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EVALUATING CREW FATIQUE MANAGEMENT STRATEGIES IN AVIATION: A FUZZY DEMATEL APPROACH

Research

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Evaluating Crew Fatique Management Strategies in Aviation: A Fuzzy DEMATEL Approach

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Abstract

Crew fatigue is a significant issue in aviation, affecting both safety and operational performance. This study applies the Fuzzy DEMATEL method to evaluate and prioritize strategies for managing crew fatigue, based on expert input from 12 aviation professionals. The analysis identifies workload management as the most influential factor, with direct impacts on other key elements such as rest schedules and flight duration control. Real-time monitoring technologies emerged as a critical tool, enabling more effective fatigue management by providing actionable data for adjusting crew schedules and mitigating risks in real-time. Flight duration, particularly on long-haul operations, was highlighted as a major contributor to cumulative fatigue. The novelty of this study lies in its use of Fuzzy DEMATEL to map the complex interdependencies between fatigue factors, providing a structured, data-driven framework for decision-making in aviation management. The findings offer practical insights for improving crew performance and safety by prioritizing strategies that directly target the most influential causes of fatigue. These insights are valuable for aviation companies seeking to enhance fatigue risk management systems, particularly through the implementation of real-time monitoring and workload adjustments. Future research should explore integrating quantitative data from actual operations to further validate these findings and examine emerging decision-making models for fatigue management.

Keywords: Crew fatique, aviation safety, fuzzy DEMATEL, fatique risk management, aviation management.

JEL Code: J81, M12, L93, C61, D81, O33

Havacılıkta Ekip Yorgunluk Yönetim Stratejilerinin Değerlendirilmesi: Bulanık bir DEMATEL Yaklaşımı

Özet

Mürettebat yorgunluğu havacılıkta hem güvenliği hem de operasyonel performansı etkileyen önemli bir sorundur. Bu çalışma, 12 havacılık profesyonelinden alınan uzman girdilerine dayanarak mürettebat yorgunluğunu yönetmeye yönelik stratejileri değerlendirmek ve önceliklendirmek için Bulanık DEMATEL yöntemini uygulamaktadır. Analiz, dinlenme programları ve uçuş süresi kontrolü gibi diğer önemli unsurlar üzerinde doğrudan etkisi olan iş yükü yönetimini en etkili faktör olarak tanımlamaktadır. Gerçek zamanlı izleme teknolojileri mürettebat programlarını ayarlamak ve riskleri gerçek zamanlı olarak azaltmak için eyleme dönüştürülebilir veriler sağlayarak daha etkili yorgunluk yönetimini mümkün kılan kritik bir araç olarak ortaya çıktı Özellikle uzun mesafeli operasyonlarda uçuş süresinin kümülatif yorgunluğa önemli bir katkı sağladığı vurgulanmıştır. Bu çalışmanın yeniliği, havacılık yönetiminde karar alma için yapılandırılmış, veriye dayalı bir çerçeve sağlayarak, yorgunluk faktörleri arasındaki karmaşık karşılıklı bağımlılıkları haritalamak için Bulanık DEMATEL'in kullanılmasındadır.. Bulgular, yorgunluğun en etkili nedenlerini doğrudan hedef alan stratejilere öncelik vererek mürettebat performansını ve güvenliğini artırmaya yönelik pratik bilgiler sunmaktadır. Bu bilgiler, özellikle gerçek zamanlı izleme ve iş yükü ayarlamalarının uygulanması yoluyla yorgunluk riski yönetim sistemlerini geliştirmek isteyen havacılık şirketleri için değerlidir. Gelecekteki araştırmalar, bu bulguları daha fazla doğrulamak için gerçek operasyonlardan elde edilen niceliksel verileri birleştirmeyi keşfetmeli ve yorgunluk yönetimi için ortaya çıkan karar verme modellerini incelemelidir.

Anahtar Kelimeler: Mürettebat yorgunluğu, havacılık emniyeti, bulanık DEMATEL, yorgunluk risk yönetimi, havacılık yönetimi.

JEL Kodu: J81, M12, L93, C61, D81, O33

Introduction

Crew fatigue remains a critical issue in the aviation industry, directly impacting both safety and operational efficiency. Fatigue among flight crews is influenced by several human factors, including extended duty hours, irregular shift patterns, and disruptions to circadian rhythms. These factors are known to impair cognitive performance, slow reaction times, and hinder decision-making, ultimately posing significant risks to flight safety (Mallis et al., 2023 p. 310; Li et al., 2023). Despite the implementation of regulatory frameworks such as Flight Duty Time Limitations (FTL) and Fatigue Risk Management Systems (FRMS), the challenge of managing fatigue effectively persists (Sprajcer et al., 2022, p. 1; Maisey et al., 2022, p. 408).

The importance of addressing crew fatigue in aviation cannot be overstated. Fatigue is one of the leading contributors to human error in flight operations, with studies showing that it accounts for a significant portion of aviation incidents and accidents (Bourgeois-Bougrine, 2020, p. 1). With flight crew members operating in highly demanding environments, often across different time zones and under varying environmental conditions, managing fatigue is critical to maintaining both the mental and physical performance required for safe operations. Effective fatigue management not only enhances crew safety but also improves overall operational performance, reducing the likelihood of errors that could compromise passenger safety or lead to costly operational disruptions.

FRMS has been adopted worldwide as a tool to mitigate fatigue risks by incorporating continuous monitoring and control mechanisms (Bérastégui & Nyssen, 2022). While these systems have contributed to fatigue management, concerns have been raised about their ability to predict fatigue accurately and manage the complex nature of fatigue-related risks, particularly for long-haul and ultra-long-range flights (Signal et al., 2024). Existing systems often fall short in addressing the multidimensional factors of fatigue, which include both physiological and operational aspects (Mannawaduge et al., 2024, p.75). For instance, individual variability in fatigue susceptibility, workload demands, and environmental conditions are not always adequately captured by current fatigue models, highlighting the need for more sophisticated, data-driven approaches.

Moreover, the economic impact of fatigue in aviation extends beyond safety concerns. Fatigue-related incidents lead to flight delays, cancellations, and operational inefficiencies that can result in significant financial losses for airlines. Addressing fatigue through effective management strategies can thus reduce operational costs, improve crew well-being, and contribute to the financial stability of aviation organizations. Regulatory bodies like the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA) have recognized the importance of fatigue management and continue to evolve regulations aimed at mitigating these risks. However, the effectiveness of these regulatory measures is contingent on their ability to account for the complexity of operational fatigue.

Despite these efforts, fatigue-related incidents continue to threaten aviation safety. Research suggests that many fatigue prediction models fail to capture the complexity of operational, environmental, and human factors that contribute to fatigue (Wilson et al., 2024; Rodrigues et al., 2023, p. 1). This calls for a more comprehensive approach to fatigue management that prioritizes the key contributing factors and offers strategic interventions. Evaluating and prioritizing these strategies is crucial to improving safety outcomes. One promising method for tackling this complexity is the Fuzzy DEMATEL approach, which helps identify key factors and determine their causal relationships, offering a more holistic understanding of the fatigue management landscape (Huang et al., 2023, p. 2).

This study aims to evaluate and prioritize crew fatigue management strategies in aviation using the Fuzzy DEMATEL method. By applying this methodology, we seek to identify the most critical fatigue factors, analyze the causal relationships among fatigue management strategies, and rank these strategies based on their relative importance and influence on crew safety and performance. In doing so, this research addresses the following key questions:

- What are the most critical factors contributing to crew fatigue in aviation?
- How do different fatigue management strategies interrelate and influence each other?
- Which fatigue management strategies should be prioritized to improve crew safety and operational performance?

This study is expected to make a significant contribution to the aviation industry by providing a structured approach to analyzing and prioritizing fatigue management strategies. The Fuzzy DEMATEL approach enables a deeper understanding of the relationships between these strategies, helping aviation decision-makers implement more targeted and effective interventions (Bongo & Seva, 2023, p.15). In turn, this will enhance crew safety, reduce fatigue-related incidents, and provide insights for regulatory bodies to refine FRMS frameworks (Mizrak & Akkartal, 2024). By prioritizing the most influential strategies, the industry can move toward more effective fatigue risk management, ultimately improving the working conditions for flight crews and enhancing overall aviation safety.

Theoretical Background

Crew Fatigue in Aviation

Crew fatigue is a widespread issue in aviation, affecting both short-haul and long-haul operations. Fatigue in aviation personnel is primarily caused by long working hours, irregular shift patterns, and disruptions to natural circadian rhythms (Mallis et al., 2023). These factors impair the cognitive performance of pilots and crew members, reducing their ability to make quick decisions, react to emergency situations, and maintain alertness during flight operations. Research has consistently shown that fatigue negatively affects flight safety, with studies linking it to reduced situational awareness and increased error rates (Rodrigues et al., 2023). Moreover, cognitive fatigue not only impacts flight performance but also increases the risk of accidents during takeoff, landing, and mid-flight tasks (Quental et al., 2021, p. 16). Studies have highlighted that fatigue is particularly problematic in short-haul flights due to the frequent takeoffs and landings, requiring constant high levels of attention and decision-making (Bourgeois-Bougrine et al., 2018, p. 177).

Fatigue is not only a safety concern but also a significant operational issue. Pilots and crew members who experience high levels of fatigue are less efficient in performing routine tasks, leading to delays and increased operational costs (Sprajcer et al., 2022). Fatigue-related performance decrements also contribute to more subtle operational inefficiencies, such as slower reaction times during flight management and less precise communication with ground control. As aviation moves towards more technologically advanced systems, including automation and AI-assisted operations, the human factor of fatigue continues to be a weak link, as fatigued personnel may not fully capitalize on these systems' capabilities (Bendak & Rashid, 2020, p. 1). This interplay between human fatigue and advanced aviation technology further exacerbates the risk of human error, necessitating stronger fatigue mitigation strategies. Additionally, fatigue has been shown to contribute to stress and burnout among aviation personnel, further impacting performance and job satisfaction (Göker, 2018).

In response to these concerns, several regulatory frameworks have been introduced to mitigate fatigue among aviation personnel. One of the key frameworks is the Flight Duty Time Limitations (FTL) regulation, which sets restrictions on flight hours and mandates rest periods to reduce the risk of fatigue. The International Civil Aviation Organization (ICAO) and various national aviation authorities, including the Federal Aviation Administration (FAA) and European Union Aviation Safety Agency (EASA), have implemented FTL standards to ensure that pilots and crew members receive adequate rest before, during, and after flights (Efthymiou et al., 2021, p. 280). These frameworks aim to reduce the risk of fatigue-related incidents by placing clear limits on the number of consecutive hours crew members can work and by mandating minimum rest periods. However, these regulations are often criticized for their lack of flexibility and for not accounting for individual variations in fatigue tolerance, as well as other operational factors such as time zone changes and flight complexity (Signal et al., 2024). Research has found that fatigue mitigation policies are often inconsistently implemented across airlines, which can undermine their effectiveness (Kandera et al., 2019, p. 278).

While FTL regulations have undoubtedly played a role in improving safety, they are not without limitations. Research has shown that ultra-long-haul flights present unique challenges that FTL regulations alone cannot fully address (Sun et al., 2023, p. 3). Fatigue risks are more pronounced on these flights due to extended flight times and the physical and psychological demands placed on crew members. Additionally, environmental factors, such as cabin pressure, temperature fluctuations, and noise levels, can exacerbate fatigue, further complicating the management of fatigue in these settings (Rodrigues et al., 2023). Airlines operating in different regions or under varying operational conditions often adopt different fatigue management practices, leading to inconsistencies in the application and effectiveness of FTL regulations (Bérastégui & Nyssen, 2022). Moreover, studies conducted in the aftermath of the COVID-19 pandemic have indicated that fatigue risk was significantly heightened due to altered work schedules and operational adjustments during the crisis (Sun et al., 2022).

Fatigue remains a critical factor in aviation safety despite these regulatory efforts. Research highlights that even with FTL regulations in place, the effectiveness of fatigue management varies significantly across different airlines and regions (Bendak & Rashid, 2020). Studies suggest that fatigue management systems must account for individual differences in fatigue susceptibility, the operational demands of specific flight routes, and the impact of environmental factors such as weather and cabin conditions (Rodrigues et al., 2023). For instance, pilots flying across multiple time zones may experience circadian rhythm disruptions that are not fully addressed by FTL standards, leading to persistent fatigue even after mandated rest periods. Consequently, there is a growing need to integrate more sophisticated and personalized approaches to fatigue management in aviation. In this context, fatigue risk management systems (FRMS) that incorporate predictive modeling and real-time monitoring have been proposed to bridge the gaps left by traditional FTL regulations (Sun et al., 2023).

One of the primary challenges in addressing crew fatigue is the difficulty in measuring and predicting fatigue levels accurately. Current fatigue models often rely on biomathematical predictions, which, while useful, do not fully capture the complexities of human fatigue (Wilson et al., 2024). These models typically focus on sleep and work schedules, failing to account for the multitude of factors that contribute to fatigue, such as individual variability in sleep needs, the quality of rest, and non-work-related stressors. Fatigue is influenced by numerous factors, including workload, sleep quality, and personal stress levels, making it difficult to create a one-size-fits-all solution. As a result, many aviation organizations are exploring new approaches, such as real-time monitoring of fatigue indicators, to supplement existing regulatory frameworks. Wearable technology and data-driven models that assess real-time physiological and cognitive states are emerging as valuable tools in fatigue management (Mallis et al., 2023). These innovations allow for a more dynamic approach to fatigue management, enabling tailored interventions based on the specific needs and conditions of individual crew members. For instance, fatigue monitoring systems using EEG-based technology and other biometric markers have been developed to detect early signs of fatigue and provide real-time alerts (Kandera et al., 2019).

In conclusion, while significant progress has been made in addressing crew fatigue through regulatory measures, challenges remain in ensuring comprehensive and effective fatigue management in aviation. The development of more advanced fatigue prediction models and personalized management strategies is necessary to mitigate the risks associated with crew fatigue and enhance overall flight safety. Future efforts should focus on integrating real-time data, individual variability, and environmental factors into fatigue management frameworks to provide a more holistic approach to mitigating fatigue risks in aviation. In addition, leveraging advancements in AI and machine learning to enhance predictive models and fatigue assessment tools may provide more proactive solutions for fatigue management (Göker, 2018). As fatigue remains a persistent challenge in aviation safety, a multi-faceted approach combining regulatory oversight, technological advancements, and organizational commitment is essential to ensure the well-being of crew members and the safety of flight operations.

Fatigue Risk Management Systems (FRMS)

Fatigue Risk Management Systems (FRMS) are comprehensive frameworks designed to address the limitations of traditional regulatory approaches, such as Flight Duty Time Limitations (FTL), by providing a more flexible and data-driven method for managing crew fatigue. Unlike prescriptive regulatory frameworks that apply blanket rules across all operations, FRMS allows organizations to tailor their fatigue management strategies to specific operational demands, utilizing real-time data and predictive analytics to assess and mitigate risks more effectively (Bourgeois-Bougrine, 2020). This shift towards data-driven fatigue management has been increasingly supported by research that emphasizes the need for proactive rather than reactive fatigue mitigation strategies (Cabon et al., 2012, p. 41). FRMS integrates various components, including continuous monitoring, fatigue reporting systems, and feedback loops, to ensure that fatigue is managed proactively rather than reactively. The flexibility of FRMS makes it particularly valuable for complex aviation operations, such as ultra-long-haul flights and multi-leg schedules, where traditional regulations may not adequately address the nuances of fatigue (Rodrigues et al., 2023). Additionally, new advancements in FRMS methodologies suggest that integrating pilot sleep monitoring with physiological and cognitive tracking can further enhance fatigue mitigation strategies (Xiao et al., 2024).

A key feature of FRMS is its reliance on continuous fatigue monitoring and risk assessments, which use both objective and subjective data to provide a comprehensive picture of crew fatigue levels (Maisey et al., 2022). Objective data, such as biomathematical fatigue models and physiological indicators, are combined with subjective assessments from crew members to forecast fatigue risks. These models consider factors like time of day, duration of sleep, and the cumulative effects of multiple work shifts, allowing airlines to anticipate when fatigue is likely to become a safety issue (Rodrigues et al., 2023). Emerging research suggests that integrating human digital twin (HDT) technology into FRMS can further refine fatigue risk predictions by simulating individual fatigue responses based on real-time physiological data (You et al., 2025, p. 10). For example, biomathematical models such as the Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE) model and the Three-Process Model of Alertness (TPMA) have been widely used to predict performance declines related to fatigue (Wilson et al., 2024). By integrating these predictive models with real-time data, FRMS can identify when crew members are likely to experience fatigue, enabling airlines to adjust flight schedules, implement additional rest breaks, or modify flight operations accordingly. The effectiveness of these models has been further validated in various industries beyond aviation, such as human-robot collaborative assembly and grain farming, demonstrating their broad applicability in fatigue risk assessment (Dyall et al., 2025, p. 6; You et al., 2025).

In addition to monitoring and predictive modeling, FRMS incorporates a range of fatigue mitigation strategies tailored to the specific needs of the organization. These strategies range from simple operational adjustments, like reworking crew schedules to allow for more rest, to more advanced interventions that incorporate technological solutions. For instance, pilot sleep monitoring validation experiments have shown that personalized fatigue mitigation plans based on individual circadian rhythms can significantly enhance flight crew alertness (Xiao et al., 2024). Fatigue-monitoring technologies, such as wearable devices that track sleep patterns, heart rate variability, and cognitive performance, are increasingly being adopted to provide real-time insights into crew fatigue (Bérastégui & Nyssen, 2022). These technologies can detect early signs of fatigue, prompting immediate corrective actions such as scheduling changes or providing in-flight rest opportunities. Moreover, research on human circadian rhythmicity has revealed that optimizing in-flight lighting and cabin environments to align with natural sleep cycles can enhance crew recovery during long-haul flights (Mallis et al., 2023). For long-haul operations, where the risk of fatigue is exacerbated by time zone shifts and extended duty periods, airlines have introduced in-flight rest facilities, optimized cabin lighting to align with circadian rhythms, and sleep-promoting interventions, such as improved sleep environments during layovers (Signal et al., 2024). Such interventions are critical for maintaining performance levels during long flights and reducing the cumulative effects of fatigue over multiple flight segments.

Despite the technological and procedural advancements brought about by FRMS, its effectiveness is heavily influenced by the organizational culture within which it is implemented. Research has shown that airlines with a strong safety culture, where open communication about fatigue is encouraged and reporting is free of stigma, are more likely to successfully integrate FRMS into their operations (Sprajcer et al., 2022). In these organizations, pilots and crew members feel empowered to report fatigue-related issues without fear of retribution, leading to more accurate data collection and more effective fatigue management interventions. Conversely, in organizations with weaker safety cultures, crew members may be reluctant to report fatigue due to concerns about job security or disciplinary actions, thereby limiting the effectiveness of the system (Bourgeois-Bougrine, 2020). This highlights the need for targeted policy interventions that foster a culture of transparency in fatigue reporting, as research indicates that underreporting of fatigue significantly undermines FRMS effectiveness (Cabon et al., 2012). The success of FRMS also depends on the extent to which airlines are willing to invest in the necessary resources, such as training, technology, and ongoing evaluations, to ensure that the system is both operationally feasible and scientifically sound.

Another challenge facing the implementation of FRMS is the variability in how different airlines adopt and enforce fatigue management practices. While some airlines have fully embraced the flexibility and data-driven nature of FRMS, others may struggle with implementation due to resource constraints or a lack of expertise in fatigue science (Sprajcer et al., 2022). Additionally, there is variability in the regulatory oversight of FRMS across different jurisdictions, with some regulatory bodies providing more detailed guidance and support for implementing FRMS than others (Efthymiou et al., 2021). For example, research on fatigue risk management in French regional airlines has shown that the effectiveness of FRMS depends on the regulatory support and operational adaptability of each airline, leading to disparities in safety outcomes (Cabon et al., 2012). This inconsistency can lead to disparities in the effectiveness of fatigue management strategies across the global aviation industry, with some airlines more adept at managing fatigue risks than others. Furthermore, the long-term success of FRMS depends on continuous improvement, as fatigue science evolves and new technologies emerge. Studies suggest that integrating AI-driven automation into FRMS could enhance its adaptability by continuously updating fatigue models based on real-time operational data (You et al., 2025). Airlines must remain committed to updating their FRMS protocols and integrating the latest research findings to ensure that their fatigue management practices remain at the cutting edge (Bourgeois-Bougrine, 2020).

Overall, FRMS represents a significant advancement in fatigue management by offering a more dynamic and data-driven approach to mitigating fatigue risks. However, the success of FRMS hinges on several factors, including the strength of an organization's safety culture, its willingness to invest in fatigue management resources, and the support it receives from regulatory bodies. The application of FRMS beyond aviation, in fields such as human-robot collaborative work and agriculture, underscores its broader relevance and potential for cross-industry learning (Dyall et al., 2025; You et al., 2025). As aviation operations become more complex and flight durations increase, the importance of robust, flexible, and scientifically sound fatigue management systems will only grow. The aviation industry must continue to refine and enhance FRMS practices to address emerging challenges and ensure the safety and well-being of crew members and passengers alike. Future efforts should focus on integrating real-time biometric monitoring, AI-enhanced predictive analytics, and industry-wide standardization to create a more effective and universally adopted FRMS framework (Xiao et al., 2024; You et al., 2025).

Fuzzy Decision-Making Models

Fuzzy decision-making models, including the Fuzzy DEMATEL (Decision-Making Trial and Evaluation Laboratory) method, have gained widespread application in various industries, including aviation, to address complex problems characterized by uncertainty and interrelated factors. Fuzzy DEMATEL is particularly well-suited for evaluating and prioritizing strategies because it allows for the analysis of causal relationships between factors, providing a structured approach to decision-making in uncertain environments (Chang et al., 2011, p. 1851). By incorporating fuzzy logic, the method can handle ambiguity and imprecise data, making it an effective tool for evaluating fatigue management strategies where human factors and operational variables are difficult to quantify (Huang et al., 2023).

The Fuzzy DEMATEL method has been applied in several aviation-related studies to prioritize factors influencing safety, efficiency, and performance. For example, Bongo & Seva (2023) used the method to evaluate the performance-shaping factors of air traffic controllers, identifying key elements that influence controller workload and decision-making capabilities. Similarly, Huang et al. (2023) applied Fuzzy DEMATEL to explore the relationships between resilience factors at international airports, providing insights into how these factors contribute to overall safety and operational resilience. These studies demonstrate the versatility of Fuzzy DEMATEL in handling complex, multi-faceted problems in aviation.

The application of Fuzzy DEMATEL in the context of crew fatigue management is particularly promising because it allows for the identification of the most critical factors contributing to fatigue and their interdependencies. Unlike traditional decision-making models that treat factors as independent, Fuzzy DEMATEL recognizes that fatigue risk factors are often interrelated, with some factors influencing others in complex ways (Mizrak & Akkartal, 2024). By mapping these relationships, the model provides a clearer understanding of how different fatigue management strategies interact, enabling more effective prioritization of interventions.

One of the key advantages of Fuzzy DEMATEL is its ability to provide a ranking of factors based on their influence and importance, helping decision-makers focus on the strategies that will have the greatest impact on reducing fatigue risks (Chang et al., 2011). This is particularly useful in the aviation industry, where resources for fatigue management are often limited, and it is essential to allocate them efficiently. By using Fuzzy DEMATEL, airlines can prioritize the most critical fatigue management strategies and ensure that they are implemented effectively.

In conclusion, the Fuzzy DEMATEL approach offers a powerful tool for evaluating and prioritizing fatigue management strategies in aviation. Its ability to handle uncertainty and complex interrelationships between factors makes it particularly well-suited for addressing the challenges of crew fatigue, providing a more structured and data-driven approach to decision-making in this critical area of aviation safety.

Methodology

Research Design

This study uses a mixed-methods approach that incorporates both qualitative and quantitative components to evaluate and prioritize crew fatigue management strategies in aviation. The qualitative component involves structured interviews and surveys to gather expert insights on the factors influencing fatigue. The quantitative component utilizes the Fuzzy DEMATEL method to analyze the causal relationships and interdependencies among these fatigue-related factors. The Fuzzy DEMATEL approach is chosen because it allows for a detailed exploration of complex interrelationships between factors, which is crucial for understanding the multifaceted nature of fatigue in aviation. Fuzzy logic is particularly useful when dealing with human factors, where data may be uncertain or imprecise. By using this method, the study identifies the most influential factors and maps the relationships between them, enabling a structured prioritization of fatigue management strategies based on expert input.

Data Collection

The data collection involved gathering information from 12 experts in the aviation industry, selected for their experience in managing fatigue and their expertise in operational and human factors in aviation. The expert panel includes senior pilots, flight operations managers, aviation HR professionals, safety managers, and fatigue risk management specialists, ensuring a diverse set of perspectives. Before conducting the interviews, informed consent was obtained from all participants. Each expert was informed about the study's purpose, methodology, and how their input would be used. Consent was also documented before beginning each interview. The structured interviews, lasting approximately 45 to 60 minutes each, were conducted either in person or via video calls, depending on the expert's location and preference. The interviews focused on two types of questions**:**

1. Open-ended qualitative questions designed to elicit in-depth responses about the causes and effects of crew fatigue and the effectiveness of current fatigue management strategies.
2. Quantitative questions for the Fuzzy DEMATEL analysis, where experts rated the degree of influence between specific fatigue-related factors using a scale of 0 (no influence) to 4 (very high influence).

The content of the interviews covered several key topics:

- Identification of key factors contributing to crew fatigue, such as flight duration, workload, environmental conditions, and scheduling practices.
- Evaluation of the interrelationships between these factors, asking experts to assess how one factor influences another.
- Assessment of fatigue management strategies currently in place, such as real-time monitoring, rest policies, and crew scheduling adjustments.
- Prioritization of fatigue mitigation strategies, where experts were asked to rank various approaches based on their perceived effectiveness.

The quantitative data from these interviews, particularly the pairwise comparisons of fatigue-related factors, were used in the Fuzzy DEMATEL analysis to create a detailed matrix of relationships and influences. The qualitative data provided richer context, helping to interpret the findings and understand the broader implications of the relationships identified. Table 1 illustrates information about the experts.

Table 1. Expert Details

Expert ID	Position	Experience (Years)
Expert 1	Senior Pilot	20
Expert 2	Aviation Safety Manager	18
Expert 3	Human Factors Specialist	15
Expert 4	Flight Operations Manager	22
Expert 5	Airline Crew Scheduling Coordinator	10

Expert 6	Aviation Psychologist	12
Expert 7	Senior Flight Instructor	25
Expert 8	Fatigue Risk Management System (FRMS) Expert	14
Expert 9	Airline Operations Director	17
Expert 10	Crew Resource Management (CRM) Trainer	9
Expert 11	Aviation Regulatory Authority Official	21
Expert 12	Airline Human Resources Director	19

Each expert was selected for their significant experience and diverse roles within aviation, ensuring that the study benefited from a comprehensive understanding of both operational and human factors related to fatigue management.

Fuzzy DEMATEL Method

The Fuzzy DEMATEL method is a multi-criteria decision-making tool that uses fuzzy logic to handle uncertainty and imprecise information. It is particularly suited for analyzing complex systems where relationships between factors are not straightforward. This method is applied to map out and analyze the causal relationships among factors, in this case, factors contributing to crew fatigue in aviation. Fuzzy DEMATEL helps to identify the direct and indirect influences of these factors, enabling decision-makers to prioritize strategies more effectively. The steps involved in the Fuzzy DEMATEL process are outlined below, along with the equations used in each step (Tzeng & Huang, 2011).

Step 1: Define the Evaluation Factors

The first step in the Fuzzy DEMATEL method is identifying the key factors to be evaluated. These factors are the ones contributing to crew fatigue, such as flight duration, workload, environmental conditions, and rest opportunities. In this study, experts identified the most important factors influencing crew fatigue, which are then used for pairwise comparisons in the next steps.

Step 2: Construct the Direct-Relation Matrix

Once the factors are defined, the experts are asked to assess the degree of influence one factor has over another. This is done using a scale that ranges from 0 (No Influence) to 4 (Very High Influence), allowing for the construction of the Direct-Relation Matrix (D).

Let:

x_{ij} represent the influence of factor i on factor j as rated by the experts.

The Direct-Relation Matrix (D) for n factors is:

$$\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nn} \end{bmatrix} \tag{1}$$

Each x_{ij} value is derived from expert ratings and reflects the direct influence factor i has on factor j.

Step 3: Normalize the Direct-Relation Matrix

Next, the direct-relation matrix D is normalized to create a matrix with values between 0 and 1. The normalization process ensures that all elements of the matrix fall within this range, making it easier to compute the total influence of each factor.

The normalization process is as follows:

$$S = \frac{D}{\max\left(\sum_{i=1}^{n} x_{ij}, \sum_{j=1}^{n} x_{ij}\right)} \tag{2}$$

Where:

$\max\left(\sum_{i=1}^{n} x_{ij}, \sum_{j=1}^{n} x_{ij}\right)$ is the maximum row sum or column sum of matrix D.

This produces the Normalized Direct-Relation Matrix (S), with elements between 0 and 1.

Step 4: Calculate the Total-Relation Matrix

The Total-Relation Matrix (T) is calculated to represent both the direct and indirect influences of each factor on every other factor. This matrix is obtained by solving the following equation:

$$\mathrm{T} = \mathrm{S} \times (\mathrm{I} - \mathrm{S})^{-1} \tag{3}$$

Where:

I is the identity matrix.

$(I - S)^{-1}$ is the inverse of the matrix $(I - S)$.

The Total-Relation Matrix T includes the total impact of each factor, including both direct and indirect effects.

Step 5: Calculate the Row and Column Sums

From the Total-Relation Matrix T, the sum of each row and the sum of each column are computed. These sums help identify which factors are primarily "causal" and which are primarily "affected."

Row sum (D_i) : Represents the total influence that factor i exerts on other factors (direct and indirect).

$$D_i = \sum_{j=1}^{n} t_{ij} \tag{4}$$

Column sum $\left(R_j\right)$: Represents the total influence received by factor j from all other factors (direct and indirect).

$$R_j = \sum_{i=1}^{n} t_{ij} \tag{5}$$

Step 6: Determine the Prominence and Net Effect
The prominence of each factor is calculated as the sum of its row and column sums ($D_i + R_j$), indicating how critical the factor is within the system. The net effect of each factor is the difference between the row and column sums ($D_i - R_j$), showing whether the factor is primarily a cause or an effect in the system.

Prominence:

$$D_i + R_j \tag{6}$$

Net Effect:

$$D_i - R_j \tag{7}$$

If $D_i - R_j > 0$, the factor is considered to be primarily a "cause."

If $D_i - R_j < 0$, the factor is considered to be primarily an "effect."

Step 7: Construct the Causal Diagram

The results of the prominence and net effect calculations are used to create a causal diagram. This diagram visually maps the relationships between the factors, showing which factors are the most influential (causes) and which are primarily affected (effects). Factors with a positive net effect are placed in the cause group, while those with a negative net effect are in the effect group. The prominence determines the relative importance of each factor in the overall system.

Criteria and Factor for Evaluation

In this study, several key factors were identified as influencing crew fatigue management strategies in aviation. These factors were defined based on both existing literature and expert input, and they cover operational, environmental, and human-related aspects of fatigue. Each factor plays a significant role in determining the effectiveness of fatigue management strategies and must be carefully evaluated for its direct and indirect impact on crew performance. Table 2 demonstrates the criteria, their influence on fatigue and sources.

Table 2. Criteria for Evaluation

Criteria	Description	Influence on Fatigue	References
Workload	Physical, cognitive, and emotional demands on crew during flight operations.	High workload accelerates fatigue due to increased mental and physical strain.	Mallis et al. (2023), Rodrigues et al. (2023)
Flight Duration	Length of flight duty, including pre-flight and post-flight operations.	Longer flights lead to cumulative	Signal et al. (2024),

		fatigue, impacting alertness and decision-making.	Quental et al. (2021)
Rest Schedules	Timing and duration of rest periods provided to crew members.	Effective rest schedules reduce fatigue buildup; poorly timed or insufficient rest increases fatigue risks.	Bérastégui & Nyssen (2022), Maisey et al. (2022)
Environmental Conditions	Cabin pressure, temperature, lighting, and noise levels during flight.	Suboptimal conditions exacerbate fatigue, particularly over long-haul flights.	Rodrigues et al. (2023), Signal et al. (2024)
Monitoring Technologies	Tools and systems used to track fatigue levels in real-time (e.g., wearable devices, software models).	Real-time monitoring enhances fatigue risk assessments and supports proactive management.	Maisey et al. (2022), Wilson et al. (2024)
Crew Scheduling Practices	Policies and methods used to assign shifts and flight duties.	Effective scheduling balances duty and rest periods; poor scheduling leads to cumulative fatigue.	Sprajcer et al. (2022), Bendak & Rashid (2020)
Cumulative Fatigue	Fatigue buildup over time due to successive flights or extended duty periods.	Cumulative fatigue severely impacts crew performance over long-haul flights and back-to-back shifts.	Bourgeois-Bougrine (2020), Sun et al. (2023)
Personal Factors	Individual circumstances, such as sleep quality, stress, and health.	Personal factors can exacerbate fatigue, making it important to consider individual crew differences.	Wilson et al. (2024), Mallis et al. (2023)

Software and Tools

For the analysis of expert data using the Fuzzy DEMATEL method, the study primarily employed MATLAB and Excel. MATLAB was chosen for its advanced matrix-handling capabilities and its ability to implement the Fuzzy DEMATEL algorithm, including the construction of the Direct-Relation Matrix, normalization, and calculation of the Total-Relation Matrix. MATLAB's powerful computational tools were essential for performing complex matrix operations, such as inversions and multiplications, necessary for DEMATEL. In addition to MATLAB, Microsoft Excel was used for initial data entry and organizing the expert ratings. Excel served as a convenient platform for recording pairwise comparisons from the experts and conducting preliminary calculations, such as averaging scores and preparing the Direct-Relation Matrix before the advanced analysis in MATLAB. This combination of tools allowed for seamless data processing, ensuring the accurate evaluation of causal relationships among fatigue management factors.

Results

Expert Feedback and Evaluation

The experts provided valuable insights into fatigue management strategies, focusing on five main factors: workload, flight duration, rest schedules, environmental conditions, and monitoring technologies. These factors were assessed for their contributions to crew fatigue. The experts rated workload and flight duration as the most critical contributors to fatigue, especially during long-haul flights. They also stressed the importance of well-designed rest schedules and the use of real-time monitoring technologies to track fatigue levels and mitigate risks. This expert input guided the subsequent Fuzzy DEMATEL analysis to quantify the relationships and dependencies between these strategies.

Fuzzy DEMATEL Results

The Fuzzy DEMATEL analysis revealed both the direct and indirect effects of fatigue management strategies on each other. The Total-Relation Matrix combines these effects and provides insight into which factors are causes (influential drivers) and which are effects (dependent on other factors).

Table 3. Total-Relation Matrix

Factors	Workload	Flight Duration	Rest Schedules	Environmental Conditions	Monitoring Technologies
Workload	0.000	3.056	4.012	2.211	3.025
Flight Duration	3.152	0.000	3.221	3.045	2.158
Rest Schedules	2.253	2.127	0.000	3.045	4.102
Environmental Conditions	1.315	2.143	3.101	0.000	2.121
Monitoring Technologies	3.025	4.123	3.134	2.112	0.000

The Total-Relation Matrix shows that workload and flight duration exert the highest influence on other factors. Monitoring technologies also play a balanced role; both influencing and being influenced by other strategies.

Prioritization of Strategies

The row and column sums of the Total-Relation Matrix allow for the calculation of Prominence and Net Effect for each factor, which helps in ranking the strategies. Table 4 gives the Prominence and Net Effect values for each factor.

Table 4. Prominence and Net Effect Values

Factors	Prominence (D_i + R_j)	Net Effect (D_i - R_j)
Workload	12.504	1.231
Flight Duration	11.703	0.932
Rest Schedules	10.578	-0.722
Environmental Conditions	8.725	-1.065
Monitoring Technologies	12.543	-0.376

- Prominence represents the overall importance of each factor in the system. A higher prominence indicates that the factor plays a more central role.
- Net Effect differentiates whether a factor is primarily a cause (positive value) or an effect (negative value).

From the Net Effect values, we observe that workload and flight duration are causal factors, meaning they have a strong influence on other strategies. Rest schedules and environmental conditions, on the other hand, are effects, indicating that they are more dependent on improvements in other areas.

Based on the Prominence and Net Effect values, fatigue management strategies are ranked. Table 5 shows the details.

Table 5. Prominence and Net Effect Values

Rank	Strategy	Prominence (D_i + R_j)	Net Effect (D_i - R_j)
1	Workload Management	12.504	1.231
2	Monitoring Technologies	12.543	-0.376
3	Flight Duration Control	11.703	0.932
4	Rest Schedules	10.578	-0.722
5	Environmental Conditions	8.725	-1.065

The highest-ranked strategy is workload management, indicating that controlling workload has the most significant impact on managing crew fatigue. Monitoring technologies come next, playing a dual role of influencing and being influenced by other factors. Flight duration control is also critical, particularly for long-haul operations. Finally, while rest schedules and environmental conditions are essential for managing fatigue, they are more dependent on improvements in workload and flight duration. These findings suggest that prioritizing workload management, monitoring technologies, and flight duration control will provide the most effective results in reducing crew fatigue and enhancing operational safety.

Figure 1 presents the Causal Diagram of Crew Fatigue Management Factors based on the results of the Fuzzy DEMATEL analysis.

The diagram illustrates the key factors contributing to crew fatigue, highlighting the direct and indirect relationships between these factors. Workload emerges as a central factor, exerting influence on multiple other variables, including flight duration, rest schedules, and environmental conditions. The arrows represent the directional influence of one factor on another, with workload and flight duration playing pivotal roles in driving changes in rest schedules and contributing to cumulative fatigue.

Monitoring technologies and crew scheduling are positioned as key tools to mitigate fatigue, with monitoring technologies influencing crew scheduling and environmental conditions.

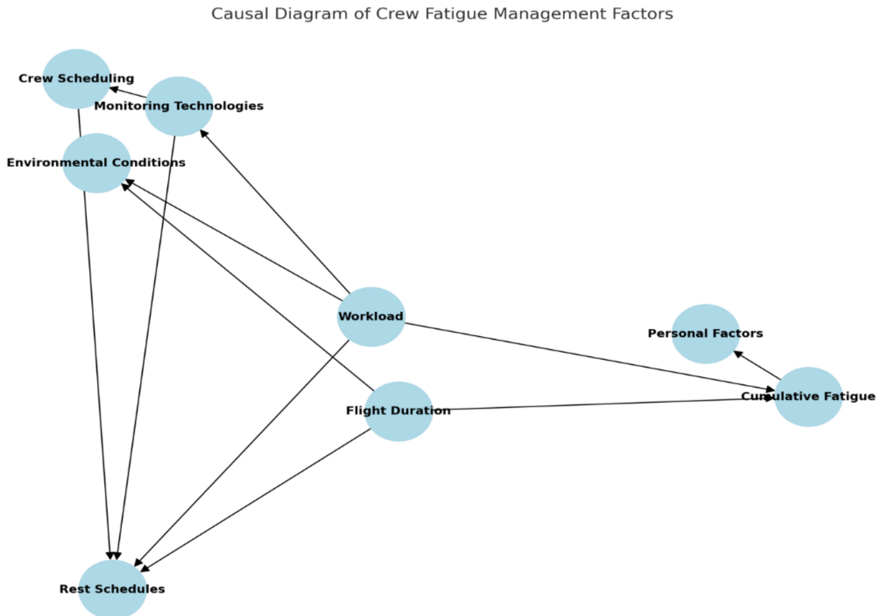

Figure 1. Causal Diagram of Crew Fatigue Management Factors

The personal factors and cumulative fatigue relationship underscores the importance of individual variability in fatigue susceptibility, which further impacts overall fatigue levels. Overall, the diagram captures the complex interdependencies in crew fatigue management, demonstrating that addressing workload and flight duration is likely to have widespread effects on improving crew safety and performance.

Discussions

Implications of Findings

The findings from this study provide critical insights for aviation companies and crew management teams seeking to mitigate the risks of crew fatigue. The identification of workload management as the most significant factor highlights the need for aviation companies to prioritize strategies that reduce cognitive and physical strain on crew members during flight operations. Managing workload effectively can prevent the accumulation of fatigue, which is often exacerbated by high-demand tasks, particularly in complex and stressful flight environments. By balancing workloads through improved task allocation, crew rotation, and enhanced in-flight decision support systems, airlines can reduce fatigue-related errors and improve overall safety and performance (Rodrigues et al., 2023). This implies the need for airlines to evaluate current practices and make necessary adjustments, such as optimizing duty schedules and ensuring adequate distribution of tasks among crew members to avoid overloading any individual.

Furthermore, effective workload management should extend beyond flight operations to include ground operations and administrative duties that also contribute to crew fatigue. Aviation companies can benefit from adopting comprehensive Fatigue Risk Management Systems (FRMS) that not only monitor in-flight workloads but also consider the cumulative impact of pre- and post-flight duties. Such systems could automate the process of adjusting workloads in real-time, factoring in unexpected delays or operational changes, further minimizing fatigue risks.

Monitoring technologies, which ranked second in importance, offer a practical tool for real-time fatigue assessment. These technologies, such as wearable devices that track physiological indicators (e.g., heart rate variability, sleep quality, and alertness levels), can provide valuable data to inform decisions about crew rest and scheduling adjustments (Bérastégui & Nyssen, 2022). By continuously monitoring crew fatigue levels, airlines can proactively identify fatigue risks and intervene before they affect flight safety. Incorporating such systems into regular operations could lead to more dynamic and responsive fatigue management, allowing airlines to adapt schedules based on real-time fatigue indicators rather than relying solely on predefined rest periods. This offers an opportunity for airlines to move towards a more individualized approach to fatigue management, tailoring rest and work schedules to the specific needs of each crew member.

For example, monitoring technologies could alert crew members and operational teams when fatigue thresholds are reached, triggering rest breaks or adjustments to the crew's workload in real time. This is particularly useful in long-haul and ultra-long-haul operations, where fatigue levels can fluctuate unpredictably. In addition, data collected from monitoring technologies can be used for post-flight analysis, helping airlines refine their fatigue management strategies over time by identifying trends in crew fatigue and adjusting policies accordingly. As these technologies continue to evolve, the aviation industry can expect greater accuracy in predicting fatigue and more effective interventions to mitigate its effects.

The findings also suggest that flight duration control plays a vital role in fatigue management. Long-haul flights, in particular, pose a significant risk, as fatigue accumulates over extended duty periods. Aviation companies should explore strategies like crew augmentation for long-haul flights, ensuring that crew members receive sufficient rest during flights to maintain performance and safety standards. Crew augmentation, which involves increasing the number of crew members to allow for in-flight rest rotations, is a proven strategy for mitigating the effects of long flight durations on fatigue. This can be supplemented by optimizing flight schedules to ensure that crew members have adequate recovery time between long-haul assignments, reducing the likelihood of cumulative fatigue.

In addition to crew augmentation, strategic layovers can be an effective way to manage fatigue for long-haul operations. By scheduling layovers that provide sufficient rest and recovery time, airlines can ensure that crew members are fully rested before returning to duty. This is especially important for flights crossing multiple time zones, where circadian disruptions can exacerbate fatigue. Companies may also consider shortening flight legs or adjusting flight paths to avoid excessive flight durations where feasible.

In practice, focusing on these top-ranked strategies—workload management, monitoring technologies, and flight duration control—can lead to enhanced crew performance, reduced operational risk, and improved safety outcomes for both passengers and crew. These strategies offer a multi-faceted approach to fatigue management that addresses the root causes of fatigue while providing flexible, real-time solutions to mitigate its effects. For aviation companies, implementing these strategies requires an investment in technology and policy development, but the long-term benefits in terms of safety, crew well-being, and operational efficiency far outweigh the initial costs.

Comparison with Existing Literature

The results of this study align with much of the existing literature on crew fatigue management but also offer some unique insights. Previous research has consistently identified workload and flight duration as major contributors to crew fatigue, with studies emphasizing that extended duty periods and high cognitive demands can impair crew performance and elevate the risk of errors. For instance, Mallis et al. (2023) and Quental et al. (2021) underscore that long flight durations, particularly during complex flight operations, are linked to reduced alertness, slower reaction times, and diminished decision-making capacity. Bourgeois-Bougrine et al. (2018) further elaborate that short-haul flight crews, despite having shorter duty periods, also experience significant fatigue due to frequent takeoffs and landings, requiring continuous high-alert decision-making. This study confirms these findings, as workload and flight duration were identified as highly influential factors in both direct and indirect relationships within the fatigue management system. This reinforces the critical need for airlines to carefully manage crew workloads and regulate flight durations to mitigate fatigue and enhance operational safety.

However, the emphasis on monitoring technologies as a key factor in this study brings a more modern and data-driven perspective to fatigue management. While previous studies have acknowledged the potential of real-time fatigue monitoring systems, few have emphasized their central role in mitigating fatigue as effectively as the current study. Bérastégui & Nyssen (2022) explored the emerging potential of fatigue monitoring technologies, but this study goes further by ranking monitoring technologies second only to workload management in terms of their importance in managing fatigue. This is in line with Göker (2018), who highlighted the increasing reliance on biometric monitoring and wearable technology as a game-changer in fatigue detection, enabling preemptive interventions. This highlights a growing shift in the aviation industry toward proactive fatigue management through the use of technology. Real-time monitoring systems that assess physiological indicators (e.g., heart rate, alertness, sleep quality) allow airlines to adjust crew schedules dynamically, based on real-time fatigue data rather than static regulations, and this could potentially reshape the future of fatigue management in aviation.

The increasing integration of wearable technologies and other fatigue-tracking tools into fatigue risk management frameworks marks a significant evolution in how fatigue is addressed. While regulatory frameworks like Flight Duty Time Limitations (FTL) provide predefined rest periods, monitoring technologies offer the flexibility to identify fatigue risks in real-time, thus offering a more tailored and responsive solution. Bendak & Rashid (2020) emphasize that traditional fatigue mitigation approaches, while effective to an extent, lack adaptability to real-world operational demands, making real-time fatigue tracking systems a crucial advancement. This study's findings suggest that as these technologies evolve and become more widespread, they may surpass traditional methods in terms of effectiveness, paving the way for more individualized fatigue management solutions.

In contrast, environmental conditions—widely recognized in literature as a contributor to fatigue (Rodrigues et al., 2023)—were found to be less critical in this study. Factors such as noise levels, cabin pressure, and temperature, though influential, did not rank as high as workload or monitoring technologies. This could be due to the fact that environmental factors, while known to exacerbate fatigue, are inherently more difficult to control or predict compared to operational factors like workload or scheduling. Sun et al. (2023) found that while cabin conditions such as humidity and lighting influence crew fatigue levels, their impact is relatively minor compared to circadian misalignment and flight duty periods. For instance, while cabin conditions can be optimized to an extent (e.g., through better ventilation systems or noise reduction efforts), their direct influence on fatigue may not be as immediate or controllable as real-time adjustments to crew workload or rest opportunities.

Moreover, previous studies, such as those by Wilson et al. (2024), have acknowledged the importance of environmental conditions but often view them as secondary contributors to fatigue, working in conjunction with more dominant factors like workload and circadian disruptions. Sun et al. (2022) further highlight those pilots operating under pandemic-era flight exemptions reported increased fatigue primarily due to altered schedules and extended duty hours rather than environmental stressors. The current study's findings suggest a similar conclusion: operational control of fatigue, through direct management strategies like workload balancing, flight duration regulation, and the use of monitoring technologies, may have a more immediate and tangible impact on fatigue than environmental factors. While the aviation industry can continue to improve cabin environments, the most effective strategies for mitigating crew fatigue are likely to remain operational rather than environmental.

Additionally, this study extends beyond traditional approaches by providing a holistic understanding of interdependencies between fatigue factors using the Fuzzy DEMATEL method, which has not been widely applied in previous literature on aviation fatigue. This novel application allows for a more nuanced understanding of how these factors interact, offering a clear roadmap for prioritizing strategies. Unlike some earlier studies that treat fatigue factors in isolation, the current study identifies key causal relationships, revealing how managing one factor (such as workload) can positively influence others (such as rest schedules and flight duration). This approach aligns with Kandera et al. (2019), who stress the importance of viewing fatigue as a multi-dimensional issue requiring interconnected solutions rather than isolated interventions. This interconnected view reinforces the need for integrated fatigue management strategies that address the root causes of fatigue and their ripple effects throughout the system.

In conclusion, while this study confirms many established insights from the literature, such as the centrality of workload and flight duration in managing fatigue, it also introduces new perspectives, particularly in highlighting the growing importance of monitoring technologies and downplaying the relative influence of environmental conditions. The findings complement previous work by Bourgeois-Bougrine et al. (2018), who noted that effective fatigue mitigation depends not just on operational policies but also on how new technologies are integrated into fatigue risk management frameworks. These findings suggest that as technology advances, the aviation industry will increasingly shift toward more real-time, data-driven approaches to fatigue management, complementing or even surpassing traditional methods focused solely on operational scheduling and environmental control.

Challenges and Limitations

This study faced several challenges during the data collection and analysis phases. One of the primary challenges was ensuring consistency in expert opinions during the structured interviews and surveys. Given the subjective nature of expert assessments, variations in how different experts rated the influence of factors may have introduced some level of bias into the analysis. Additionally, the reliance on qualitative expert input, while valuable, meant that the analysis was influenced by the experiences and perspectives of a relatively small number of participants. A larger sample size of experts or the inclusion of quantitative fatigue data from actual flight operations could further validate the findings.

The use of Fuzzy DEMATEL also presents certain limitations in the context of aviation fatigue management. While this method effectively handles the complexity and interdependence of fatigue factors, it assumes that all factors can be accurately quantified and compared. However, fatigue is a multi-dimensional human factor, influenced by personal, environmental, and operational variables that may not be fully captured through pairwise comparisons alone. Additionally, Fuzzy DEMATEL relies heavily on expert judgment, which may not always align with real-world data or the experiences of frontline crew members.

Despite these limitations, Fuzzy DEMATEL proved to be a useful tool for identifying the most influential factors in crew fatigue management. Its ability to account for both direct and indirect relationships between factors offers valuable insights that more traditional decision-making models may overlook. However, future research could benefit from combining Fuzzy DEMATEL with other methods, such as real-time fatigue monitoring data or simulation models, to provide a more comprehensive understanding of fatigue dynamics in aviation.

Conclusion

This study highlighted the critical strategies for managing crew fatigue in aviation, with workload management, monitoring technologies, and flight duration control emerging as the most influential factors. Through the application of the Fuzzy DEMATEL analysis, it was demonstrated that managing crew workload effectively could have the most significant impact on reducing fatigue, as workload exerts considerable influence over other factors such as rest schedules and environmental conditions. This finding is especially important because it suggests that targeting workload can have a ripple effect, alleviating several secondary contributors to fatigue and enhancing overall crew well-being. Similarly, real-time monitoring technologies were identified as essential tools for assessing and mitigating fatigue in dynamic operational environments. These technologies enable airlines to adjust schedules and implement fatigue mitigation strategies based on real-time data, making fatigue management more responsive and individualized. Flight duration, particularly on long-haul routes, remains a key driver of cumulative fatigue, making it critical for airlines to carefully manage flight schedules and crew rotations to prevent fatigue from compromising safety and performance.

These findings offer a practical roadmap for aviation companies seeking to improve crew performance and safety by prioritizing these strategies in their fatigue management frameworks. By focusing on workload management, airlines can directly target one of the primary drivers of fatigue. At the same time, integrating monitoring technologies into regular operations can provide real-time data to optimize crew scheduling and rest periods. Additionally, effectively managing flight duration, particularly by ensuring adequate in-flight rest through strategies such as crew augmentation—can further reduce fatigue risks, especially for long-haul operations.

This study contributes to the growing body of knowledge on fatigue management in aviation by providing a structured, data-driven approach to prioritizing fatigue management strategies. The application of the Fuzzy DEMATEL method in this context is a novel contribution, offering a way to map and analyze the complex interrelationships between different fatigue factors. By using expert input to inform the analysis, the study provides actionable insights that aviation companies can implement to enhance their crew management practices. The identification of workload management and monitoring technologies as top priorities offers a clear focus for aviation managers looking to improve both crew well-being and operational safety. The findings also underscore the importance of integrating real-time fatigue monitoring into daily operations, providing practical solutions for mitigating fatigue risks before they escalate into safety concerns. By proactively addressing fatigue risks, airlines can improve safety, efficiency, and crew satisfaction, which are all crucial for long-term operational success.

Moreover, this study emphasizes the dynamic nature of fatigue, highlighting the need for flexible and adaptable management strategies. The results suggest that while regulatory frameworks like Flight Duty Time Limitations (FTL)provide a baseline for managing crew fatigue, they may be insufficient without the support of real-time monitoring and data-driven adjustments. The integration of monitoring technologies not only enables a more individualized approach but also allows airlines to refine their fatigue risk management systems over time, making operations more resilient to fatigue-related challenges.

While this study has shed light on the most critical strategies for managing crew fatigue, there are several areas that warrant further exploration. Future research could focus on integrating quantitative fatigue data from operational settings with expert assessments to create a more comprehensive model of fatigue risk management. This would allow researchers to validate the relationships identified in this study with real-world data, improving the accuracy and relevance of fatigue management frameworks. Studies could also investigate the long-term effectiveness of monitoring technologies, particularly how real-time fatigue assessments impact crew performance and safety outcomes over time. As monitoring technologies become more advanced, their potential to predict and prevent fatigue-related risks will likely increase, making them an essential component of modern fatigue management systems.

Additionally, exploring personal factors such as stress, health conditions, and individual variability in fatigue susceptibility could provide deeper insights into how to tailor fatigue management strategies to the specific needs of crew members. While this study focused on operational factors, personal factors also play a critical role in determining how fatigue affects performance, and addressing these factors could lead to more holistic fatigue management solutions.

Finally, future research could examine how emerging decision-making models, such as machine learning algorithms, could complement traditional approaches like Fuzzy DEMATEL in enhancing the predictive accuracy of fatigue management systems. Machine learning models, which can analyze large datasets and identify patterns in crew fatigue, could work alongside Fuzzy DEMATEL to provide even more detailed insights into the causes and effects of fatigue. This would further support the development of innovative, data-driven solutions for reducing fatigue-related risks in aviation, ultimately contributing to safer, more efficient flight operations and better crew well-being.

In conclusion, this study not only confirms the importance of workload management, monitoring technologies, and flight duration control but also paves the way for future innovations in fatigue management. By continuing to develop and refine these strategies, the aviation industry can create safer, more sustainable, and more efficient working conditions for flight crews, ensuring that fatigue risks are effectively mitigated at all stages of flight operations.

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