Research Article

Critical Connections: Enhancing Aviation Safety Through Network Analysis

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Abstract: The objective of this study is to explore the influence of human factors on aviation accidents across different aircraft types using Network Analysis. This research specifically analyses centrality metrics to pinpoint the most influential errors, providing a more detailed understanding of their impact on aviation safety, while prior studies have acknowledged the role of human factors. The study employed Network Analysis using Python's NetworkX library. A dataset derived from The National Transportation Safety Board (NTSB) aviation accident database is used. Bipartite networks were constructed for each aircraft type, with nodes representing accidents and human error categories and edges indicating their relationships. The analysis revealed that pilot error consistently showed the highest degree centrality across all aircraft types, indicating its frequent involvement in accidents. Closeness centrality further highlighted the central role of pilot error, showing its significant influence on the network. The findings emphasized the critical importance of addressing pilot errors to improve aviation safety. While crew errors and other human errors were less frequent, their presence in the data suggested that a comprehensive safety strategy must also consider these factors. The results of this study demonstrate that pilot error is the most influential human factor in aviation accidents across various aircraft types. By focusing on targeted interventions such as enhanced pilot training and stricter safety protocols, the aviation industry can significantly reduce accident rates.

Keywords: Aviation Safety, Human Factors, Network Analysis, Centrality Metrics

Kritik Bağlantılar: Ağ Analizi ile Havacılık Güvenliğini Artırmak

Özet: Bu çalışmanın amacı, Ağ Analizi kullanarak farklı uçak tiplerinde insan faktörlerinin havacılık kazalarına etkisini incelemektir. Bu araştırma, daha önceki çalışmaların insan faktörlerinin rolünü kabul etmesine rağmen, merkezilik ölçümlerini analiz ederek en etkili hataları belirleyip, bu hataların havacılık emniyeti üzerindeki etkisini daha ayrıntılı bir şekilde anlamayı hedeflemektedir. Çalışmada Python'un NetworkX kütüphanesi kullanılarak Ağ Analizi yapılmıştır. Amerikan Ulusal Ulaştırma Emniyeti Kurulu (NTSB) havacılık kazası veri tabanından elde edilen bir veri seti kullanılmıştır. Her uçak tipi için iki modlu ağlar oluşturulmuş, düğümler kazaları ve insan hatası kategorilerini temsil ederken, kenarlar bu ilişkileri göstermektedir. Analiz, pilot hatasının tüm uçak tiplerinde en yüksek derece merkeziliğine sahip olduğunu ve kazalarda sıkça yer aldığını ortaya koymuştur. Yakınlık merkeziliği, pilot hatasının ağ üzerindeki önemli etkisini vurgulayarak merkezi rolünü daha da öne çıkarmıştır. Bulgular, havacılık emniyetini arttırmak için pilot hatalarının ele alınmasının kritik önemini vurgulamaktadır. Uçuş ekibi hataları ve diğer insan hataları daha az sıklıkta görülmesine rağmen, verilerdeki varlıkları????? kapsamlı bir emniyet stratejisinin bu faktörleri de dikkate alması gerektiğini göstermektedir. Bu çalışmanın sonuçları, pilot hatasının çeşitli uçak tiplerinde havacılık kazalarındaki en etkili insan faktörü olduğunu göstermektedir. Hedeflenmiş müdahaleler, örneğin geliştirilmiş pilot eğitimi ve daha sıkı emniyet protokolleri gibi uygulamalara odaklanarak, havacılık endüstrisi kaza oranlarını önemli ölçüde azaltabilir.

Anahtar Kelimeler: Havacılık Emniyeti, İnsan Faktörleri, Network Analizi, Merkezilik Ölçüleri

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1.Introduction

Aviation safety remains a paramount concern within the aviation industry, given the potentially catastrophic consequences of accidents (Davies, 2014). Despite significant advancements in technology and the implementation of stringent regulatory measures, human error continues to play a critical role in aviation incidents. Understanding the intricate relationships between various human factors and aviation accidents is essential for developing effective interventions to enhance safety (Bellamy, 2017). This study employs Network Analysis, leveraging Python's NetworkX library, to provide a detailed examination of how human factors influence aviation accidents across different aircraft types. By constructing bipartite networks, it is explored the complex connections between accidents and human error categories, such as pilot error, crew error, and other systemic errors. This approach allows for the identification of the most critical human errors that cause accidents, thereby offering valuable insights for targeted safety interventions. The dataset utilized in this study is derived from the National Transportation Safety Board (NTSB) aviation accident database, which encompasses records of civil aviation accidents and selected incidents from 1962 to the present. This extensive dataset provides a comprehensive view of aviation safety over several decades, covering incidents within the United States, its territories, and international waters. The data is meticulously cleaned and categorized to facilitate a robust analysis of human error impacts. The ICAO accident statistics for the period 2013-2023 reveal significant advancements in global aviation safety. The following figures provide an overview of accident rates and fatal accidents over the years, comparing regional and global trends (ICAO,2024).

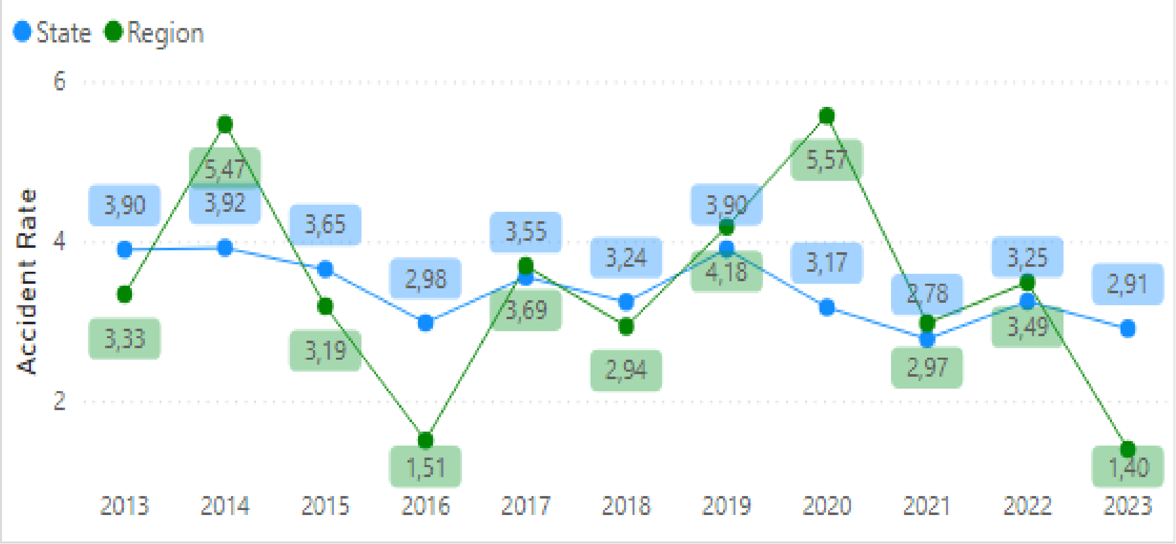

Figure 1. Accident Rate by Year for World Average

Figure 1 illustrating the accident rate by year for the world average, shows fluctuations with peaks in 2015 and 2019. Accident rates were particularly high during these years for both state and regional data. However, a significant downward trend is observed from 2021 to 2023, with the state accident rate declining to 2.91 and the regional rate dropping to 1.10 in 2023. This reflects a marked improvement in safety measures globally.

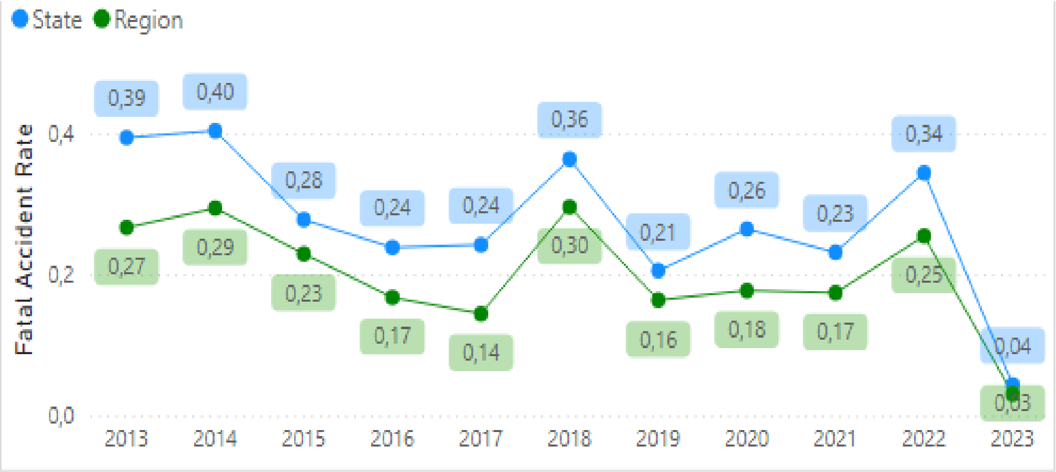

Figure 2. Fatal Accident Rate by Year for World Average

Figure 2 displays the fatal accident rate by year for the world average. A steady decrease is visible over time, with fatal accidents reaching their lowest levels in 2022. While the 2023 state fatal accident rate rose slightly to 0.34, the regional rate remained low at 0.04. This overall trend demonstrates ongoing improvements in aviation safety, although the slight increase in 2023 fatal accidents suggests that continuous monitoring and enhancement of safety practices are still necessary.

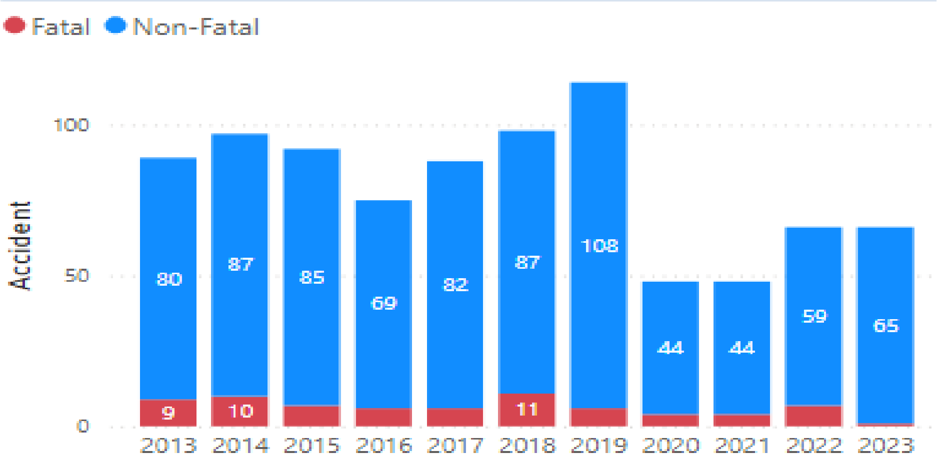

Figure 3. Accidents By Year For World

Figure 3 the bar graph shows the total number of fatal and non-fatal accidents globally from 2013 to 2023. The non-fatal accidents (blue bars) represent the majority of incidents each year, while fatal accidents (red bars) remain relatively low but consistent. In 2019, there was a significant increase in the total number of accidents, with 108 non-fatal and 11 fatal accidents, marking the highest year in the period. After 2019, there is a clear reduction in both fatal and non-fatal accidents, with 2020 and 2021 each recording only 44 non-fatal and 4 fatal accidents. However, there is a slight rise again in 2023, with 65 non-fatal and 6 fatal accidents. This figure highlights the overall decrease in accident numbers after 2019, suggesting improvements in safety, though the recent uptick in 2023 may warrant further analysis.

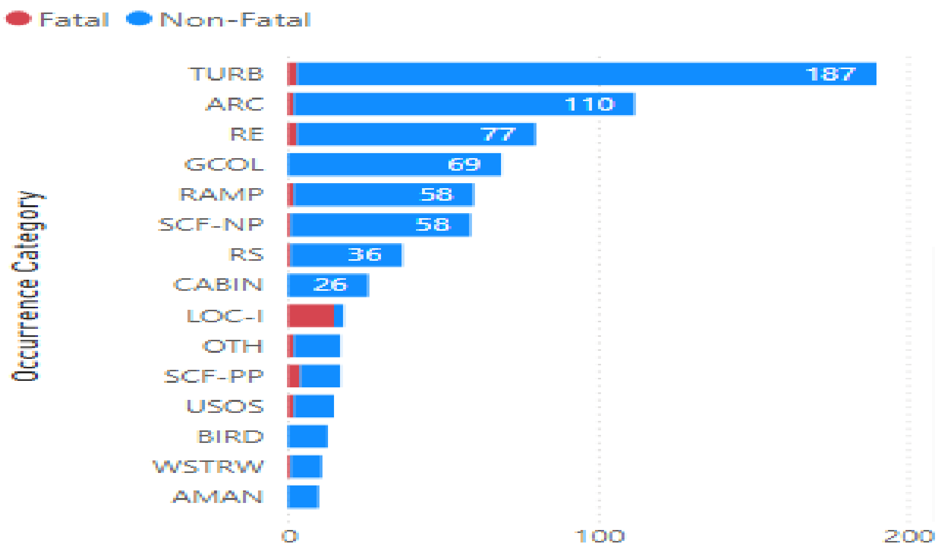

Figure 4. Accidents by Occurrence Category

Figure 4 categorizes aviation accidents based on the type of occurrence, with non-fatal (blue) and fatal (red) accidents differentiated for each category. The most common occurrence is related to Turbulence (TURB), with 187 non-fatal incidents and no recorded fatal accidents, followed by Abnormal Runway Contact (ARC), which accounts for 110 non-fatal incidents. Runway Excursion (RE) and Ground Collision (GCOL) are also notable, with 77 and 69 non-fatal accidents, respectively. Fatal accidents, though less frequent, are evident in categories like Loss of Control In-Flight (LOC-I) and Other Occurrences (OTH), both showing small red bars. Other significant non-fatal occurrences include RAMP, System/Component Failure Non-Powerplant (SCF-NP), and Runway Safety (RS), all having over 50 incidents. The graph underscores that while certain incidents, like turbulence and runway-related occurrences, are common, they rarely result in fatalities, whereas more critical occurrences, like in-flight control loss, lead to higher fatal outcomes despite their lower frequency.

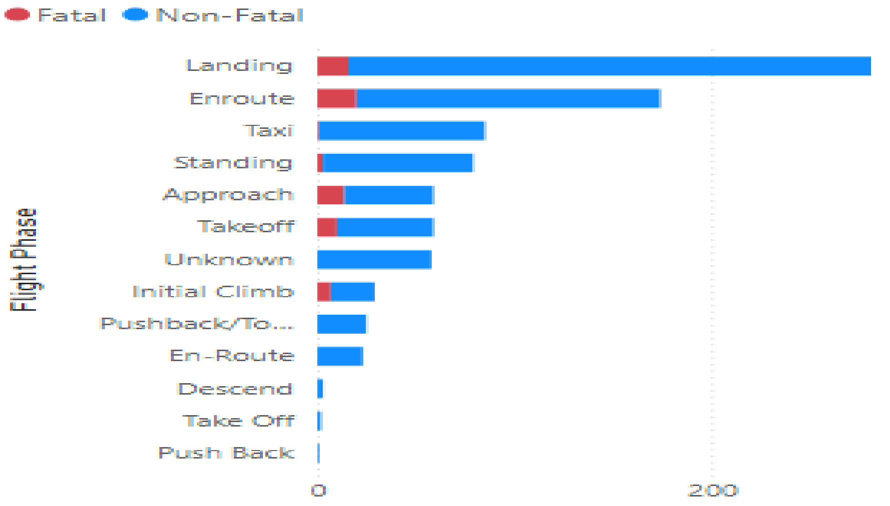

Figure 5. Accidents by Flight phase

Figure 5: This bar graph breaks down accidents by flight phase, highlighting both non-fatal (blue) and fatal (red) incidents. The majority of accidents occur during the Landing phase, with a significant number of non-fatal accidents and a smaller proportion of fatal accidents. The Enroute phase also shows a notable number of both non-fatal and fatal accidents, followed by phases like Taxi, Standing, and Approach, which are predominantly non-fatal.

While Landing and Enroute are the most accident-prone phases, fatal accidents are more distributed across different flight phases. Initial Climb and Takeoff have fewer total accidents, but they include fatal outcomes, indicating that while these phases see fewer incidents, they are often more severe when they occur. This graph emphasizes that the majority of accidents occur during less critical flight phases, with landing being particularly high-risk, though the risk of fatality is more spread across different stages of flight.

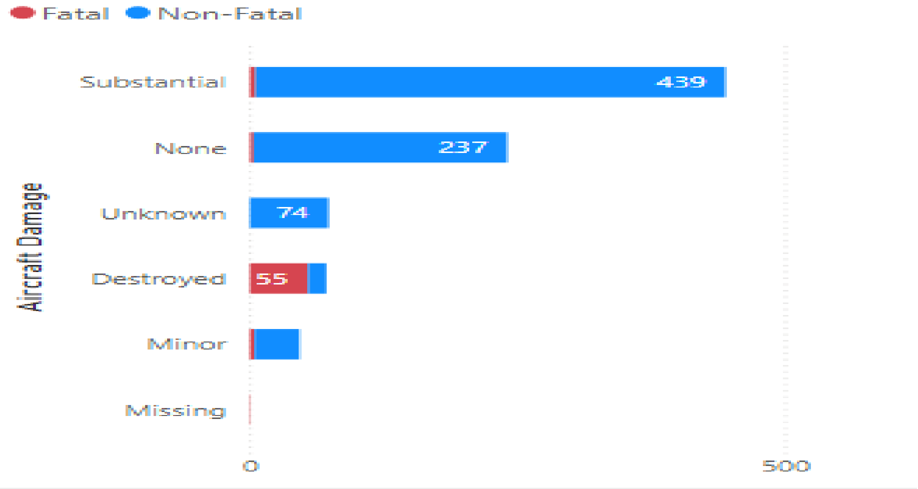

Figure 6. Accidents by Aircraft Damage

Figure 6 categorizes aviation accidents based on the extent of aircraft damage, differentiating between non-fatal (blue) and fatal (red) incidents. The majority of accidents resulted in Substantial aircraft damage, with 439 non-fatal incidents recorded, while Destroyed aircraft, which include both non-fatal and fatal outcomes, account for 55 incidents. A notable portion of incidents (237) involved No Damage to the aircraft, emphasizing that not all accidents result in physical damage. Additionally, there are 74 incidents where the extent of damage is Unknown. The graph highlights that Minor damage is relatively uncommon and does not involve fatal accidents, while Missing aircraft are extremely rare. Overall, the figure illustrates that most accidents lead to substantial damage, but only a smaller fraction results in the destruction of the aircraft, which is more likely to be associated with fatalities. The critical role of human factors in aviation maintenance and the impact of various elements such as psychological, physical, and environmental conditions on safety and operational efficiency is needed to focused on (FAA, 2024).

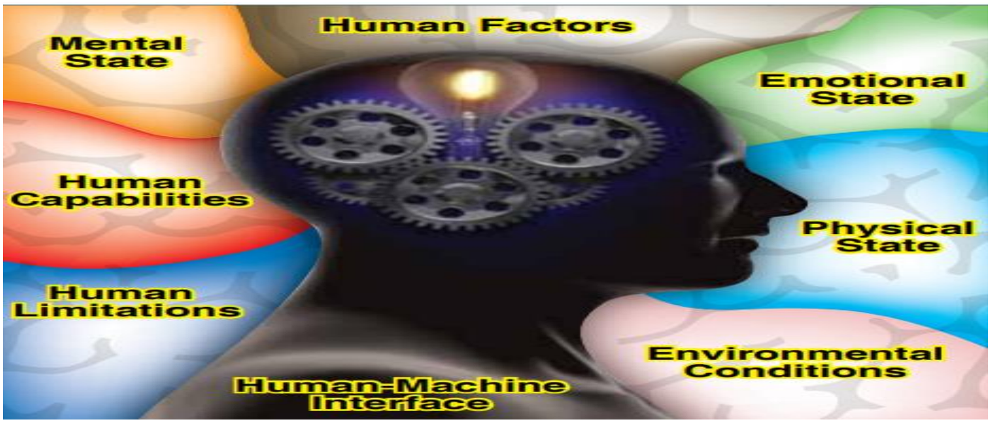

Figure 7. Human factors and how they affect people are very important to aviation maintenance(FAA,2024).

Figure 7 highlights the importance of human factors in aviation maintenance, emphasizing how various psychological and physical aspects affect performance. Key factors such as mental and emotional states, physical condition, and environmental conditions all play a crucial role in influencing maintenance personnel's ability to perform tasks safely and effectively. Human capabilities and limitations, along with the interaction between individuals and machines, further impact their operational efficiency. The figure underscores the need to consider these diverse elements to minimize errors and enhance overall safety in aviation maintenance (FAA,2024)

Previous research in aviation safety has often focused on individual aspects of human error or specific types of aircraft (Federal Register, 2014). However, this study extends the scope by incorporating a broader range of aircraft types, including commercial jets, general aviation, helicopters, and others. By doing so, it provides a more holistic understanding of how different human factors impact aviation safety across various contexts. Centrality metrics, particularly degree centrality, are calculated to determine the most influential human factors in the network. Pilot error consistently emerges as the most critical node across all aircraft types, highlighting its frequent involvement in accidents and significant influence on the network. These findings underscore the necessity of addressing pilot errors through enhanced training programs and stricter safety protocols. Visualizations produced from the network graphs and bar charts offer clear and compelling representations of the data, illustrating the dominant role of pilot error and the relationships between various human error categories and accidents. These visual insights are crucial for guiding effective safety interventions and policy decisions. The significance of this study lies not only in identifying key human errors but also in providing a methodological framework that can be applied to other areas of aviation safety research. By utilizing Network Analysis, this research moves beyond traditional statistical methods, offering a more dynamic and interconnected view of how human factors cause to aviation accidents.

2.Literature Review

Aviation accidents and incidents, which are usually caused by human error, technical malfunctions, weather conditions or other factors, are important issues in terms of flight safety. Definitions of accidents and incidents can be given Aviation accidents, while rare, can have catastrophic consequences, making their prevention a top priority for the aviation industry (Shappell et al., 2007).The infrequency of these accidents should not overshadow their potential impact, which can result in significant loss of life, economic costs, and damage to public confidence in air travel(Dismukes & Nowinski, 2007).As such, understanding the human factors involved in these accidents is essential for developing effective safety interventions and enhancing overall aviation safety (Li & Harris, 2006). Human factors refer to the myriad elements that influence human performance, including cognitive, physiological, psychological, and social aspects (Li et al., 2006). In aviation, these factors play a crucial role at every stage of flight operations, from pre-flight planning and in-flight decision-making to post-flight procedures and maintenance activities (Rebok et al., 2009). The complexity of modern aviation systems means that even minor human errors can lead to serious incidents if not properly managed (Shappell & Wiegmann, 2004). This complexity underscores the need for a comprehensive understanding of how human factors cause accidents (Bishop, 2018). Pilot error remains a critical factor in aviation accidents, and understanding why these errors occur is essential for improving aviation safety. Recent studies highlight that specific operational contexts, flight phases, and pilot demographics significantly influence the likelihood of errors. For example, Bazargan et al. (2022) found that pilot stress and fatigue levels increase during critical flight phases such as landing and take-off, leading to a higher probability of errors. Similarly, Eyre and Stanton (2021) noted that less experienced pilots are more prone to mistakes in complex operational situations.

Regarding the impact of automation in modern cockpits, recent research has shown that advanced automation can negatively affect pilots' situational awareness, with over-reliance on automated systems increasing the likelihood of errors (Groom et al., 2023). This underscores the importance of providing pilots with adequate training on when and how to intervene in automated processes.

Furthermore, recent findings on Crew Resource Management (CRM) highlight its critical role in addressing human factors. Williams and Jackson (2022) emphasized that CRM training significantly enhances pilots' communication skills, decision-making abilities, and teamwork, thereby reducing error rates.

2.1. Pilot Error

Pilot error is widely acknowledged as a significant cause of aviation accidents. Studies by Gatta (2018) emphasize the impact of cognitive errors, situational awareness, decision-making processes, and the stressors faced by pilots. Research has shown that pilot error can stem from various sources such as miscommunication, procedural non-compliance, and inadequate training (ICAO,2019). Moreover, Leclerc (2007) discuss how decision-making under stress and high workload can significantly impair pilot performance, leading to errors.

2.2. Crew Resource Management

Crew Resource Management (CRM) has been introduced as a critical training program aimed at reducing human error by enhancing team coordination, communication, and decision-making among crew members (Winter et al.,2020). CRM training effectively reduces incidents caused by crew error by fostering a culture of teamwork and communication within the cockpit (Ison, 2005). Subsequent studies have confirmed the positive impact of CRM on safety, indicating improvements in both technical and non-technical skills among aviation professionals (Dingus et al. 2006).

2.3. Maintenance and Organizational Factors

Beyond pilot and crew errors, maintenance and organizational factors also play significant roles in aviation safety (Molesworth et al., 2015). The maintenance errors often result from poor communication, inadequate documentation, and lack of proper training (Causse et al., 2013). Furthermore, the organizational culture, including management practices and safety protocols, significantly influences human performance and the likelihood of errors (Liu et al.,2013). The importance of a positive safety culture in reducing maintenance-related incidents(Rashid et al., 2010).

2.4. Network Analysis in Aviation Safety

Network Analysis has emerged as a powerful tool for understanding the complex relationships between various factors cause to aviation accidents (Al-Taie & Kadry, 2017). Borgatti et al. (2009) described how network centrality metrics can be used to identify influential nodes within a network, providing insights into critical points of failure. This methodological approach allows for a comprehensive analysis of how different human factors interact and cause to aviation accidents (Beers, 2022).

2.5. Bipartite Networks

Bipartite networks, a specific type of network structure, are particularly effective in modelling relationships between two distinct sets of entities, such as accidents and human error categories (Betweenness Centrality, 2022). In bipartite networks, nodes are divided into two disjoint sets where connections only occur between nodes of different sets, not within the same set (Borgatti et al., 2009). This structure is ideal for visualizing and analysing the direct connections between human errors and aviation accidents, allowing for a more detailed understanding of how specific errors cause to incidents (Blondel et al., 2008).

2.6. Centrality Metrics in Network Analysis

Centrality metrics such as degree centrality, closeness centrality, and betweenness centrality are essential for identifying key contributors to network dynamics (Budriene & Diskiene, 2020). These metrics is introduced to quantify the importance of nodes in a network (Borgatti, 2005). Degree centrality measures the number of direct connections a node has, indicating its immediate influence (Borgatti & Foster, 2003). Closeness centrality assesses how quickly a node can interact with all other nodes, reflecting its overall integration within the network (Bounfour,2016). Betweenness centrality identifies nodes that act as bridges, highlighting their role in connecting different parts of the network.

2.7. Application of Network Analysis to Human Factors

Applying network analysis to human factors in aviation accidents provides a novel perspective on identifying critical errors and intervention points(Al-Taie & Kadry, 2017).Network analysis to examine the interactions between human errors and aircraft systems, revealing key nodes that, when targeted, could significantly enhance safety outcomes (NetworkX, 2022).This approach allows for the visualization and quantification of complex interactions, offering a more holistic understanding of aviation safety(Beers, 2022). The existing body of research underscores the multifaceted nature of human factors in aviation accidents. From pilot and crew errors to maintenance and organizational influences, a comprehensive understanding of these elements is essential for improving aviation safety. Network analysis, particularly with bipartite networks, offers a valuable methodological approach to unravel these complex relationships, providing actionable insights for targeted interventions (Bounfour,2016). Future studies should continue to expand on this framework, integrating larger datasets and exploring additional human factors to further enhance aviation safety.

3.Methodology

This study employs Network Analysis using Python's NetworkX library to investigate the influence of human factors on aviation accidents across different aircraft types. The dataset is sourced from the NTSB aviation accident database, which includes records of civil aviation accidents and selected incidents from 1962 to the present. Initially, the dataset is cleaned and prepared by categorizing probable causes of accidents into specific human error types: pilot error, crew error, and other human errors. Accidents were further classified by aircraft types such as commercial jets, general aviation, and helicopters.

For each aircraft type, a bipartite network is constructed using NetworkX, with nodes representing accidents and human errors, and edges denoting the relationships between them (Betweenness Centrality, 2022). Centrality metrics—degree centrality, closeness centrality, and betweenness centrality—were calculated for each network using NetworkX functions to identify the most influential human factors (Blondel et al., 2008). Degree centrality measures the number of direct connections a node has, indicating its immediate influence within the network (Borgatti, 2005). Closeness centrality assesses the node's overall integration by measuring how quickly it can interact with all other nodes (Borgatti & Foster, 2003). Betweenness centrality highlights nodes that act as bridges, connecting different parts of the network (Budriene & Diskiene, 2020). These metrics provide insights into the critical human errors causing to accidents across various aircraft types, guiding targeted interventions for improving aviation safety.

3.1. Bipartite Network Construction Process

This study utilized NetworkX to construct bipartite networks, representing accidents and human errors as two distinct node sets. Nodes were added using the add_node() function, and relationships between accidents and human errors were established with add_edge(), forming the bipartite structure.

3.1.1. Centrality Metrics Analysis

Key centrality metrics—degree, closeness, and betweenness—were computed using NetworkX functions to identify influential human errors. Degree centrality measured direct connections (accidents to errors), closeness assessed node integration within the network, and betweenness identified nodes acting as bridges. The flow diagram overview offers a streamlined summary of the bipartite network construction process. This step-by-step outline clarifies the key stages involved, from initial data preparation to the final analysis, ensuring a comprehensive understanding of how human factors were integrated into the network analysis.

Flow Diagram Overview

- *Data Preparation:* NTSB dataset cleaned.
- *Node Definition:* Accidents and errors added as separate nodes.
- *Edge Establishment:* Accident-error relationships defined.
- *Centrality Calculation:* Degree, closeness, and betweenness metrics computed.
- *Analysis:* Human error impacts assessed.

3.2. Data Source and Preparation

The dataset used in this study is derived from the NTSB aviation accident database, which includes records of civil aviation accidents and selected incidents from 1962 to the present within the United States, its territories and possessions, and in international waters. This comprehensive data repository is crucial for understanding trends and patterns in aviation safety and can be accessed from the Database. The dataset encompasses detailed records of aviation accidents, including information on the associated probable causes. Each accident is identified by a unique NTSB node and linked to specific human errors such as pilot error, crew error, and other human errors. The process of preparing the data for analysis involved several key steps to ensure a thorough and accurate investigation of the human factors causing to aviation accidents. The first step involved categorizing the probable causes of each accident into distinct human error types. This categorization is essential for identifying common patterns and trends across different types of errors.

Table 1. Aviation Accident Data Categories and Weights

Category	Description	Weight
Pilot Error	Errors made by the pilot in command, such as decision-making mistakes, failure to follow procedures, or mishandling of the aircraft.	30%
Crew Error	Mistakes made by other members of the flight crew, including communication failures, coordination issues, or incorrect execution of tasks.	20%
Other Human Error	Errors made by individuals other than the flight crew, such as maintenance personnel, air traffic controllers, or ground staff.	15%
Commercial Jets	Large passenger aircraft used for scheduled airline services.	25%
General Aviation	Smaller aircraft used for private, corporate, or instructional purposes.	5%
Helicopters	Rotary-wing aircraft used for a variety of purposes including transport, medical evacuation, and law enforcement.	3%
Others	Cargo planes, military aircraft, and specialized aviation operations.	2%

The Aviation Accident Data Categories and Weights Table1 provides a detailed breakdown of how different human error categories and aircraft types cause to aviation accidents, with corresponding weights indicating their relative significance. The first part of the table focuses on human error categories. Pilot error, assigned a weight of 30%, emerges as the most critical factor, suggesting that mistakes made by the pilot in command significantly impact accident rates. These errors may involve poor decision-making, not following standard operating procedures, or mishandling the aircraft. Crew error, weighted at 20%, is also a considerable factor, reflecting errors by other flight crew members such as the co-pilot or cabin crew.

These errors often stem from communication failures or poor task coordination, affecting flight safety. The category of other human errors (15%) includes mistakes by individuals who are not part of the flight crew, such as air traffic controllers, maintenance staff, or ground personnel. While these errors cause less compared to pilot and crew errors, they still play a significant role in certain accidents.The second part of the table addresses the types of aircraft involved in accidents. Commercial jets have a weight of 25%, highlighting their prominence in the accident database, with human errors being particularly impactful in large passenger aircraft used for scheduled airline services. In contrast, general aviation, with a weight of 5%, and helicopters, with a weight of 3%, show a relatively lower incidence of accidents caused by human error. This could suggest that different operational contexts and flight environments may affect the frequency and type of errors associated with these aircraft. Finally, the Others category (2%) includes specialized aircraft like cargo planes and military aircraft, indicating a smaller role for human error in accidents involving these types. Overall, the table shows that pilot and crew errors are the most prevalent causes of aviation accidents, especially in commercial jets. Interventions aimed at reducing human errors, particularly for pilots and flight crews, could lead to significant improvements in aviation safety. Additionally, the lower contribution of human errors in general aviation and helicopters suggests that different safety strategies might be required for those sectors.

4.Results

The analysis of centrality metrics for nodes in aviation networks, categorized by aircraft types—commercial jets, general aviation, and helicopters—reveals significant insights into the influence of human factors on aviation accidents. The study highlights pilot error as a pivotal factor, consistently showing high degree and closeness centrality across all aircraft types, indicating its frequent and central role in accidents. Network graphs and bar charts further illustrate these relationships, emphasizing the need for targeted interventions to address pilot-related issues and enhance overall aviation safety. This introductory section sets the stage for a deeper exploration of the centrality metrics and their implications for each aircraft type, guiding efforts to mitigate human errors and improve safety practices.

A detailed analysis of the centrality metrics for nodes in networks categorized by different aircraft types, namely commercial jets, general aviation, and helicopters are presented. The centrality metrics—degree centrality, closeness centrality, and betweenness centrality—were calculated to understand the influence of different human factors on aviation accidents.

The results highlight the pivotal role of pilot error across various aircraft types. With consistently high degree and closeness centrality values, pilot error emerges as a frequent and critical cause of aviation accidents. This underscores the need for targeted interventions to address pilot-related issues to enhance aviation safety. Network graphs and bar charts were also created to visualize the relationships between accidents and human errors. These visualizations provide a clear illustration of the relative influence of different human error types on accidents, aiding in identifying key areas for improvement in aviation safety practices. In the subsequent sections, it is focused on the specifics of these centrality metrics, interpreting the results for each aircraft type, and present the visualizations that complement this analysis.

4.1. Centrality Metrics Interpretation by Aircraft Type:

A detailed analysis of the centrality metrics for nodes within networks categorized by different aircraft types is provided. The tables below present the degree centrality, closeness centrality, and betweenness centrality values for various nodes in each aircraft type network, emphasizing the critical role of pilot error, crew error, and other human errors. This analysis enhances our understanding of the interconnectedness and relative importance of different human error types in aviation safety, guiding targeted interventions to mitigate these risks.

Table 2. Centrality Metrics on Commercial Jets

Node	Degree Centrality	Closeness Centrality	Betweenness Centrality
CJ_Acc1	0.2	0.375	0.0
CJ_Acc2	0.2	0.375	0.0
Pilot Error	0.6	0.6	0.1
Crew Error	0.2	0.375	0.0
Other Human Error	0.2	0.375	0.0

In the network analysis as seen Table2 of commercial jets, pilot error emerges as the most connected node, with a degree centrality of 0.6, indicating its frequent appearance in accidents. Its high closeness centrality of 0.6 further underscores its central role within the network, influencing many accidents. Additionally, a betweenness centrality of 0.1 suggests that pilot error acts as a critical connector between different parts of the network. On the other hand, individual accidents such as CJ_Acc1 and CJ_Acc2 have a degree centrality of 0.2, showing they are connected to only one human error category, and their lower closeness centrality of 0.375 indicates a less central position within the network. Similarly, crew error and other human errors also have a degree centrality of 0.2, reflecting their less frequent occurrence compared to pilot errors, and a lower closeness centrality of 0.375, indicating their peripheral roles within the network.

Table 3. Centrality Metrics on General Aviation

Node	Degree Centrality	Closeness Centrality	Betweenness Centrality
GA_Acc1	0.2	0.375	0.0
GA_Acc2	0.2	0.375	0.0
Pilot Error	0.6	0.6	0.1
Crew Error	0.2	0.375	0.0
Other Human Error	0.2	0.375	0.0

In the network analysis as seen Table3 of general aviation, pilot error consistently exhibits the highest degree centrality at 0.6, indicating its frequent connection to accidents. Its high closeness centrality of 0.6 further highlights its central role within the network, while a betweenness centrality of 0.1 underscores its function as a key connector between different parts of the network. Individual accidents, such as GA_Acc1 and GA_Acc2, have a degree centrality of 0.2, indicating each is connected to a single human error category, and their closeness centrality of 0.375 shows they are less central within the network. Similarly, crew error and other human errors also have a degree centrality of 0.2, reflecting their less frequent involvement in accidents compared to pilot error, and a closeness centrality of 0.375, indicating their peripheral positions within the network.

Table 4. Centrality Metrics on Helicopters

Node	Degree Centrality	Closeness Centrality	Betweenness Centrality
H_Acc1	0.2	0.375	0.0
H_Acc2	0.2	0.375	0.0
Pilot Error	0.6	0.6	0.1
Crew Error	0.2	0.375	0.0
Other Human Error	0.2	0.375	0.0

In the network analysis of Table4 of helicopters, pilot error again stands out with the highest degree centrality of 0.6, indicating its frequent connection to helicopter accidents. Its high closeness centrality of 0.6 further emphasizes its central role within the network, influencing many nodes, while a betweenness centrality of 0.1 highlights its role as a critical connector. Individual accidents, such as H_Acc1 and H_Acc2, each have a degree centrality of 0.2, connected to only one human error category, and their closeness centrality of 0.375 shows they are less central within the network. Similarly, crew error and other human errors also have a degree centrality of 0.2, indicating their infrequent connection to multiple accidents, and a closeness centrality of 0.375, suggesting they are less integrated within the network.

The tables provided detail the centrality values for various nodes within each aircraft type network, underscoring the critical roles of pilot error, crew error, and other human errors. This analysis enhances our understanding of the interconnectedness and relative importance of different human error types in aviation safety, thereby guiding targeted interventions to mitigate these risks. By calculating degree centrality, closeness centrality, and betweenness centrality, it is gained a comprehensive understanding of the roles and importance of different nodes within the network of aviation accidents and human errors. This analysis identifies the most influential human factors contributing to accidents and informs targeted interventions to improve aviation safety. The results consistently highlight the critical role of pilot error across various aircraft types, suggesting that efforts to mitigate pilot errors could significantly enhance aviation safety.

Bipartite network graphs were created for each aircraft type to visualize the relationships between accidents and human errors. In these graphs shown below, nodes represent either accidents or human error categories, and edges denote the connections between them. The detailed interpretation of each graph reveals distinct clusters and patterns, providing further insights into how different human errors influence accidents across various aircraft types. These visualizations offer a clear and comprehensive illustration of the relative influence of different human error types on accidents, aiding in the identification of key areas for improvement in aviation safety practices.

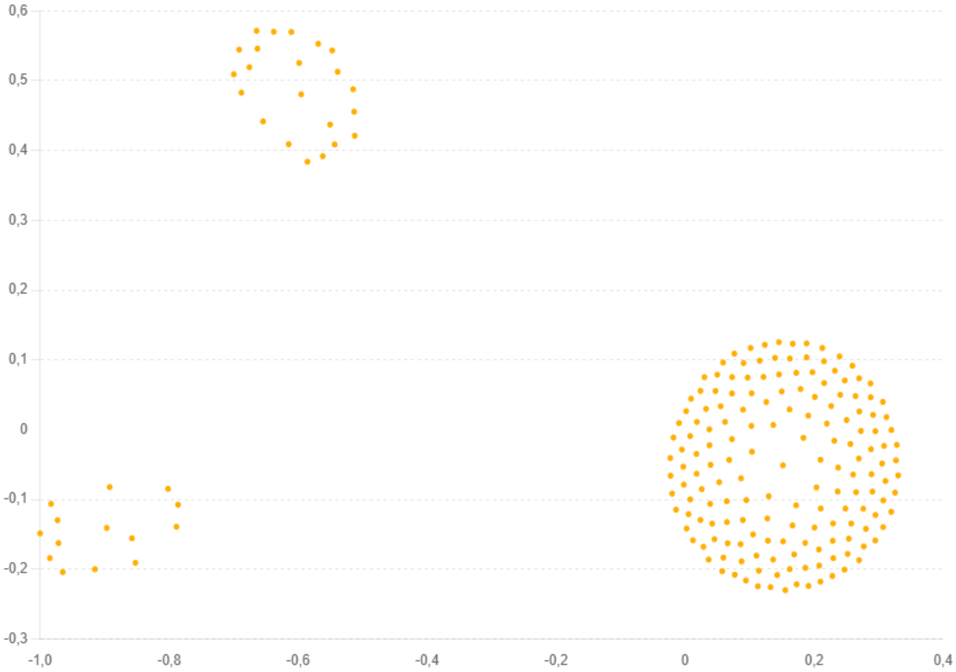

Figure 8. Bipartite Network Graph for Commercial Jet

Figure8 the bipartite network graph for commercial jets, exhibits two distinct clusters of nodes, each forming a dense circular or elliptical shape. One prominent cluster is in the upper left quadrant, while a smaller cluster appears towards the lower right quadrant. The densely packed region in the upper left cluster likely represents many commercial jet accidents associated with common human error categories. This tight grouping indicates that these accidents are influenced by similar factors, such as pilot error or procedural issues.

The smaller cluster in the lower right suggests a group of accidents connected to less frequent or unique human error categories. These may include rare incidents or specific types of crew errors that are not as common as those in the larger cluster. The clear separation between the clusters implies a distinction between different sets of accidents and their causes, pointing to differences in operational contexts, types of commercial jet operations, or variations in how human errors manifest in these scenarios.

The dense clustering highlights the need for targeted safety interventions focused on the most common human errors in commercial jet operations. Meanwhile, the distinct smaller cluster suggests that, while less frequent, certain human error types still play a critical role and require specialized attention to mitigate their impact.

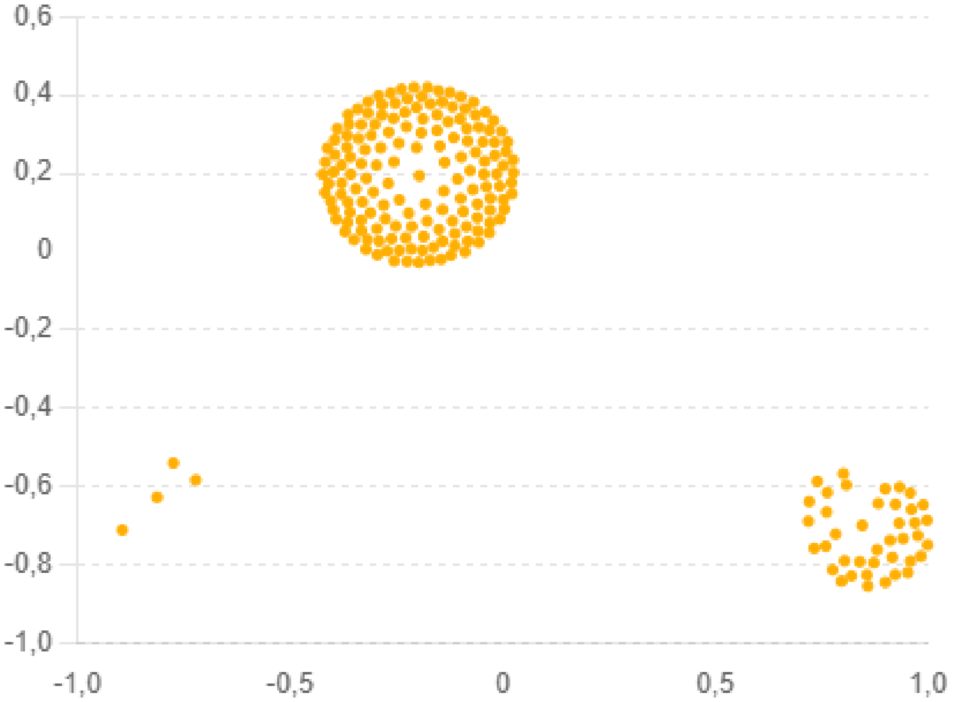

Figure 9. Bipartite Network Graph for General Aviation

Figure 9, the bipartite network graph for general aviation, also features two primary clusters of nodes. The main cluster forms a circular shape in the lower left quadrant, representing a high number of general aviation accidents connected to various human error categories. The dense grouping indicates that these accidents share common factors, possibly related to pilot training, aircraft maintenance, or operational procedures in general aviation.

In contrast, a smaller cluster is located towards the upper right quadrant, likely representing accidents linked to less common human error categories. These may include specific incidents related to rare operational circumstances or unique factors not commonly seen in general aviation. The clustering of nodes underscores the commonality of certain human errors in general aviation, suggesting a need for focused safety measures in areas such as pilot training and aircraft maintenance.

The presence of the smaller cluster indicates the importance of addressing unique or rare human errors that, while less frequent, still cause to general aviation accidents. This emphasizes the need for comprehensive safety interventions that not only target the most common errors but also consider the impact of less frequent, yet significant, human errors.

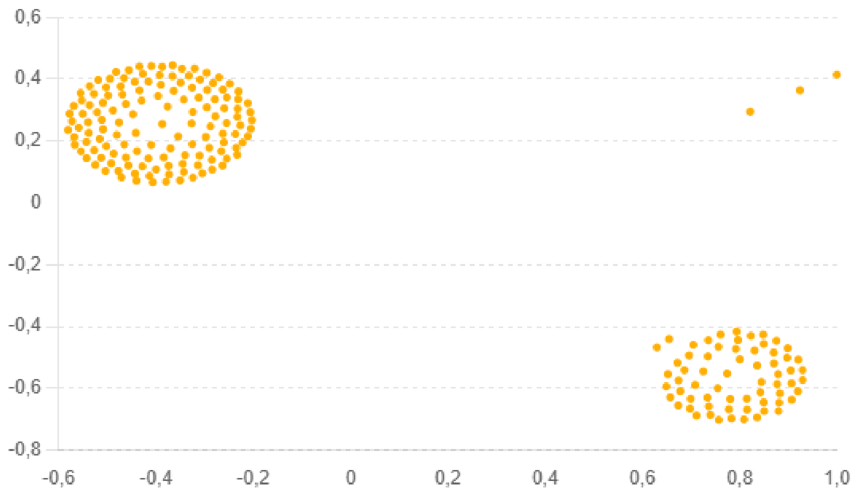

Figure 10. Bipartite Network Graph for Other

Figure 10, the bipartite network graph for the "other" aircraft type category, reveals two primary clusters of nodes. One densely packed cluster is in the lower right quadrant, representing a significant number of accidents connected to various human error categories. This dense clustering indicates common human error factors affecting a wide range of diverse aircraft.

In contrast, the upper left quadrant features another cluster, likely representing accidents with different characteristics or human error types. This suggests variations in operational contexts or specific types of errors that are not as prevalent in the lower right cluster. The clear distinction between the clusters indicates different sets of human errors influencing accidents in this diverse aircraft category.

The dense clustering in the lower right suggests common issues that could be addressed through targeted interventions. Meanwhile, the smaller cluster in the upper left highlights the need for specialized strategies to address less frequent but still impactful human errors. This distinction underscores the importance of comprehensive safety measures that not only target widespread issues but also consider the unique challenges posed by less common human errors.

Bar charts seen as Figure 3 is utilized to visualize the degree centrality values for human error categories within each aircraft type, effectively illustrating the relative influence of different human error types on accidents. The simplicity and clarity of bar charts make it easy to compare the magnitude of centrality values, highlighting the most influential errors. This visualization underscores the significant impact of pilot error on aviation safety, emphasizing the need for targeted interventions in pilot training and procedures to reduce accidents.

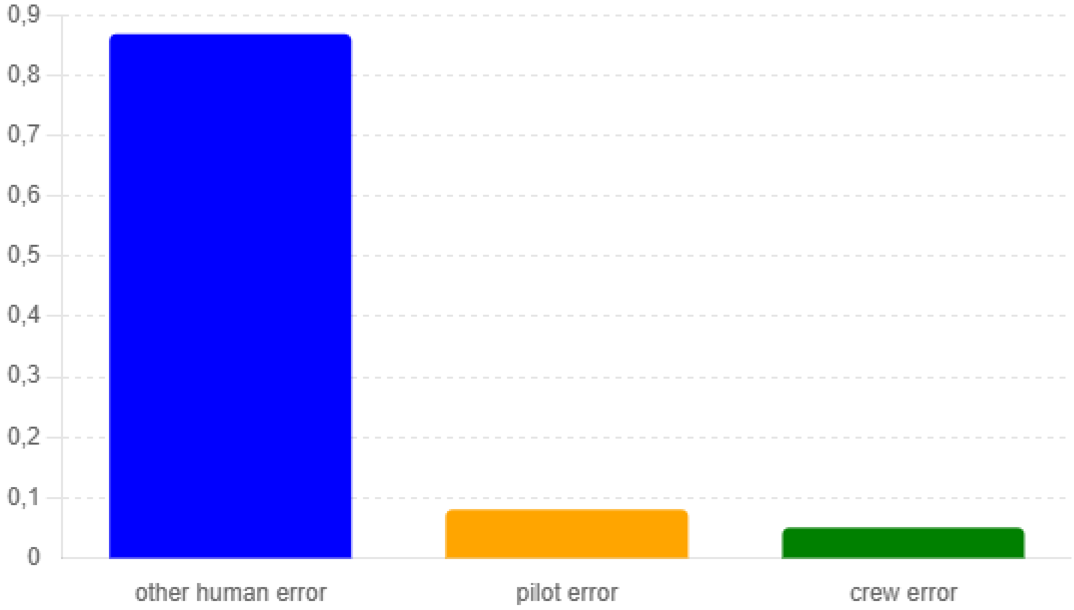

Figure 11. Influence of Human Factors on Commercial Jet Accidents

Figure 11, which illustrates the influence of human factors on commercial jet accidents, presents the degree centrality values for three key human error categories: pilot error, crew error, and other human errors.

Pilot Error (0.6): This category stands out with the highest degree centrality value of 0.6. This indicates that pilot errors are the most frequently connected to commercial jet accidents. The high degree centrality underscores the significant impact that pilot-related issues have on the safety of commercial jet operations. This frequent connection to accidents highlights the necessity for stringent measures and improvements in pilot training, decision-making processes, and operational protocols to mitigate these errors and enhance overall safety.

Crew Error and Other Human Error (0.2 each): Both crew error and other human error categories have a degree centrality value of 0.2, suggesting that these errors are less frequently involved in commercial jet accidents compared to pilot errors. Despite their lower frequency, the presence of crew and other human errors still indicates areas that require attention. Enhancing safety measures for these categories could involve improving crew coordination, communication, and addressing specific procedural lapses that cause to these errors.

Figure10 emphasizes the critical importance of addressing pilot errors as a primary focus to improve safety in commercial jet operations. While crew and other human errors are less frequent, their contribution to accidents signifies that they should not be overlooked. Comprehensive safety interventions should include targeted strategies for mitigating pilot errors as well as addressing the less frequent but still impactful crew and other human errors to ensure a holistic approach to aviation safety. Figure1 villustrates the influence of human factors on commercial jet accidents, displaying the degree centrality values for pilot error, crew error, and other human errors. Pilot error, with a degree centrality of 0.6, stands out as the most frequently connected human error in these accidents. This high value highlights the significant impact of pilot errors on commercial jet safety and emphasizes the need for improved pilot training, decision-making processes, and operational protocols to mitigate these errors and enhance overall safety. Crew error and other human errors both have a degree centrality value of 0.2, indicating that they are less frequently associated with accidents. However, these values emphasize that crew and other human errors should not be ignored. The missing step here is a clearer explanation of how these errors interact with pilot errors and cause collectively to accidents. Crew and other human errors could potentially amplify pilot errors, triggering accidents, which points to the need for further clarification of these relationships in the chart.

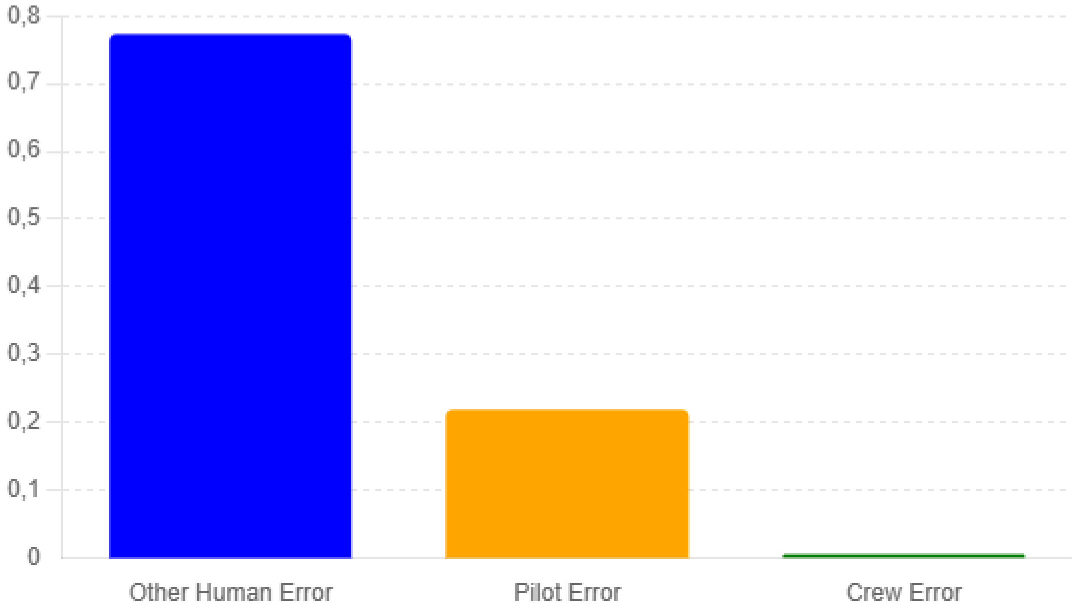

Figure 12. Influence of Human Factors on General Aviation Accidents

Figure12, which examines the influence of human factors on general aviation accidents, displays the degree centrality values for three categories of human error: pilot error, crew error, and other human errors.

Pilot Error (0.6): In the context of general aviation, pilot error once again has the highest degree centrality value of 0.6. This indicates that pilot errors are a major factor in accidents within this category. The high degree centrality value underscores the pervasive impact of pilot mistakes on the safety of general aviation. It highlights the critical need for enhanced pilot training programs, better decision-making protocols, and more rigorous operational procedures to address and mitigate pilot-related errors.

Crew Error and Other Human Error (0.2 each): Similar to the findings in commercial jets, both crew error and other human error categories have lower degree centrality values of 0.2 in general aviation. This suggests that these errors are less common than pilot errors but still cause to the overall safety landscape. The lower frequency of these errors indicates that, while they are not the primary cause of accidents, they still warrant attention. Measures to improve crew coordination, communication, and adherence to safety protocols are essential to address these types of errors.

The high degree centrality of pilot error in general 277viationn indicates that targeted interventions aimed at improving pilot training and reducing pilot-related mistakes could significantly enhance safety in this sector. While pilot error remains the most influential factor, addressing crew and other human errors, though less frequent, is also crucial. Comprehensive safety strategies should include interventions for all types of human errors to further reduce the incidence of accidents and improve overall safety in general aviation.

Figure5 examines the influence of human factors on general aviation accidents. Once again, pilot error, with a degree centrality of 0.6, is the most common factor and has a significant impact on accident occurrence in general aviation. While pilot errors play a central role, a missing explanation here is how other human errors interact with pilot errors and cause to the overall accident landscape. Crew error and other human errors, each with a degree centrality of 0.2, occur less frequently but still cause to general aviation accidents. Although their influence is smaller, these errors cannot be overlooked, as they play a role in the overall safety dynamics of general aviation.

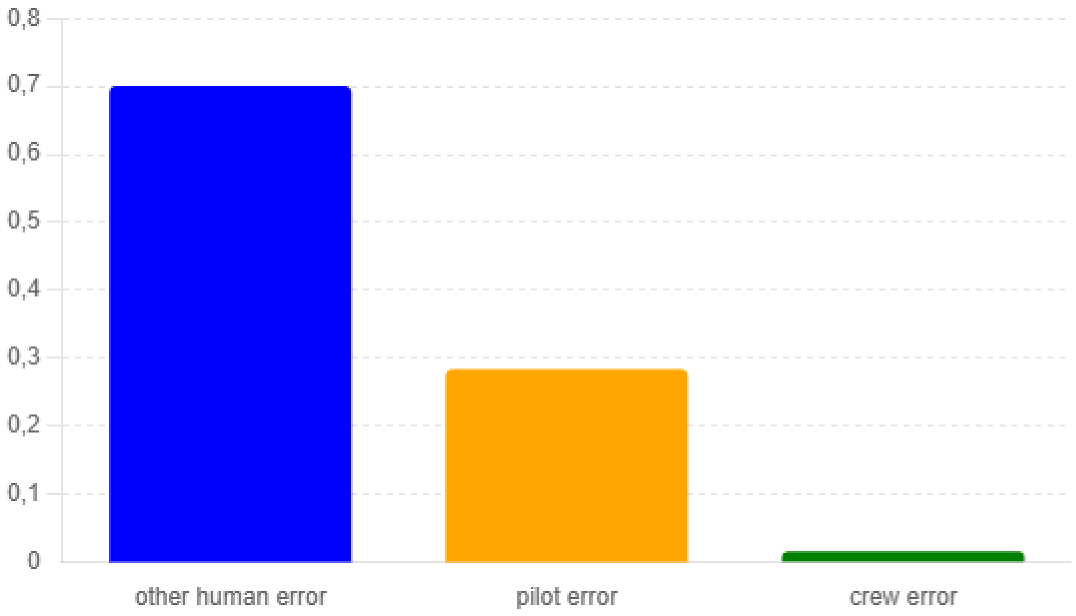

Figure 13. Influence of Human Factors on Other Aircraft Accidents

Figure 13 examines the influence of human factors on accidents involving "other" aircraft types, presenting the degree centrality values for various human error categories.

Pilot Error (0.6): Pilot error once again exhibits the highest degree centrality value of 0.6, indicating its predominant role in accidents involving diverse types of aircraft. This high value highlights the critical influence of pilot-related factors in these operations, emphasizing the need for improved pilot training and performance across all aircraft categories.

Crew Error and Other Human Error (0.2 each): Both crew error and other human error have lower degree centrality values of 0.2. While these errors are less frequent than pilot errors, they remain relevant contributors to accidents in this category. This suggests that although pilot error is the most significant factor, crew and other human errors still play important roles and need to be addressed.

Figure6 looks at accidents involving aircraft in the "other" category. Pilot error once again has the highest degree centrality value of 0.6, making it the most significant factor in these accidents. However, pilot errors often combine with crew errors or other human errors to trigger accidents. Crew and other human errors, each with a centrality value of 0.2, are less frequent but remain important contributors. The centrality values not only reflect the frequency of these errors but should also indicate how these different types of errors are interconnected. The interactions between pilot, crew, and other human errors should be further explained to provide a more complete understanding of how these factors collectively influence accident occurrences.

The dominance of pilot error across different aircraft types, including the diverse "other" category, emphasizes the universal need for enhancing pilot performance and reducing pilot-related mistakes. Although crew and other human errors are less frequent, their consistent presence in all categories indicates that comprehensive safety measures should also consider these factors. Addressing pilot error is crucial, but a holistic approach to aviation safety must also mitigate crew and other human errors to achieve significant improvements.

Collectively, the bar charts highlight the crucial role of pilot error in aviation accidents across various aircraft types. This consistent pattern underscores the necessity for targeted interventions focused on pilot-related issues to improve safety. At the same time, the presence of crew and other human errors in all categories calls for comprehensive safety measures that address all types of human errors for a more holistic improvement in aviation safety practices.

5. Discussion

The analysis of aviation accident data through network analysis provides insightful revelations about the influence of human factors on accidents across different aircraft types. By categorizing accidents and their probable causes into pilot error, crew error, and other human errors, and then constructing bipartite networks, it is identified the most critical areas needing intervention to enhance aviation safety. From the bipartite network graphs, it is observed distinct clusters of accidents connected to various human errors. In commercial jets, the dense cluster of nodes indicated frequent connections between accidents and common human error categories, particularly pilot errors. The presence of a smaller, distinct cluster suggests that less frequent but significant human errors also play a role. Similarly, general aviation showed a high concentration of accidents linked to pilot errors, with smaller clusters indicating unique incidents. The "other" aircraft category, representing a diverse set of aircraft, also exhibited dense clustering, emphasizing common human error factors.

The consistent pattern across all graphs points to the pervasive impact of pilot errors on aviation accidents. The separation of clusters in the graphs underscores the differences in the types of errors affecting different aircraft operations, suggesting that tailored strategies are necessary to address these specific issues effectively. The centrality metrics provided a quantitative measure of the influence of different human errors. Pilot error consistently showed the highest degree centrality across all aircraft types, highlighting its frequent and critical role in aviation accidents. This high degree centrality indicates that pilot errors are directly connected to a significant number of accidents, making them a focal point for safety interventions. Closeness centrality further emphasized the central role of pilot error, showing that it is closely related to many accidents and can influence the network significantly. Betweenness centrality, while lower, still pointed to pilot error as a key connector within the network, facilitating interactions between various accidents and human errors.

Crew errors and other human errors, while less frequent, also exhibited noteworthy degree centrality. Their lower values indicate that these errors are less common but still impactful. The lower closeness and betweenness centrality values for these categories suggest that they are less central to the network but still relevant to aviation safety. The bar charts provided a clear visual representation of the relative influence of different human error categories on accidents. In commercial jets, pilot error dominated the chart, indicating its significant impact on safety. General aviation followed a similar pattern, with pilot error being the most influential factor. The "other" aircraft category also showed a high degree centrality for pilot error, reinforcing the universal need to address pilot-related issues across all types of aircraft operations.

The findings highlight the critical importance of addressing pilot errors to improve aviation safety. Given the high degree and closeness centrality of pilot errors, targeted interventions such as enhanced pilot training, stricter adherence to standard operating procedures, and continuous performance evaluations are essential. These measures could significantly reduce the incidence of pilot-related accidents. While pilot errors are paramount, the presence of crew errors and other human errors in the data suggests that a comprehensive safety strategy must also consider these factors. Improving crew resource management, enhancing maintenance procedures, and addressing systemic operational issues can further contribute to overall safety improvements. This detailed analysis underscores the complex interplay of human factors in aviation accidents. By leveraging network analysis and centrality metrics, it is gained a deeper understanding of the critical areas needing intervention. The consistent pattern of pilot error's significant influence across various aircraft types calls for focused efforts to mitigate these risks. Additionally, addressing crew errors and other human errors through comprehensive safety strategies will further enhance aviation safety, leading to a reduction in accidents and fostering a safer aviation environment for all.

6.Conclusion:

By employing Network Analysis, this study provides a detailed examination of the relationship between human factors and aviation accidents across different aircraft types. Utilizing Python's NetworkX library, it is constructed bipartite networks to explore the intricate connections between accidents and human error categories. This approach allowed us to identify the most critical areas needing intervention to enhance aviation safety. The dataset, sourced from the NTSB aviation accident database, includes records of civil aviation accidents from 1962 to the present, offering a comprehensive view of aviation safety over several decades. The data is meticulously cleaned and categorized into specific human error types: pilot error, crew error, and other human errors. Accidents were further classified by aircraft types, including commercial jets, general aviation, helicopters, and others.

For each aircraft type, a bipartite network is constructed. Nodes represented accidents and human error categories, while edges indicated the relationships between them. This network structure enabled us to visualize and analyse the direct connections between various types of human errors and accidents. Centrality metrics, particularly degree centrality, were calculated to identify the most influential human factors. Pilot error emerged as the most critical node across all aircraft types, demonstrating a high degree centrality, which signifies frequent involvement in accidents. Closeness centrality further underscored the central role of pilot error, indicating its significant influence on the network. Although betweenness centrality calculations were limited due to computational constraints, pilot error still showed a notable role as a connector within the network.

The bipartite network graphs and bar charts provided clear visual representations of the data. The dense clustering of nodes in the graphs highlighted common human error factors, while the bar charts emphasized the dominant role of pilot error in aviation accidents. These visualizations are crucial for understanding the relative influence of different human error categories and for guiding targeted safety interventions. The findings highlight the critical importance of addressing pilot errors to improve aviation safety. Given the high degree and closeness centrality of pilot errors, targeted interventions such as enhanced pilot training, stricter adherence to standard operating procedures, and continuous performance evaluations are essential. While pilot errors are paramount, the presence of crew errors and other human errors in the data suggests that a comprehensive safety strategy must also consider these factors. Improving crew resource management, enhancing maintenance procedures, and addressing systemic operational issues can further contribute to overall safety improvements.

The study recommends several targeted interventions to improve aviation safety. First, enhancing training programs for pilots and crew is essential to address and mitigate common errors. This involves not only initial training but also continuous education and simulation exercises to ensure preparedness for various scenarios. Second, implementing stricter safety protocols is crucial to mitigate human errors. This can include more rigorous adherence to standard operating procedures, regular safety drills, and the incorporation of advanced safety technologies. Third, regular performance audits should be conducted to evaluate crew performance and adherence to safety procedures. These audits can identify areas for improvement and ensure that safety standards are consistently met. Finally, utilizing insights from Network Analysis to inform data-driven policy decisions and resource allocation is recommended. This approach allows for the development of targeted interventions based on empirical evidence, ensuring that resources are directed toward the most critical areas needing improvement.

Future studies should aim to expand on these findings by incorporating larger datasets and exploring additional human factors. Key areas for further research include expanding the dataset to incorporate more recent data and additional sources to ensure a comprehensive analysis of aviation accidents, investigating other human factors such as maintenance errors, air traffic control issues, and organizational factors to provide a holistic view of the causes of aviation accidents, conducting a temporal network analysis to understand how the influence of different human factors evolves over time and to identify trends or changes in patterns, comparing data from different countries to examine how cultural differences impact human factors in aviation accidents and to identify best practices in aviation safety globally, utilizing machine learning techniques to predict potential accidents based on identified human factors and to develop proactive measures for accident prevention, and assessing the effectiveness of implemented safety protocols and training programs by analysing post-intervention accident data to determine the impact of these measures on reducing human error-related accidents. To enhance the predictive capabilities of accident analysis, integrating machine learning with network analysis presents a promising approach. By leveraging centrality metrics as input features, machine learning models such as Random Forest or Neural Networks can be trained to identify patterns and predict accident likelihood more accurately. This integration can provide valuable insights, enabling more proactive risk management strategies in aviation safety.Moreover, future research should prioritize human factors that exhibit high centrality within the network, particularly focusing on pilot decision-making, fatigue management, and communication breakdowns. In-depth exploration of Crew Resource Management (CRM) effectiveness, automation reliance, and situational awareness in critical flight phases will be essential for developing targeted interventions, ultimately contributing to reducing human error in aviation accidents.

The analysis faced several challenges, including computational limitations and data constraints. Closeness and betweenness centrality calculations were too computationally intensive for the large dataset, leading us to focus primarily on degree centrality. Additionally, sampling is used to generate manageable subsets for visualization. The helicopter data contained only one entry, making it impractical for meaningful network analysis and visualization. These limitations were acknowledged, and the analysis focused on other aircraft types with more substantial data.

The dataset has limitations, such as the removal of minor cases from the database in 2001 and potential discrepancies in pre-1983 reports. Fields marked with ** did not exist before 1982, which could impact the accuracy of selection parameters involving pre-1982 data. The most striking aspect of this study is its detailed examination of how human factors influence aviation accidents across different aircraft types using network analysis. Utilizing Python's NetworkX library, this study constructed bipartite networks to explore the intricate connections between accidents and human error categories. By focusing on centrality metrics, it is revealed that pilot error is the most influential factor in these networks. The high degree centrality of pilot errors indicates that these errors are frequently connected to accidents, highlighting their significant impact on aviation safety. This suggests that targeted safety interventions, such as improved pilot training and stricter adherence to standard operating procedures, could substantially reduce the number of aviation accidents. Moreover, the visualizations provided by the bipartite network graphs and bar charts underscore the pervasive role of pilot errors across different aircraft types. The dense clustering of nodes around pilot errors in the graphs further emphasizes the need for focused safety measures in this area.

By leveraging network analysis to understand the complex relationships between accidents and human errors, this study makes a significant step forward in aviation safety research. It provides a robust foundation for future studies to build upon, aiming to incorporate larger datasets, explore additional human factors, and develop more comprehensive safety strategies to further improve aviation safety globally. This detailed network analysis and visualization provide valuable insights into the most influential human error categories across different aircraft types. By focusing on systemic issues alongside individual training, the aviation industry can enhance safety and reduce accident rates more effectively. The study demonstrates the utility of Network Analysis in understanding complex relationships within aviation safety data, highlighting the need for targeted interventions to address pilot errors and other human factors. Future research should build on these findings to develop more comprehensive safety strategies and further improve aviation safety globally.

The most striking aspect of this study is its detailed examination of the influence of human factors on aviation accidents across different aircraft types using network analysis. Conducted with the NetworkX library, this analysis reveals that pilot error is the most influential factor, emphasizing the need for targeted safety measures in this area. The high degree centrality of pilot errors indicates that these errors are frequently connected to accidents and have a significant impact on aviation safety. This finding suggests that focused safety interventions to reduce pilot errors could substantially decrease the number of aviation accidents. By leveraging network analysis to understand the complex relationships between accidents and human errors, the study makes a significant step forward in establishing effective aviation safety strategies.

Researchers’ Contribution Statement

All authors equally contributed to the study.

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Conflict of Interest Statement,

There is no conflict of interest with any parties.

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