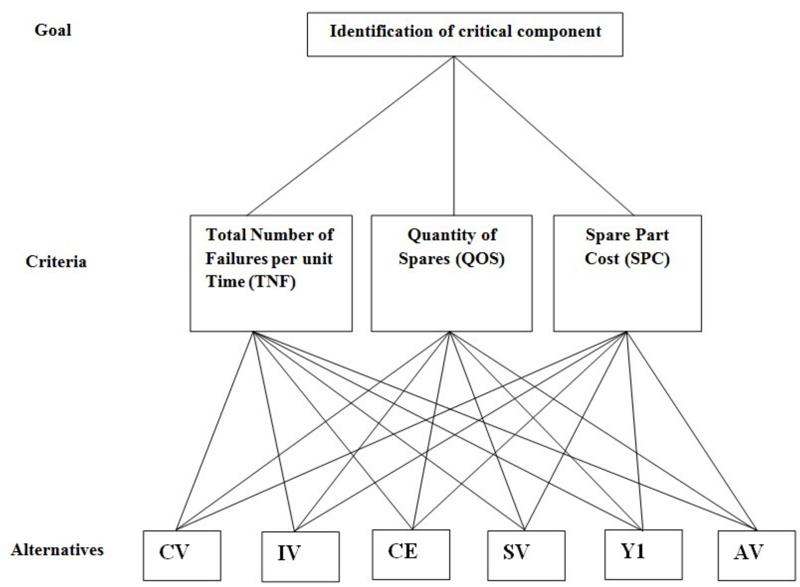

Figure 4. Hierarchy Diagram.

Table 7. Attributes and their values.

Name	ID	Total Number of Failures per unit Time (In Numbers)	Quantity of Spares (In Numbers)	Spare Part Cost (Indian Rupees)
Check Valve	**CV**	10	70	65053.83
Inlet valve	**IV**	16	123	53871.3152
Compressor Element	**CE**	29	83	445560.952
Safety Valve	**SV**	8	20	7297.01
Solenoid Valve	**Y1**	6	28	64841.6
Outlet Valve	**AV**	11	150	27038.77

The methodology mentioned in section 3.2 applied to evaluate the values of weights. The weightages are: W_{TNF} = 0.626696471, W_{QOS} = 0.093616018and W_{SPC} = 0.279687511. This work targeted the most critical component, therefore, the lowest TNF, the lowest QOS and the lowest SPC selected for normalization. After normalization, the score of each alternative is calculated using equation (6).

4.2.2. PROMETHEE

Here again, the same weights used as obtained with AHP. Now Equation (7), (8) and (9) applied and Table 8 contains results -

Table 8. Row Summation & Column Summation.

	CV	**IV**	**CE**	**SV**	**Y1**	**AV**	**ϕ+**
CV	….	0.27968	0	1	1	0.27968	2.559375
IV	0.72031	….	0.09361	1	0.72031	0.62669	3.160937
CE	1	0.90638	….	1	1	0.90638	4.812767
SV	0	0	0	….	0.62669	0	0.626696
Y1	0	0.27968	0	0.37330	….	0.27968	0.932678
AV	0.72031	0.09361	0.09361	1	0.72031	….	2.627857
ϕ-	2.44062	1.55937	0.18723	4.37330	4.06732	2.09245	….

4.3. Combination of NDT

This section covered the procedure adopted for making the combination of NDT. The steps are as follows -
Step 1. Identify techniques and types of equipment available in this heavy industry.
Step 2. Selection of attributes
Step 3. Data Collection
Step 4**.** Perform the AHP procedure (See Section 3.2) for decision making.

As the compressor element came out to be as a most critical component, therefore this section covered the procedure adopted for making suitable NDT combination to achieve better reliability in fault detection/assessment of defects in industrial equipment/components in multiple applications. Each steps description is as follows –
Step 1. Identify techniques and types of equipment available in this heavy industry: Vibration, Ultrasonic Testing, Thermography, Oil Analysis, and Magnetic Particle Testing.
Step 2. Selection of Attributes – It is necessary [8] to compare various NDT's before making their combination as if the combination made randomly then, it may not result in higher reliability of fault detection and may lead to wastage of resources (man-machine-time). Various researchers suggest various parameters to be considered before making a combination. Multiple research papers reviewed for this purpose and attribute selected (Table 9). The attributes selected for this study are based on two principal factors, viz. internal procedures deficiency and plant maintenance priorities.
Step 3. Data Collection – As it is a bit difficult to get quantified data for comparison. Therefore qualitative data collected after reviewing the work of Christian Garnier et al. [27], MPh Papaelias et al. [28], Malcolm K. Lim et al. [21], Verma et al. [22], D.M. McCann [23], A.Mccrea [24] and tabulated in Table 10.

Table 9. Details of attributes used in for combining multiple NDT.

Attribute	Description	Author (Year)
Process Lead Time (PLT)	The time between the start and end of a process.	Malcolm K. Lim et al. (2013, 21), Verma et al. (2014,22)
Accuracy	The state of being correct.	Malcolm K. Lim et al. (2013, 21), Verma et al. (2014, 22), D.M. McCann (2001, 23), A.Mccrea (2002, 24)
Probability of detection (POD)	Shows the chances that a technique can detect a fault.	S. Khangar et al. (2012, 25), A.Mccrea (2002, 24)
Reliability (R)	Shows the chances that technique can give accurate results.	S. Khangar et al. (2012, 25), Prayaswal Pratesh Wadhwani et al. (2008, 26), D.M. McCann (2001, 23), A.Mccrea (2002, 24)
Process Cost (PC)	It includes resources needed like support structure, sensors, surface cleaners etc.	Verma et al. (2014, 22), D.M. McCann (2001, 23), A.Mccrea (2002, 24)

Table 10. NDT Data.

Technique/Attribute	Process Lead Time	Accuracy	Probability of detection (POD)	Reliability	Process Cost
Vibration	Medium	Medium	High	Above average	Medium
Ultrasonic Testing	Above average	High	Above average	Medium	High
Thermography	low	Medium	Medium	Medium	Above average
Oil Analysis	High	Above average	Above average	High	Above average
Magnetic Particle Testing	Medium	Medium	Medium	Below average	Low

Step 4. As for analysis it was not possible to use qualitative data, therefore, a five point fuzzy scale (Table 11) used to convert the qualitative data into quantitative one. The Table 12 contains the converted values. A hierarchical diagram also prepared as shown in Figure 5.

Table 11. Five point Fuzzy Scale [10].

Linguistic term	Detail	Crisp score
Low	One attribute is very less significant than the other	0.115
Below average	One attribute is less significant than the other	0.295
Medium	Two attributes are equally significant	0.495
Above average	One attribute is more significant than the other	0.695
High	One attribute is much more significant than the other	0.895

Table 12. Crisp Score of Attributes.

Technique/Attribute	Process Lead Time (PLT)	Accuracy (A)	Probability of detection (POD)	Reliability (R)	Process Cost (PC)
Vibration	0.495	0.495	0.895	0.695	0.495
Ultrasonic Testing	0.695	0.895	0.695	0.495	0.895
Thermography	0.115	0.495	0.495	0.495	0.695
Oil Analysis	0.895	0.695	0.695	0.895	0.695
Magnetic Particle Testing	0.495	0.495	0.495	0.295	0.115

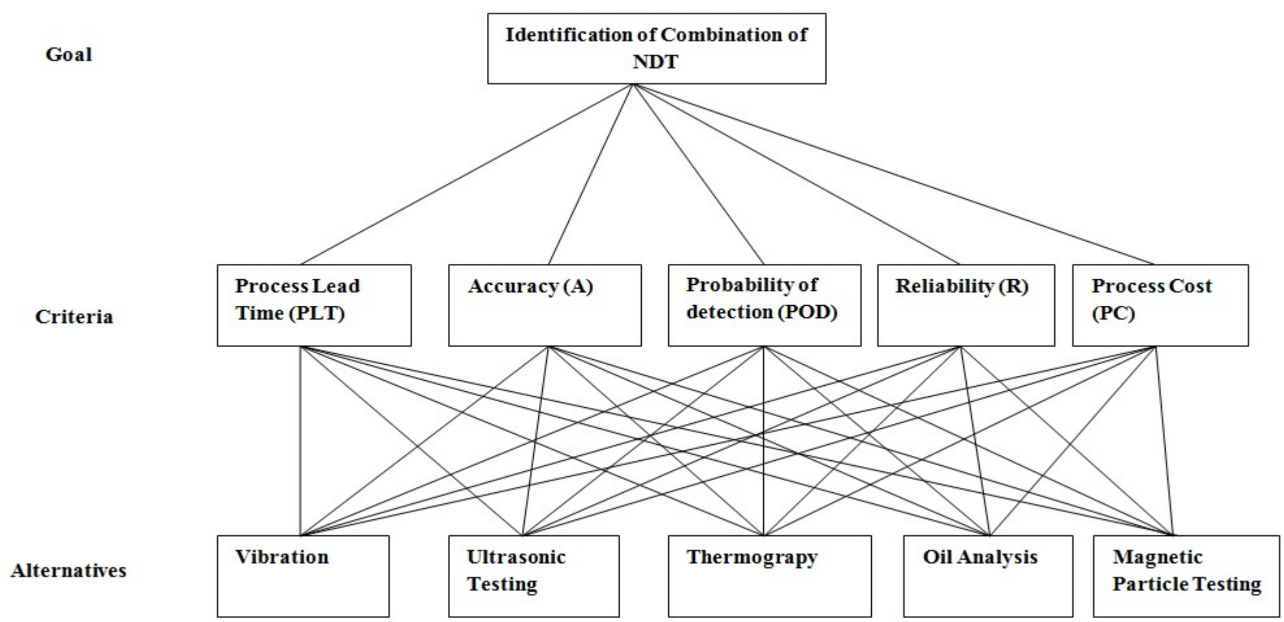

Figure 5. Hierarchy Diagram.

The methodology mentioned in section 3.2 applied to evaluate the values of weights. The weightages are: W_{PLT} = 0.491130, $W_{Accuracy}$ = 0.086212, W_{POD} = 0.206686, W_R = 0.136636 and W_{PC} = 0.079337. The Equation (6) used to evaluate the weighted score and technique with the highest weighted score assigned rank 1.

5 Result and discussion

This section covered the result and discussion part of this research work. The function-failure (EF) matrix (which links product function to potential failure modes) is obtained from the matrix multiplication of the two matrices viz Function-Component matrix and Component-Failure Matrix using Equation 2. Through the function-failure (EF) matrix, product function is linked to potential failure modes by indicating the number of times that any component solving a particular function exhibited a failure.

Table 13. Function – Potential Failure Matrix (EF).

		Potential Failures					
		f_1	f_2	f_3	f_4	f_5	f_6
Functions	$\mathbf{e_1}$	0	0	0	2	1	3
	$\mathbf{e_2}$	0	1	0	0	1	0
	$\mathbf{e_3}$	3	3	4	4	1	4
	$\mathbf{e_4}$	0	0	1	0	0	0
	$\mathbf{e_5}$	0	2	1	0	1	0
	$\mathbf{e_6}$	0	1	0	0	1	0

It is evident from the above table that for the analyzed screw compressor, the highest chance of defect is for Seizure (f_3), Improper unload of the compressor (f_4) and Insufficient Pressure (f_6) which is for components realizing function "Control or Regulate **($\mathbf{e_3}$)**" (Table 13). The components realizing the function $\mathbf{e_3}$ are C_1, C_6, C_7, C_8, C_9, C_{12}, C_{14}, C_{18}, C_{20}, C_{22}, and C_{23}. Now the next step is to select those components which are prone to defect f_3, f_4, and f_6. This includes the components C_1, C_7, C_9, C_{18}, C_{22}, and C_{23}. After this, AHP applied to find the most critical component among these. This gives checkpoints for maintenance. If AHP applied at the start of this process in place of matrix FMEA then it becomes necessary to deal with all the 24 components as alternatives which increase the amount of analysis and time. Apart from this, the failure data for all these 24 components needed. Therefore, incorporation of matrix FMEA before AHP reduces the time consumption for both data collection and analysis.

Now the used weightages for decision making part are: $W_{TNF} = 0.626696471$, $W_{QOS} = 0.093616018$ and $W_{SPC} = 0.279687511$. Figure 6 shows that the weighted score of the compressor element is higher as compared with other components. After AHP, the PROMETHEE method applied and the component with the highest net domination assigned as rank 1. Here compressor element came out as the most critical component among other components in this screw compressor. The result obtained with PROMETHEE is the same as the results obtained with AHP (Table 14). In this way, the results are cross-validated.

Table 14. Ranking of Components.

ID	**Net Domination (PROMETHEE)**	**Weighted Score (AHP)**	**Ranking**
Check Valve	-0.1346429	0.3006253	4
Inlet valve	2.60156244	0.45634481	2
Compressor Element	5.625536	0.95818485	1
Safety Valve	-4.18723	0.1899444	6
Solenoid Valve	-3.57527	0.1878387	5
Outlet Valve	0.2820086	0.34830125	3

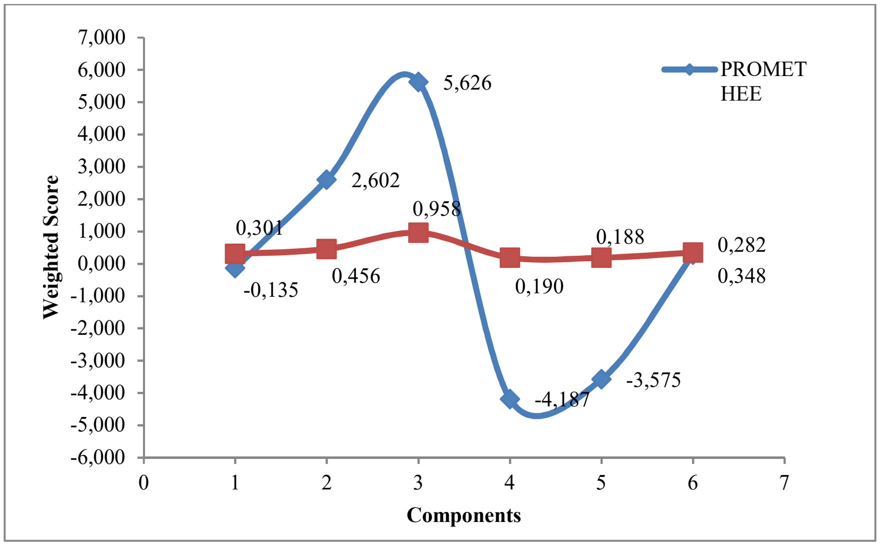

Figure 6. Ranking of Components using AHP and PROMETHEE.

Here the weightages used are W_{PLT}= 0.491130, W_A = 0.086212, W_{POD} = *0.206686*, W_R = 0.136636 *and* W_{PC} = 0.079337. The technique with the highest weighted score assigned as Rank 1 and remaining ranked in decreasing order. Figure 7 and Table 15 show that the weighted score of vibration is higher as compared with the other NDTs. Therefore, the vibration is come out to be as most beneficial NDT. Apart from this, it is also possible to use top 2 or 3 NDTs in combination as the below graph gives their ranking as per their score and it doesn't mean that rank 2 or other NDTs cannot be used.

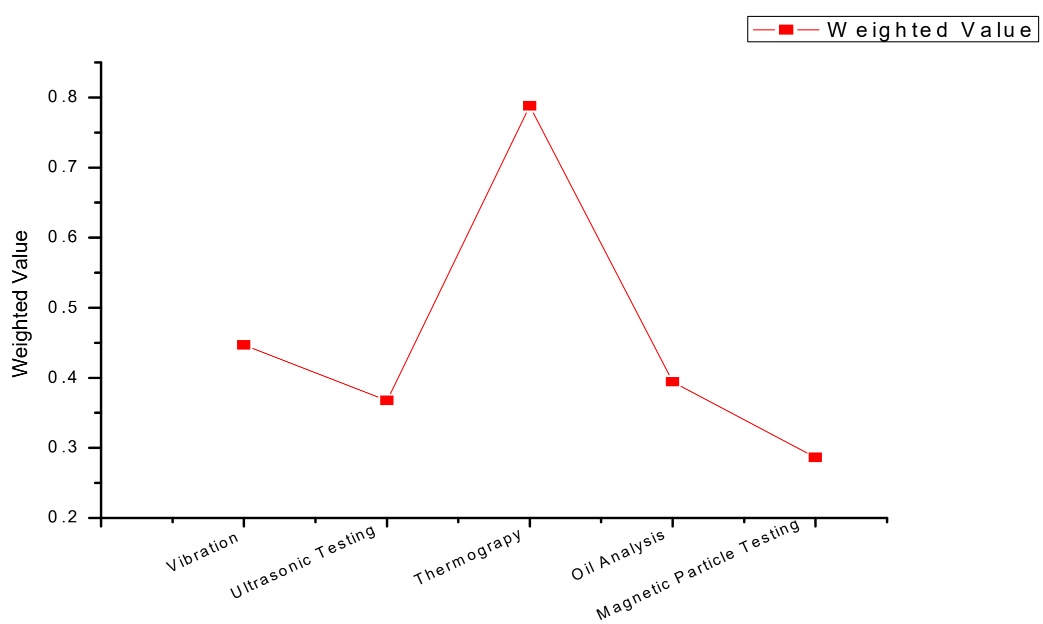

Figure 7. Ranking of NDTs using AHP.

Table 15. Ranking of NDTs.

Technique/Attribute	Weighted Value	Rank
Vibration	0.446815927	2
Ultrasonic Testing	0.367553811	4
Thermography	0.788007308	1
Oil Analysis	0.394128654	3
Magnetic Particle Testing	0.286155375	5

6 Conclusion

It was discussed in previous sections, that Matrix-FMEA is a proven technique for identifying the potential cause of failure and design out them in new product design. This method works on inter-relation between function, component, and failure. Although the method is very versatile when the data becomes huge then this method's complexity increases, therefore in this research work decision-making techniques are incorporated to widen this method's usability. The conclusions obtained are as follows:

- This work was divided into two parts: ***part A*** covered the matrix-FMEA and found that most common defects were Seizure (f_3), Improper unload of the compressor (f_4) and Insufficient Pressure (f_6) for components realizing function Control or Regulate **(e_3).** The components realizing the function $\mathbf{e_3}$ are C_1, C_6, C_7 , C_8, C_9, C_{12}, C_{14}, C_{18}, C_{20}, C_{22}, and C_{23}. The components which are prone to defect f_3, f_4 and f_6 are C_1, C_7, C_9, C_{18}, C_{22}, and C_{23}.
- P***art B*** covered decision making with AHP and PROMETHEE to identify the most critical component among these. This work evaluated the weighted score with AHP and then, net flow or domination with PROMETHEE.
- The component with the highest net domination assigned as rank 1. Hereafter analysis, the compressor element came out to be the most critical one among others.
- The result shows that the weighted score of thermography is higher as compared with the other NDTs. Therefore, the vibration is come out to be as most beneficial NDT.
- Apart from this, it is also possible to use top 2 or 3 NDTs in combination as the table gives their ranking as per their score and it doesn't mean that rank 2 or other NDTs cannot be used.
- Each technique has some hindrances; therefore, making combination helps in countering these hindrances.

This AMFMEA is a generalized approach and it has great potential for solving failure related issues; therefore, a similar approach can be applied to different applications and industries too. Apart from this, there is still scope for further improvement like another researcher may apply different decision-making techniques to further refine the result and shorten the overall procedure. Furthermore, after combining NDT's the next part is to quantify the effect of combining multiple NDT's and for this, key performance indicators of maintenance needed to measure. If after combination, the parameters don't get improved then it means either combination is not appropriate or single NDT'S is better. This methodology of AMFMEA is most suitable for industrial and research applications.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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