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Prioritizing Potential Risks based on Failure Mode and Effects Analysis Using Data Envelopment Analysis: a case study

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Abstract

The need to establish power plants to supply the required electricity of the country has been rising due to increasing demand levels as well as the lack of governmental resources. Furthermore, the available traditional attitude in performing and conducting power plant projects has made government seek a modern attitude. This paper tries to use the topics that have been employed in automotive industry of the company for many years to detect and analyse failure reasons as well as the solutions that are suggested to prevent and improve them. The present study has used Failure Mode & Effects Analysis along with Data Envelopment Analysis to evaluate 17 failure modes of South Esfahan Power Plant. Severity, Occurrence and Detection are 3 failure factors considered in this study. Failure mode dealing with Scaling on rotor and diaphragms blades has the highest importance with the highest Risk Priority Number, Severity and its first grade.

Keywords: Evaluation, Risk, Failure Mode and Effects Analysis (FMEA), Data Envelopment Analysis (DEA)

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1. Introduction

   Nowadays, all professions have been willing toward risk management to be protected against various dangers surrounding them, and also to keep their competitive condition in modern era [18]. Risk Management provides the ability of detecting factors leading to risks. On the other hand, it results in risk analyzing and proper solution selecting to control and remove them [3, 12]. Due to this fact that failure priority of an organization differ in case of effect and importance, it is important to specify indicators through which importance degree of each factor is defined and they can be ranked.

Thus, Failure Mode and Effects Analysis (FMEA) can be employed to rank failure modes and specify protective steps to remove them. Through a protective and forward looking approach, this technique can help the organization detect potential problems and remove them before they would affect system, services and customers [14]. Failure Mode and Effects Analysis is a systematic method to detect and prevent problem Occurrence in product and its process. This technique focuses on avoiding defect emergence, Severity increase and customers' satisfaction increase [19]. Also, this technique is to provide information to make risky management decisions. During years, some various FMEA versions have been developed; many of them include a quantative concept that deals with prediction of similarities among certain types of system failure [20].

Analysing failure factors in production process and their effects is an analytical and principal technique that detects either potential or clear defects and makes modification decisions before beginning by production line. This is done by production lines. This analysis is done for new processes or the processes that include any kind of change in their initial status. This technique focuses on security increase and customers' satisfaction increase to prevent defects. Moreover, it is regarded as a tool with the lowest risk to predict problems and defects in production processes in an organization [25].

The effect of these failures on organizations' performances are different and it is possible to detect highly important failures by a number of methods. Data Envelopment Analysis (DEA) is one of these methods in evaluating organizational performance. In fact, this technique is a border non-parametric evaluation model that is used to measure the relative efficiency. It is also regarded as a system of comparable items (which is called Decision Making Unit (DMU)) in converting inputs to outputs. Using related data to the amount of real inputs and outputs of Decision Making Units, this technique studies a border function surrounding input and output factors. This border contains linear sections that present not only the most efficient current units, but also inefficient unit analysis [13].

Taking the undeniable importance of modifying steps and recognizing the failures in an organization. This study tries to highlight the evaluation of failure modes based on FMEA; therefore, Data Envelopment Analysis is employed. Accordingly, first all failure mode are detected. Then, triple factors (Severity, Occurrence and Detection) are specified and RPN (Risk Priority Number) is found out of multiplying these 3 numbers. In next phase, DEA model is formed through specifying related inputs and outputs. In fourth phase, Unit efficiencies will be found by using output-oriented modified CCR model. In the end, ranking is done. In this research, South Esfahan Power Plant is selected as the case study.

2. Literature review

   Studies conducted about failures reflect the importance of prevention, risk decrease, and modification steps in organization. Some of influential studies are mentioned.

Employing Failure Mode and Effect Analysis and Data Envelopment Analysis, Abadian et al. evaluate service quality of DSL. First, they have detected qualitative failures in the systems and have collected the opinions of members of failure analysis team. Then, fuzzy risk priority importance in each failure mode is found in geometrical mean relation. Data Envelopment Analysis for both minimum and maximum failure modes is found in the model proposed by Chin et al. [6], is finally ranking is done by doing related statistical operation and solving DEA models [1].

Garcia et al., use both fuzzy DEA and FMEA in their research. The employed fuzzy model is taken from Lertworasirikul et al. s' article [15]. Risk factors of S, O and D are considered as fuzzy values and a special fuzzy model is used to rank factors among failure modes [11].

Chin et al., have suggested DEA approach based on FMEA that calculated relative weights of risk factor. Weights are specified in DEA models and change from a failure mode to another one. The suggested MEA measures the maximum and minimum errors of each failure mode. These minimum and maximum, measured through geometrical mean, are regarded as a based to rank failure modes. In this process, with two CCR models, the best and worst conditions for each Decision Making Units will be found as failure modes. This is what exactly ideal and non-ideal options in TOPSIS[1] do [6].

In another research conducted by Dong and Kuo, a new approach was proposed to boost evaluation capabilities along with FMEA detection. This approach supports this hypothesis that DEA not only completes traditional FMEA, but also provides correct information for failure parameters (Severity, Occurrence and Detection). This information reduces failure probability. Findings reveal that this method is useful to manage resource dedication and risks [9].

In order to improve the validity of pure systems, Sawhney et al., have looked for using a modification FMEA. This research aims at intensifying validity unification of pure principle in a long-term period, and suggests a modified FMEA that lets experts grasp the validity of pure systems and improve it. According to this approach, 4 critical sources are needed to help us retain pure systems including staff (personnel), equipment, ingredients and time-table [23].

In a study in an automotive organization, Vinodh and Santhosh use FMEA as a decision-making and ranking tool. Modification steps of this research result in raising system efficiency and product number along with failure rate decrease. Results show the activities that bring design and process improvement about lean to the increasing production quality [24].

3. Failure Mode and Effects Analysis (FMEA)

Failure Mode and Effects Analysis is an important technique to detect potential failure modes which was employed in air and space industry as an official design method in 1960 [4]. Afterwards, it was used a powerful and useful method to evaluate potential errors and failures as well as prevent them [22]. In recent years, FMEA has been noticed more because of developing automotive industry in the US and QS9000 Standards for part manufacturers. Nowadays, this technique is regarded as an efficient tool in not only selection of equipment and machinery, but also selection of production technology of a product [2].

The aim of FMEA in a production process is to avoid a disaster occurrence. In other words, FMEA leads to decreasing costs by optimizing processes of products. Since cost reduction happens in first steps of process development. Changes are often simple and low-cost [21].

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[1]Technique for Order Preference Similarity to Ideal Solution

First, all potential failure modes are detected in a systematic brainstorming session; then, risk triple factors (Occurrence (O), Severity (S) and Detection (D)) are found which are put in 1-10 range. Failure Ranking is done to reduce and modify based on Risk Priority Number (RPN) which is the result of 3 factor multiplying [16].

RPN = O * S * D

4. Data Envelopment Analysis (DEA)

Efficiency measurement has been highlighted by researchers due to its significance in performance evaluation of a company or an organization. Using a technique similar to efficiency measurement in engineering discussion, Farrell in 1957 measured the efficiency for a production unit [10]. Charnes, Cooper and Rhodes developed Farrell's approach and suggested a model that was able to measure the efficiency with some inputs and outputs. This model was called Data Envelopment Analysis [5]. This technique used mathematical decision making techniques to evaluate the performance of a system of similar decision making units with some inputs and outputs. Coeli has shown that among various performance evaluation methods, Data Envelopment Analysis has 2 main advantages in measuring efficiency:

First, it does not need to make a function among data and inputs; it means that researcher can avoid limiting conditions of form selection of production function or cost function that can affect efficiency analysis results. Second, it does not mean statistical distribution for efficiency details [5, 7, 8].

Charnes, Cooper and Rhodes presented CCR model with efficiency on stable scale whose modified version is stated as follow:

$$\text{Max}\, Z = \theta - \varepsilon\left(\sum_{i=1}^{m} S_i^- + \sum_{r=1}^{S} S_r^+\right)$$

$s.t$

$$\sum_{j=1}^{n} \lambda_j x_{ij} + S_i^- = \theta x_{ip}$$

$$\sum_{j=1}^{n} \lambda_j y_{rp} - S_r^+ = y_{rp}$$

$$\lambda_j \geq 0 \qquad\qquad j = 1, \dots, n$$

$$S_r^+, S_i^- \geq 0 \qquad\qquad i=1,\dots, m \ , r=1,\dots, s$$

Here, X_{ij}, Y_{ij} and Θ are the value of i th input, the value of i th output and efficiency, respectively. S_i^- and S_r^+ are lack variables of input and output and λ_j is reference weights related DMUs.

The usual models of DEA just evaluate the performance and determine efficient and inefficient units. After specifying efficient and inefficient DMUs, units can be ranked. Therefore, inefficient units are ranked based on their efficiency numbers. However, efficient units cannot be ranked easily. Accordingly,

a number of models have been introduced that rank DMUs. One of them is Makui et al. s' [17]. In this research DMUs are ranked by using ideal planning and efficiency evaluation. The difference of this DMU model with the common ones is that it finds same input and output values for all DEAs.

In this technique, CCR is used to find Θ value for each DMU:

$$Max\ Z = \sum_{r=1}^{s} u_r y_{rp} \tag{1}$$

St

$$\sum_{i=1}^{m} v_i x_{ip} = 1$$

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=0}^{m} v_i x_{ij} \le 0 \quad j = 1, \dots, n$$

$$U_r \ge \varepsilon \qquad\qquad r = 1, \dots, s$$

$$V_i \ge \varepsilon \qquad\qquad i = 1, \dots, m$$

Then, in next level, Θ_{CCR} helps to solve the relation 2 to calculate common u and v numbers for each input and output.

$$Min\ \sum_{j=1}^{n}\left(d_j^- + d_j^+\right) \tag{2}$$

$St.$

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i \Theta_j^* x_{ij} \le 0 \qquad\qquad j = 1, 2, \dots, n$$

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i \Theta_j^* x_{ij} + d_j^- - d_j^+ = 0 \quad j = 1, 2, \dots, n$$

$$\sum_{r=1}^{s} u_r + \sum_{i=1}^{m} v_i = 1$$

$$d_j^-, d_j^+ \ge 0 \qquad j = 1, 2, \dots, n$$
$$u_r \ge 0 \qquad\quad r = 1, 2, \dots, s$$
$$v_i \ge 0 \qquad\quad i = 1, 2, \dots, m$$

Solving equation 2 results in finding the common u and v for all DMUs. Next, efficiency value of DMU$_j$ (j = 1, 2,…,n) is calculated through using relation 3:

$$\theta = \frac{\sum_{r=1}^{s} u_r^* y_{rj}}{\sum_{i=1}^{m} v_i^* x_{ij}} \tag{3}$$

If through using (u*, v*), efficiency equals 1, it is possible to DMU$_p$ efficient. It is worth mentioning that if DMU$_p$ of relation 3 is efficient, input-oriented CCR will be efficient as well.

Finally, efficiency number can be used to rank DMUs and ranking will be done accordingly.

5. Methodology

Due to the vast association between modifying activities and organizational performance, companies need to adopt appropriate methods of risk analysis to boost their efficiency. The present study deals with risk ranking in South Esfahan Power Plant.

A five steps process is required in this research based of Failure Mode and Effects Analysis, which is a protection technique and Data Envelopment Analysis. As shown in figure 1, first failure modes are specified.
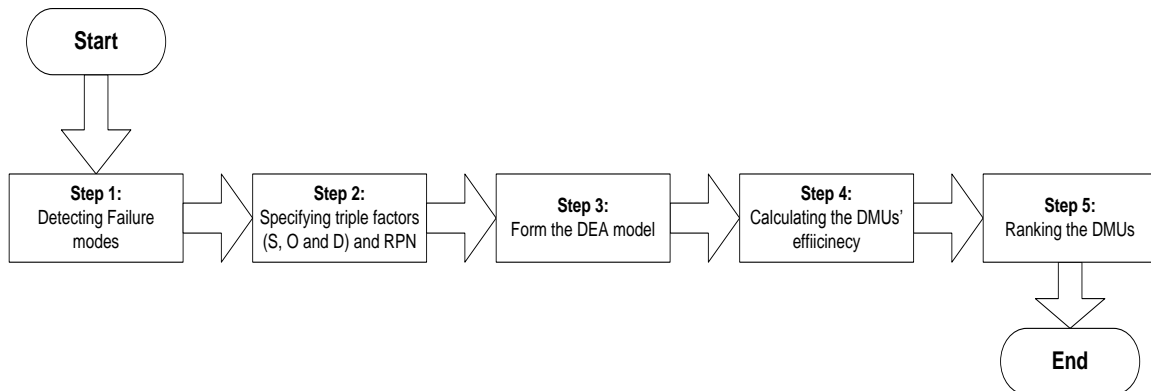

Figure 1: Research Methodology

In next phase, failure triple factors (Severity, Occurrence and Detection) are specified, and consequently RPN is found out of multiplying these 3 numbers. Furthermore, DEA model will be determined by specifying inputs and outputs. In the fourth step, relative efficiency of failure modes is calculated in output-oriented covering modified CCR. Finally, DMUs are ranked through Makui et al. s' method.

First step: The first step to specify failure modes to analyse potential risks of South Esfahan Power Plant by using Failure Mode and Effects Analysis. According to the library research and experts' opinions, as well as considering related literature and surrounding status, 17 failure modes were selected which are shown in table 1.

Table 1:

Failure Modes

Failure mode	Number of Failure mode	Failure mode	Number of Failure mode
Wrong control signal	10	Scaling on rotor and diaphragms blades	1
Failure of protective relay	11	Wear and corrosion	2
CO_2	12	Sticking of valves	3
failure in waters pumps	13	Rotor vibration of turbine	4
Failure in Firefighting system	14	Rotor vibration of generator	5
Failure of diesel generator	15	Loose stator coils	6
Failure in switch gears	16	Arcing of switches	7
Failure in control system of emergency power	17	Failure of motors	8
		Failure of transformers	9

Second step: After specifying failure modes, failure triple factors (Severity, Occurrence and Detection) will be found by considering experts' opinions in range of 1-10. The bigger numbers and closer to 10, the higher the importance and Vice Versa. However, detection works differently. Smaller values and numbers indicate the better detection of that failure mode to other ones. Failure analysis is done based on risk priority number (RPN) which is the outcome of multiplying 3 factors to decrease failure and modify them. (Table2)

Table 2:

FMEA worksheet of South Esfahan Power Plant

Function	Failure	Effect	S	Cause	O	Control	Control Type	D	RPN	Recommended action
Turbine and auxiliaries	Scaling on rotor and diaphragms blades	Reduced efficiency, vibration of rotor	8	Turbine worn blades, vibration	5	Review operating pressures and flow	Prevention	4	160	Address the cause
	Wear and corrosion	Reduced safety	8	Blocked blades	3	Measure of blade clearance	Prevention	5	120	Repair failed part
	Sticking of valves	Reduced efficiency	2	Sticking, leaking	7	Regular checking of axial motion of the valves	Prevention	7	98	Redesign the system
	Rotor vibration of turbine	Loss of control	2	Inadequate flow, low pressure	6	control of vibration	Prevention	8	96	Detect and identify the problem
Generator and electrical systems	Rotor vibration of generator	Misalignment	2	Poor lubrication of bearing	7	Ensure turbine generator exciter alignment	Prevention	7	98	Detect and identify the problem
	Loose stator coils	Cost of repair, downtime	2	Wrong operating	6	Eliminate causes of corona effects	Prevention	8	96	Replace stator coils

	Arcing of switches	Poor cooling, corona effect	4	Wrong operating	3	Maintain correct switch gear operations and contacts	Prevention	7	84	Address the cause
	Failure of motors	Downtime	10	Excitation under voltage	2	Monitor all motors performance	Prevention	4	80	Redesign the system
	Failure of transformers	Downtime	9	Excitation under voltage	2	Regular test transformer oil, Contacts and temperatures	Prevention	3	54	Redesign the system
Control system	Wrong control signal	Inefficiency, downtime	8	Damage cables	6	Install backup safety	Prevention	2	96	Calibrate equipment
	Failure of protective relay	Inefficiency, downtime	2	Wrong calibration	5	Install backup control circuits	Prevention	5	50	Repair or replace damaged parts
Firefighting system	CO$_2$	Failure in fire extinguish	6	Empty of the capsule	3	Control pressure gauge	Prevention	1	18	Eliminate of defect
	failure in waters pumps	Reduced efficiency	5	Failure of motors	2	Periodic start	Prevention	5	50	Repair of motors' defect and auxiliary circuit
	Failure in Firefighting system	No alarm for system	3	Failure of relays	3	Check the circuits	Prevention	4	24	Identify the problems and repair
Emergency Power	Failure of diesel generator	Reduced efficiency, problem in starting	2	Failure of battery	2	Control of battery voltage	Prevention	2	8	Charge or replace the batteries
	Failure in switch gears	Problem in power supply	3	Failure of switches	4	Periodic start	Prevention	5	60	Replace of switches
	Failure in control system	start circuits disconnected	3	Failure of power supply	4	Control of alarms	Prevention	2	24	Connect the power supply

Third step: In order to rank failure modes of South Esfahan Power plant, one of the most common evaluation techniques (DEA) is employed. To form DEA model, specifying inputs and outputs is the first requirement shown in figure 2.
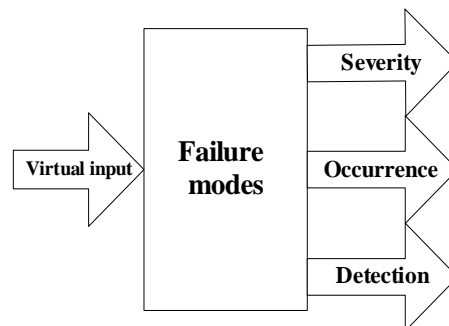

Figure 2: inputs and outputs of DEA model

According to the library research, experts' opinions and reviewing previous literature, the same input is considered for all modes which is called "virtual input". Moreover, 3 outputs of (Severity, Occurrence and Detection) are taken into account to form DEA model, shown in table 3.

Table 3:
The numbers of inputs and outputs

DMU	input	outputs			DMU	input	Outputs		
	virtual	S	O	D		virtual	S	O	D
1	1	8	5	4	10	1	8	6	2
2	1	8	3	5	11	1	2	5	5
3	1	2	7	7	12	1	6	3	1
4	1	2	6	8	13	1	5	2	5
5	1	2	7	7	14	1	3	3	4
6	1	2	6	8	15	1	2	2	2
7	1	4	3	7	16	1	3	4	5
8	1	10	2	4	17	1	3	4	2
9	1	9	2	3					

Fourth step: CCR model is employed to calculate the efficiency of 17 failure modes of South Esfahan Power Plant. Due to this fact, evaluation is done based on failure triple factors (Severity, Occurrence and Detection), these three are considered as outputs of DEA model.

According to this issue and stable efficiency on unit scale, modified version of output-oriented covering CCR has been chosen which was described in theoretical parts. DMUs with relative efficiency of 1 are efficient; those whose efficiency is bigger than 1 are inefficient. After calculation, these modes have been recognized as efficient ones, shown in table 4: Scaling on rotor and diaphragms blades, Wear and corrosion, Sticking of valves, Rotor vibration of turbine, Rotor vibration of generator, Loose stator coils, Failure of motors and Wrong control signal.

Table 4:
Objective Values of potential failure modes

Failure mode	θ(CCR)	Failure mode	θ(CCR)
1	1	10	1
2	1	11	1.34286
3	1	12	1.46747
4	1	13	1.20096
5	1	14	1.61290
6	1	15	2.76471
7	1.00120	16	1.35135
8	1	17	1.63043
9	1.10036		

Fifth step: Makui et al. s' model is used to evaluate the performance and rank potential failure modes. Thus, first related data to each input and output was normalized through a linear technique. Then, failure performance is evaluated in next phase. The results are displayed in table 5.

Table 5:

Efficiency rate and ranking

Number of failure mode	(Makui)θ	Rank	Number of failure mode	(Makui)θ	Rank
1	1	1	10	0.94117647	2
2	0.94117647	3	11	0.70588235	12
3	0.94117647	3	12	0.58823529	14
4	0.94117647	7	13	0.70588235	12
5	0.94117647	3	14	0.58823529	15
6	0.94117647	7	15	0.35294118	17
7	0.82352941	10	16	0.70588235	11
8	0.94117647	3	17	0.52941176	16
9	0.82352941	9			

According to the findings of table 5, as well as Makui's model, the only efficient DMU, is "failure mode of Scaling on rotor and diaphragms blades". Additionally, efficiency number was used to rank organizational units leading to this point that two failure modes "failure mode of Scaling on rotor and diaphragms blades" and "wrong control signal" are in the first and second place with the highest value of efficiency number. Furthermore, "failure mode of control system of emergency power" is put in the last place.

6. Conclusion

Protective steps before occurrence for projects that have not been started yet as well as modifying steps for projects that are being implemented can be really significant resulting in delay prevention or reduction in power plant projects. The main objective of this study is to prioritize potential failure modes of South Esfahan Power Plant based on Failure Mode and Effects Analysis along DEA.

DEA was selected to rank and evaluate because of high significance of Severity and Occurrence rather than Detection and also not complete RPN number. In comparison with other performance evaluation techniques, DEA has plenty of functions due to great relation between various inputs and outputs. In this research, after detecting failure modes and specifying severity, occurrence and detection. RPN is calculated. According to having a stable efficiency on scale of all units and outputs along with considering occurrence, severity and detection, modified version of output-oriented covering CCR has been selected for this research.

CCR findings reveal that modes of Scaling on rotor and diaphragms blades, Wear and corrosion, sticking of valves, Rotor vibration of turbine, Rotor vibration of generator, Loose stator coils, Failure of motors and Wrong control signal are efficient because of an efficiency number of 1. Therefore, some activities are needed to avoid or modify then. On the other hand, Arcing of switches, Failure of protective relay,

CO_2, failure in waters pumps, control system of emergency power, diesel generator, switch gears, Firefighting system and failure of motors are inefficient. Findings of last phases which was DMU evaluation showed that failure modes of Scaling on rotor and diaphragms blades, Wear and corrosion, Sticking of valves, Rotor vibration of turbine, Rotor vibration of generator, Loose stator coils, Failure of motors and Wrong control signal have the highest importance, whereas failure of diesel generator had the lowest significance.

Based on findings of DEA model, Makui et al.s' model and RPN, in second step of methodology, it is possible to analyze 8 failure modes with the highest significance. Failure mode of Scaling on rotor and diaphragms blades was still efficient in Makui et al., model. This failure mode has the highest significance in evaluation and modification with RPN of 160 and Severity of 8. Also, the engine failure with RPN of 80 is put in next level but its high Severity requires great attention. It is worth stating that in regulated inefficient mode, it is possible to mention failure mode of transformers with very high severity which needs prevention & modification. Finding count in both attitudes of scientific and theoretical.

Organizations need to find some techniques to reduce their prominent failures. This study tries to make a new perspective for managers and researches to make then know that an organization needs not only materials, equipment and capital, but also an appropriate approach to avoid & modify failure modes. These findings reveal that which sections are the related to o the neediest modes and management can focus and plan on failure modes to save time and money. The challenges expressed for these investigations are just a part of managers' problems.

Making some of these factors active needs high time and maintenance. This research is limited to one organizations and can be replicated for other organizations as well. Another limitation deals with lack of unit ranking. It is possible to have a more optimum mode through considering weight control of failure triple factors. Also, we can have a more precise analysis on failure mode ranking by drawing an area RPN diagram. Other ranking methods can be applied in future studies.

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