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Failure Mode and Effects Analysis (FMEA) using Neutrosophic Best Worst Method (BWM) : A Case Study of Helicopter Assembly Line for Military Aviation Area

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ABSTRACT

One of the most popular structured approaches in risk assessment is Failure Mode and Effects Analysis (FMEA) that helps in discovering potential failures existing within the design of a product or process. Determining the risk weights of failure types correctly is a critical part of the decision-making process of the analysis. In this study, the Best Worst Method (BWM) was integrated with the Neutrosophic Fuzzy Set and applied to the FMEA problem. The aim of the study is to determine the failure types encountered in the helicopter assembly line in the military aviation field and to offer solution suggestions. A case study was conducted for AH-64E Apache type helicopters for the effectiveness of the proposed method. The results show that gap and mismatch for structural elements, molds should not be used appropriately, unnecessary materials should be brought to the assembly line and attention should be paid to cabling problems.

1. Introduction

The aviation industry is distinctly differentiated from other sectors in terms of production and manufacturing processes. Among the primary differences are high safety standards, quality requirements, and international certification procedures. The materials used in the production of aircraft and helicopters are typically advanced technology composites or alloys, chosen for their lightweight and durability properties. Moreover, the tests conducted to ensure the compatibility of each component, and the meticulously executed quality control processes set this sector apart from others. In particular, high automation technologies and robotic systems are frequently employed in manufacturing processes to minimize human error. However, these advanced technologies and precision requirements lead to increased costs and extended production timelines.

Military aviation takes these challenges to an even higher level. In military aircraft and helicopters, factors such as not only safety and durability but also operational agility, low radar cross-section, high maneuverability, and extended mission profiles are of critical importance. This results in the use of specialized materials, more complex design, and engineering processes. Additionally, the production of military aviation products involves stringent confidentiality measures for national

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security reasons, and supply chain management becomes more intricate. All these factors significantly increase the costs and complexity of military aviation projects.

In both civil and military aviation sectors, the assembly processes of aircraft and helicopters are among the most time-consuming and costly stages of production. During assembly, each component must be placed with micron-level precision, and thousands of cables and connections need to be properly integrated. Even the smallest error on the assembly lines can lead to severe consequences in terms of operational safety and performance. Therefore, assembly processes are often supported by dual control mechanisms and require intensive human labor. Although high automation is utilized, some critical points still require manual intervention, which adds another factor to the cost and duration of the process. Comprehensive testing and certification procedures conducted post-assembly are also significant factors that extend the production time. Research indicates that between 10% and 30% of the total manufacturing cost is attributed to assembly activities [1]. Thus, the assembly line is one of the areas where continuous improvement is most intensively applied, and most of these improvements are carried out with a strong focus on attention to detail [2].

Failure Mode and Effects Analysis (FMEA) plays a critical role in minimizing assembly process disruptions and improving production quality [3]. This method systematically identifies potential failure modes and their effects on the assembly process, enabling the prioritization of risks. FMEA, especially in the aviation sector, where complex and delicate components are integrated, allows for the early detection of potential issues and the implementation of necessary preventive measures. For example, issues such as incorrect component placement, connection errors, or wiring harness problems can be identified at an early stage through analysis, and the process design can be optimized to mitigate these risks. This analysis not only prevents costly rework or delivery delays but also enhances flight safety and assembly efficiency. A systematic application of FMEA enables teams to address the root causes of errors and facilitates continuous improvement in processes [4].

In recent years, the integration of fuzzy set extensions with MCDM has been frequently addressed in literature due to their ability to effectively reflect uncertainties in decision-making processes. [5-6]. Neutrosophic sets are one of these extensions. These sets, as extensions of Pythagorean and intuitionistic fuzzy sets, were developed to represent the uncertainties existing in the real world. They propose three different membership functions: truth, indeterminacy, and falsity. By doing so, they better reflect ambiguous situations [7]. Classical fuzzy sets are based on a single membership function in decision-making processes. These sets are used in integration with MCDM in solving decision problems. This study will focus on one of these integrations, the neutrosophic fuzzy set Best Worst Method (N-BWM) approach, and apply it to the FMEA problem. Thus, a significant contribution will be made to FMEA literature. The proposed N-BWM application has been implemented in the analysis of common defects in the assembly line of military helicopters. Unlike classical FMEA, the weight of risk parameters is considered in this problem.

The study includes neutrosophic BWM in the second part, literature summary in the third part, analysis of problems encountered in helicopter assembly field and FMCDM application in the fourth part, and conclusion explanations in the last part.

2. Neutrosophic BWM

Neutrosophic sets are a general version of classical, fuzzy, and intuitive fuzzy sets, and they better represent uncertainty, inconsistency, and real-world issues compared to classical fuzzy sets [8]. A single-valued triangular neutrosophic number is expressed as $\tilde{n}$ = $\{(n_1 n_2 n_3); \alpha \sim \beta \sim \theta\}$. Here, n_1, n_2, n_3 represent the lower, middle, and upper values of the neutrosophic number. $\alpha_{\tilde{n}}, \beta_{\tilde{n}}, \theta_{\tilde{n}}$ refer to the truth membership, uncertainty membership, and falsity membership functions, respectively.

The Best Worst Method (BWM), proposed by Rezaei (2015) [9], is one of the fundamental MCDM methods [10]. BWM can produce consistent results using fewer comparison data. It allows for consistency calculations by utilizing two vectors. In this method, integer values between 1 and 9 are used. This feature makes the BWM method more practical and easier to understand compared to other methods [11]. To better express uncertainties, N-BWM was proposed by Yucesan and Gul [8]. The procedural steps of this approach are as follows:

Step 1. In this step, the decision criteria to be evaluated are determined. The n number of criteria can be represented as $[c_1, c_2, c_3, \dots, c_n]$.

Step 2. The best and worst criteria are identified. When evaluating the criteria, the best criterion is denoted as c_B, and the worst criterion is represented as c_W.

Step 3. In this step, the best preference A_B = $(\widetilde{a_{B1}}, \widetilde{a_{B2}}, \dots, \widetilde{a_{Bn}},)$ is determined with respect to all other criteria using a neutrosophic number from Table 1.

Step 4. Similar to Step 3, the worst preference of the other criteria relative to the worst criterion A_B = $(\widetilde{a_{B1}}, \widetilde{a_{B2}}, \dots, \widetilde{a_{Bn}},)$ is determined using a neutrosophic number from Table 1.

Step 5. The neutrosophic evaluations made in Steps 3-4 are converted into definite values. The conversion procedure uses Equations 1-2.

$$S(\tilde{\boldsymbol{n}}) = \frac{1}{8}[n_1 + n_2 + n_3]x(2 + \alpha_{\tilde{n}} - \beta_{\tilde{n}} - \theta_{\tilde{n}}) \quad (1)$$

$$A(\tilde{\boldsymbol{n}}) = \frac{1}{8}[n_1 + n_2 + n_3]x(2 + \alpha_{\tilde{n}} - \beta_{\tilde{n}} - \theta_{\tilde{n}}) \quad (2)$$

These two terms are, respectively, scores and accuracy degrees. After this conversion, the expert's assessment regarding the related disruptions is transformed into a deterministic decision platform.

Table 1. Evaluation Scale and Corresponding Neutrosophic Numbers

Saaty Scale	Linguistic Term	Neutrosophic Triangular Scale	Opposite of Neutrosophic Triangular Scale
1	Equally Effective (EE)	{(1, 1, 1);0,5, 0,5, 0,5}	{(1, 1, 1);0,5, 0,5, 0,5}
2	EE and SE Evaluation	{(1, 2, 3);0,4, 0,65, 0,}	{(0,33 0,5, 1);0,4, 0,65, 0,6}
3	Slightly Effective (SE)	{(2, 3, 4);0,3, 0,75, 0,7}	{(0,25 0,33, 0,5);0,3, 0,55, 0,7}
4	SE and STE Evaluation	{(3, 4, 6);0,6, 0,35, 0,4}	{(0,2 0,25, 0,33);0,6, 0,35, 0,4}
5	Strongly Effective (STE)	{(4, 5, 6);0,8, 0,15, 0,2}	{(0,17 0,2, 0,25);0,4, 0,65, 0,6}
6	STE and Very Strongly Effective (VSTE) Evaluation	{(5, 6, 7);0,7, 0,25, 0,3}	{(0,33 0,5, 1);0,8, 0,15, 0,2}
7	Very Strongly Effective (VSTE)	{(6, 7, 8);0,9, 0,1, 0,1}	{(0,14 0,17, 0,2);0,7, 0,25, 0,3}
8	VSTE and Absolute Effective (AE) Evaluation	{(7, 8, 9);0,85, 0,1, 0,15}	{(0,11 0,13, 0,14);0,85, 0,1, 0,15}
9	Absolutely Effective (AE)	{(9, 9, 9);1, 0, 0}	{(0,11 0,11, 0,11);1, 0, 0}

Step 6. In this step, optimal criterion weights $(w_{1,}^*, w_2^*, \dots, w_n^*)$ are determined. The optimal weight for criteria is the weight corresponding to each w_B/w_j and w_j/w_w pair where w_B/w_j = a_{jw}. To match them for all j's, a solution should be found that minimizes the maximum absolute

differences $|\frac{w_B}{w_j} - a_{Bj}|$ ve $|\frac{w_j}{w_w} - a_{jw}|$ for all j's. Considering the non-negativity and total conditions for weights, the mathematical problem can be arranged as follows [12-15]:

min maks $\{\left|\frac{w_B}{w_j} - a_{Bj}\right|, |\frac{w_j}{w_w} - a_{jw}|\}$

under the conditions

$\sum w_j = 1$

$w_j \geq 0 \; for \; \forall \; j$

The problem should be transformed as follows:

Min ξ

$\left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi$ for $\forall \; j$

$|\frac{w_j}{w_w} - a_{jw}| \leq \xi$ for $\forall \; j$

$\sum w_j = 1$

$w_j \geq 0 \; for \; \forall$ (3)

When solving the problem, the optimal weights ($w_1^*, w_2^*, \ldots, w_n^*$) and ξ^* are calculated. Then, the consistency ratio is computed using the consistency index. In classical BWM, the evaluations range from 1 to 9. Since the evaluations change in N-BWM, a new consistency table is required. The Consistency Index (CI) for each evaluation is calculated using Equation (4).

$(a_{Bw} - \xi)\,(a_{Bw} - \xi) = (a_{Bw} + \xi)$

$\xi^2 - (1 + 2a_{Bw})\,\xi + (a_{Bw}{}^2 - a_{Bw}) = 0$ (4)

The maximum ξ value is calculated for each a_{Bw} where $a_{Bw} \in \{\tilde{1}, \tilde{2}, \ldots, \tilde{9}\}$. The calculated values are presented in Table 2.

Table 2. Consistency Index Table for N-BWM [8]

a_{Bw} (*Neutrosophic*)	$\tilde{1}$	$\tilde{2}$	$\tilde{3}$	$\tilde{4}$	$\tilde{5}$	$\tilde{6}$	$\tilde{7}$	$\tilde{8}$	$\tilde{9}$
a_{Bw} (Deterministic)	0,563	0,863	0,956	2,775	4,594	4,838	7,088	7,800	10,125
CI	2,2235	2,768	2,927	5,683	8,166	8,488	11,386	12,281	15,153

Using the consistency indices in Table 2, the Consistency Ratio (CR) is calculated as follows. For a more consistent evaluation, the CR value is expected to be close to zero.

$CR = \frac{\xi}{CI}$ (5)

3. Literature Review

FMEA is a systematic method used in the safety and risk assessment of systems [16]. This method has been successfully applied in many fields in recent years [17-18]. FMEA has three parameters—severity, probability, and detectability—used to obtain a risk priority score. The risk priority score is calculated by multiplying these three parameters. Each parameter has a numerical scale ranging from 1 to 10. Error types with higher risk priority scores are more significant and can be ranked higher than those with lower risk priority scores [19]. Although this method provides a good and systematic way to prioritize error types in system reliability and safety assessments, there are several disadvantages mentioned in the literature [20]. Some of these disadvantages can be summarized as follows:

a. In classical FMEA, the weights of the three parameters are not considered in the calculation of the risk priority score.

b. Despite having different scores for each parameter for two different error types, they may still have the same risk priority score.
c. The calculation of risk priority can be sensitive to changes when evaluating risk parameters. Even small variations may lead to significantly different effects on the risk priority score.
d. Classical FMEA considers only three risk parameters.

To address the disadvantages of a classical FMEA study, a new approach combining neutrosophic numbers and the BWM method is proposed in this work. Neutrosophic sets, proposed by Smarandache [21], better reflect the uncertainty in real-world problems compared to classical fuzzy set theory. It addresses the three aspects of decision-making situations: accuracy, uncertainty, and falsity. In classical fuzzy set theory, a fuzzy set has only a membership function degree. However, in a neutrosophic environment, there are three different membership conditions to cope with real-world uncertainty. Neutrosophic sets are an extension of intuitive fuzzy sets. In intuitive fuzzy sets, a hesitation degree exists, whereas, in neutrosophic sets, an uncertainty degree is proposed instead. Neutrosophic sets encompass intuitive fuzzy sets by considering accuracy membership, uncertainty membership, and falsity membership. Neutrosophic sets offer several advantages [22,23]:

- They offer an uncertainty degree that helps experts explain their judgments more accurately.
- They clarify the scope of disagreements among decision-makers. Considering these advantages of neutrosophic sets, this study proposes an N-BWM-based FMEA model.

Regardless of neutrosophic sets, the BWM method is also a popular Multi-Criteria Decision-Making (MCDM) method that has recently found applications in many areas [24]. It was proposed by Rezaei [9] and offers advantages over other pairwise comparison-based methods such as AHP. This method reaches results by making fewer pairwise comparisons and producing more consistent decision matrices. It is applied from the best criterion to the others, and from other criteria to the worst criterion. FMEA is one of the areas where this is used. There are several recent studies where FMEA and BWM are used together [25-29]. In addition, FMEA is currently being applied in many sectors and academic studies are being conducted on its analysis [30-33].

4. Analysis of Problems Encountered in Helicopter Assembly Area and FMCDM Application

Helicopter components and their assembly process are carried out using the fixed position layout approach, like aircraft [34]. In this layout, the product being worked on remains fixed in a specific area throughout the entire assembly process, while equipment and workers move around it. The variability present in each process leads to problems that vary due to the complexity of the equipment and product, as well as variability in controllable inputs and noise parameters during helicopter assembly. The use of fixtures, large and contoured parts, and the presence of very tight tolerances further complicate the process [2]. Errors that arise during assembly due to unknown causes are unacceptable, as they indicate an uncontrolled process. A study conducted in various projects at a helicopter factory has tried to group these problems under general headings. For this purpose, the content of recorded problems related to the AH-64E Apache Attack Helicopter was examined and classified. The Apache helicopter represents a revolutionary development in the history of warfare. It is essentially a flying tank—designed to survive heavy attacks and inflict massive damage. It can zero in on specific targets, day or night, even in terrible weather. As expected, it is a terrifying machine for ground forces. However, there are challenges encountered during the assembly of this powerful machine.

Table 3. Failure Type

#	Failure type
FT1	Inappropriate use of tools and molds for their intended purpose.
FT2	The arrival of unsuitable materials, parts, or components at the assembly area, or disruptions in the material flow.
FT3	Wiring problems (routing, hook up).
FT4	Gaps and Misalignments in Structural Components (Gap, Alignment, Mismatch Problems)
FT5	Errors related to ignition systems (e.g., Hellfire missiles, rockets, chain guns, sensors).
FT6	Processes that exceed the capabilities of the assembly area.
FT7	Insufficient clear process specifications
FT8	Losses in traceability records, requiring additional operations, including disassembly, to complete the record chain.

A general visual illustrating the problems that may arise from all of these issues and their positions on the helicopter fuselage is provided in Figure 1.

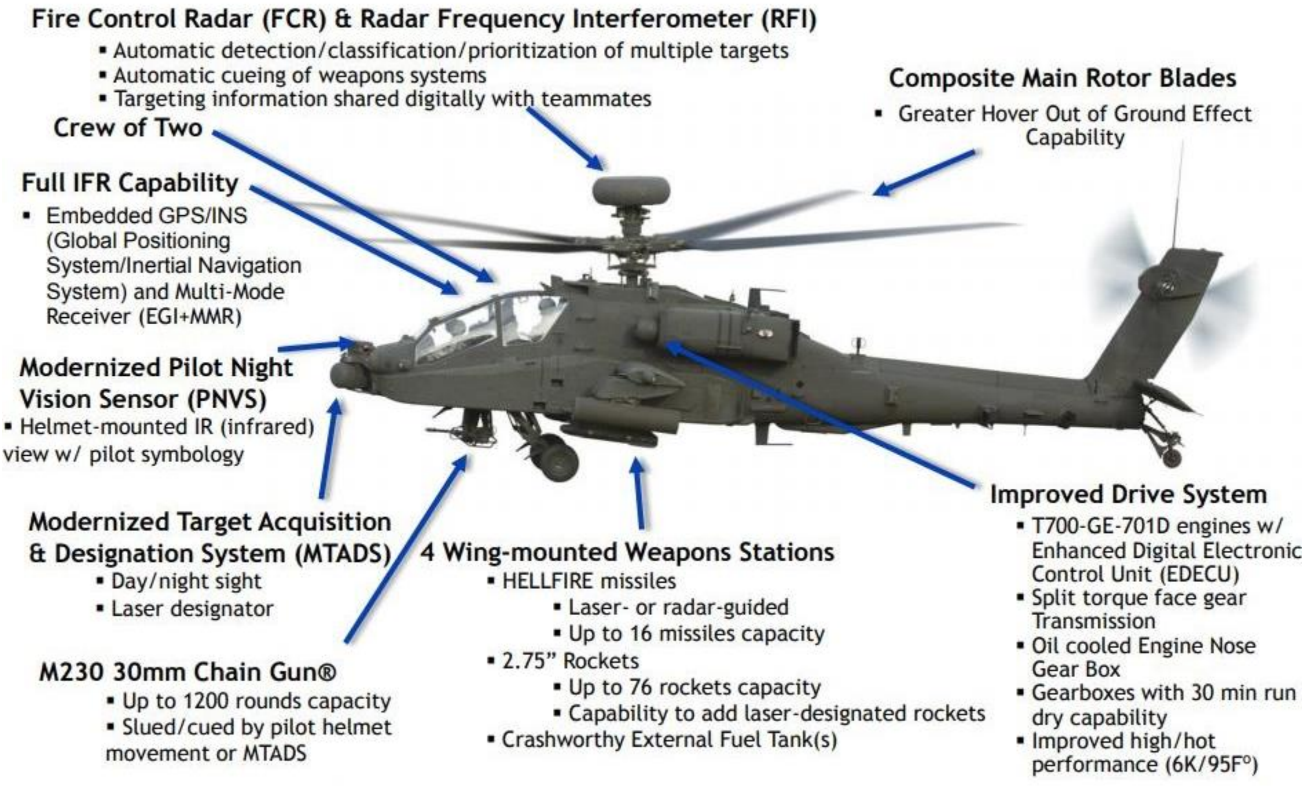

Fig.1. AH-64E Apache Helicopter Features

In this section, an example application study is conducted by analyzing the errors encountered in the military helicopter assembly line using the interval-valued N-BWM. Eight different types of errors, as shown in Table 3, have been identified in the study. Initially, N-BWM is used to determine the importance weights of the three basic parameters of FMEA: severity, probability, and detectability.

Subsequently, a pairwise comparison of the eight different failure types (FTs) is made according to these parameters, and priority values are calculated again using N-BWM. From this, a matrix is obtained, reflecting the importance weights of the FMEA parameters and the priority levels of the FTs associated with each of the three parameters. Finally, to obtain the risk priority scores for the FTs, this matrix is multiplied. After completing the first two steps of N-BWM, namely the expert and FT determination steps, in the third step, pairwise comparisons for each FT are made by applying BWM under neutrosophic numbers. In this step, the best and worst criteria are identified. Then, the neutrosophic scale provided in Table 1 is used for pairwise comparisons. The pairwise comparison values for the FMEA risk parameters and the values for the severity, probability, and detectability parameters under each FT are determined accordingly.

Mathematical models are then constructed for these four comparison tables. Below, the mathematical model for the evaluation of the FMEA parameters is presented. Other models are constructed in a similar manner.

Min ξ

st.

$$\left|\frac{w_{\text{Severity}}}{w_{Probability}} - \tilde{9}\right| \leq \xi \tag{6}$$

$$\left|\frac{w_{\text{Severity}}}{w_{Detectability}} - \tilde{6}\right| \leq \xi \tag{7}$$

$$\left|\frac{w_{Detectability}}{w_{Probability}} - \tilde{9}\right| \leq \xi \tag{8}$$

$$w_{\text{Severity}} + w_{Probability} + w_{Detectability} = 1 \tag{9}$$

$$w_{\text{Severity}}, w_{Probability}, w_{Detectability} \geq 0 \tag{10}$$

The values expressed with neutrosophic numbers in the models are converted into deterministic values, transforming the problem into a classical BWM. The models are solved by following the process outlined by Rezaei [9]. The results for the risk priority scores and priority rankings are presented in Figure 2. The consistency values of the evaluation matrices were checked.

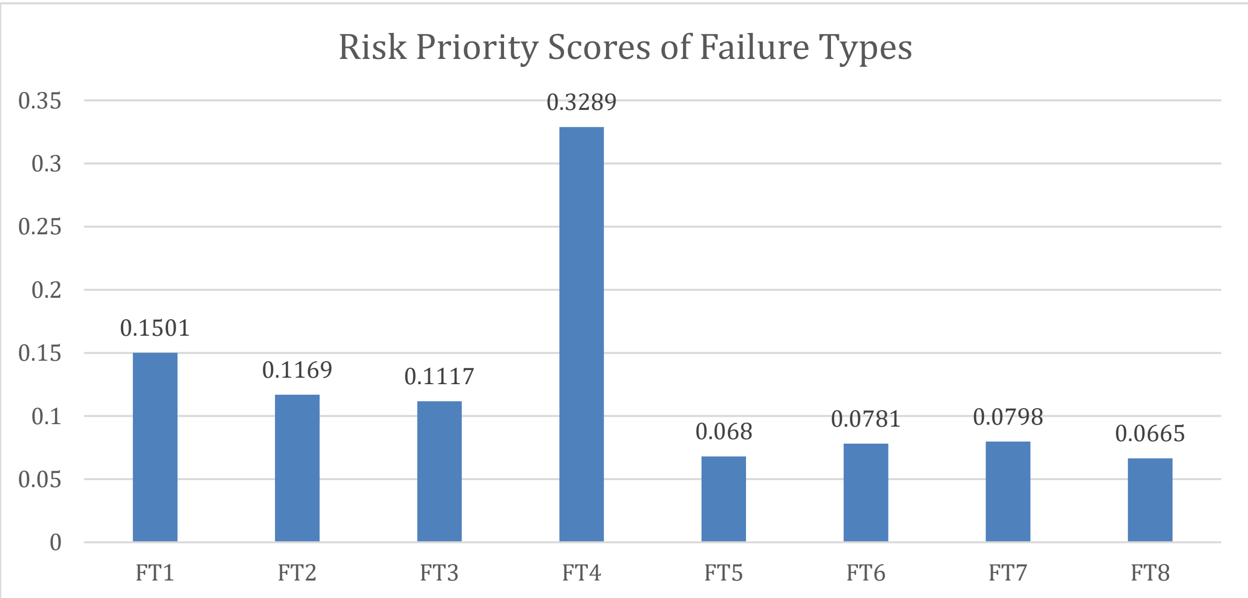

Fig.2. Risk Priority Scores of Failure Types

In order to show the points to be considered in the assembly line after FMEA, the visual of the Apache attack helicopter cutaway diagram is shared in Figure 3 [35].

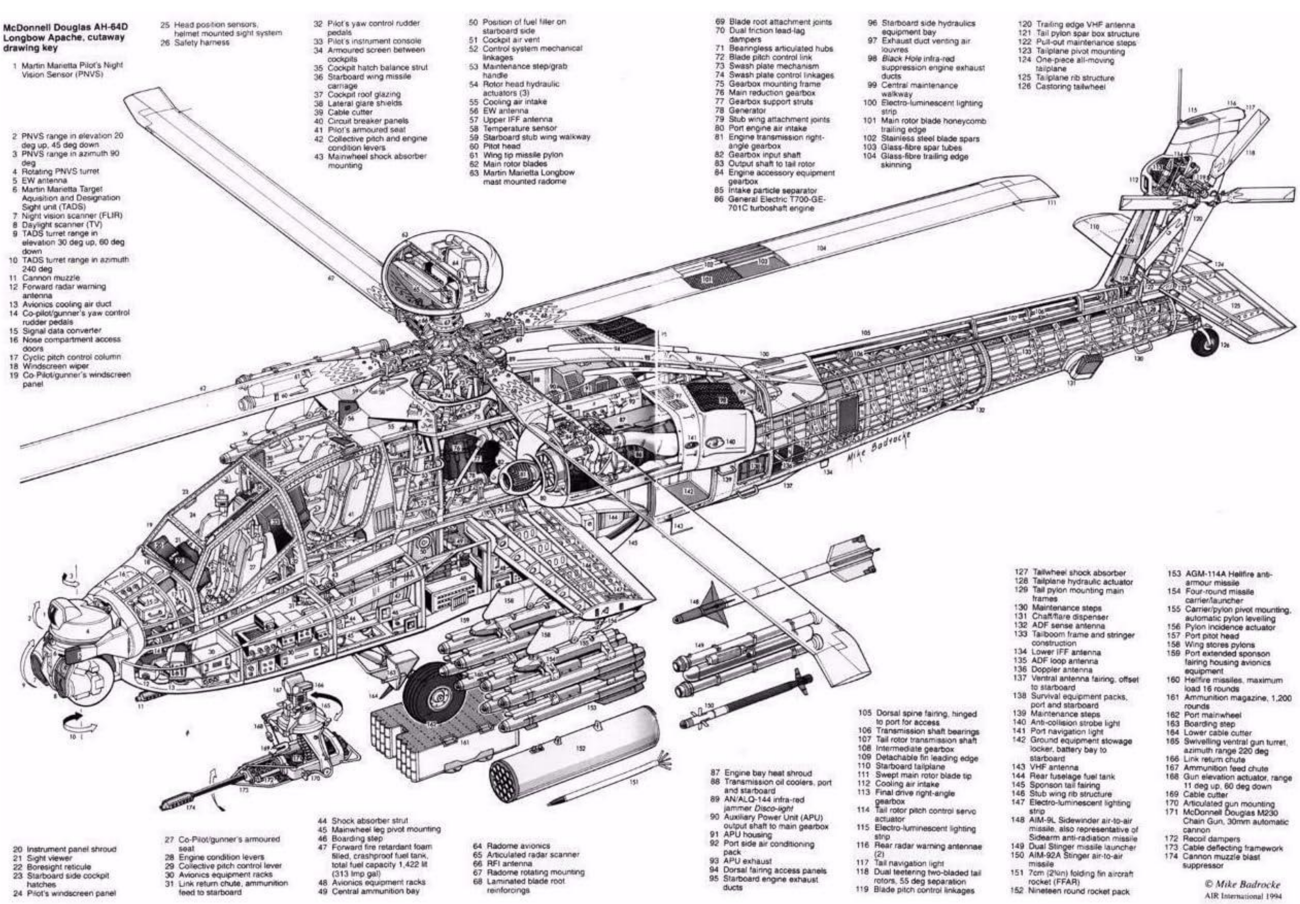

Fig.3. Apache Attack Helicopter Diagram of Assembly Line

Using diagrams such as Figure 3, analyses can be performed using different methods that produce analytical solutions for stock control to solve problems such as interruptions in the material flow in helicopters and errors due to firing system [36-38]. Thus, the findings of FMEA will become more meaningful and can be effectively translated into practice.

5. Conclusions

Errors that may occur in helicopter assembly lines can lead to critical problems that hinder the timely and cost-effective completion of the production process. Each of these errors is a significant risk factor that requires separate attention, and appropriate corrective and preventive measures should be applied for each. According to the findings of the study, the errors are addressed in order of importance.

1. Gaps and Misalignments in Structural Components (Gap, Alignment, Mismatch Problems)

When the structural components of the helicopter are not properly positioned during assembly, gaps or alignment issues may arise. This can affect structural integrity and may require corrective actions such as the use of shims and sealants, which increase weight. These issues not only extend the assembly time but also impact on the helicopter's flight performance and efficiency. To prevent such errors, the use of high-precision measuring devices and automation technologies, along with regular calibration of tools and molds, is essential.

2. Inappropriate Use of Tools and Molds for Their Intended Purpose

Improper use of tools and molds during assembly is one of the leading causes of assembly errors. This situation may lead to the inability to hold structural components in the correct position or to process them to the required dimensions. Regular training for workers, periodic maintenance and calibration of equipment, and the integration of ergonomic designs into processes are critical for solving this issue.

3. The Arrival of Unsuitable Materials, Parts, or Components at the Assembly Area, or Disruptions in the Material Flow

The arrival of incorrect materials at the assembly area or discontinuities in the material flow can halt the production line and cause time losses. This situation leads to significant cost increases, especially in aviation projects, which are highly time sensitive. The effective use of Material Requirement Planning (MRP) systems, tight control of supply chain management, and strengthening of incoming quality control processes will help prevent this issue.

4. Wiring Problems (Routing, Hook Up)

The complex electronic systems in helicopters require proper wiring arrangements. Incorrect wiring or faulty connections may lead to system failures and security vulnerabilities. To prevent such issues, detailed wiring diagrams should be prepared, the use of automation technologies during wiring should be increased, and workers should undergo technical training.

5. Insufficient Clear Process Specifications

Inadequate or ambiguous process instructions used during assembly can cause workers to make errors. Providing clear, visually enriched instructions at each stage of the processes will minimize errors by preventing uncertainties. Additionally, continuous feedback mechanisms should be established, and these instructions should be regularly updated.

6. Errors Related to Ignition Systems (e.g., Hellfire Missiles, Rockets, Chain Guns, Sensors)

When ignition systems (such as Hellfire missiles, rockets, chain guns, and sensors) are not properly integrated during assembly, serious operational and safety risks can arise. These systems require high precision and safety standards. Therefore, it is essential to employ trained personnel in specialized areas and to implement systematic control processes.

7. Processes that Exceed the Capabilities of the Assembly Area

Executing processes that exceed the existing technical capacity of the assembly line can lead to quality issues and disruptions in workflow. This may require outsourcing of processes or redesigning the assembly area. To prevent such issues, comprehensive capacity analysis should be conducted, and each process should be adapted to the physical and technical capacity of the assembly area.

8. Losses in Traceability Records, Requiring Additional Operations, Including Disassembly, to Complete the Record Chain

Problems with traceability records can make it difficult to identify the root causes of errors and may necessitate disassembly or additional operations to complete the record chain. This results in significant time and cost losses. To prevent traceability issues, the use of digital record systems, RFID tagging, and serial numbering technologies should be increased, and processes should be strictly monitored.

All these errors can be minimized with effective management and continuous improvement processes. Developing customized solution strategies for each problem reduces production costs and enhances the safety and performance of the helicopter.

In this study, FMEA was conducted with a unique approach by combining neutrosophic sets with BWM. The approach was carried out using the AH-64E Apache helicopter as an example for examining helicopter assembly processes. Although it focuses on a single type, the methodology can be easily applied to all military helicopters and aircraft. In future studies, sensitivity analyses can be performed to test robustness, and comparisons can be made with different extensions of BWM.

Conflicts of Interest

The author declare no conflicts of interest.

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