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# Human Error Management in Aviation Maintenance Using Hybrid FMEA With a Novel Fuzzy Approach

Om Prakash Bohrey* and A.S. Chatpalliwar

*Shri Ramdeobaba College of Engineering and Management, Nagpur - 440 013, India*

**E-mail: anshbohrey4321@gmail.com*

**ABSTRACT**

Human errors significantly contribute to aviation accidents during aircraft maintenance. Therefore, managing human errors becomes a critical aspect of aviation maintenance. The existing literature has extensively analysed human errors. However, there is a gap in accurately identifying and prioritising critical human errors and effectively managing them to reduce incidents and accidents. This research work proposes a novel fuzzy approach for human error analysis using a hybrid FMEA with Fuzzy AHP-TOPSIS. We identified inadequate maintenance processes, attention/memory, inadequate documentation, inadequate supervision, judgement/decision-making, and knowledge/rule-based as some of the critical human errors in aircraft maintenance. Based on these findings, we recommended practically implementable solutions at the organisational, workspace, and individual levels to mitigate human errors in aircraft maintenance.

**Keywords:** Aviation maintenance; Human errors; Fuzzy logic; AHP; TOPSIS

## 1. INTRODUCTION

In the aviation industry, one of the major challenges from the safety point of view is, reducing human errors. About seventy percent of all aviation accidents resulted from human error and out of these, at least fifteen to twenty percent resulted due to maintenance errors. Thus, human error is an important aspect of aviation maintenance[1-2].While the technical characteristics of system performance, such as reliability, maintainability, serviceability, quality, and availability have received emphasis in system design, however, comparatively less attention has been directed towards human factors, although it is an important aspect in aviation maintenance[3].Our investigation addresses human errors related to aircraft maintenance.

## 2. LITERATURE REVIEW

To analyse the human factors in accidents, Embrey, proposed a systematic approach to human error reduction analysis (SHERPA)[4] and Williams, proposed the human error assessment and reduction technique (HEART)[5]. HEART was applied for analysis of maintenance procedures of a condensate pump[6]. Root cause analysis (RCA) was used to analyse human factors in the health system[7]. Methods such as Maintenance Error Decision aid (MEDA)[8], the Technique for Retrospective/Predictive Analysis of Errors (TRACE)[9], and Human Error Identification (HEI)[10] were extensively used in Human Factor Analysis. Human Factor Analysis and Classification System-Maintenance Extension (HFACS-ME)[11] was used for error classification in air accidents[12].

Failure Mode and Effect Analysis (FMEA) was frequently used for human factor analysis in studies[13-14]. Traditional FMEA utilises Risk Priority Numbers (RPNs) for prioritisation. However, the efficacy of RPN has been questioned frequently in existing literature[15-17]. Linguistic description or range of values can be used wherever exact quantification of risk assessment is not feasible[15-18]. Although FMEA has been extensively used for quantitative analysis of risk assessment in various failure modes of engineering systems. However, it lacks in other aspects like the interaction of man, machine, and organisation[14].

Multi Criteria Decision Making (MCDM) with a fuzzy approach, enables analysis of qualitative and incomplete information[19-20]. The Fuzzy Technique for Order Preference by Similarity to Ideal Solution (FTOPSIS) was applied in the selection of weapon systems, selection of shipping companies, ranking of airlines, selection of managers, agriculture risk management, and oil and gas processing system[21-26]. Kutlu and Ekmekciogli used the fuzzy Analytical Hierarchy Process FAHP-TOPSIS analysis in the automotive industry[27]. Yilmaz used TOPSIS and AHP integration for the aircraft selection process[28]. TOPSIS with fuzzy logic was also used in a few human factor studies, in Small and Medium-sized Enterprises, risk analysis in the copper industry, and in emergency departments[29-32]. However, no specific work was found on human errors in aircraft maintenance using FMEA with the MCDM technique. A gap was, therefore, identified for an accurate analysis of human errors using integrated FMEA with HFACS-ME and MCDM techniques.

## 3. METHODOLOGY

In this study, a hybrid FMEA approach is proposed for evaluating human errors in aircraft maintenance. The approach

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integrates fuzzy logic to prioritise and mitigate incidents related to human error in aircraft maintenance. The incidents were classified using the HFACS-ME taxonomy and analysed using the hybrid FMEA-fuzzy AHP-TOPSIS model. The impact of human errors on Severity (*S*), Occurrence (*O*), and Detection (*D*) forms the assessment criterion. The severity of human errors affects safety, causes undue delays, or has considerable economic repercussions. Severity was, thus, further divided into sub-factors: effect of severity at safety ($S_S$), effect of severity at time ($S_T$), and effect of severity at cost ($S_C$) of maintenance. The FAHP was used for determining the weights of the human error assessment criteria. Subsequently, FTOPSIS was applied for accurate ranking of critical human errors. A total of ten critical human errors were identified and prioritised. Based on the findings of the study, measures to mitigate critical human errors were recommended. The proposed framework for human error management is presented in Fig. 1.

### 3.1 Data Source and Classification

Aircraft incidents data, related to human errors, reported in the past four years was obtained from the Electronic Maintenance Management System of a maintenance control centre. Out of a total of 225 incidents, a dataset of 137 incidents, containing clear and unambiguous findings was analysed. Incomplete and ambiguous data of 85 incidents was excluded from the study. The HFACS-ME framework[33] was used to classify human errors, as shown in Fig. 2. There are a total of 34 third-order categories in the HFACS-ME classification. 137 aircraft incidents were categorised into 20 of these categories and briefly discussed in *Para 3.2*. Ten categories with four or more incidents were prioritised. There were no incidents reported in the other 14 categories such as crew medical conditions, violations, infringements, and so on.

### 3.2 Human Errors

Breakdown of human errors in third order of HFACS-ME framework is presented in Table 1.

137 aircraft incidents were categorised into 20 of these categories. There were no incidents reported in the other 14 categories. Ten categories with four or more incidents discussed in this paragraph were prioritised. A brief discussion on human errors is given in the following sub-paragraphs.

#### *3.2.1 Inadequate Maintenance Processes*

Inadequate process refers to complex or confusing tasks with incomplete or non-standard procedures, such as an omission in a technical manual on how to install a sealing ring.

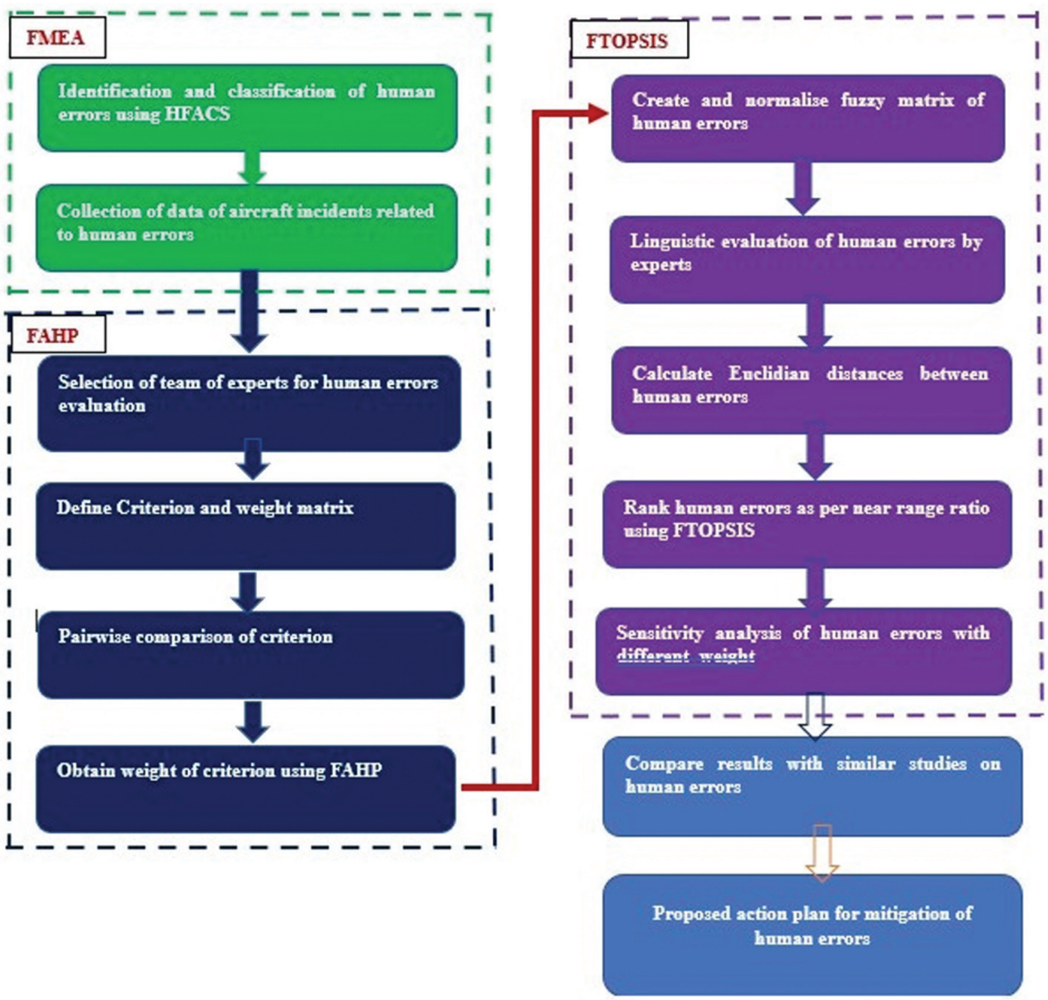


**Figure 1. Proposed framework for human error management.**

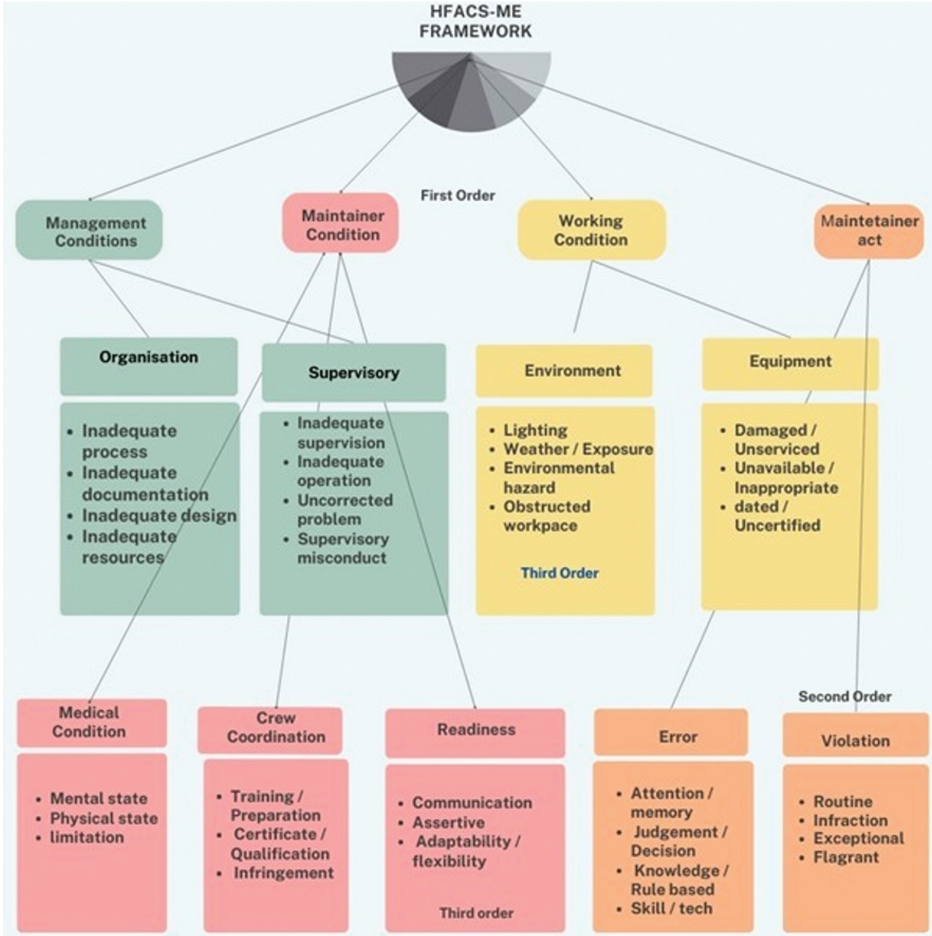


**Figure 2. HFACS-ME framework.**

**Table 1. Breakdown of human errors as per HFACS-ME framework**

| Human error | Frequency | Human error | Frequency |
|---|---|---|---|
| Inadequate maintenance process | 30 | Communication | 2 |
| Skill/ techniqueerror | 4 | Training/ preparation | 2 |
| Attention/ memory error | 20 | Lighting | 1 |
| Obstructed workspace | 7 | Damaged/ unserviced | 1 |
| Inadequate design | 5 | Unavailable resource | 1 |
| Inadequate supervision | 18 | Weather/ exposure | 1 |
| Knowledge/ rule-based error | 10 | Dated/ uncertified | 1 |
| Inadequate documentation | 14 | Adoptability/ flexibility | 1 |
| Environmental hazards | 5 | Inappropriate operations | 1 |
| Judgement/ decision-making error | 12 | Assertiveness | 1 |

### *3.2.2 Inadequate Documentation*

Inadequate documentation occurs when information is unavailable, outdated, or unclear. For instance, technical publications that fail to specify torque or pressure requirements.

### *3.2.3 Inadequate Design*

Improper layout and poor component accessibility are examples of inadequate design.The likelihood of incorrect installation increases in the absence of a foolproof design.

### *3.2.4 Inadequate Supervision*

Inadequate supervision occurs when guidance, oversight, or training is lacking, resulting in inefficient task planning, delegation, and failure to track subordinates' performance.

### *3.2.5 Environmental Hazards*

Ensuring conducive environmental conditions at the workplace is crucial for safe maintenance operations. Neglecting basic precautions such as working at night without proper lighting can lead to significant human errors in aviation maintenance. Avoiding high noise levels and trip and fall hazards is necessary to ensure safe maintenance practices.

### *3.2.6 Obstructed Workspace*

Improper equipment layout or poor housekeeping can obstruct the workspace, resulting in equipment damage or injury to personnel.

#### *3.2.7 Knowledge and Rule-Based Error*

It is essential for an aircraft technician to have sufficient knowledge and awareness of rules and regulations. Without a proper understanding of the pressure requirement in a particular system, charging gas or fluid may result in damaging the system and putting their safety at risk. Therefore, it is necessary for a technician to possess adequate knowledge about the system before performing any tasks.

#### *3.2.8 Attention and Memory Error*

A technician who is not attentive or alert during maintenancetasks is likely to commit mistakes. Over reliance on memory without referring to publications can lead to errors.

#### *3.2.9 Judgment/Decision-Making Errors.*

It is crucial for aviation maintenance personnel to make the right judgments and decisions. A mistake in judgment or a misperceived situation can lead to errors in decision-making, which can be dangerous. For instance, if a maintainer misjudges the distance between a tow tractor and an aircraft wing, it may result in damage to the aircraft. Therefore, it is important for aviation maintenance personnel to exercise caution and take the necessary steps to avoid such errors.

**Table 2. Description and TFN for criterion weight of human errors in FAHP**

| Description | Symbol | Triangular fuzzy number |
|---|---|---|
| Absolutely strong | (AS) | 2, 5/2, 3 |
| Very strong | (VS) | 3/2, 2, 5/2 |
| Strong | (ST) | 1, 3/2, 2 |
| Slightly strong | (SS) | 1, 1, 3/2 |
| Equal | (EQ) | 1, 1, 1 |
| Slightly weak | (SW) | 2/3, 1, 1 |
| Weak | (WK) | 1/2, 2/3, 1 |
| Very weak | (VW) | 2/5, 1/2, 2/3 |
| Absolutely weak | (AW) | 1/3, 2/5, 1/2 |

#### *3.2.10 Skill and Technique Error*

An aircraft technician must possess adequate skills and undergo sufficient on-the-job training to learn correct techniques and safely carry out maintenance procedures.

### 3.3 Selection of Experts

Three experts from the aircraft maintenance field were selected for the evaluation of human errors in aircraft maintenance. All experts were qualified aircraft maintenance engineers(AME) and current on the system. Equal weightage of all three experts was considered in the fuzzy AHP-TOPSIS calculations as they had similar qualifications and experience.

### 3.4 Fuzzy AHP

The fuzzy AHP, is utilised in this research to obtain weight of criterion[33]. The description and Triangular Fuzzy number (TFN) spectrum for criterion weight of human errors used in FAHP is presented in Table 2.

The preference of experts on the impact of detection, severity, and occurrence on human errors captured using linguistic variables and corresponding TFN is presented in Table 3. After obtaining the comparison matrix, the consistency ratio (CR) was also checked[34]. The experts' comparative judgements were found consistent as the CR value was less than 0.1.

Suppose $M_{gi}^{j}$ is a TFN in the $i_{th}$ row and $j_{th}$ column of the criterion assessment, then:

$$\sum_{j=1}^{m} M_{gi}^{j} = \left( \sum_{j=1}^{m} a_{ij}, \sum_{j=1}^{m} b_{ij}, \sum_{j=1}^{m} c_{ij} \right) \tag{1}$$

where, a, b and c, are TFNelements.As per AHP, $M_{gi}^{j}$ can be calculated from Eqn. (1) as given in Eqn. (2-4).

$$C_1=(1+0.72+1,1+0.89+1,1+1.17+1.17)=(2.72,2.89,3.34) \tag{2}$$

**Table 3. Linguistic variables and corresponding TFN**

| Criteria | Detection | | | Severity | | | Occurrence | | |
|---|---|---|---|---|---|---|---|---|---|
| Detection | EQ | EQ | EQ | ST | SS | SW | VS | WK | SS |
| | 1 | 1 | 1 | 0.72 | 0.89 | 1.17 | 1 | 1 | 1.17 |
| Severity | WK | SW | SS | EQ | EQ | EQ | WK | WK | EQ |
| | 0.89 | 1.17 | 1.5 | 1 | 1 | 1 | 1 | 1.7 | 1.5 |
| Occurrence | VW | ST | SW | ST | ST | EQ | EQ | EQ | EQ |
| | 0.89 | 1 | 1 | 0.72 | 0.89 | 1 | 1 | 1 | 1 |

**Linguistic assessment of experts in severity sub-criteria**

| Criteria | $S_S$ | | | $S_C$ | | | $S_T$ | | |
|---|---|---|---|---|---|---|---|---|---|
| $S_S$ | EQ | EQ | EQ | SW | SS | WK | EQ | SS | EQ |
| | 1 | 1 | 1 | 1.17 | 1.67 | 2.17 | 1 | 1 | 1.5 |
| $S_C$ | SS | SW | ST | EQ | EQ | EQ | ST | SS | EQ |
| | 0.47 | 0.61 | 0.89 | 1 | 1 | 1 | 0.83 | 0.89 | 1.17 |
| $S_T$ | EQ | SW | EQ | WK | SW | EQ | EQ | EQ | EQ |
| | 0.67 | 1 | 1 | 0.89 | 1.17 | 1.3 | 1 | 1 | 1 |

Similarly, $C_2$ = (0.89+1+1,1.17+1+1.17,1.5+1+1.5)=(2.89,3.34,4.0) (3)

$C_3$ = (0.89+0.72+1,1+0.89+1,1+1+1) = (2.61,2.89,1). (4)

Column-wise sum of $M_{gi}^{j}$ is given in Eqn. (5) and it's inverse is calculated in Eqn. (6).

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j} = (2.72+2.89+2.61, 2.89+3.34+2.89, 3.34+4.0+1.0) = (8.22, 9.12, 8.34) \quad (5)$$

$$\text{and } \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{8.34}, \frac{1}{9.12}, \frac{1}{8.22}\right) \quad (6)$$

Therefore, the fuzzy synthetic index $F_i$ can be given from Eqn. (7) as presented in Eqn. (8-10).

$$F_i = \sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} \quad (7)$$

$F_1$ = (2.72,2.89,3.34)⊗ (0.12,0.11,0.12) = (0.33,0.32,0.40) (8)

$F_2$ = (2.89,3.34,4.0) ⊗ (0.12,0.11,0.12) = (0.35,0.37,0.48) (9)

and $F_3$ = (2.61,2.89,1.0) (0.12,0.11,0.12) = (0.31,0.32,0.12) (10)

The magnitude of $F_2(x_2, y_2, z_2) \geq F_1(x_1, y_1, z_1)$ is presented in Eqn. (11).

$$(F_2 \geq F_1) = \begin{cases} 1 & \text{if } x_2 \geq x_1 \\ 0 & \text{if } y_1 \geq y_2 \\ \dfrac{(x_1 - z_2)}{(y_2 - z_2) - (y_1 - x_1)}, & \text{Otherwise} \end{cases} \quad (11)$$

where, $(x_2, y_2, z_2)$ and $(x_1, y_1, z_1)$ are TFN.

The relative magnitude of fuzzy synthetic extent can be given as:

$M(F \geq F_1, F_2, \ldots, F_k) = M[(F \geq F_1), (F \geq F_2) \ldots (F \geq F_k)]$
$= min\, M(F \geq F_i)$, $i$=1,2,…$k$. (12)

The degree of possibility for all the $F_i$ was calculated from Eqn (12) and given in Eqns (13-15).

M ($F_1 \geq F_2$) = 0.5 *and* M ($F_1 \geq F_3$) = 1,
min {M ($F_i \geq F_k$)} = 0.5 (13)

M ($F_2 \geq F_1$) = 1 *and* M ($F_2 \geq F_3$) = 1,
min { M ($F_i \geq F_k$)} = 1 (14)

M ($F_3 \geq F_1$) = 1 *and* M ($F_3 \geq F_2$) = 1.2,
min { M ($F_i \geq F_k$)} = 1 (15)

Weight vector obtained from fuzzy synthetic index is given in Eqn. (16) andthe normalised weight vector is given in Eqn. (17).

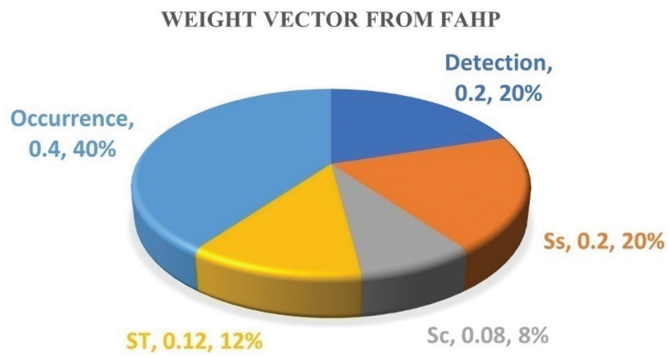


**Figure 3. Final weight vector of criterion and sub-criterion from FAHP.**

**Table 4. Evaluation of human errors by experts**

| Human error | *O* | | | *S_S* | | | *S_T* | | | *S_C* | | | *D* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.40 | | | 0.20 | | | 0.12 | | | 0.08 | | | 0.20 | | |
| Skill/techerror | (357,135,357) | | | (113,113,113) | | | (357,135,357) | | | (113,113,113) | | | (357,579,579) | | |
| | 1 | 4.3 | 7 | 1 | 1 | 3 | 1 | 4.3 | 7 | 1 | 1 | 3 | 3 | 6.33 | 9 |
| Inadequate design | (135,113,135) | | | (799,579,579) | | | (135,357,357) | | | (579,799,579) | | | (135,357,135) | | |
| | 1 | 2.3 | 5 | 5 | 7.7 | 9 | 1 | 4.3 | 7 | 5 | 7.7 | 9 | 1 | 3.66 | 7 |
| Inadequate supervision | (135,113,579) | | | (799,799,357) | | | (579,579,357) | | | (579,579,799) | | | (357,357,579) | | |
| | 1 | 3.7 | 9 | 3 | 7.7 | 9 | 1 | 4.3 | 7 | 5 | 7.7 | 9 | 3 | 5.67 | 9 |
| Obstructed workspace | (135,113,135) | | | (579,357,357) | | | (579,579,799) | | | (135,113,135) | | | (357,579,135) | | |
| | 1 | 2.3 | 5 | 3 | 5.7 | 9 | 3 | 6.3 | 9 | 1 | 2.3 | 5 | 1 | 5 | 9 |
| Judgement/decision making | (579,799,579) | | | (135,135,135) | | | (799,799,579) | | | (579,357,135) | | | (135,113,135) | | |
| | 5 | 7.7 | 9 | 1 | 3 | 5 | 5 | 7.7 | 9 | 1 | 5 | 9 | 1 | 2.3 | 5 |
| Environmental hazards | (357,579,357) | | | (135,357,135) | | | (357,357,357) | | | (357,357,579) | | | (357,135,135) | | |
| | 3 | 5.7 | 9 | 1 | 3.7 | 7 | 5 | 8.3 | 9 | 3 | 5.7 | 9 | 1 | 3.66 | 7 |
| Inadequate documentation | (357,579,357) | | | (135,135,357) | | | (579,357,799) | | | (799,799,579) | | | (357,135,135) | | |
| | 3 | 5.7 | 9 | 1 | 3.7 | 7 | 3 | 5 | 7 | 5 | 8.3 | 9 | 1 | 3.66 | 7 |
| Attention/memory error | (579,579,799) | | | (135,135,357) | | | (579,579,579) | | | (799,579,579) | | | (135,113,357) | | |
| | 5 | 7.7 | 9 | 1 | 3.7 | 7 | 3 | 7 | 9 | 5 | 8.3 | 9 | 1 | 3 | 7 |
| Inadequate process | (579,579,799) | | | (799,579,579) | | | (799.799.799) | | | (799,799,799) | | | (135,113,135) | | |
| | 5 | 7.7 | 9 | 5 | 7.7 | 9 | 5 | 7 | 9 | 7 | 9 | 9 | 1 | 2.3 | 5 |
| Knowledge/ rule-based error | (357,579,357) | | | (113,113,113) | | | (799,579,357) | | | (113,113,113) | | | (135,113,113) | | |
| | 3 | 5.7 | 9 | 1 | 1 | 3 | 7 | 9 | 9 | 1 | 1 | 3 | 1 | 1.7 | 5 |

Weight vector $W' = (0.5,\ 1,\ 1)$ (16)

Normalised weight vector

$$W = \left(\frac{0.5}{2.5} = 0.20,\ \frac{1}{2.5} = 0.40,\ \frac{1}{2.5} = 0.40\right) \quad (17)$$

Similarly, the sub-criterion weight vector of, severity at safety($S_S$), severity at cost ($S_C$), and severity at time ($S_T$) was calculated as 0.2, 0.08, and 0.12. The result of the final weight vectors of criterion ($S$, $O$ and $D$) and sub-criterion ($S_S$, $S_C$ and $S_T$) as obtained from FAHP is given in Fig. 3.

### 3.5 Fuzzy TOPSIS

The Fuzzy TOPSISis utilised in the research work to analyse and prioritise human errors in aircraft maintenance[35]. The language description and corresponding Triangular Fuzzy Number (TFN) utilised in the assessment of human errors are as follows:

- Very Poor (VP): [1, 1, 3]
- Poor (PR): [1, 3, 5]
- Fair (FR): [3, 5, 7]
- Good (GD): [5, 7, 9]
- Very Good (VG): [7, 9, 9]

The Evaluation of human errors by experts in linguistic variables of the criteria and alternatives converted to corresponding TFN is given in Table 4.

The normalised criterion and alternatives decision matrix $\tilde{C}$ in FTOPSIS is given by Eqn. (18).

$$\tilde{C} = [\tilde{r}_{ij}]_{m\times n}$$

where, $i_1^m$ and $j_1^n$ (18)

Here, $\tilde{r}_{ij}$ is the rating of alternatives. The normalisation is done using the Eqn. (19-20) for benefit and cost criteria, detection had reciprocal effect on errors. Therefore, it was computed on the basis of cost criteria.

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^b}, \frac{b_{ij}}{c_j^b}, \frac{c_{ij}}{c_j^b}\right), \text{where, } c_j^b = \max c_{ij} \text{ (Benefit)} \quad (19)$$

**Table 5. Ranking of human errors from FTOPSIS**

| **Human error** | ***O*** | $S_S$ | $S_T$ | $S_C$ | ***D*** | $D_i^p$ | $D_i^n$ | $C_{C_i}$ | **Rank** |
|---|---|---|---|---|---|---|---|---|---|
| Skill/technique errors | 0.01 | 0.05 | 0.03 | 0.02 | 0.02 | | | | |
| | 0.01 | 0.20 | 0.03 | 0.07 | 0.02 | 4.68 | 0.38 | 0.075 | 10 |
| | 0.02 | 0.32 | 0.08 | 0.11 | 0.05 | | | | |
| Inadequate design | 0.04 | 0.05 | 0.13 | 0.02 | 0.02 | | | | |
| | 0.06 | 0.10 | 0.20 | 0.07 | 0.04 | 4.51 | 0.56 | 0.110 | 7 |
| | 0.07 | 0.23 | 0.23 | 0.11 | 0.15 | | | | |
| Inadequate supervision | 0.04 | 0.05 | 0.08 | 0.05 | 0.02 | | | | |
| | 0.06 | 0.17 | 0.20 | 0.10 | 0.03 | 4.48 | 0.61 | 0.119 | 5 |
| | 0.07 | 0.41 | 0.23 | 0.14 | 0.05 | | | | |
| Obstructed workspace | 0.01 | 0.05 | 0.08 | 0.08 | 0.02 | | | | |
| | 0.02 | 0.10 | 0.15 | 0.12 | 0.03 | 4.55 | 0.53 | 0.104 | 8 |
| | 0.04 | 0.23 | 0.23 | 0.14 | 0.15 | | | | |
| Judgement/decision making | 0.01 | 0.23 | 0.03 | 0.08 | 0.03 | | | | |
| | 0.04 | 0.35 | 0.08 | 0.13 | 0.07 | 4.37 | 0.69 | 0.136 | 3 |
| | 0.07 | 0.41 | 0.13 | 0.14 | 0.15 | | | | |
| Environmental hazards | 0.02 | 0.05 | 0.03 | 0.05 | 0.02 | | | | |
| | 0.04 | 0.17 | 0.09 | 0.08 | 0.03 | 4.59 | 0.48 | 0.095 | 9 |
| | 0.07 | 0.32 | 0.18 | 0.11 | 0.05 | | | | |
| Inadequate documentation | 0.04 | 0.14 | 0.03 | 0.05 | 0.02 | | | | |
| | 0.06 | 0.26 | 0.09 | 0.11 | 0.04 | 4.42 | 0.67 | 0.131 | 4 |
| | 0.07 | 0.41 | 0.18 | 0.14 | 0.15 | | | | |
| Attention/memory error | 0.04 | 0.23 | 0.03 | 0.08 | 0.05 | | | | |
| | 0.06 | 0.35 | 0.09 | 0.11 | 0.15 | 4.29 | 0.76 | 0.151 | 2 |
| | 0.07 | 0.41 | 0.18 | 0.14 | 0.15 | | | | |
| Inadequate maintenance process | 0.05 | 0.23 | 0.13 | 0.11 | 0.03 | | | | |
| | 0.07 | 0.35 | 0.20 | 0.14 | 0.07 | 4.23 | 0.81 | 0.161 | 1 |
| | 0.07 | 0.41 | 0.23 | 0.14 | 0.15 | | | | |
| Knowledge/rule-based error | 0.01 | 0.14 | 0.03 | 0.05 | 0.03 | | | | |
| | 0.01 | 0.26 | 0.03 | 0.11 | 0.09 | 4.49 | 0.57 | 0.113 | 6 |
| | 0.02 | 0.41 | 0.08 | 0.14 | 0.15 | | | | |

$$\tilde{r}_{ij} = \left(\frac{a_j^c}{c_{ij}}, \frac{a_j^c}{b_{ij}}, \frac{a_j^c}{a_{ij}}\right), \text{ where, } a_j^c = \min a_{ij} \text{ (Cost)} \quad (20)$$

The weighted normalised decision matrix $\tilde{D}$ is given by Eqn. (21).

$$\tilde{D} = \left[\tilde{v}_{ij}\right]_{m \times n} \quad (21)$$

where, $\tilde{v}_{ij} = \tilde{r}_{ij} \times w_C$ and $w_c$ is the criteria weight obtained from FAHP.

The fuzzy positive ideal *FPI* of criterion and fuzzy negative ideal *FNI* is given in Eqn. (22-23).

$$FPI = \left\{\tilde{v}_1^p, \tilde{v}_j^p, \ldots, \tilde{v}_m^p\right\} \quad (22)$$

$$FNI = \left\{\tilde{v}_1^n, \tilde{v}_j^n, \ldots, \tilde{v}_m^n\right\} \quad (23)$$

where, $\tilde{v}_j^p = (1,1,1)\ \tilde{v}_j^n = (0,0,0)$.

The distance of alternatives from *FPI* and *FNI* was calculated from Eqn. (24-27).

$$C_{C_i} = \frac{D_i^n}{D_i^p + D_i^n} \quad (24)$$

$$D_i^n = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^n), i = 1,2,\ldots,m. \quad (25)$$

Where, $d(\tilde{v}_{ij}, \tilde{v}_j^p) = \sqrt{\frac{1}{3}\left[(l-1)^2 + (m-1)^2 + (n-1)^2\right]}$ (26)

and $d(\tilde{v}_{ij}, \tilde{v}_j^n) = \sqrt{\frac{1}{3}\left[(l-0)^2 + (m-0)^2 + (n-0)^2\right]}$ (27)

The ranking of the alternatives in FTOPSIS is defined with respect to the closeness coefficient index ($C_{C_i}$).The closeness coefficient is defined as $C_{C_i} = \frac{D_i^n}{D_i^p + D_i^n}$ (28)

The distances $D_i^p$ and $D_i^n$, $C_{C_i}$ as obtained using Eqn. (18-28) and ranking of human errors from FTOPSIS is presented in Table 5.

## 4. RESULTS AND DISCUSSION

The ranking of human errors, as obtained after the FTOPSIS analysis, is presented in Table 5, and a graphical representation is given in Fig. 4. The analysis found that the most critical human error was the inadequate maintenance process, while skill/technique was identified as the least critical. This information can be instrumental in prioritising areas for improvement in aircraft maintenance procedures.

### 4.1 Sensitivity Analysis

The effect of the weight of criteria on the ranking of human errors was investigated through sensitivity analysis using different weights of criteria. The sensitivity analysis validated the results of FTOPSIS and the robust nature of the proposed hybrid model. Case 0 was the original criteria weight, whereas the other cases were different random criteria weights of possible combinations. The different weightages of criteria considered for sensitivity analysis are given in Fig. 5.

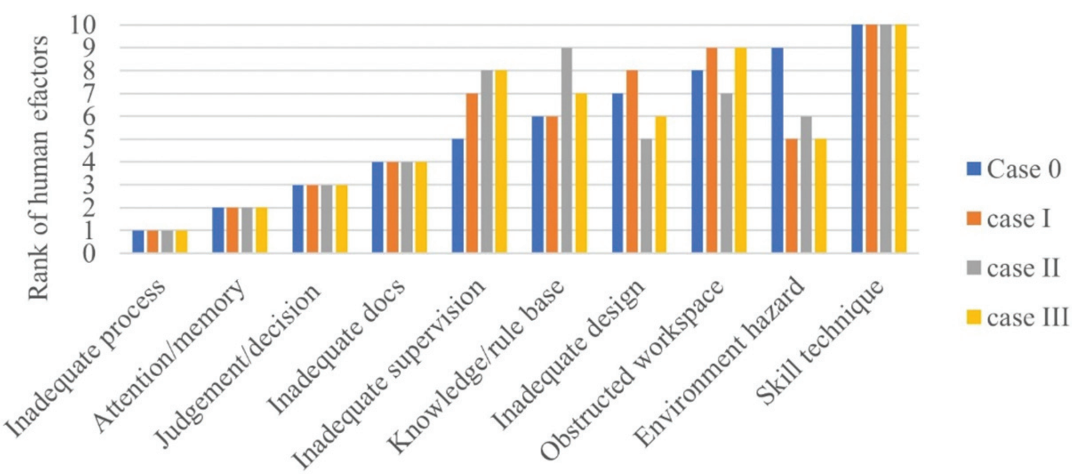


**Figure 4. Ranking of human errors from FTOPSIS.**

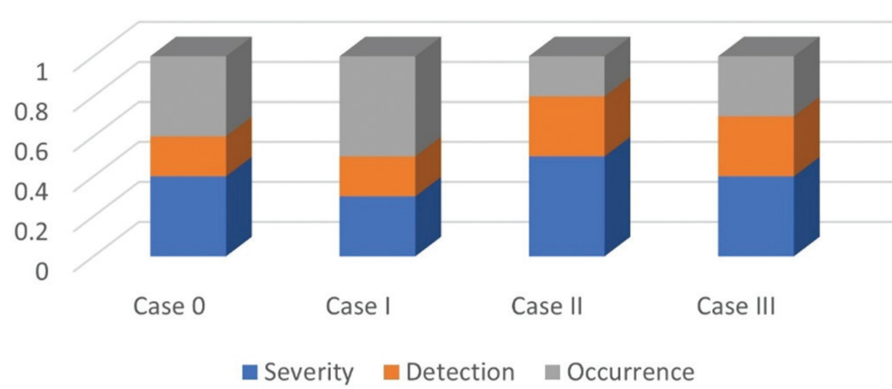


**Figure 5. Different weightage of criterion considered for sensitivity analysis.**

The $C_{C_i}$ for each case with different weightage were calculated from the Eqn. (18-28). The graphical representation of the ranking of human errors with different weightage of criteria is presented in Fig. 6. The results show that the application of different weight factors resulted in variation in the ranking of human errors. Supervision, knowledge/rule-based, inadequate design, obstructed workspace, and environmental hazard found different priority with different criteria weightage. The surge in ranking of attention/memory in Case II could be related to higher frequency, and environmental hazard in Case 0 could be linked to higher weightage of severity. Inadequate supervision was ranked as the fifth priority in three out of the four cases. However, it is worthwhile to notice that the priority did not change in respect of the top four and bottom-ranked human errors. Inadequate process, attention/memory, judgement/decision-making, and inadequate documentation retained the same priority one, two, three, and four respectively, even after changing the weight of criteria in all four cases. Skill/technique was also prioritised the same at rank 10 in all four cases.

## 4.2 Observations and Recommendations

The improvement gaps related to organisation, workplace and individual brought out during this study are discussed in the subsequent paragraphs.

### *4.2.1 Inadequate Maintenance Process*

Inadequate maintenance processes at the organisational level include a lack of updated regulations and Standard Operating Procedures (SOPs) for certain critical activities. Ineffective planning and monitoring by maintenance managers have also contributed to a few incidents. Analysis of incidents revealed that outsourcing and part-tasking of components were found not meeting the required specifications. Storage environment or transportation standards like temperature and humidity control and shock-proof packaging for electronic components, as per laid down regulations, were not maintained or ensured by the vendor/supplier.

Performance of the components post-DI needs to be monitored for residual life up to their Total Technical Life (TTL). The availability of SOPs for all critical activities, meticulous planning, regular monitoring of maintenance tasks, and formulation of stringent terms and conditions for vendors/suppliers would ensure reduced human errors related to inadequate processes in aircraft maintenance. Implementation of effective supervision at vendor premises is recommended to ensure safety in aircraft maintenance tasks.

### *4.2.2 Attention/Memory Errors*

Attention/memory errors were prominent human errors in aviation incidents during maintenance. Following incorrect procedures or omitting certain steps due to overreliance on memory and non-adherence to maintenance manuals and SOPs, leading to faulty or inadequate repairs, was unfortunately found to be a common issue even amongst experienced aircraft maintenance technicians. We recommend that maintenance manuals and publications be redesigned with creative presentations using the latest multimedia technology. Publications may be provided in easy-to-use electronic formats like interactive portable device applications to encourage and interest technicians to refer to such information.

### *4.2.3 Judgement/Decision*

Judgement and decision-making errors have resulted in damage to aircraft and equipment in maintenance incidents. Regular training programs to enhance judgement and decision-making and leadership skills amongst technicians need to be conducted.

### *4.2.4 Inadequate Documentation*

Inadequate documentation was identified as a critical human error among the technicians in aircraft maintenance. It was observed that maintenance activities undertaken by technicians were not recorded in the log books on a day-to-day basis, resulting in missing entries even though the activities could have been performed. However, without proper documentation, the completion of maintenance activity could not be ascertained. Adequate checks and balances are required to ensure timely completion and correctness of documentation. A dedicated maintenance control center element is required to function at the shop floor in tandem with aircraft maintenance technicians to closely monitor the documentation as per procedures during maintenance and provide real-time feedback

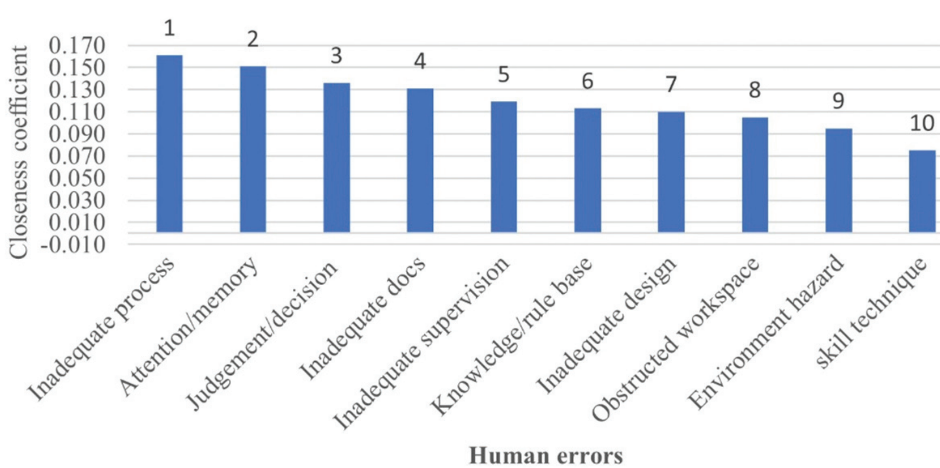


**Figure 6. Ranking of human errors with different weightage of criterion.**

to technicians and shop floor manager. Maintenance technicians may also be facilitated with adequate electronic maintenance management terminals and portable data entry devices for recording the maintenance task on completion.

#### 4.2.5 Inadequate Supervision

Critical activities on aircraft maintenance undertaken by aircraft maintenance technicians were not adequately supervised by competent supervisors, resulting in a few incidents. Supervisory lapses resulted in wrong or incomplete maintenance operations. Competent supervision with keen observation is an inescapable requirement of aviation maintenance set up. The organisation also needs to formulate stringent qualification and skill requirements with adequate experience, to be qualified as a supervisor on a particular system.

#### 4.2.6 Knowledge/Rule Based Error

Incorrect application of torque and pressure in systems due to lack of adequate knowledge and non-referring to publications led to incidents of maintenance errors. It was observed that the maintenance manuals were bulky and needed physical effort while referring. It is recommended that the maintenance manuals and publications need to be re-designed with creative presentations using the latest multimedia technology. Publications may be provided in easy-to-use electronic formats like interactive applications on a mobile device (mobile app) to encourage and interest technicians to refer to such information. A culture of e-libraries and knowledge sharing needs to be encouraged among technicians in the organisation.

#### 4.2.7 Inadequate Design

Certain errors were attributed to inadequate or faulty design. Techogene, FDR trans-receiver, autopilot connector plug, aircraft starting aggregate changeover box, and rubberised diaphragm in oxygen connector were modules contributing to the inadequate design incidents. The failures need to be addressed by the Original Equipment Manufacturer (OEM) to find a feasible solution.

#### 4.2.8 Environmental Hazard and Obstructed Workspace

Environmental hazards and obstructed workspace were also found as critical errors during aviation maintenance. Damage to sensitive electronic systems and precious aircraft ground testers due to fluctuations in power supply or inadequate earthing resistance, as well as storage of rubberised fuel tanks and seals and gaskets in uncontrolled environmental conditions, were attributed to environment-related human errors.

A few incidents related to damage to aircraft during the movement of tools, testers, and ground support equipment in the proximity of aircraft during maintenance resulted due to an obstructed workspace. Ground incidents of damage to aircraft pitot tube and control surfaces during parking/towing operations were attributed to obstructed workspace. Structural damages due to falling off of hangar light/hangar door and foreign object debris damage (FODD) also resulted in workspace-related errors.

To mitigate these issues, the movement of vehicles plying in proximity of aircraft should be restricted and strictly monitored. All laid down advisories on the subject like driving by only authorised personnel, and adhering to specified speed need to be followed. Meticulous supervision must be ensured to monitor any movement in the proximity of the aircraft. Further, periodic inspection by the quality control team and subsequent fixing of loose items/fittings and power supply earthing at the workplace could reduce the ground incidents and damage to aircraft.

#### 4.2.9 Skill/Technique Errors

Skill technique errors were observed in four of the incidents during aircraft maintenance. These errors highlight the need for regular continuity training, on-the-job training (OJT), and upskilling of maintenance technicians. To motivate technicians to strive to achieve higher skill levels, it is recommended to formulate a policy at the organisational level that links the technicians' skill levels with individual recognition, financial benefits, and promotional prospects.

**Table 6. Comparison of current study with similar previous studies**

| Rank | Fixed wing aircraft[36] | Rotorcraft[37] | Military aircraft (Current study) |
|---|---|---|---|
| 1 | Inadequate supervision | Inadequate process | Inadequate maintenance process |
| 2 | Judgement/decision making error | Inadequate documentation | Attention/memory error |
| 3 | Attention/memory error | Attention/memory error | Judgement/decision making error |
| 4 | Inadequate process | Skill/technique error | Inadequate documentation |
| 5 | Knowledge/rule-based error | Inadequate design | Inadequate supervision |
| 6 | Inappropriate operation | Routine norm/ violations | Knowledge/rule-based error |
| 7 | Inadequate documentation | Knowledge/rule based error | Inadequate design |
| 8 | Inadequate communication | Inadequate supervision | Obstructed workspace |
| 9 | --- | Uncertified equipment | Environmental hazards |
| 10 | --- | Infraction violation | Skill/technique error |

This approach can help ensure that technicians are adequately equipped with the necessary skills and knowledge to perform their tasks effectively and safely.

### 4.3 Corroboration of Results with Similar Studies

Table 6 presents a comparison of the findings of the current study on human errors in military fighter aircraft with the results of two previous studies that analysed human error using the HFACS-ME method on fixed-wing civil aircraft[36] and rotary-wing helicopters[37], respectively.

It is essential to acknowledge that the operational requirements of military fighter aircraft are significantly different from those of civil airliners or helicopters. The differences in operational and environmental factors lead to different human error preferences, as depicted in the three studies. Although individual maintenance technicians' errors are similar, there are variations in organisational and environmental factors due to differences in organisational culture and workplace environment. Notably, the three studies showed almost similar rankings for individual errors like knowledge/rule-based, judgment and decision-making, and attention/memory errors, which are common human factors. Additionally, supervisory lapses and inadequate documentation were common errors found across different aircraft fleets and organisations.

## 5. CONCLUSIONS

This research investigated human errors in aircraft maintenance through the development of a hybrid FMEA model adopting a novel fuzzy approach. The proposed model for identification and prioritisation would help in the effective control and mitigation of human errors in aircraft maintenance.

## 6. LIMITATIONS AND FUTURE SCOPE

The results in the presented study were determined through pairwise comparisons of linguistic variables by experts. It is important to note that the weightage of factors as well as experts' opinions may vary in different fields, and with different individuals. As a result, the development of our proposed model involves a degree of subjectivity that should not be disregarded. The study was carried out with limited data on aircraft incidents of a particular fleet. The results obtained in the present work can be further validated by other MCDM techniques like PROMETHEE, COPRAS-G, VIKOR, etc. The measurable impact of human factors on aviation maintenance may be investigated for their effective control and mitigation in future work.

## REFERENCES


1. Wenner, C.A. & Drury, C.G. Analysing human error in aircraft ground damage incidents. *Int. J. Ind. Ergon.,* 2000, **26**(2), 177-199. doi: 10.1016/S0169-8141(99)00065-7.
2. Latorella, K.A. & Prabhu, P.V. A review of human error in aviation maintenance and inspection. *Int. J. Ind. Ergon.,* 2000, **26**, 133-161. doi: 10.1016/S0169-8141(99)00063-3.
3. Shappell, S.A. & Wiegmann, D.A. Applying reason: The human factors analysis and classification system (HFACS). *Hum. Factors Aerosp. Safety.,* 2001, **1**(1), 59-86.
4. Embrey, D.E. SHERPA: A systematic human error reduction and prediction approach. *In* International Topical Meeting On Advances In Human Factors In Nuclear Power Systems, Knoxville, TN (USA), 21-24 Apr 1986.
5. Williams, J.C. A data-based method for assessing and reducing human error to improve operational performance. *In IEEE* 4th Conference on Human Factors and Power Plants, Monterey, CA, USA, 1988, 436-450. doi: 10.1109/HFPP.1988.27540.
6. Noroozi, A.; Khan, F.; MacKinnon,S.; Amyotte, P. & Deacon, T. Determination of human error probabilities in maintenance procedures of a pump. *Process Saf. Environ. Prot.*, 2014, **92**(2), 131-141 doi: 10.1016/j.psep.2012.11.003.
7. Cacciabue, P.C. & Vella, G. Human factors engineering in healthcare systems: The problem of human error and accident management. *Int. J. Med. Inf.,* 2010, **79**(4), 1-17. doi: 10.1016/j.ijmedinf.2008.10.005.
8. Rankin, W.L. Development and evaluation of the maintenance error decision aid (MEDA) process. *Int. J. Ind. Ergon.,* 2000, **26**(2), 261-276. doi: 10.1016/S0169-8141(99)00070-0.
9. Shorrock,S. T. & Kirwan,B. Development and application of a human error identification tool for air traffic control. *Appl. Ergon.*, 2002, **33**(4), 319-336. doi: 10.1016/S0003-6870(02)00010-8.
10. Stanton, N.A.; Salmon, P.M.; Rafferty, L.A.; Walker, G.H.; Baber, C. & Jenkins, D.P. Human factors methods: A practical guide for engineering and design, CRC Press, 2017.
11. Schimidt, J.K. & Lawson, D. Human factor analysis and classification system - maintenance extension. Review of select NTSB maintenance mishaps: An update. Department of the Navy, US Government, 2001.
12. Daramola, A.Y. An investigation of air accidents in Nigeria using the human factors analysis and classification system (HFACS) framework. *J. Air Transp. Manag*., 2014, **35**, 39-54. doi: 10.1016/j.jairtraman.2013.11.004.
13. Abdelgawad, M. & Fayek, A.R. Risk management in the construction industry using combined fuzzy FMEA and fuzzy AHP. *J. Constr. Eng. Manag.,* 2010, **136**(9), 1028–1036. doi: 10.1061/(ASCE)CO.1943-7862.0000210.
14. Illankoon, P.; Tretten, P. & Kumar, U. A prospective study of maintenance deviations using HFACS-ME, *Int. J. Ind. Ergon.,* 2019, **74**(2), 102852. doi: 10.1016/j.ergon.2019.102852.
15. Gilchrist, W. Modeling failure modes and effects analysis. *Int. J. Qual. Reliab.,* 1993, **10**(5), 16-23.
16. Sankar, N.R. & Prabhu, B.S. Modified approach for prioritization of failures in a system failure mode and effects analysis. *Int. J. Qual. Reliab. Manag.*, 2001, **18**(3), 324–336.

doi: 10.1108/02656710110383737.
17. Pillay, A. & Wang, J. Modified failure mode and effects analysis using approximate reasoning. *Reliab. Eng. Syst. Saf.,* 2003, **79**, 69–85. doi: 10.1016/S0951-8320(02)00179-5.
18. Ben-Daya, M. & Raouf, A. A revised failure mode and effects analysis model. *Int. J. Qual. Reliab.,* 1993, **13**(1), 43-47. doi: 10.1108/02656719610108297.
19. Kulak, O.; Durmuşoğlu, M.B. & Kahraman, C. Fuzzy multi-attribute equipment selection based on information axiom. *J. Mater. Process. Technol.*, 2005, **169(**3), 337-345. doi: 10.1016/j.jmatprotec.2005.03.030.
20. Kannan D.; Jabbour, A.B.L. & Jabbour, C.J. Selecting green suppliers based on GSCM practices: Using fuzzy TOPSIS applied to a Brazilian electronics company. *Eur. J. Oper. Res.,* 2014, **233**(2), 432-447. doi: 10.1016/j.ejor.2013.07.023.
21. Dağdeviren, M.; Yavuz S. & Kılınç, N. Weapon selection using the AHP and TOPSIS methods under fuzzy environment. *Expert Syst. Appl.*, 2009, **36**(4), 8143-8151. doi: 10.1016/j.eswa.2008.10.016.
22. Ding, J.F. An integrated fuzzy TOPSIS method for ranking alternatives and its application. *J. Mater. Process. Technol.,* 2011, **19**(4), 341-352. doi: 10.51400/2709-6998.2174.
23. Torlak, G.; Sevkli, M.; Sanal, M. & Zaim, S. Analysing business competition by using fuzzy TOPSIS method: An example of Turkish domestic airline industry. *Expert Syst. Appl.,* 2011, **38**(4), 3396-3406. doi: 10.1016/j.eswa.2010.08.125.
24. Kelemenis, A.; Ergazakis, K. & Askounis, D. Support managers' selection using an extension of fuzzy TOPSIS. *Expert Syst. Appl.*, 2011, **38**(3), 2774-2782. doi: 10.1016/j.eswa.2010.08.068.
25. Zandi, P.; Rahmani, M.; Khanian, M. & Mosavi, A. Agricultural risk management using fuzzy TOPSIS Analytical Hierarchy Process (AHP) and Failure Mode and Effects Analysis (FMEA). *Agriculture.,* 2020, **10**, 0504. doi: 10.3390/agriculture10110504.
26. Wang, L.; Sun, L.; Kang, J.; Wang, Y. & Wang, H. Risk identification of FPSO oil and gas processing system based on an improved FMEA approach. *Appl. Sci.,* 2021, **11**(2), 567. doi: 10.3390/app11020567.
27. Kutlu, A.C. & Ekmekçioglu, M. Fuzzy failure modes and effects analysis by using fuzzy TOPSIS-based fuzzy AHP. *Expert Syst. Appl.,* 2012, **39,** 61–67. doi: 10.1016/j.eswa.2011.06.044.
28. Yilmaz, A.K.; Malagas, K.; Jawad, M. & Nikitakos, N. Aircraft selection process with technique for order preference by similarity to ideal solution and AHP integration. *Int. J. Sustain. Aviat.*, 2020, **6**(3), 220-235. doi: 10.1504/IJSA.2020.112091.
29. Chiu, M.C. & Hsieh, M.C. Latent human error analysis and efficient improvement strategies by fuzzy TOPSIS in aviation maintenance tasks. *Int. J. Ind. Ergon.,* 2016, **54**, 136-147. doi: 10.1016/j.apergo.2015.11.017.
30. Velmurugan, K.; Saravanasankar, S.; Venkumar, P.; Sudhakarapandian, R. & Gianpaolo, D.B. Hybrid fuzzy AHP-TOPSIS framework on human error factor analysis: Implications to developing optimal maintenance management system in the SMEs. *Sustain Futures.*, 2022, **4**, 100087. doi: 10.1016/j.sftr.2022.100087.
31. Mangelia, M.; Shahrakia, A. & Saljooghib, F.H. Improvement of risk assessment in the FMEA using nonlinear model, revised fuzzy TOPSIS, and support vector machine. *Int. J. Ind. Ergon.,* 2019, **69**, 209-216. doi: 10.1016/j.ergon.2018.11.004.
32. Hsieh, M.C.; Wang, E.M.; Lee, W.C.; Li, L. W.; Hsieh, C. Y.; Tsai, W.; Wang, C. P.; Huang, J.L. & Liu, T.C. Application of HFACS, fuzzy TOPSIS, and AHP for identifying important human error factors. *Int. J. Ind. Ergon.*, 2018, **67**, 171-179. doi: 10.1016/j.ergon.2018.05.004.
33. Chang, D.Y. Theory and methodology applications of the extent analysis method on fuzzy AHP. *Eur. J. Oper. Res.,* 1996, **95**(3), 649-655. doi: 10.1016/0377-2217(95)00300-2.
34. Saaty, T.L. The analytic hierarchy process, McGraw-Hill,New York, 1980.
35. Chen, T.C. Extensions of the TOPSIS for group decision-making under fuzzy environment. *Fuzzy Sets Syst.,* 2000, **114**(1), 1–9. doi: 10.1016/S0165-0114(97)00377-1.
36. Krulak, D.C. Human factors in maintenance - impact on aircraft mishap frequency and severity. *Aviat. Space Environ. Med.,* 2004, **75**(5), 429-432.
37. Rashid, H.S.J.; Place, C.S. & Braithwaite, G.R. Helicopter maintenance error analysis: Beyond the third order of the HFACS-ME. *Int. J. Ind. Ergon.,* 2010, **40,** 636-647. doi: 10.1016/j.ergon.2010.04.005.

## CONTRIBUTORS

**Mr Om Prakash Bohrey** obtained his ME in Aeronautical Engineering from HIET, Chennai. Presently he is pursuing PhD at RCOEM, RTMNU, Nagpur, India. His areas of interest include: Reliability, maintainability, aircraft maintenance, and quality control.
In the current study, he contributed to conceptualisation, literature review, methodology, formulation, and manuscript writing.

**Dr A.S. Chatpalliwar** is an Associate Professor at the Department of Industrial Engineering at Shri Ramdeobaba college of engineering and management, Nagpur, India. His areas of interest include: Reliability, risk management, and quality control.
In the current study, he guided in reviewing the manuscript and provided insight into formulation and results.