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Application of Probabilistic Risk Analysis in the Overhaul of Aero-engines using a Combination of Bayesian Networks and Fuzzy Set Theory - A Case Study

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Identifying and responding to risks in aircraft maintenance activities is fundamental since an engine failure during a flight may cause a forced landing and, tragically, cause deaths. This reality makes monitoring, identifying, and prioritizing risk treatment during aero-engine maintenance essential. In the last European Congress for Reliability and Safety, held in 2022 in Dublin, the author presented a method for Probabilistic Risk Analysis in the Overhaul of Aero-engines using a combination of Bayesian Networks and Fuzzy Set Theory aiming at meeting Civil Aviation Agency Regulations and the requirements AS9100. This study complements the one presented in Esrel 2022 and demonstrates the method application. As a result, combining the Bayesian network modeling method with the Fuzzy Set Theory, referred to as Fuzzy Bayesian Network (FBN), proved to be a more effective and precise method to combine risks generated from different sources. The contribution is significant since the proposed method allows process optimization and risk reduction in the repair station and permits decision-makers to assign funds for critical activities. It can affect the company's risk management processes and help understand performance and safety during engine overhaul. Although conducted in a repair station, it can be generalized to other industries and fields of work whose safety is affected by risks resulting in waste, rework, and unnecessary energy consumption.

Keywords: Bayesian Belief Networks (BBN), Fuzzy Set Theory (FST), Fuzzy Bayesian Network (FBN), Risk Management and Operational Safety

1. Introduction

As technology advances over the years, its complexity increases directly proportional. These advances measurelessly extend the boundaries of performance, efficiency, and sustainability. Consequently, new risks are identified in the production of these technologies. According to Netjasov (2008), the air transportation system is recognized as one of the fastest-growing areas in the transportation sector; within this growth, there are new aircraft and, consequently, new engines. Identifying and mitigating risks is fundamental in aero-engine maintenance activities since an engine failure during a flight can take many lives. This reality makes monitoring, prioritizing, and identifying risks during aero-engine maintenance essential. The prioritization of risks becomes essential and complex due to the many identified risks. Several authors have addressed the topic in similar ways.

Pereira (2017) suggests combining Bayesian networks with bow-tie diagrams to define the global risk in the manufacturing of aero engines but leaves a suggestion for the combined use of an AHP (Analytic Hierarchy Process) matrix for modeling the correlation between the processes. Di Maio (2020) also proposes using Bayesian networks with bow-tie diagrams to find weaknesses in an oil and gas system.

Several papers have been published addressing the use of BBN in different domains in the latest years. However, no previous study could be found covering the application of BBN to identify risks in operating an aero-engine repair station.

This study aims to conduct a literature review in scientific databases, coupled with a case study on how an aero-engine repair station works, and propose a method to combine risks found in different ways in a single model to estimate the overall operation risk score. The model uses Bayesian networks to assist in prioritizing the taking of actions regarding the risks affecting this type of operation. The case study was conducted on how an aero-engine repair station operates to identify gaps and opportunities to improve risk management, safety, and quality. The study aims to respond to the following research questions:

Research Question 1: How can Bayesian networks integrated with Fuzzy Logic be applied in prioritizing risks identified in the aero-engine overhaul process?

Research Question 2: How can the aero-engine overhaul process be integrated with an operational Safety Management System using Bayesian Networks to improve quality performance and compliance to Civil Aviation Agency Regulations and the requirements AS9100?

Research Question 3: How can the organization's operational safety management system be optimized to prioritize risks using Bayesian Networks to reduce quality costs? The study is structured as follows: Section 2 covers Literature Review, presenting previous studies on Operational Safety and Safety Management systems, Probabilistic Risk Analysis, BBN (Bayesian Belief Networks), Compliance with Civil Aviation Agency Regulations, Requirements AS9100, and Fuzzy Method and Risk Assessment.

Section 3 addresses Methodology. Section 4 shows the results. Section 5 discusses the results, and section 6 is the conclusion.

2. Literature Review

2.1 *Operational Safety and Safety Management System*

Major accidents in the industry and critical infrastructure failures have generated an absolute need for new and efficient approaches to risk assessment and security management (Santhosh and Patelli, 2020). Risk management starts by reviewing all relevant information, particularly the combined risk assessment, consisting of both risk and concern assessments. Together with the judgments made in the risk characterization and assessment phase, this information forms the input material on which management options are evaluated and selected (Aven, 2012). From a technical point of view, there is a consensus that "zero accidents" is an unachievable index. "The accident rate involving a maintenance deficiency has not decreased in 25 years" (Boyd and Stolzer, 2015). Rocha (2010) describes how the attitude of companies has been changing from a reactive nature to events, that is, acting to solve after the failure has occurred, to a more proactive and preventive approach focusing on the use of data to take actions of failure prevention. Pereira (2017) stated that aeronautical engine production companies have as their primary objective the production of engines with high reliability and durability, i.e., with a minimum probability of failure in a long time. Boyd and Stolzer (2015) note that the accident rate in general aviation remains high. Although most general aviation accident studies have focused on pilots, there is little research on the involvement of aircraft maintenance errors. Pereira (2017) also demonstrates the concept of security over the years through an in-depth literature review. In the mid-1970s came a new view that failures were due to human factors. At the end of the 1990s, the concept of security took a new view regarding organizational factors. A failure is probably not an isolated event but the result of several organizational factors that cause failures by human factors and ultimately generate failures.

2.2 *Probabilistic Risk Analysis, BBN (Bayesian Belief Networks)*

Tartakovsky (2007) describes a typical Probabilistic Risk Analysis (PRA), which starts by identifying relevant components of the system and proceeds using uncertainty quantification techniques to estimate the probability of its failure. Ouchi (2004) describes probabilistic risk analysis as an efficient method in cases where the probability of occurrence of a given risk is very low. Pereira (2017) observes that in many aircraft engine production companies, there is no application of a formal model for probabilistic risk analysis, which compromises the safety of the operation. Belobaba, Odoni and Barnhart (2009) state that aviation safety is a key and essential factor for the economic viability of this industry.

2.3 *Compliance with Civil Aviation Agency Regulations, Requirements AS9100*

In recent years, some studies on AS9100 are as follows: Gordon (2000) studied the aerospace industry's need to create a sector-specific standard based on ISO 9001. The author stated that the standard needs to be acceptable to aerospace manufacturers, customers, and regulatory agencies. Richter (2002) provided an overview of AS9100 for the aerospace industry and QS-9000 for the automotive industry. Tarach (2002) studied quality, safety, and security in aviation repair stations. Corli (2011) investigation included the analysis of quality documents, the development of the quality system, and a description of the implementation. This study aimed to provide the focus group (SMEs) with more knowledge when developing quality management systems to implement the AS 9100 requirement to compete in the aerospace industry. Peter et al. (2011) discussed the rigidity in quality management standards within aerospace and defense industries that counter many lean principles. Yeo and Byun (2011) reviewed how the AS9100 requirement has been established and improved and the communication of significant changes from AS9100, Rev. B to Rev. C, focusing on reasons for revisions.

2.4 *Fuzzy Method and Risk Assessment*

He et al. (2022) conducted a case study that showed fuzzy analytic hierarchy process (FAHP)-Bayesian Network (B.N.)–based risk analysis. The method provided real-time and dynamic decision support for gas overrun control and treatment in coal mines to ensure safe and efficient mining.
Wang et al. (2021) concluded that Fuzzy evaluation provided the risk interval and membership degree, contained more parameter information, quantified and reduced parameter uncertainty, provided more comprehensive results, and compensated for the deficiency of deterministic evaluation.
Eskandari et al. (2021) studied the Bow-tie model and fuzzy-Bayesian network and considered compressor gas leakage in an explosive probabilistic risk assessment.

3 Methodology

The methodological structure used to develop the study is presented in Figure 1, which shows the steps followed to arrive at the responses to the research questions. The research adopted was exploratory, with the research method taking the form of a literature review and case study. The exploratory research was conducted to obtain more information on the subject, enabling its definition and delineation to facilitate the research topic's delimitation and guide the setting of objectives.

The investigation was conducted from different angles and aspects, such as literature review, interviews with people who have had practical experiences with the researched problem, and analysis of examples that stimulate understanding. The literature review was organized by dividing themes and their subsequent research questions. Papers, books and dissertations in physical and digital media related to operational safety management systems in aero-engines repair stations were consulted and cited. These publications helped search for proposals to solve the problem later compared with the content raised in the field research. Google Scholar, Web of Science, and Scopus databases were used for the literature search in the research stage.

The following keywords were used: Bayesian belief networks (BBN); Bayesian belief networks; Fuzzy set theory; Risk management; Operational Safety; Probabilistic Risk Assessment, Quality, and AS9100. For the development of this case study, data were collected in four different ways. The first was interviews with experienced individuals, and the remaining information was collected through process mapping. The 30 employees interviewed had experience in quality management and SMS (Safety Management System). The data collected was defined based on the literature search results, which helped define the parameters needed to create the mathematical model that is the objective of this research. Data were analyzed by the team participating in this study. The information collected in the interviews was compared with the literature. A simulation was conducted to show how BBN is combined with Boolean Logic, and another to show how BBN is combined with Fuzzy Logic. Finally, sensitivity analysis results with Boolean and Fuzzy Logic were compared. The flowchart in figure 1 shows the methodology steps.

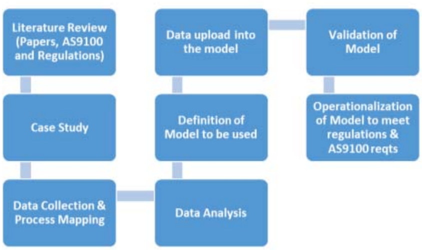

Figure 1 – Methodology steps

4 Results

4.1 *Aero-engine Overhaul Process*

In Step 0 (zero), the engine is received and submitted to receiving inspection in the first step. Results and data on the flight history and engine performance for the preliminary definition are used to define the scope of work. This step is called the "Work scope Definition." It is presented to the customer, who will decide about the work to be started on the engine. Then, in Step 1 (one), disassembly, cleaning, and engine inspection are carried out. This step consists of a cycle where the engine is divided into modules. The modules are cleaned and inspected; depending on the inspection result, it may cause its subdivision into sub-modules until it reaches a level of unique and indivisible parts. The parts are cleaned and repaired, and then the engine is assembled and balanced with parts already replaced or repaired. After assembly, it undergoes the test on the test bench. A series of critical parameters for engine performance is reviewed (checking the exhaust temperature of gases, vibration, thrust, and consumption), which can last more than 3 hours. Suppose the acceptance parameters are not met or something out of the ordinary is found. In that case, the engine is inspected and may have to be disassembled for something to be adjusted or even a part to be replaced.

4.2 *Safety Management System (SMS)*

The operational safety management system implemented in the studied repair station is mainly based on the regulations issued by Aviation Authorities, which follow ICAO (International Civil Aviation Organization) guidelines. The objective of the system is to increase productivity and reduce non-quality costs. These non-quality costs can be internal or external quality failures. Internal failures happen before the engine reaches the customer and generally do not impact the end customer directly. These failures cause rework, component repair, schedule delay, materials scrapping, inspections, and failure reason analysis. External failures are much more critical since they happen while the customer uses the product. In addition to customer complaints and dissatisfaction, these failures are costly to the company and can cause disasters whose responsibility may be covered in the quality assurance contract; this can cause the loss of customers and, depending on the size, can cause severe problems for the company.

4.3 *Risk Assessment and Management Process*

As per ICAO guidelines, hazard Identification occurs by voluntary reports or proactive events such as PFMEAs (Process of Failure Mode and

Effects Analysis) and even by investigations of problems that occurred in the past. As per aviation authorities' regulations, all the hazards raised are entered into a single system, and it is a digital form linked to a process that goes through 4 steps. The hazard is raised in the first step of this process, a qualitative and quantitative analysis is made, a risk owner is assigned for risk response, and the last step is controlling the risk.

4.4 *Prioritization in the Treatment of Risks*

The number of hazards raised is substantial. Treatment prioritization is critical because if it is not done adequately, it can cause a disaster with a high human and financial impact. Currently, the risks have their priority defined by the value of each risk index, and risks with a higher index have a preference over lower indexes. After the risks are treated and reassessed, the SAG member defines the need to reassess the action taken in the treatment at a future date to ensure that the action remains effective. If deemed necessary, the member defines a future date on which the system will automatically notify the item to be revisited. All the items that enter the system are stored in the database. Metrics are generated in real-time based on the database to analyze trends in the system and indicate the need for action. The number of hazards to be treated is significant. It requires a model to respond to the most impactful risks first, so the need to use mathematical modeling for prioritization. The BBN used for modeling had all nodes used in the network defined as Boolean, where the two (2) states, true and false, indicated failure or non-failure of what the node was representing. A node with a high probability will indicate a high probability of failure. The empirical BBN used in the simulation is shown in Figure 2.

Figure 2 – BBN Model

Figure 2 shows the top event as a Failure in Operation (FIO) and the several intermediate events (I.E.) in blue circles. The basic events are all connected to these Intermediate events.

4.5 *Application of Probabilistic Risk Analysis*

4.5.1 *Boolean Logic*

All nodes of basic events (B.E.) used in the network had their type defined as Boolean, where the two (2) states, true and false, indicated failure or non-failure of what the node was representing. Figure 3 shows the Top event (T.E.), the Intermediate Event (I.E.) and the basic events (B.E.)

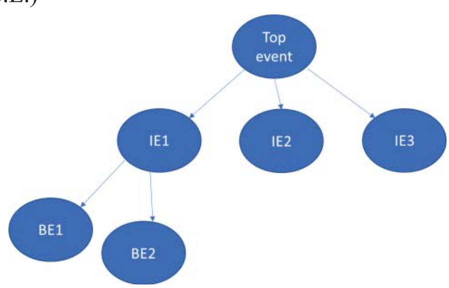

Figure 3 – BBN Nodes

Table 1 shows a sample of the conditional probability table for the intermediate event (I.E.) using the logical gate "OR". According to the traditional Logic, I.E. will be true if one basic event causes 1, 2 to be true.

Table 1 - Conditional Probability Table in the traditional Logic.

B.E. 1	True		False	
B.E. 2	True	False	True	False
I.E. -True	1	1	1	0
I.E. - False	0	0	0	1

As an example, a result is illustrated in the BBN and tornado graph of Figures 4 and 5, where the process indicated that the most critical to the system is the "Preparation to test and De_Preparation after test" process. This tornado graph was generated with all nodes as Boolean.

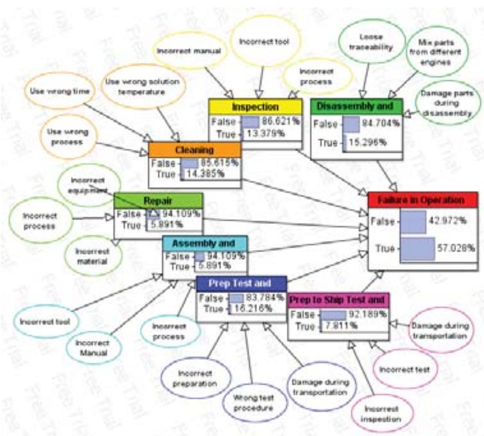

Fig. 4 – BBN for Failure In Operation in the traditional Logic.

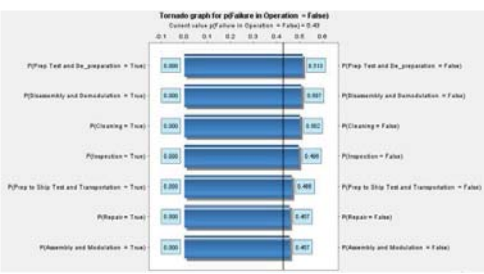

Fig. 5 – Tornado Graph for Failure In Operation in the Traditional Logic.

4.5.2 *Fuzzy Logic*

Instead of defining all nodes used in the network as Boolean, the concept of pertinence in Fuzzy Logic can be used. Fuzzy Logic is a valuable tool for handling uncertainty in decision-making; the accuracy of using fuzzy Logic instead of Boolean Logic in BBNs is applicable in this specific context, considering the quality of the available data. The performance of both approaches was evaluated in practical situations. For example, Table 2 shows a sample of the conditional probability table for the intermediate event (I.E.) using the logical gate "OR." According to Fuzzy Logic, the I.E., will be partially true if one basic event 1 and 2 are true.

Table 2 - Conditional Probability Table in the Fuzzy Logic.

B.E. 1	True		False	
B.E. 2	True	False	True	False
I.E. -True	0.7	0.8	0.6	0.1
I.E. - False	0.3	0.2	0.4	0.9

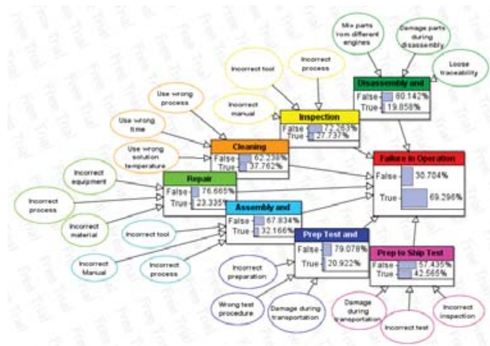

Fig. 6 – BBN for Failure In Operation in the fuzzy Logic.

Figure 7 shows the tornado graph considering the top event and the Intermediate Events of the Bayesian Network according to Fuzzy Logic.

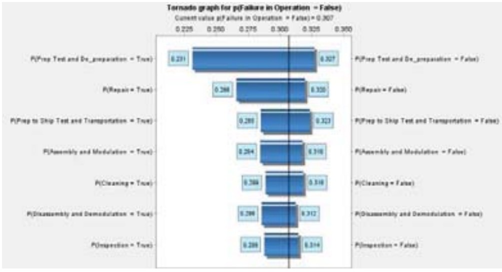

Fig. 7 – Tornado Graph for Failure In Operation in the Fuzzy Logc.

Due to the degree of pertinence, it has been observed that the order of criticality of risk factors has changed. This shows the accuracy of fuzzy Logic. The application of Fuzzy Logic to the model is currently being tested in practice and shows promising results.

5 Discussion of Results

The target of the study was to propose a model to prioritize the risks in an aero-engine repair station and provide responses to these risks that could affect operational safety and sustainability. Safety is a fundamental resource for the industry, especially in aviation, which carries thousands of lives daily. The results found in the case study using the model developed in this project support the results found in the literature review. They contribute by showing that the most critical risks for an operation failure should be prioritized based on their probability of detectability and severity and consider the nature of the space that these risks affect. Thus, risks that affect critical processes have a higher chance of generating a failure in operation and should be prioritized, given which processes could be affected if this risk were to occur. The model helps repair stations better understand how to prioritize the allocation of resources for the treatment of its operational risks. This study contributes to other researchers' previous findings since most were based only on qualitative approaches, did not cover a quantitative approach using BBN, and focused on quality and organizational sustainability. This paper aimed to complete this gap by proposing a model to apply BBN and fuzzy Logic to prioritize risks in the aero-engine repair station operation that could optimize quality, safety, and sustainability. The implications are relevant since operational processes can be conducted more safely when adopting the proposed model. By using the model, operational failures and catastrophic accidents can be prevented.

The proposed method revealed some vital results and may help overcome some of the challenges operational leaders and other professionals looking for safety and quality through effective risk management. The study was conducted based on the experience and knowledge of experts on the subject. Notably, this paper proposes an optimized approach that could be used in any organization. Changing how risk is prioritized encompasses changes in human behavior, work patterns, and values in response to raised risks anticipating strategic, resource, or technology changes. The big challenge is not technological change using the model but changing how people think and the organizational culture to gain a competitive advantage.

Following the proposed model, this proposed process can guide the companies under the traditional management of risks to change processes to achieve their safety and quality improvement aims. That helps to significantly impact operational results, such as quality and safety improvement cost reduction, representing considerable productivity gains and sustainability. Even for companies in other fields, the proposed Methodology can enrich their risk management process, helping it to be more effective.

Enhanced by improved communication, the proposed model enables any enterprise to increase productivity through risk management. This study shows evidence that the quality of the risk management process is affected by several factors, some of which can compromise the reliability and safety of the repair station. In this regard, process analysis played a crucial role in understanding and implementing actions to improve it.

6 Conclusion

This study is noteworthy because understanding the most impactful risk factors in the operation of repair stations and responding correctly to risks can influence the attitude of operational managers, engineers, and decision-makers. As evidenced by the results, the model can help optimize risk management. As expected, the contribution is significant; it is believed that the present study will augment the knowledge of safety managers, engineers, and decision-makers concerning the use of the model to improve the quality and effectiveness of the risk assessment process. In addition to productivity, the model has increasingly been an essential element of quality and a necessary part of quality systems, mainly in pandemic times when risks are more frequent.

In response to the first research question, *" How can Bayesian networks integrated with Fuzzy Logic be applied in prioritizing risks identified in the aero-engine overhaul process?* The proposed model was presented, showing the application of Bayesian Networks to assist in the decision-making process for allocating resources for the treatment of risks in the engine overhaul. The current process of prioritizing risk treatment and allocating resources for risk treatment was described in detail. Simulations were conducted successfully comparing Boolean and Fuzzy Logic in the BBN Network. The simulation result shows that BBN integrated with fuzzy Logic is more accurate and effective in combining and prioritizing risks generated from different sources.

In response to the second research question, *"How can the aero-engine overhaul process be integrated with an operational safety management system using Bayesian Networks to improve quality performance and compliance to Civil Aviation Agency Regulations and the requirements AS9100?"* The various processes of the overhaul of aero-engines were detailed. The operational safety management system was described, showing how the repair stations work is integrated with BBN's in the safety management system. The results show that the interaction of these processes helps the treatment of risks and reduces the chance of failures in operation, so meeting Civil Aviation Agency Regulations and the requirements AS9100.

In response to the third research question, "*How can the organization's operational safety management system be optimized to prioritize risks using Bayesian Networks to reduce quality costs?"* The Operational Safety Management System and its operation were analyzed, showing the processes contributing to operational safety. Similar practical applications of Bayesian Networks in safety assessment, risk management, and assessment in several different industry segments were reviewed. The results show that BBN in this specific application is important to prioritize risks for properly allocating resources and to reduce quality costs, ensuring safety in highly complex systems.

Scope for future research: - This study opened new avenues for the future. Opportunities for other case studies are abundant, and they could be related to a broader modeling application on specific cases, enhancing the current Methodology and reducing the risk of failures. One example to be explored would be artificial intelligence to speed up and improve the process even more.

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