FUZZY BAYESIAN BASED BOWTIE RISK ASSESSMENT OF AN UNSTABILIZED APPROACH: A METHOD FOR AIRLINE FLIGHT OPERATIONS

CANER ACARBAY

PhD Dissertation

Department of Avionics

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Eskişehir

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ABSTRACT

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Risk is inevitable part of life. As in all areas of life, risk management is of great importance in aviation. Matrices are one of the most frequently used methods in safety risk management in aviation. In this method, risks are classified according to probability and severity. In this sense, matrix risk assessment process has a static and discrete structure. However, operations in aviation consist of dynamic components. Outputs of dynamic components change over time. Dynamic and continuous system risk assessment in aviation can contribute to the risk assessment process and improve overall performance of safety risk management.

In this study, a dynamic risk assessment system design based on fuzzy logic and Bayesian network is combined with the bowtie method to analyze unstabilized approaches in flight operations. This approach forms a network structure with conditional probabilities and can be used with both quantitative and/or qualitative data. Each event in the system is connected to each other with conditional probabilities. Any change in probability of each basic event will update overall probability of the analysis. Hence, autonomous, and dynamic risk assessment process that produces fast results can be achieved.

Keywords: Flight Safety, Risk Assessment, Bowtie Analysis, Unstabilized Approach, Fuzzy Logic

ÖZET

İSTİKRARSIZ BİR YAKLAŞMANIN BULANIK BAYES TEMELLİ BOWTIE RİSK DEĞERLENDİRMESİ: HAVAYOLU UÇUŞ OPERASYONLARI İÇİN BİR YÖNTEM

CANER ACARBAY

Havacılık Elektrik ve Elektroniği Anabilim Dalı

Eskişehir Teknik Üniversitesi, Lisansüstü Eğitim Enstitüsü, Ağustos 2021

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Risk hayatın kaçınılmaz bir parçasıdır. Yaşamımızın her alanında olduğu gibi havacılıkta da risklerin yönetimi büyük önem arz etmektedir. Havacılıkta emniyet risklerinin yönetiminde sıklıkla kullanılan yöntemlerin başında risk matrisleri gelmektedir. Bu yöntemde riskler olasılık ve bu durumun yaratacağı şiddete göre sınıflandırılırlar. Bu anlamıyla risk değerlendirme aşaması statik ve kesikli bir yapıya sahiptir. Havacılıkta operasyon dinamik bileşenlerden oluşmaktadır. Dinamik sistemlerin çıktıları zamanla değişir. Bu sebeple risk değerlendirme aşamasında kullanılabilecek dinamik ve sürekli bir sistem, risk yönetim performansının artmasına katkı sağlayabilecektir.

Bu çalışmada bulanık mantık ve bayes ağlarını temel alan bowtie yöntemi kullanılarak oluşturulan dinamik risk değerlendirme sistemi uçuş operasyonlarında istikrarsız yaklaşma örneği üzerine uygulanmıştır. Bu yöntem sayesinde nicel ve nitel verilerin bir arada veya ayrı ayrı kullanılabildiği, ağ yapısına sahip, koşullu olasılıklarla ifade edilebilen bir risk değerlendirmesi amaçlanmıştır. Sistemi oluşturan olaylar birbirlerine koşullu olasılıklar ile bağlandığından sistem bileşenlerinin herhangi birinde meydana gelen olasılık değişimi tüm sistemi etkilemekte ve sonraki olasılık değerleri otomatik olarak güncellenmektedir. Bu sayede havacılık operasyonlarında kullanılabilecek hızlı sonuç üreten, otonom ve dinamik bir risk değerlendirme süreci gerçekleştirilmesi hedeflenmiştir.

Anahtar Sözcükler: Uçuş Emniyeti, Risk Yönetimi, Bowtie Analizi, İstikrarsız Yaklaşma, Bulanık Mantık.

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29/08/2021

STATEMENT OF COMPLIANCE WITH ETHICAL PRINCIPLES AND RULES

I hereby truthfully declare that this thesis is an original work prepared by me; that I have behaved in accordance with the scientific ethical principles and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be obtained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with "scientific plagiarism detection program" used by Eskişehir Technical University, and that "it does not have any plagiarism" whatsoever. I also declare that, if a case contrary to my declaration is detected in my work at any time, I hereby express my consent to all the ethical and legal consequences that are involved.

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GLOSSARY OF SYMBOLS AND ABBREVIATIONS

AAL	:	Above Airfield Level
ACA	:	Air Commerce Act
AH	:	Absolute High
AHP	:	Analytical Hierarchy Process
AL	:	Absolute Low
ATC	:	Air Traffic Control
BAC	:	Bureau of Air Commence
BEx	:	Basic Event x
c(1)	:	Consequence 1 - Safe State
c(2)	:	Consequence 1 - Unsafe State
CAA	:	Civil Aviation Authority
CAO	:	Civil Aviation Organization
CFIT	:	Controlled Flight into Terrain
DA	:	Decision Altitude
DAG	:	Directed Acyclic Graph
E	:	Environment
ETA	:	Event Tree Analysis
FAC	:	Final Approach Course
FAF	:	Final Approach Fix
FCOM	:	Flight Crew Operation Manual
FCTM	:	Flight Crew Training Manual
FDR	:	Flight Data Recorder
FMECA	:	Failure Mode Effect and Critically Effect Analysis
F_{ml}	:	Minimum of Left Intersection
F_{mr}	:	Maximum of Right Intersection
FORAS	:	Flight Operations Risk Assessment System
Ft	:	Feet
FTA	:	Fault Tree Analysis
GNSS	:	Global Navigation Satellite System

GPWS	:	Ground Proximity Warning Systems
H	:	Hardware
HACCP	:	Hazard Analysis and Critical Control Point
HAZOP	:	Hazard and Operability Studies
IAN	:	Integrated Approach Navigation
IATA	:	International Air Transport Association
ICAO	:	International Civil Aviation Organization
IE1	:	Intermediate Event 1
ILS	:	Instrument Landing System
IMC	:	Instrument Meteorological Conditions
ISO	:	International Standardization Organization
K	:	Possibility Constant
L	:	Low, Liveware
LNAV	:	Lateral Navigation
LOPA	:	Layer Protection Analysis
M	:	Medium
MCDA	:	Multi-criteria Decision Analysis
MDA	:	Minimum Descent Altitude
MH	:	Medium High
ML	:	Medium Low
NDB	:	Non-Directional Beacon
P(x)	:	Probability of x
PDF	:	Portable Document Format
PF	:	Pilot Flying
PM	:	Pilot Monitoring
RNP	:	Required Navigation Performance
RNP APCH	:	Required Navigation Performance Approach
RNP AR	:	Required Navigation Performance Authorization Required
S	:	Software
SARP	:	Standards and Recommended Practices
SBx	:	Safety Barrier x
SMS	:	Safety Management System
SPI	:	Safety Performance Indicator

SPT	:	Safety Performance Target
TCAS	:	Traffic Collision Avoidance System
TE	:	Top-Event
TEM	:	Thread and Error Management
VAPP	:	Approach Speed
VH	:	Very High
VL	:	Very Low
VMC	:	Visual Meteorological Conditions
VNAV	:	Vertical Navigation
VOR	:	Very High Frequency Omnidirectional Radio Range
VREF	:	Reference Speed
XTK	:	Cross Track Error
λ	:	Lambda

1. INTRODUCTION

The first powered flight in history was flown by the Wright brothers in 1903. Since then, the aviation industry has progressed from a flight duration of 12 seconds to 18-hour non-stop flight. Since that first flight a century of innovation has made aviation a key market for passenger transportation. The latest Boeing market outlook forecast states that the commercial aviation industry will reach a market value of 9 trillion dollars by the end of 2039 (Boeing, 2020). Aviation includes many national and international activities such as passenger transportation, cargo transportation, alliances, trade agreements, code sharing, and partnerships. Since the aviation industry is required to follow an enormous number of national and international regulations, airliners must design their frameworks to comply with these settlements. Therefore, standardization of operations and compliance with the laws are of great importance.

Safety is the most important component for a company to exist in commercial operations. In other words, associations cannot create a competitive revenue with a poor safety record. With a poor safety record, these companies will eventually collapse and disappear from aviation world. A well-designed safety framework within a company not only contributes to commercial stability, but also helps to identify early threats and improve safety.

From the outset of examining civil aviation, it can be observed that the states were the first operators rather than the legislative bodies of aviation. The first civil aviation activity in the United States (US) started in the form of an air cargo service. All aircrafts and personnel that operated in this era were financed by the state. At the beginning of the 1920s, measures like pilot selection criteria, timely and detailed implementation of maintenance of the airplanes and detailed checklists into operations contributed to the high-safety results obtained by civil aviation activities. As a result of this, state organized aviation operations have enjoyed a safety quality status fifty-eight times that of private sector organized operations. The high safety factor provided by the state has attracted the attention of investors in the industry. Due to the increased cost of operations brough about by a poor safety record, the private sector has sought out supervision of their operations by the government to improve their safety factors. As a result of this, aviation is one of the few areas where private entrepreneurs want their businesses to be regulated and controlled by the state.

Initial regulatory developments in aviation lead the formation of the Air Commerce Act (ACA) in 1926. The goal of the ACA was to create sustainable safety within aviation in the US. The ACA contained six areas. These were audit, licensing, medical, engineering, statistics, and execution. The driving force behind the ACA came from the private sector's goal to improve their safety record. For this reason, the policymakers prepared the first laws in the form of a minimum regulation so as not to break the incentives of the private sector. However, the budget to inspect airline operations as stipulated by ACA was inadequate which resulted in the state delegating its duty to a non-state organization. For this reason, standardization of the inspections could not be achieved.

Safety-enhancing modifications to ACA were introduced in 1935. With this modification, ACA became the Bureau of Air Commence (BAC). The BAC was tasked with additional duties to regulate civil aviation. Twin engine aircrafts, single engine night flights, flight time limitations for the pilots, aircraft dispatch procedures, navigational system designs are only a few examples that have been implemented under the BAC authority. In 1938, all responsibilities of the BAC were transferred to a new independent agency. This agency was named as Civil Aviation Authority (CAA). In addition to the regulatory oversight previously discussed the CAA had federal authority to regulate airfares, airway designs, Air Traffic Control (ATC), accident investigation, and safety rulemaking.

The introduction of multi-engine long endurance aircrafts, ATC, and airway structures, international flights between countries having different regulations in each country made aviation complex and difficult to manage. In the 1940s, airlines and governments realized a standardized framework around globe was needed in order to have an efficient, safe, and economically viable civil aviation market. As a result of this, the International Civil Aviation Organization (ICAO) was established at the Chicago Convention of 1944. The ICAO mandate was to develop international civil aviation standards and practices for states to ensure that flight operations continued in a safe, efficient, and economically robust structure. With the help of ICAO's standardization, approximately one hundred thousand flights each day are performed safely within the same regulatory framework around the globe. Figure 1.1 shows the hierarchy of the regulatory requirement for an aviation organization.

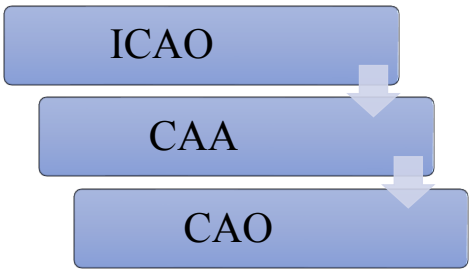


Figure 1.1. *Regulatory framework hierarchy*

The objective of the ICAO is to support strengthening civil aviation institutions, design safe infrastructure and services. In addition to that, technology transfer, human resources development, and promotion of Standards and Recommended Practices (SARPs) are also main objectives of the ICAO. The mission of the ICAO is to serve as the global convention of the states for international civil aviation. Each country's CAA is responsible to adapt ICAO's framework and function as a rulemaking regulatory body regarding aviation within the state. All CAOs registered under national CAAs must follow regulatory requirements set by the CAA.

ICAO's SARPs are described in annexes. Annexes contain internationally accepted SARPs for states. States use these technical documents as a blue print for designing their aviation regulatory frameworks, to insure that it adheres to the same standard as rest of the world. There are 19 annexes created by ICAO. Table 1.1 shows ICAO Annexes.

Table 1.1. *ICAO annexes*

Annex 1 - Personnel Licensing
Annex 2 - Rules of the Air
Annex 3 - Meteorological Services
Annex 4 - Aeronautical Charts
Annex 5 - Units of Measurement
Annex 6 - Operation of Aircraft
Annex 7 - Aircraft Nationality and Registration Marks
Annex 8 - Airworthiness of Aircraft
Annex 9 - Facilitation
Annex 10 - Aeronautical Telecommunications
Annex 11 - Air Traffic Services
Annex 12 - Search and Rescue
Annex 13 - Aircraft Accident and Incident Investigation
Annex 14 - Aerodromes
Annex 15 - Aeronautical Information Services
Annex 16 - Environmental Protection
Annex 17 - Security
Annex 18 - The Safe Transportation of Dangerous Goods by Air
Annex 19 - Safety Management

In addition to global standardization of civil aviation, airliners collaborated in 1945 to create a transport association to improve the understanding of the air transport industry among decision makers as well as increase awareness of the benefits that aviation brings to national and international economies. International Air Transport Association (IATA) was established in Havana, Cuba to provide safe, economical, and sustainable aviation services. In 2021, IATA is serving more than 82% of total air traffic in the world in membership with 290 airlines.

The 1950s saw a rapid change in the aviation industry bought about by an increase in technological advancements. In this era, non-pressurized flights were replaced with high altitude pressurized flights. This enabled fuel-efficient, long distance, and more comfortable air travel between countries. Also, the advent of jet engines facilitated quicker travel time and reduced refueling stops. Sophisticated airplane designs made

airplanes complex, consequently the human error rate in aviation increased. In the 1970s, several technological advancements were introduced to enhance flight safety. A few of the systems designed to help pilots maintain safe operations were glass cockpit display, fly-by-wire control system, Ground Proximity Warning System (GPWS) and Traffic Collision Avoidance System (TCAS).

The enhancement in technology has reduced the accident rate in aviation. However, accidents still occur today. For this reason, since the 1970s, organizations have shifted their approach on accident investigations from a focus on technical factors to human factors. After 1990s approach to aviation focused on in a different dimension, from individuals to organizations. In this approach, safety is shared by all stakeholders within the framework.

This study focuses on risk assessment part of flight safety management. Regulatory organizations promote the usage of matrix risk assessment technique. As a result of this, matrix risk assessment is widely used in aviation. This approach offers ease-of-use and simplicity for risk assessment. Moreover, matrix risk assessment approach is easy to understand and does not require intensive training requirements. However, risk matrix approach does suffer a few limitations to assign and classify risks. Firstly, analysis to be performed is highly dependent on individuals. Based on individual's analysis, a false sense of safety analysis outcome may be produced. As a result of this, resource allocation for the mitigation strategy may be different than the optimum solution. Secondly, matrix analysis highly relies on qualitative tools. Unlike qualitative data, quantitative data helps to prevent cognitive biases. Moreover, dynamic analysis is not possible by using risk matrix approach solely. Lastly, matrix approach does not offer any assessment for timeframe analysis. For example, overall risk of aircraft accident in three days would be totally different than in three years. To overcome certain limitations mentioned in the paragraph and enable dynamic and quantitative assignment, fuzzy-bayesian based dynamic risk assessment tool has been introduced for airliners in this study. Specific method is applied on unstabilized approach example as a risk assessment tool.

Aviation industry, by nature, is an environment that requires dynamic operations. Operations include hazards and these hazards create risks. From this basic statement, dynamic risk assessment for airlines and their operations are extremely important. Aim of the study is to propose a better approach on risk assessments for airline operations.

Incident of unstabilized approach is taken as an example in the study for risk assessment. The study used fuzzy logic and Bayesian network together to form dynamic structure in the analysis. By doing so, prior and posterior probabilities for the analysis are calculated. One of the most challenging factors of the analyses in aviation is to get quantitative data. In this study, data quantification technique is used to perform analysis. Safety Performance Indicator (SPI) data are introduced to measure the effectiveness of the analysis. Dynamic relationship in the analysis is obtained by transforming bowtie model into Bayesian network equivalent.

Throughout the study inductive reasoning method is used. However, this study does not aim to give all technical background about theoretical discussions. As it is not possible to attain full apprehension about aviation safety, risk, fuzzy logic, and Bayesian network by reading this study. More detailed technical explanation about theory and its application can be found in authority guidance, safety lessons, and related textbooks.

In the beginning of the study basic introduction about aviation safety and its importance have been revised. In the second chapter, safety management concept has been introduced to give basic theoretical knowledge to the readers. This chapter starts with basic definitions and continues with aviation safety history. Two important models (SHELL and Swiss cheese) for safety science have also been introduced in this chapter. Last part of the second chapter supplies technical background of risk and risk assessment process. In addition to that, bowtie model and its components have been introduced in the second chapter. Third chapter is constructed to give a conceptualization of fuzzy-bayesian bowtie analysis. After short introduction to aviation related terms such as approach stabilization and safety performance indicators, mathematical model of fuzzy logic and Bayesian network have been introduced. Fourth chapter explains proposed model in detail. Mathematical background of the study and algorithms are stated in this chapter. Finally, last chapter focusses on outcome and results of the study. Pros and cons of proposed model have also been discussed in the conclusion part.

2. AVIATION SAFETY MANAGEMENT CONCEPT

Safety management in aviation requires a systematic approach to manage the risks within the aviation framework. Airlines must implement Safety Management Systems (SMS) to manage the risks and evaluate the safety requirements within the framework. Safety policy, safety planning, safety assurance, safety improvement and safety culture are only a few requirements mandated by ICAO Annex 19. Safety management annex is a regulatory document for all service providers to adapt the SMS requirements. The following service providers within civil aviation are required to establish SMS framework:

- Aircraft operators – Airliners
- Aviation maintenance organizations
- Airport operators
- Training organizations
- Aircraft manufacturers
- Air navigation service providers

Before divulging into aviation safety management, the basic definitions of safety related terms will be elucidated. In the next section, basic definitions of threat, risk, undesired aircraft state, Shell model, and Swiss cheese model is explained to facilitate a more comprehensive understanding of SMS.

2.1. Basic Definitions

Risk is an inevitable part of life. Directly or indirectly, we take risks in our daily life based on actions and decisions. International Standardization Organization (ISO) defines risk as “effect of uncertainty on objectives”. Effect is the deviation from expectation in a positive or negative way. This new risk explanation defined by ISO is an objective based approach. Traditional risk definition uses event-based approach. In aviation, the traditional risk definition is widely used. Aviation authorities accept risk as the combination of frequency or probability of occurrence of a harmful effect induced by a hazard and severity of that outcome (Gerede, 2018). Throughout the study, traditional risk definition is accepted as a reference. Based on this approach there are three important aspects of a risk:

- Probability or frequency
- Hazard
- Severity

ICAO defines risk as an assessment which is defined in terms of predicted probability and severity of the consequences of a hazard taking as reference the worst foreseeable situation (ICAO, 2008). A hazard can be defined as any condition that can lead to injury, illness, or loss of life of a person, or loss of a system, equipment, or damage to the environment. In other words, a hazard can be classified as anything that can harm, damage, or cause an injury. Figure 2.1 illustrates the basic idea of the risk in aviation framework.

Figure 2.1. *Risk definition*

An example of hazard, risk and consequence is given in Table 2.1.

Table 2.1. *Hazard, consequence, and risk relationship*

Hazard	Contaminated Runway
Consequence	The potential that a pilot cannot maintain control of the aircraft on the runway during takeoff or landing.
Risk	The assessment of the consequences of the potential loss of the control of the aircraft in terms of probability and severity.

Risk and safety in aviation have a direct correlation. Safety can be defined as keeping the risks of aviation related activities such as flight operations, maintenance etc. in an acceptable level for the continuation of the operations. As previously stated, risk cannot be eliminated entirely within the framework. For example, to eliminate the entire risk in a flight operation there should not be any hazard present. This would only be possible if there were no flight operations. As a result of this, managing the risk is an exceptionally important aspect in aviation safety management. The aim of aviation safety management is to identify the hazard and mitigate the risk within the acceptable level.

SMS also aims to prevent accidents and incidents in aviation. ICAO annex13 describes accident as (ICAO Annex 13,2001):

"An occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, in which:

a) a person is fatally or seriously injured as a result of: — being in the aircraft, or — direct contact with any part of the aircraft, including parts which have become detached from the aircraft, or — direct exposure to jet blast, except when the injuries are from natural causes, self-inflicted or inflicted by other persons, or when the injuries are to stowaways hiding outside the areas normally available to the passengers and crew; or

b) the aircraft sustains damage or structural failure which: — adversely affects the structural strength, performance or flight characteristics of the aircraft, and — would normally require major repair or replacement of the affected component, except for engine failure or damage, when the damage is limited to the engine, its cowlings or accessories; or for damage limited to propellers, wing tips, antennas, tires, brakes, fairings, small dents or puncture holes in the aircraft skin; or

c) the aircraft is missing or is completely inaccessible."

An incident is defined as any occurrences other than that of accident associated with the operation of an aircraft which jeopardize the safety. Accidents and incidents can happen due to lack of safety and security management. Safety and security are often confused and used as a synonym. In fact, safety and security are two different concepts. Whilst safety refers all kind of activities to keep airplanes free from accidents and errors that may lead injury or loss, security on the other hand, refers to the measurements taken to prevent deliberate actions. In the Turkish language, safety and security are frequently and incorrectly referred under the same meaning (Gerede, 2006). In this study, the safety aspect of risk management will be examined.

In aviation SMS uses an organizational approach and human factors to assess and manage the risks. System design should eliminate errors and violations in operations. Violations are deliberate act of deviation from the rules whereas errors are not. The next section expresses details about safety concept on human factors perspective.

2.2. Evolution of Safety in Aviation

Technological evolution in aviation led to a complex system and aircraft design. Since engineering design processes requires a multidisciplinary approach between many areas, it is not possible for a pilot to have a complete understanding of the technological background of the aircraft. As a result of this, from a pilot's perspective, airplane design should be simple and efficient to prevent human induced errors. A new generation cockpit instruments are typical example of simple and efficient system design (Acarbay, 2014). In the first jet designs, all performance and system indicators were displayed individually. This made it impossible for the pilot to monitor all the systems requiring the addition of an extra crew member to the flight deck, namely flight engineer. The invention of glass cockpits significantly improved situational awareness of the pilots. This was done by showing the pilot only the most important flight and performance indicators to the pilot thus reducing the pilot's workload to monitor system parameters. A benefit of this approach was the elimination of the requirement of a third person in the cockpit. As a result of this, operation and maintenance cost of flights were reduced.

Technological advances in aviation and aircraft design in the 1970s improved overall safety. However, accidents persisted despite all efforts that put into design.

Consequently, the approach on accidents have been shifted from technical factors to human factors and then organizational factors. Nowadays, systematic approaches are commonly preferred methods to analyze accidents. Figure 2.2 shows the industry's approach to accidents. In the following section, human and organizational factors on accidents analysis will be discussed.

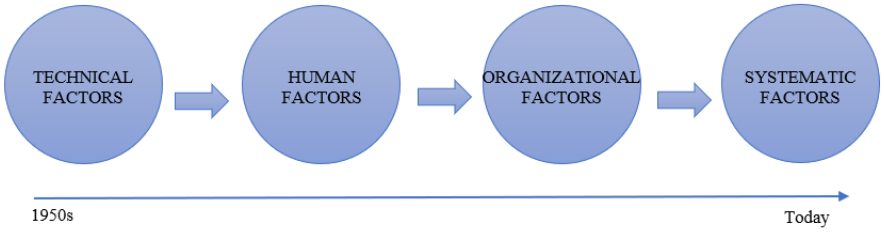


Figure 2.2. *Industry's approach on accident analysis*

2.2.1. SHELL model

SHELL model is a conceptual tool to analyze interaction of multiple system components. It is commonly used in human factor analysis to have a more comprehensive understanding of human and aviation resources/environment relationship. The SHELL model was designed in 1972 and became widely accepted in the aviation industry. SHELL name for the model was derived from the first letter of the system components which are software, hardware, environment, and liveware respectively (Miller and Holley, 2008).

In the SHELL model, the blocks that are only in a relation with liveware are illustrated. The main purpose of the model is to analyze human factors. Therefore, H-H, H-S, H-E blocks, and their reciprocals are not mentioned in the system. Some examples of the system components are given below. Figure 2.3 illustrates SHELL model.

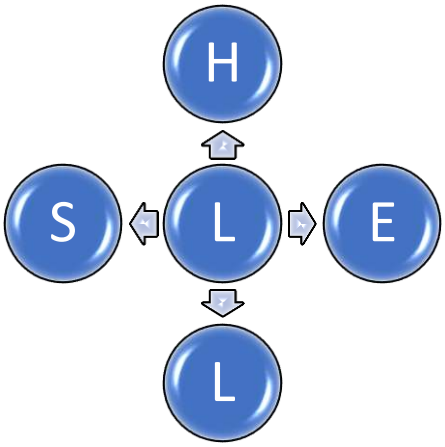


Figure 2.3. *SHELL model*

- S – software covers the rules, documents, procedures, checklists, training, culture.
- H – hardware covers control and surfaces, cockpit equipment, displays, machines, tools.
- E – environment is a hub which covers S-H-L connections. Environment does not only cover physical surrounding, but also covers social and economic climate in the analysis.
- L – liveware are described as human beings. Pilots, engineers, ATC, cabin crew are only a few examples of the liveware.

In the SHELL model, human (liveware) is in the center of analysis and interacts with any other components in the system. Humans have a natural tendency to make mistakes and can be easily disturbed by external factors. In contrast to hardware, liveware cannot be modelled within rigid boundaries. Each person's natural reaction to environmental factors (temperature, sound, cultural influence) may vary. Consequently, it is almost impossible to design a system which can consider each liveware's behaviors based on same inputs. To overcome this problem, the SHELL model uses liveware centered human factor analysis to identify lacking points in the system and take precautionary steps to prevent threats in the system.

Liveware-hardware interaction in the model effects human performance from the outset. Human factors should be considered in the design phase in order to prevent hull loss of the system. Well-designed display layouts, ergonomics of the seat design for pilots, and proper tools for engineering work positively affect the performance of the outcome. Hardware in the system must be designed in a user-friendly manner and must satisfy the ease-of-use principle.

Liveware-software interaction plays vital role for the support of the operation. Therefore, software tools must be designed in such a way that users are not prone to make errors. Checklists, computer software, interface designs, operational procedures are some of the most important conditions for safe and reliable operations.

Liveware-environment interaction can be reviewed under two habitats. These are environmental and organizational respectively. Environmental effects can be that relating to temperature, humidity, noise, lighting, meteorological, and turbulence. Providing

appropriate working conditions, well-adjusted resting periods are example of organizational interactions, and they will improve efficiency in the L-E interaction.

Liveware-liveware interaction is the most challenging interaction in the SHELL model due to the complex nature of human beings. It is highly probable to attain different outputs for the same input for each L-L interaction. Therefore, traditional design techniques for L-S, L-H cannot be applied to L-L interaction. To overcome this problem, liveware must share the same motivation and safety culture within the organization. Effective communication, training, standardization, and culture in organizations help to manage L-L interaction efficiently.

As previously discussed, the SHELL model has a human centered approach. Block based analysis gives a good opportunity for the analyzer to view interactions between each block. Although the SHELL model is useful source to analyze interactions, there is usually more complex reasoning behind incidents or accidents. Accidents do not happen for a single reason. In the next section, James Reason's (1990) Swiss cheese model will be explained to understand an organization's role on the success or failure of the operations.

2.2.2. James Reason (Swiss cheese) model

Generally, accidents in aviation do not occur because of a single failure. In general, many organizational and/or individual failures happen before causing an accident. The Swiss cheese model was introduced by James Reason and uses a layered series of barriers to prevent an accident from happening. Each barrier in the model is called a slice of cheese. The holes in the slices represent the weaknesses of the slice or weakness of the barrier. These holes are dynamic by nature. They can grow or shrink; they can move within the slice or the numbers of holes in a slice can increase or decrease based on organization's and/or individual's behavior. If the holes in each slice are aligned together momentarily, a projection towards to an unsafe act or accident is created so that a hazard can pass through each hole and possibly create an unsafe situation or an accident. Figure 2.4 summarizes the Swiss cheese model.

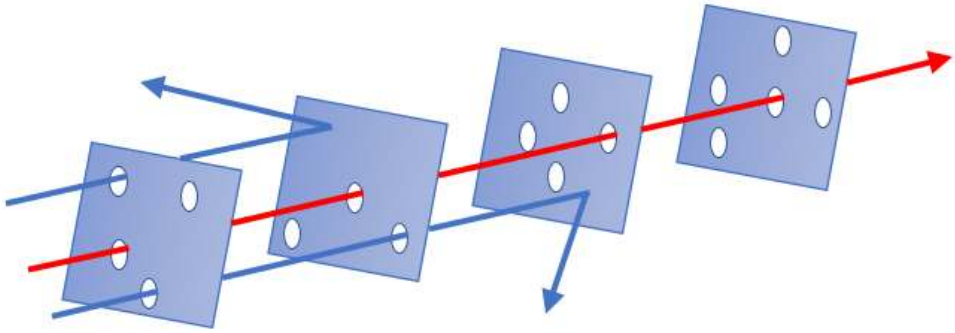


Figure 2.4. *Swiss cheese model*

In this model, most of the accidents can be traced back through 4 different levels (slices). These layers are described as follows and shown in Figure 2.5.

- Organizational influence
- Workplace
- People
- Defenses

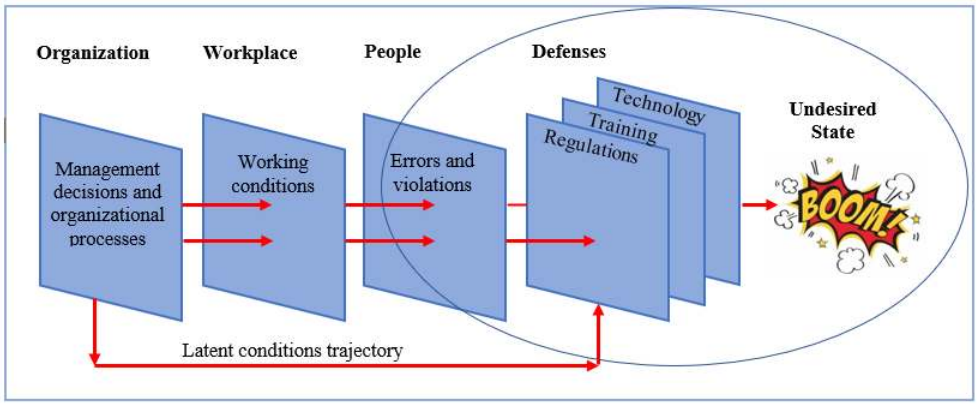


Figure 2.5. *Four main level in Swiss cheese model*

Failures on these layers are described as holes. Failures can be active or latent. Whilst active failures contribute to accident directly, latent failures may be hidden for a long time before it finally contributes to an accident. The main purpose of SMS is to decrease the size and number of failures (holes) in the system.

SMS plays vital role in aviation organizations. If it is not designed properly an accident can happen directly without being caught by any defensive layer. In other words,

if risk management is not achieved properly all defensive layers in the Swiss cheese can be bypassed. The next section explains the basics of SMS.

2.3. Safety Management

ICAO defines safety in "Doc 9859 Safety Management Manual" (ICAO, 2013) as "the state in which the possibility of harm to persons or of property damage is reduced to, and maintained at or below, an acceptable level through a continuing process of hazard identification and safety risk management." As it can be easily understood from the previous definition, safety assurance within an organization is a continuous process. Therefore, it needs to be managed.

SMS is described by ICAO as a systematic approach to manage safety, including the necessary organizational structures, accountabilities, policies, and procedures. There are four components in the SMS. These components are safety policy, safety assurance, safety risk management and safety promotion. Figure 2.6 shows components of the SMS.

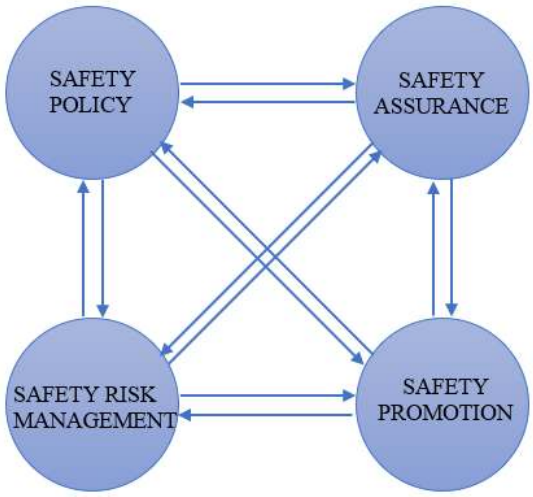


Figure 2.6. *SMS components*

A safety policy is the declaration of senior management's commitment to improve safety continuously. It defines written procedures, methods, and the organizational structure needed to meet the organization's aim on safety.

Safety assurance is an evaluation of implemented risk mitigation strategy and a supportive tool for hazard identification. It is a continuous process of monitoring a organization's safety performance. Based on this performance, the inadequate feature of

the system should be detected. Once detected the organization must implement corrective actions to achieve organization's safety goal.

Safety promotion plays a vital role in SMS, all stakeholders in an organization must share same perspective on the safety policies and work together. Safety promotion is a supportive tool for the organizations and is built on other safety management components (safety policy, safety assurance, and safety risk management).

The elimination of all risks in aviation is an unrealistic approach. Risks should be kept within acceptable level for the safe operations. Therefore, risk identification and mitigation strategies have a critical importance on safety. The safety risk management component of SMS is the center of the management model. In the next section, safety risk management is going to be described briefly.

2.3.1. Safety risk management

The risk concept accepted by ICAO takes risks into account as inevitable entities in an ontological setting. It also adopts organizational theory and engineering approach partially associated with actuarial approach (Uyar, 2019). Risk management is a continuous process to identify, analyze, and mitigate the hazards as well as subsequent risks. The objective of safety risk management is to identify the hazards and develop appropriate mitigation strategies for those hazards. A supportive layout for a safety risk management designed by ISO (2009) is shown in Figure 2.7.

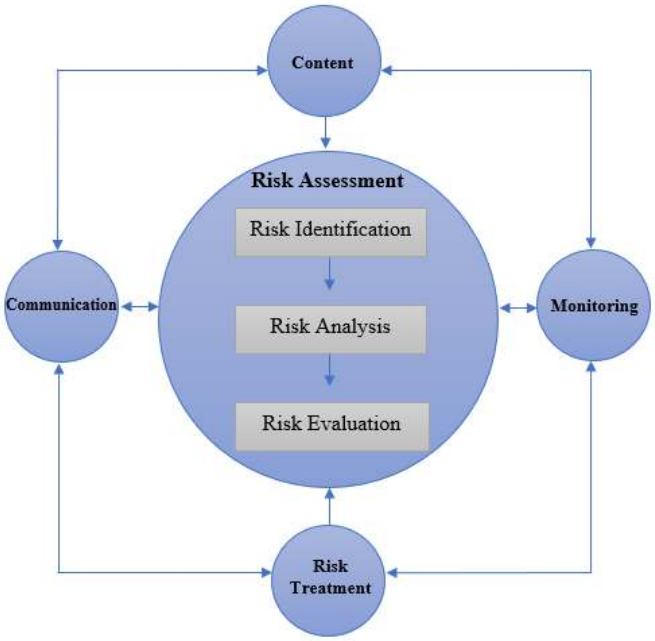


Figure 2.7. *Safety risk management*

Risk assessment is a process of risk identification, analysis, and evaluation. The risk identification step aims to accomplish a comprehensive list of risks associated with the nature of the operation. Misconducted risk identification may not be caught in the further analysis. Therefore, it is important to have a detailed identification process. Safety reporting, past occurrences and experiences, expert opinions, auto-monitoring, internal and external investigations, can all be used to identify risks. Risk assessment steps are illustrated in Figure 2.8

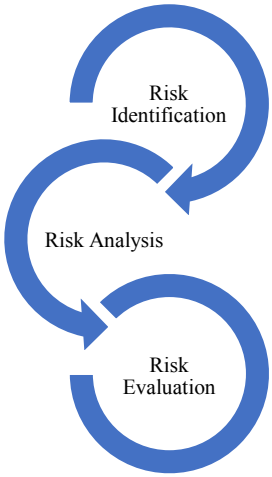


Figure 2.8. *Risk assessment steps*

Risk analysis is conducted to eliminate undesired states. It also aims to create safe and efficient control barriers to prevent the negative consequences. To achieve this goal, it is important to comprehend risk identification process. If the first step (risk identification) is not examined thoroughly, the analysis will not generate an integrative solution. Risk analysis considers cause and source of the risk as well as potential consequences. Safety risk assessment is the base of this study.

Risk evaluation is the last step of the risk assessment process. It facilitates making decisions based on the outcome of the analysis. Moreover, it shows both strong and weak points of the system as well as rendering an understanding about the treatment process.

The risk assessment process can be quantitative, qualitative or combination of both. Table 2.2 summarizes ISO recommended techniques for risk assessment. (ISO 31010, 2019).

Table 2.2. *Risk assessment process*

Tools and techniques	**Risk assessment process**				
	Risk Identification	**Risk analysis**			**Risk Evaluation**
		Consequence	**Probability**	**Level of risk**	
Brainstorming	1	3	3	3	3
Structured or semi-structured interviews	1	3	3	3	3
Delphi	1	3	3	3	3
Checklists	1	3	3	3	3
Primary hazard analysis	1	3	3	3	3
Hazard and operability studies (HAZOP)	1	1	2	2	2
Hazard Analysis and Critical Control Points (HACCP)	1	1	3	3	1
Environmental risk assessment	1	1	1	1	1
Structure “What If?”	1	1	1	1	1
Scenario analysis	1	1	2	2	2
Business impact analysis	2	1	2	2	2
Root cause analysis	3	1	1	1	1
Failure model effect analysis	1	1	1	1	1

Fault tree analysis	2	3	1	2	2
Event tree analysis	2	1	2	2	3
Cause and consequence analysis	2	1	1	2	2
Cause-and-effect analysis	1	1	3	3	3
Layer protection analysis (LOPA)	2	1	2	2	3
Decision tree	3	1	1	2	2
Human reliability analysis	1	1	1	1	2
Bow tie analysis	3	2	1	1	2
Reliability centered maintenance	1	1	1	1	1
Sneak circuit analysis	2	3	3	3	3
Markov analysis	2	1	3	3	3
Monte Carlo simulation	3	3	3	3	1
Bayesian statistics and Bayes Nets	3	1	3	3	1
FN curves	2	1	1	2	1
Risk indices	2	1	1	2	1
Consequence/probability matrix	1	1	1	1	2
Cost/benefit analysis	2	1	2	2	2
Multi-criteria decision analysis (MCDA)	2	1	2	1	2
1 – Strongly applicable *2 – Applicable* *3- Not applicable*					

2.3.2. Risk assessment process

Aviation is a dynamic environment which involves many risk factors within its complex structure. For that reason, the above-mentioned tools to assess the situation may not be sufficient as a stand-alone resource. Some analysis can be achieved by expert opinions. On the other hand, some complex assessment techniques use probabilistic and/or statistics based quantitative approaches. Customarily, more than one assessment tool is required to achieve the goal of assessment. At times, this requires quantitative and qualitative techniques to be used together. A challenging factor for the quantitative analysis is to find numerical data for the analysis. Most of the time numerical values are

either obtained directly from statistical data or by quantification of linguistic values. Additionally, it is important to assess numerical and linguistic dataset in the same aircraft.

In this thesis, dynamic fuzzy-Bayesian bowtie method is used to analyze unstabilized approaches in flight operations. As it can be seen in ISO recommended risk assessment techniques (Table 2.2), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Bowtie Analysis, and Bayes networks are recommended in risk assessment. They are used altogether in a single assessment in this study. This novel approach to analyze risks in flight operations allows a probabilistic approach to analyze prior or posterior probabilities for risk factors in flight operations. In the following sections, theoretical background of FTA, ETA and Bowtie methods will be explained.

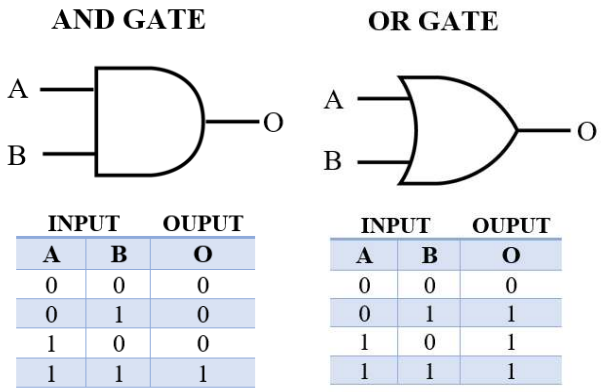
2.3.2.1. FTA

FTA is a deductive, top-down technique for analyzing contributing factors to a top-event which is an undesired event. Analysis starts with a top-event and leading factors that can contribute to top-events are listed with Boolean logic with a series of lower events. Success of the analysis (Andonov, 2018) depends on the followings:

- Characteristics of the event
- Data collection & protection method
- Determining the data: quantitative or qualitative
- Analysis methods and tools
- Experts' opinion

FTA starts from the top-event (undesired state) and proceeds backwards by determining the potential sources of the top-event. Since this analysis starts from the top and advances towards to bottom, it is a deductive technique. Logic gates are used in the analysis to represent the relationship between each event. Commonly, used logic gates are "AND" and "OR" gates. Mathematical expression of "AND" and "OR" gates are showed in Table 2.3. Figure 2.9 shows a generic example of FTA.

Table 2.3. *Mathematical expression of AND-OR gates*



INPUT		OUPUT
A	B	O
0	0	0
0	1	0
1	0	0
1	1	1

INPUT		OUPUT
A	B	O
0	0	0
0	1	1
1	0	1
1	1	1

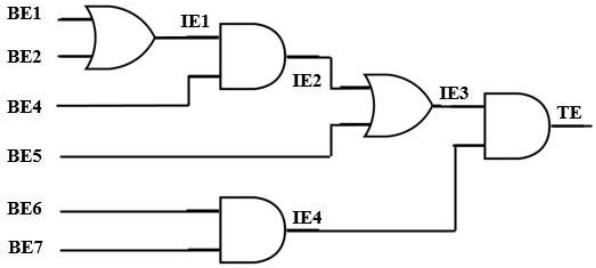


Figure 2.9. *FTA*

FTA is used to analyze failure of a system. It's commonly used in high-risk industries such as aviation, aerospace, nuclear power, and chemical engineering. It shows clear understanding of the logic leading the top-event. Moreover, it helps to optimize system by showing inter-relationship of sub events and monitor overall safety performance. On the other hand, if the analysis is complex, it is difficult to understand analysis and requires highly experienced individuals to perform the analysis. FTA is the tool to understand the contributing reasons for the top-event. It does not give any information about consequences if top-event occurs. For that, another analysis is used in literature. Next section describes basics of the ETA.

2.3.2.2. ETA

ETA analyzes the outcome and the impact of the undesired state. ETA also uses a top-down approach in the analysis. ETA is an inductive tool for the analysis. Top-event in that case can be named as initiating event. Main purpose of the ETA is to suppress the effect of the initiating event. This method can be used for both quantitative and qualitative analysis. If a system has numerical probabilistic values, ETA can be used efficiently to analyze the safety performance of the system. As a result of this, in high-tech and high-

risk sectors, ETA is used broadly. Since probabilistic approach can be used, ETA eliminates the need for anticipation. However, there are a few limitations in ETA. It can only address one event for initiating factor. Moreover, it is difficult to obtain failure probabilities of the analysis. Figure 2.10 showing the structure of ETA.

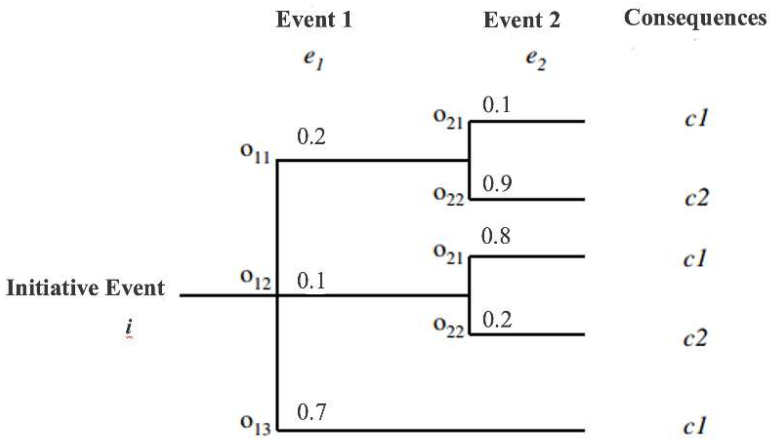


Figure 2.10. *ETA*

2.3.2.3. Bowtie analysis

Bowtie analysis is a combination of FTA and ETA. The first part of the analysis consists of FTA and identifies the events that may cause an undesired state whereas ETA, as part of the bowtie method, deals with the consequences of the top-event sequencing from the initiating event. It is a credible illustration to visualize the contributing factors and outcome for a single top-event. Figure 2.11 shows bowtie methodology. The name of the analysis stems from the shape of the method (Figure 2.12).

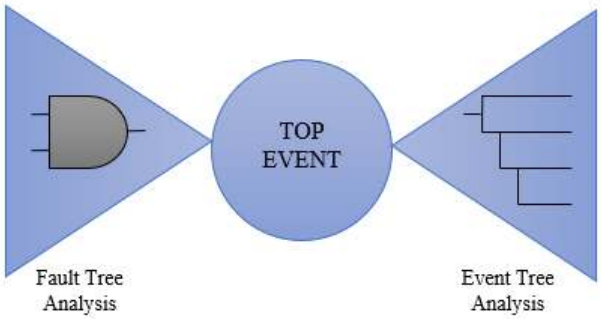


Figure 2.11. *Bowtie methodology*

Figure 2.12. *Bowtie*

High risk fields such as aviation, chemistry, and nuclear power plants also uses bowtie method which defines/illustrates/shows causal relationship in risk assessment. By incorporating human factors into bowtie analysis, Targoutzidis (2010) proposed a simplified approach for workplace risk assessment. Khakzad, Khan, and Paltrinieri (2014) studied the application of near accident data to risk analysis of major accidents. In transportation industry, bowtie method is also used. A risk management framework for seaports and offshore terminals which uses bowtie method is proposed by Mokhtari. Similarly, bowtie analysis is used by Arici, Akyuz and Aslan (2020) for maritime transportation where ship collision case during ship-to-ship operation is analyzed.

Bowtie method is a successful tool to analyze scenario-based events. In this approach, proactive and reactive risk management techniques can be used together. Analysis starts with describing a hazard. It is the potential for an organization or operation to cause damage. Once the hazard is described, the top-event related to hazard can be defined. Next, threats are described in the analysis. These threats are the causes that can give rise to the top-events. Consequences are the results of the top-event. Whereas only one top-event presents in the analysis, there are generally more than one threat and consequences in the analysis. Figure 2.13 shows the flow of the analysis.

Figure 2.13. *Bowtie analysis*

An example of bowtie analysis parallel to Figure 2.13 can be given in aviation as follow. Flight operations are hazards since they can lead to many undesired events. An unstabilized approach, on the other hand, can happen because of this flight. In this

example, the flight operation is the hazard and the unstabilized approach is the top-event. The reasons that can contribute to unstabilized approaches such as lack of pilot monitoring duties, inadequate training, degraded situational awareness, adverse weather conditions are defined as threats. Events that may happen after an unstabilized approach such as runway overrun, runway excursion, long touchdown are defined as consequences. Figure 2.14 shows an example of assignment process for bowtie methodology.

Figure 2.14. *An example of assignment process for bowtie methodology*

Four main steps in the analysis are compulsory. With these steps, bowtie analysis uses a reactive approach. There is a specific tool that can be used in the analysis to make this approach proactive. This tool is called barrier or often referred as a protection or safety measurement. Barriers can be thought as Swiss cheese slices in the analysis in attempt to eliminate an undesired state or if an undesired event occurs, the attempts to mitigate its effects. These barriers are called control measurements if they are located in the FTA region, whereas they are called recovery measurements if they are in the ETA side. Barriers in the system are not optimal and have the potential for failure. The reasons that can lead to a failure of a given barrier are called as escalation factors. Figure 2.15 shows entire bowtie elements.

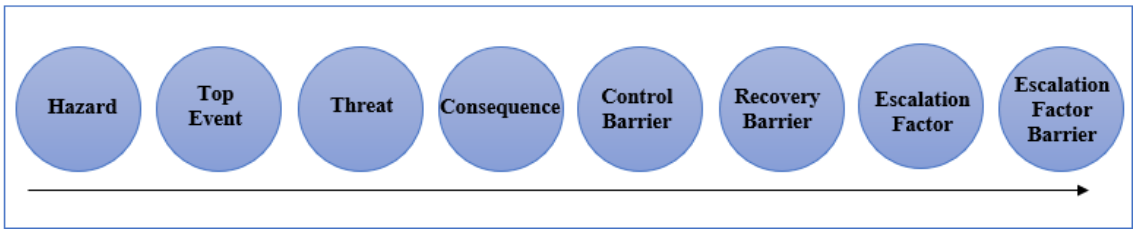


Figure 2.15. *Bowtie elements*

3. DYNAMIC RISK ASSESSMENT

Aviation is complex and dynamic structure. For that reason, most of the time single risk analysis is not enough to assess the risks within the framework. Classical risk classification promoted by ICAO uses a matrix approach to classify the risks within three groups. This approach is static and requires human interpretation to modify the risk groups. Moreover, classification requires static threshold for the tolerance groups of the risks. In this study, to overcome static nature of risk analysis, dynamic performance based fuzzy-Bayesian bowtie analysis is designed for flight operations. The system design is also illustrated with a risk analysis of unstabilized approaches in flight operations.

Risk assessment nature includes uncertainty in its framework. Lack of data to analyze often requires expert's interpretation to complete risk analysis. To overcome this problem, Ding and Ru (2008) developed a new flight risk assessment index by using Bayesian belief networks with a combination of fuzzy comprehensive evaluation. Dynamic risk analysis is widely used in engineering fields. Dynamic bowtie analysis for sugar refinery explosion is used to analyze this incident (Khakzad, Khan, and Amyotte, 2012). Meel and Seider (2006) developed plant-specific, dynamic risk assessment to predict the frequencies of abnormal events utilizing accident precursor data. Risk modeling of a hydrogen gasholder using a fuzzy Bayesian Network is performed by Aliabadi, Pourhasan, and Mohammadfam (2019). Safety assessment of process systems has been performed by Zarei, Yazdi, Khakzad, and Reniers (2019) using a fuzzy extended bowtie model. Similarly, Process system risk analysis using fuzzy evidence theory and Bayesian networks has been studied by Yazdi and Kabir (2018). Fuzzy-bayesian networks for safety risk analysis are also used in construction projects (Zhang, Wu, Skibniewski, Zhong and Lu, 2014). In chemical engineering, dynamic safety analysis is used extensively (Khakzad, Khan, and Amyotte, 2013; Cai, Hu and Zhang, 2016; Shan, Liu, and Sun, 2017). Bilal, Mohammed and Brahim (2017) used the bowtie method and Bayesian networks for the risk analysis of fire and explosion in pipelines in their study. During the risk analysis phase of this event, the difficulty of determining the probability of each major event is highlighted. Therefore, the researchers obtained the opinions of four experienced experts on the subject to get prior probabilities using fuzzy logic method. Similarly, Cai, Hu and Zhang (2016) showed risk analysis of distillation equipment using fuzzy logic and bowtie methods. Khakzad and Amyotte (2011) stated that FTA may not be sufficient alone to represent inter-event dependencies. To overcome

this problem, they carried out dynamic risk analysis for the distillation operation in the sugar production facility using bowtie method and Bayesian network. Failure distributions of the primary events in the FTA have been continuously monitored and updated by the physical reliability models. The second part of the bowtie analysis consisted of the ETA. The probability of the consequences when top-event occurs is also updated with the updated bowtie analysis. Thus, real-time updating of the probabilities in the risk analysis is achieved (Khakzad, Khan, and Amyotte, 2012). Similarly, Real-time risk analysis of road tanker containing flammable liquid has been performed by Li, Xu, and Shuai (2019) by using Fuzzy Bayesian Network. Zhang, Wu, Skibniewski, Zhong and Lu (2014) carried out tunnel construction risk analysis using Bayes networks and fuzzy cluster theory. In the study by Khakzad, Khan, and Amyotte (2013), dynamic safety analysis is shown by an example of vapor cloud firing. Similarly, Meel and and Seider (2008) presented plant-specific, real-time, risk assessment using Bayesian analysis to design forecasting and reliability analyzer. Li, Chen and Zhu (2016) performed quantitative risk analysis on leakage failure of submarine oil and gas pipelines using Bayesian network. Finally, Zio (2018) performed an extensive review of a risk assessment techniques on his study about the future of risk assessment. His paper explains and compares different risk assessment techniques in risk assessment.

Main concentration of this study is to create a dynamic risk assessment system using a fuzzy-Bayesian bowtie method. Bowtie analyses illustrate clear pathway between cause to risk and risk to consequence with a simple diagram. Moreover, control and escalation factors can be defined in the analysis to prevent, mitigate, or control the hazards in the analysis. On the other hand, pure bowtie analysis does not provide quantitative assessment unless it is linked to FTA or ETA. In addition to that, numerical data or quantification of linguistic inputs are not easy to obtain in the analyses. To overcome this problem, fuzzy logic is introduced for the quantification of linguistic expressions. This method helps resolve the quantification problems that are generally seen in bowtie analysis. To have dynamic analysis in bowtie, analysis is mapped into Bayesian network equivalent. Prior probabilities of the analysis are obtained by expert opinions and verified by SPIs. Thus, posterior probabilities of the analysis are calculated based on prior probabilities and changing risk factors. Figure 3.1 shows the orientation of the study in aviation safety literature.

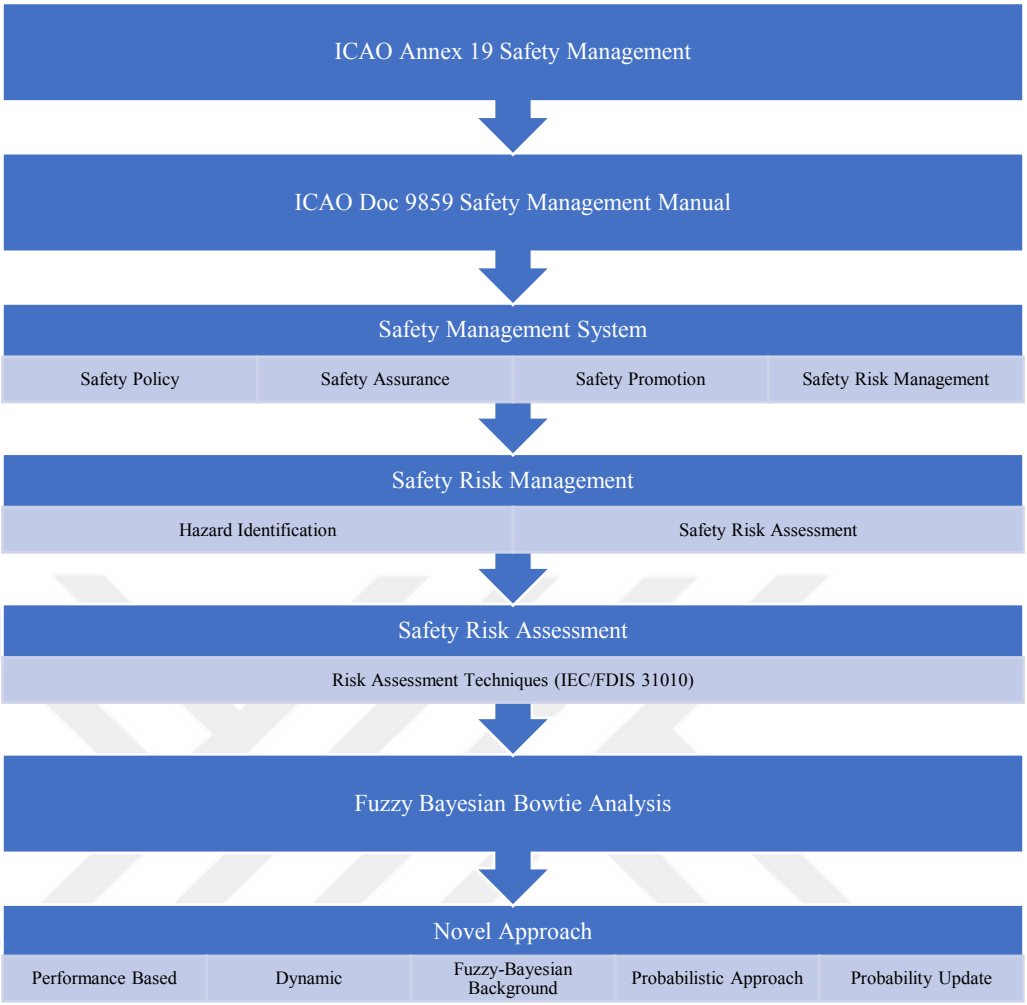


Figure 3.1. *Orientation of the study*

A new approach to assess the risks in flight operations will contribute to the field of safety risk management. From top-down approach, study positions itself under ICAO Safety Management, DOC 9859 Safety Management Manual, Safety Management System chapter, Safety Risk Management sub chapter, Safety Risk Assessment subtopic. The aim of the study is to contribute to the risk assessment process of airlines by supplying fast, dynamic, and autonomous risk assessment in their operations. Proposed model is applied on unstabilized approach case study from the outset.

3.1. Approach Stabilization

Establishing and maintaining stabilized approaches are great ways to avoid the undesired aircraft states. Therefore, it's a necessity to define a barrier to meet certain parameters within specified altitude. Stabilization concept uses flight parameters (speed, configuration, position) to define stabilized approach. Failure to meet defined parameters at certain altitude requires go around or discontinuation of the approach. Each operator

decides their own stabilization criteria and state these requirements in their manuals. Boeing defines stabilized approach gate (Flight Crew Training Manual-FCTM, 2020) as:

- If the approach is flown under Instrument Meteorological Conditions (IMC), airplane should meet stabilized approach criteria latest 1000 feet (ft) above airfield level (AAL).
- If the approach is flown in Visual Meteorological Conditions (VMC), airplane should meet stabilized approach criteria latest 500 ft AAL.

These gates are merely suggestions by which a final decision is stipulated by the aircraft operator. Outside of the North America, the stabilization gate is often decided irrespective of flight meteorological conditions. For example, Turkish Airlines uses approach type-based gates rather than meteorological conditions. According to this description all straight-in approaches shall be stabilized latest 1000 ft AAL. For circling approach, sidestep maneuver and visual traffic patterns, approach stabilization criteria shall be met latest 500 ft AAL, and wings shall be level latest 300 ft AAL.

3.1.1. Stable approach criteria

An approach is classified as stabilized when it meets and maintains required parameters in the form of energy, position, and configuration. Turkish Airlines Boeing 737 fleet defines stabilized approach criteria as (THY B737 Part B, 2021):

- The aircraft is in the planned landing configuration and no configuration changes shall be made.
- All briefings and checklists have been completed.
- The aircraft is on the correct lateral and vertical flight path. Only small changes are required to maintain the correct flight path.
- Idle thrust setting shall not be considered as a factor for unstable approach, as long as rest of the stabilization criteria are met when passing 500 ft AAL.
- The aircraft shall be at approach (target) speed. Deviations of Vapp +10 knots to Vapp -5 knots are acceptable if the airspeed is trending toward approach (target) speed. No approach (target) speed is allowed below VREF. Speed requirement may be delayed until 500 ft AAL.

- Rate of descent is not greater than 1,000 fpm. Momentary deviations may be accepted, as long as a precautionary callout is made, and immediate corrections are made.
- Following a GPWS caution aural alert, the suitable Pilot Flying (PF) response should be:
    a) If VMC take immediate corrective action to correct the flight path and continue the approach,
        - Any repetitive (more than twice) GLIDE SLOPE or more than one time "SINK RATE SINK RATE" GPWS caution alerts are received, initiate go-around.
            - ❖ Example for repetitive (more than twice) GPWS glide slope caution alert "GLIDE SLOPE", "GLIDE SLOPE", "GLIDE SLOPE", initiate go-around.
            - ❖ Example for more than one-time GPWS sink rate caution alert "SINK RATE SINK RATE", "SINK RATE SINK RATE", initiate go-around.
        - Any repetitive (more than twice) combination of "GLIDE SLOPE" and "SINK RATE SINK RATE" GPWS caution alerts are received, initiate go-around.
            - ❖ Example for repetitive (more than twice) combination of "GLIDE SLOPE and "SINK RATE SINK RATE" GPWS caution alerts; "GLIDE SLOPE", "SINK RATE SINK RATE", "GLIDE SLOPE", initiate go-around.
    b) If IMC at or below 1,000 ft AAL execute go-around.
- Specific types of approaches are stabilized if they also fulfill the following:
    - o ILS approaches must be flown within one dot of the Localizer and Glide Slope.
    - o Non-precision approaches maximum deviation from VOR is ½ dot or 2.5 degrees and Non-Directional Beacon (NDB) is 5 degrees.

- Required Navigation Performance Approach (RNP APCH) (RNAV Global Satellite Navigation System (GNSS) when using LNAV/VNAV minimums) or RNP AR APCH (RNAV RNP) must be flown from FAF to MDA/DA; within vertically +/- 75 ft (or amber deviation alert) and horizontally XTK (cross track error) not exceeding 1 x RNP (or amber deviation alert).
- Approaches using Integrated Approach Navigation (IAN) shall be flown within one dot of the glide path and Final Approach Course (FAC).

- For approaches requiring a descent angle of 3.1 to 4.0 degrees, maximum allowed descent rate below 1,000 ft AAL is 1,300 fpm; if the maximum allowed descent rate is exceeded, initiate a GO-AROUND.
- In case of an emergency final authority to continue the approach or to go-around rests with the commander.

Similarly, Airbus defines stabilized approach as follows (Airbus Flight Crew Operation Manual-FCOM, 2021):

- 1 000 ft AAL in IMC, or
- 500 ft AAL in VMC, or
- Any other height defined in Operator policies or regulations.

For the approach to be stabilized, following conditions must be satisfied before, or at the stabilization height:

- The aircraft is on the correct lateral and vertical flight path.
- The aircraft is in the desired landing configuration.
- The thrust is stabilized, usually above idle, and the aircraft is at target speed for approach.

Note: In IMC, a later speed and thrust stabilization can be acceptable provided that:

- It is in accordance with Operator policies and regulations.
- The aircraft is in deceleration toward the target approach speed.

- The flight crew stabilizes speed and thrust as soon as possible and not later than 500 ft AAL.
- The flight crew does not detect any excessive flight parameter deviation.

If one of the above-mentioned conditions is not satisfied, the flight crew must initiate a go-around, unless they estimate that only small corrections are required to recover stabilized approach conditions.

Note: If the predicted tailwind at landing is greater than 10 kt, decelerated approach is not permitted, and the aircraft speed should be stabilized at around VREF + 5 kt in final.

3.1.2. Unstabilized approaches

Turkish Airlines defines unstabilized approach as an approach that aircraft does not maintain the parameters defined in chapter 3.1.1 starting from altitude gate defined in chapter 3.1. In the terminology of Threat and Error Management (TEM), unstabilized approach is a serious undesired state which can cause catastrophic loss. According to IATA statistics (2016) unstabilized approaches were identified as a root cause of 7% of total accidents (32 accidents) between 2011 and 2015. Those accidents resulted in:

- Controlled Flight into Terrain (CFIT): 6%
- Hard Landing: 41%
- In-flight Damage: 3%
- Loss of Control In-flight: 9%
- Runway / Taxiway Excursion 31%
- Tail strike: 6%
- Undershoot: 3%

There are numerous reasons for unstabilized approaches. Shortened arrival distance, lack of energy management and anticipation of late changes, degraded communication between flight crew and/or ATC, lack of situational awareness are only a few reasons of unstabilized approaches. Unstabilized approaches should not lead to landings. Whenever an approach deviates from stabilized approach parameters, an

immediate go around or discontinuation of the approach must be flown. Unstabilized approach numbers within an organization is kept in database as a safety performance indicator (SPI) to analyze the root cause of the incident and report it authorities when necessary.

3.2. Safety Performance Indicators (SPI)

Airlines must monitor safety-related parameters in their operations and report them to relevant authorities when necessary. These indicators are called as SPI and recorded in the database of the safety department. SPI's are helpful tool to assess organization's safety performance monitoring. Safety Performance Target (SPT) is defined as an objective for SPIs over a given period. Objective of the analysis is to minimize SPI values and keep it within SPT values. Table 3.1 shows an example of SPI table for flight operations from December 2015.

Table 3.1. *An example of SPI*

SPI Report : FLIGHT OPS Period : 2015.12 Number of Periodical Flights : 24018	Target			Actual Periodical		Actual Cumulative		Status	Aircraft Type					
Code SPI	# of OCC.	Ref. Scale	Unit	# of OCC.	Rate	# of OCC.	Rate (per 1M)	Result	A320	A340	B737	B777	A310	WET
4 Runway Incursion	***3***	***1M***	***Flights***	***1***	***41***	***67***	***61***		***0***	***0***	***1***	***0***	***0***	***0***
4.1 ATC Miscommunication	10	1M	Flights	0	0	76	69		0	0	0	0	0	0
4.2 Inadequate Takeoff Briefing	20	1M	Flights	0	0	9	8		0	0	0	0	0	0
4.3 Taxiway Confusion	10	1M	Flights	0	0	62	57		0	0	0	0	0	0
4.4 Taxiway Incursion	10	1M	Flights	1	41	49	45		0	1	0	0	0	0
4.5 Runway Confusion	1	1M	Flights	0	0	9	8		0	0	0	0	0	0
5 Tail Strike	***3***	***1M***	***Flights***	***0***	***0***	***15***	***14***		***0***	***0***	***0***	***0***	***0***	***0***
5.1 Tailwind Limit Exceedance	40	1M	Flights	0	0	62	57		0	0	0	0	0	0
5.2 Pitch Rate High Takeoff	100	1M	Flights	0	0	744	678		0	0	0	0	0	0
5.3 Pitch High At Takeoff	100	1M	Flights	931	38,762	17529	15983		921	2	8	0	0	0
5.4 Wrong Performance Calculation	10	1M	Flights	0	0	4	4		0	0	0	0	0	0
5.5 Improper Loading	10	1M	Flights	1	41	22	20		1	0	0	0	0	0
5.6 Pitch High At Landing	10	1M	Flights	0	0	18	16		0	0	0	0	0	0
5.7 Pitch Rate High At Landing	10	1M	Flights	13	541	457	417		4	0	8	1	0	0
5.8 Early Rotation At Takeoff	10	1M	Flights	0	0	33	30		0	0	0	0	0	0
6 Unstabilized Approach	***100***	***1M***	***Flights***	***0***	***0***	***251***	***229***		***0***	***0***	***0***	***0***	***0***	***0***
6.1 Path High At 1000ft	500	1M	Flights	13	541	1895	1728		11	1	1	0	0	0
6.2 Path High At 500ft	100	1M	Flights	24	999	1274	1162		20	1	3	0	0	0
6.3 Speed High At 1000ft	500	1M	Flights	66	2,747	8111	7395		40	25	0	1	0	0
6.4 Speed High At 500ft	100	1M	Flights	3	124	884	806		2	1	0	0	0	0
6.5 Late Configuration Change	100	1M	Flights	0	0	231	211		0	0	0	0	0	0
6.6 High Vertical Speed Below 1000-100ft	300	1M	Flights	11	457	3345	3050		4	0	6	1	0	0
6.7 GPWS Sink Rate	100	1M	Flights	17	707	1049	956		4	0	12	1	0	0
6.8 GPWS Glideslope	100	1M	Flights	28	1,165	2273	2072		13	2	12	1	0	0

As shown in Table 3.1 main events and sub-events are defined in the table. In December 2015, total 24018 flights were executed and analyzed. As an example, 8 measurable sub-items that might trigger unstable approaches are mentioned in SPI. These are path high at 1000 ft, path high at 500 ft, speed high at 1000 ft, speed high at 500 ft, late configuration change, high vertical speed below 1000 ft, GPWS sink rate and GPWS glideslope. These sub-items might contribute to an unstable approach. On the other hand, as can be seen from the chart, although item 6.3 "High Speed at 1000ft" was encountered

66 times during the specified period, no unstable approach was noted in the same period. As a result of this, sub-parameters only reflect some triggering situations and requires to be followed independently from main event. Similarly, undesirable event may not be caused by the reasons stated in sub-events. For that reason, contributing factors and main event should be recorded independently to have improved analysis. Target column in the SPI chart shows acceptable upper limit during operation. In other words, this section defines SPT values. For example, the tail strike is targeted as a maximum of 3 times per 1,000,000 flights. Actual periodical column shows how many times the relevant item has been encountered within specified period. For example, "Runway Incursion" situation stated in the undesirable event number 4 was encountered once in 24018 flights. If there is 1 runway incursion in 24018 flights per month, this event is expected to occur 41 times in 1,000,000 flights. This is direct linear correlation between actual number and projected 1.000.000 flight equivalent. Actual cumulative shows performance in long term. In this case, runway incursion happened 67 times in long term which brings the rate 61 for each 1,000,000 flights. Namely, actual period and cumulative period values give information about the current month and long term. In line with the values obtained here, it can be seen which areas needs to be improved and how likely target values will be achieved for short and/or long terms.

Turkish Airlines keeps SPI values under six different categories. These are flight operations, cabin operations, ground operations, engineering operations, cargo, and dispatcher operations and other departments (crew scheduling, flight academy and flight training). Table 3.2 shows flight operation SPI values.

Table 3.2. *Flight operations SPI*

1 Runway Excursion	***7 Unstabilized Departure***
1.1 Crosswind Limit Exceedance at Takeoff	7.1 Thrust Reduction Below 1000ft
1.2 Asymmetric Thrust Reverser Use	7.2 Flap Retraction Below 1000ft
1.3 Inappropriate Thrust Reverser Use (A340 ONLY)	7.3 Excessive Speed Below 1000ft
1.4 Early Thrust Setting at Take-Off	***8 SID/STAR Violation***
1.5 Heading Excursion	8.1 ATC Miscommunication
1.6 Thrust Asymmetry at Takeoff	8.2 Inadequate Takeoff Briefing
1.7 Crosswind Limit Exceedance at Landing	8.3 Inadequate Monitoring
1.8 Long De-rotation	***9 CFIT Risk***
2 Runway Overrun	9.1 GPWS Glideslope
2.1 High Speed at Touchdown	9.2 GPWS Sink Rate
2.2 Long Landing Distance	9.3 GPWS Pull up / Terrain
2.3 Tailwind Limit Exceedance At Landing	9.4 GPWS Don't Sink
2.4 Speed High At 500ft	***10 Air Proximity***
2.5 Inappropriate High Energy RTO	10.1 Pilot Induced TCAS RA
2.6 RTO Beyond V1	10.2 ATC Miscommunication Based TCAS RA
2.7 Wrong Performance Calculation	10.3 High v/s During Level Change (1000fpm @ 1000ft))
3 Hard Landing	10.4 High v/s During Level Change (1500fpm @ 2000ft)
3.1 High Descent Rate 100-30ft (830 fpm)	***11 Gross Navigation Error***
3.2 High Descent Rate 30-15ft (630 fpm)	11.1 ATC Miscommunication
3.3 High Descent Rate 15ft-Touchdown	11.2 Inadequate Monitoring
3.4 High Acceleration at Touchdown	11.3 Incorrect FMS Entry
4 Runway Incursion	11.5 CPDLC Usage Errors
4.1 ATC Miscommunication	***12 Level Bust***
4.2 Inadequate Takeoff Briefing	12.1 ATC Miscommunication
4.3 Taxiway Confusion	12.2 Sterile Cockpit Rule Violation
4.4 Taxiway Incursion	12.3 Missetting of Altimeters
4.5 Runway Confusion	12.4 Missetting of ALT/FL
5 Tail Strike	***13 Loss of Comm***
5.1 Tailwind Limit Exceedance	13.1 Missetting of Radio Frequency
5.2 Pitch Rate High Takeoff	13.2 Inadequate RTF Monitoring
5.3 Pitch High at Takeoff	***14 Ground Accident***
5.4 Wrong Performance Calculation	14.1 High Speed Taxi
5.5 Improper Loading	14.2 Taxi with Inadequate Wing Clearance
5.6 Pitch High at Landing	14.3 Jet Blast
5.7 Pitch Rate High at Landing	***15 Mismanagement Issues***
5.8 Early Rotation at Takeoff	15.1 Violation of Speed Restriction
6 Unstabilized Approach	15.2 Dual Input (Airbus Only)
6.1 Path High At 1000ft	15.3 ATS Armed/Engaged at Landing
6.2 Path High At 500ft	***16 Loss of Control***
6.3 Speed High At 1000ft	16.1 Excessive Roll
6.4 Speed High At 500ft	16.2 CWS mode active
6.5 Late Configuration Change	16.3 Low Speed (Stick Shaker)
6.6 High Vertical Speed Below 1000 ft	***17 Taxiway Excursion***
6.7 GPWS Sink Rate	
6.8 GPWS Glideslope	

3.3.Mathematical Model

Data needed for bowtie analysis, which constitutes the mathematical background of this study, are collected from expert opinions and SPI values. Whilst expert opinions are obtained during interviews and digitized by fuzzy logic, SPI probabilistic values are obtained from Turkish Airlines. Turkish Airlines approval to use SPI data set is given in appendix. The digitized fuzzy values are the main structure of the mathematical model. The expert opinions are applied to a fuzzification process and proportioned by Analytical Hierarchy Process (AHP). SPI values on the other hand are used to verify the outcome of the fuzzy logic process. It is also used as supportive tool to decide if the outcome of the expert analysis is aligned with the company's actual values. Once the analysis is constructed via bowtie and fuzzy logic, it is mapped into Bayesian equivalent to show better interconnection between sub-events and the main event. Moreover, it's easier to obtain posterior probabilities of the analysis with given prior probabilities. Figure 3.2 illustrates basic mathematical modelling behind the study. In the next chapters, brief introduction on fuzzy logic and Bayesian network will be introduced.

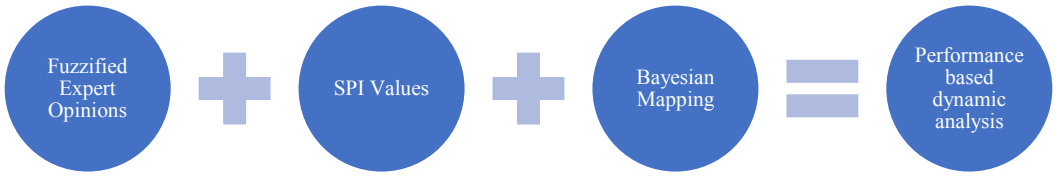


Figure 3.2. *Summary of mathematical model*

3.3.1. Fuzzy logic

Every situation in life cannot be described by an absolute value. Standard (classic) logic situations can be defined with absolute values such as 'true or false', '1 or 0', 'good or bad'. In real life, it is difficult to define everything with an absolute value. There is always uncertainty that cannot be express with '1 or 0', or 'true or false'. These uncertainties are commonly referred as grey areas. For example, in standard logic we can either say someone is tall or not tall whereas in fuzzy logic it can be said that someone is '0.8 tall' and '0.2 short'. In fuzzy logic, uncertainty principle is taken into account and

often offers wide range solution than standard logic. Figure 3.3 shows the comparison between standard logic and fuzzy logic.

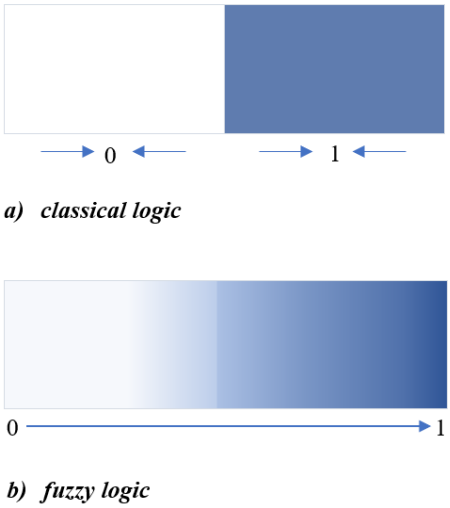


Figure 3.3. *Standard logic vs fuzzy logic*

Fuzzy logic has been introduced in many engineering related fields in the aviation. Model aircraft control (Ervin and Alptekin, 1998), aircraft conflict resolution problem solution (Sathyan, Ernest, Lavigne, Cazaurang, Kumar, and Cohen, 2017) enhancing flight controls (Schram, Fernandez-Montesinos and Verbruggen, 1999), anti-ice system control design (Gliwa, Grzesik and Kuzma, 2018), UAV swarm routing (Sathyan, Ernest, Cohen, 2016), aerodynamic modelling (Chang, 2013), takeoff and landing prediction (Wijaya, Tondang, Putera, and Siahaan, 2016), controller to drive autopilot altitude in landing phase (Rawea, and Urooj, 2015), harmonic distortion reduction of commercial airplane electrical power system (Radmanesh, and Gharehpetian, 2021), intelligent air traffic method system design (Idika and Baridam, 2018), real-time unmanned aerial vehicle control (Marcu, 2011) and aircraft system efficiency analysis (Grzesik, 2016), are only a few examples of fuzzy logic applications in aerospace industry.

Fuzzy logic is introduced to literature by Azeri system scientist Zadeh (Kiyak, 2003). The application of fuzzy logic first took place in Far East countries. Steam engine control, cement industry applications, and transportation sectors were the first fields where fuzzy logic was put into practice. Fuzzification, rule processing and defuzzification

are the three main process of fuzzy logic operations. Figure 3.4 shows brief summary of fuzzy logic process.

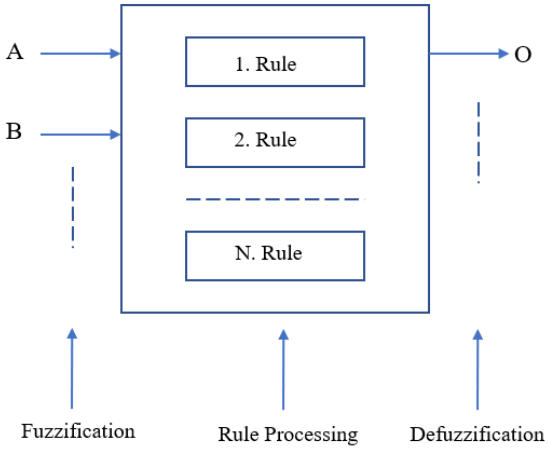


Figure 3.4. *Fuzzy logic process*

Fuzzification part uses membership functions in the process. These functions can have a range between '0 and 1'. These levels represent degree of uncertainty. For example, by the help of membership functions uncertainty of cold situation can be defined as: 0 not cold, 0.2 slightly cold, 0.4 cold, 0.6 fairly cold, 0.8 very cold and 1.0 absolute cold. Triangle, gaussian and trapezoid distributions are mainly used in fuzzification process. Mathematical expression of these distributions is given in Figure 3.5.

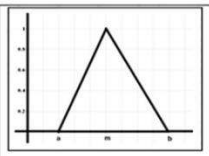
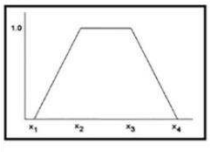
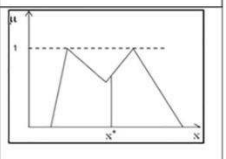
Triangular function is defined by three parameters {a, b, m}. a is lower limit, b upper limit and m is in between a and b.	$\mu A(x) = \begin{cases} 0, & x \le a \\ \frac{x-a}{m-a}, & a < x \le m \\ 1, & x = m \\ \frac{b-x}{b-m}, & m < x < b \\ 0, & x \ge b \end{cases}$	
Trapezoidal function is defined by a lower limit x1, upper limit x4, a lower support limit x2, and an upper support limit x3, where x1<x2<x3<x4.	$\mu A(x) = \begin{cases} 0, & (x < x1) or (x > x4) \\ \frac{x-x1}{x2-x1}, & x1 \le x \le x2 \\ 1, & x2 \le x \le x3 \\ \frac{x4-x}{x4-x3}, & x3 \le x \le x4 \end{cases}$	
Centroid method finds the center point of the targeted fuzzy by calculating the weighted mean of the fuzzy region.	$X^* = \frac{\int \mu\tilde{A}(x).x dx}{\int \mu\tilde{A}(x).dx}$	

Figure 3.5. *Fuzzification and defuzzification membership functions*

The methods used to assign values to the membership functions can vary. Most common methods used are:

- Intuitive Method
- Deductive Method
- Angular Fuzzy Sets
- Genetic Algorithms
- Neural Networks
- Reasoning Method

After the fuzzification process, real numbers, functions, or data are converted into fuzzy subset. Next, fuzzy values are processed via rule processors. Rule process consists of if-then rules. This rule helps to formulate conditional situations in fuzzy logic. In general, it is described as:

- IF ‘x is a’, THEN ‘y is b’

In this statement a and b are the values described linguistically by membership functions. This conditional statement consists of two different parts. ‘X is a’ is defined as premise whereas ‘y is b’ is called conclusion. For example, the statement of:

- if weather is hot then reduce the air conditioner temperature

This statement can be divided into premise and conclusion parts. In this specific example, “if weather is hot” is premise and uncertainty level of hot can be defined between ‘0 and 1’ whereas air conditioner temperature is represented as fuzzy set and consequent is an assignment of entire fuzzy set of air conditioner temperature to the output of reducing the temperature. In other words, input for ‘if-then’ rule is a value of input variable while output is entire fuzzy set. Figure 3.6 shows the algorithm used for rule processing.

Figure 3.6. *Rule processing algorithm*

Interpreting rule process involves two steps:

- Evaluation of premise
- Application of the result to the conclusion.

After fuzzy rule processing, the output must be converted into crisp values. Defuzzification is used to convert fuzzy values into crisp values with respect to fuzzy set. Center of gravity method is widely used in fuzzy logic defuzzification process.

Fuzzy logic has many advantages. It is based on natural language which make it easier to understand the conceptional design. Moreover, it is possible to make an analysis with imprecise data via fuzzy logic. Uncertainty frequently exists in risk assessment. Therefore, fuzzy logic is preferred in many applications in the risk assessment process. Additionally, fuzzy logic can be combined with conventional analysis techniques and expert opinions can be built on top of fuzzy logic. These two unique specifications allow fuzzy logic to combine different approaches altogether. On the other hand, fuzzy logic has a few disadvantages over traditional methods. Firstly, modelling is highly dependent on personal experiences that makes selection of the experts extremely important. Secondly, it requires many analyses to find the optimum method, and this is more time consuming than other analysis methods. In this study, all advantages of fuzzy logic that are mentioned above are used to convert linguistic expert opinions into probabilistic fuzzy values.

3.3.2. Bayesian network

As mentioned earlier, bowtie consists of FTA and ETA. FTA analysis focuses on reasons for the undesired event while ETA deals with the possible outcomes of the analysis. As a result of this, in safety analysis FTA and ETA are mainly used together to as subsidiary to achieve detailed analysis. In ETA, flow of the events is used during assessment process. Also, intuitional approach is widely used in ETA. This approach does not provide any information about system condition, system environmental analysis and interrelationships between subsystems. In order to overcome this problem Bayesian network solution is introduced in the study.

Bayesian approach offers wide range of solutions for dynamic safety analysis. An example of this can be given Khakzad, Khan, and Amyotte's study (2011). In their study safety analysis in process facilities by comparing FTA and Bayesian networks has been

performed. As a result of this effectiveness of Bayesian networks over FTA's has been shown.

A Bayesian network is a probabilistic model that represents set of variables and their conditional dependencies via a Directed Acyclic Graph (DAG). Bayesian approach analyze conditionally independent random variables. Bayesian networks are powerful tool to visualize probabilistic dependencies. Bayesian networks show the structure of the model as a whole and make it easy to understand the system. Moreover, they show the presence or absence of the relationship between random variables. Finally, Bayesian networks allow the complex probability calculations which in return enables complex risk analysis.

There should be three elements to design a Bayesian network. First, random variables, also called nodes should be defined. Second, relationship between random variables, also called edges, must be designed. Edges help to visualize relationships in the graphical model. Lastly, probabilistic distribution for each random variable must be determined.

Bayes theory is widely used in probability and statistics. It is used to calculate conditional probabilities of the events. Bayes theorem describes probability of an event based on prior knowledge. Therefore, Bayes theorem is widely used in the fields that uncertainty exists such as finance, risk management, machine learning, healthcare management. Bayes theory is given in equation 3.1.

$$\mathrm{P(A|B)} = \frac{P(A) * P(B|A)}{P(B)} \tag{3.1}$$

- P: probability, A and B are different events and $P(B) \neq 0$,
- P(A): The probability of A occurring (Irrespective of event B),
- P(B): The probability of B occurring (Irrespective of event A),
- P(A|B): The probability of A given B (Question that needs to be solved),
- P(B|A): The probability of B given A

In the equation given above, P(A) and P(B) are described as prior probabilities. P(B|A) and P(A|B) are called conditional probabilities. P(A|B) also called posterior probability of A given B.

Based on above explanation of conditional probability table, simple Bayesian network can be form as shown in Figure 3.7.

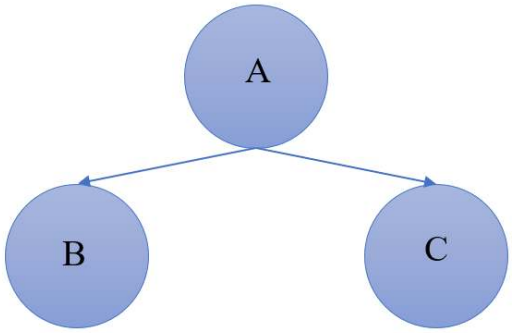


Figure 3.7. *Simple Bayesian network*

There are three random variables in this problem: A, B, and C. B is dependent on A, and C is dependent on A. Based on this information, conditional dependencies can be described as follows:

- B is conditionally dependent on A, P(B|A)
- C is conditionally dependent on A, P(C|A)
- B and C are independent from each other.

Conditional independencies can be described by the following random variables:

- B is conditionally independent from C: P(B|A, C)
- C is conditionally independent from A: P(C|A, B)

In this example conditional dependence is described in the presence of conditional independence. Namely, B is conditionally dependent on A in the presence of C. It can also be stated as B is independent of C and can be calculated from B given A alone.

$$P(B|C, A) = P(B|A) \tag{3.2}$$

It can be seen that A is unaffected by B and C. Moreover, A has no parents. Conditional independence of A from B and C can be stated as P(A, P(B|A), P(C|A)) or just P(A). It can also be written as the joint probability of B and C given A is the product of two conditional probabilities.

$$P(B, C|A) = P(B|A) * P(C|A) \tag{3.3}$$

The joint probability of P(B, A, C), calculated as:

$$P(B, A, C) = P(B|A) * P(C|A) * P(A) \tag{3.4}$$

Based on the information given by equations 3.1 through 3.4, Bayesian network given in Figure 3.7 can be designed. In this design A, B and C are nodes and based on conditional probabilities of which assigned edges are created.

4. DYNAMIC RISK ASSESSMENT OF AN UNSTABILIZED APPROACH

Aviation is a dynamic environment which includes many risk factors. Therefore, one method is not enough to analyze all risk related items within an aviation framework. In some cases, numerical analysis plays vitally important role. On the other hand, expert experiences are extremely important where subjective data is not present in the analysis. By the help of experience, individuals can perform better risk assessments. Similarly, numerical data is critically important for an aviation organization. Numerical data supply key performance parameters for the safe operation so that airlines can measure their safety performance. Analyzing flight data recorders (FDR), implementing mandatory safety reporting can contribute to obtaining numerical data to analyze the risks.

Within the scope of the thesis, a design approach that allows the evaluation of numerical and linguistic data together for a performance-based dynamic analysis has been determined. In design methodology, fuzzy logic, bayes networks and bowtie analysis are used to create dynamic risk assessment tool for an airliner.

To show structural methodology, a risk assessment technique used by ICAO will be introduced followed by a brief explanation of the SPI analysis. The next step in the methodology is to design fuzzy risk matrix and compare its outputs with the classical approach. Lastly, fuzzy-Bayesian based dynamic risk assessment system design will be shown. Fuzzy-Bayesian bowtie analysis will be applied on an unstabilized approach example. Figure 4.1 shows the evolution of dynamic risk assessment.

Figure 4.1. *Evolution of design process*

The method contains a mathematical background, formulas, and MATLAB software tools. The aim of the section is to give brief understating of the chapter. For that reason, mathematical background of the topics is not mentioned in detail. Readers can refer other sources to understand basics of the topics.

Risk Assessment technique defined by ICAO uses classical matrix approach to assess the risk. Based on this definition, risk is modelled with probability and its severity.

Classic matrix is defined by 5x5 dimensions. Severity and probability of an event is divided into five sub-groups. Sub-groups are as follows:

- Risk probability: Extremely improbable (1), Improbable (2), Remote (3), Occasional (4), Frequent (5)
- Risk Severity: Negligible (E), Minor (D), Major (C), Hazardous (B), Catastrophic (A)

Question asking technique can be used to assign the probability values for an event. Some sample questions are as follows:

- Has the company encountered same sort of event in the past?
- Can other equipment and components of similar type cause the same problems?
- How many personnel are assigned in the procedure?
- How much of the hazard exposure is being reviewed?

The questions mentioned above are just a few examples and they may be increased based on analysis. After assigning probability, the severity assignment must be made. While classifying severity, fatal events and/or injuries and possible damage should be considered. Table 4.1 gives a guidance about classification of severity.

Table 4.1. *Severity classification reference*

Severity	Explanation	Assignment
Catastrophic	• Hull loss of equipment or aircraft • Multiple fatalities	A
Hazardous	• Moving beyond from safety margin • Serious injuries • Serious equipment damage	B
Major	• Moving away from safety margin • Incident • Injuries to persons	C
Minor	• Distressed situation • Operational limitations exceedance • Implementation of emergency procedures	D
Negligible	• Undesirable results	E

Based on Table 4.1 and by asking questions to assign probability, risk matrix can be formed. An example risk matrix is shown in Table 4.2.

Table 4.2. *Classic risk matrix*

RISK	***SEVERITY***				
PROBABILITY	*Catastrophic (A)*	*Hazardous (B)*	*Major (C)*	*Minor (D)*	*Negligible (E)*
Frequent (5)	5A	5B	5C	5D	5E
Occasional (4)	4A	4B	4C	4D	4E
Remote (3)	3A	3B	3C	3D	3E
Improbable (2)	2A	2B	2C	2D	2E
Extremely Improbable (1)	1A	1B	1C	1D	1E

After assignment of probability and severity risk value should be determined. Risk value is multiplication of severity and probability. For example, if an undesired event's risk probability assigned as remote (3) and severity value is calculated as minor (D), overall risk assessment for this event is calculated as 3D. In this matrix, there are 25 different risk assessment results for any given event. Based on these events risk classification shall be made.

Three different risk classification is used in Table 4.2. These are acceptable, tolerable, and not acceptable risk levels; green, amber and red respectively. Red area in the matrix represents very high-risk group and these risks are not acceptable within the organization. Operation shall be stopped immediately until necessary precaution and safety measurements are taken. Amber band represents the middle risk classification. If a risk evaluation falls into this category, operation can be continued only if required mitigation strategies are implemented. Lastly, green band in the matrix represents low risk area. In this area, operation can be continued without any further mitigation strategy. However, in green band, aviation organizations try to mitigate their risk to a minimum available level. Based on these definitions safety risk index can be defined as it is shown in Table 4.3.

Table 4.3. *Risk classification*

Safety Risk Index	*Risk Definition*	*Suggested Action*
5A, 5B, 5C, 4A, 4B, 3A	Not Acceptable	Stop operation. Take immediate action to mitigate risk level.
5D, 5E, 4C, 4E, 3B, 3C, 3D, 2A, 2B, 2C,1A	Tolerable	Operation can continue by the approval of management if risk mitigation precautions are taken.
3E, 2D, 2E, 1B, 1C, 1D, 1E	Acceptable	Acceptable risk margin. No need for risk mitigation.

The classification described above is a method recommended by ICAO. This method is used widely to classify events that may pose the risks during operations. Main motivation behind the classification of the risk is to keep the risk level in green band and take all required mitigation and management techniques to avoid amber and red band.

Although classical risk matrix is frequently used, it is open to potential errors during analysis. Firstly, errors arising from the fact that the risk assignment is made completely linguistically while defining the matrix. Secondly, verbal assignments that are not subjectively based on any unit can affect the reliability of the matrix and expose the analysis to errors and/or extreme biases. The third most common type of error is scaling errors. This type of error occurs if probability and severity assignments on the matrix are not evenly distributed or inconsistent. If that happens, classification of risks is negatively affected and do not reflect real conditions. Lastly, the obligation to define the bandwidth in the classification of risks under three groups may cause an error-prone design in the classification phase. For example, 2A and 5E risk levels, which are both in the tolerable risk group, are evaluated under the same risk group. However, within the same group, 2A may need to be analyzed as a risk that requires more mitigation steps than 5E or vice versa. In this system, it is not possible to assess the risk level in the same group. For instance, 3D risk level cannot be assessed inside. There are only 25 levels to be assigned. However, there might be situations that cannot reflect the position of the risk exactly. A risk can be early 3D risk or late 3D risk level which can be categorized as 3D Low Risk or 3D High Risk respectively. This situation can be seen in Figure 4.2. In the classical approach it is not possible to represent these kinds of risk levels. However, it is possible

model this risk group in fuzzy assessment. In the next chapter fuzzy risk matrix will be introduced.

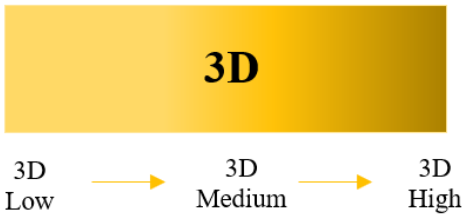


Figure 4.2. *3D inner risk classification*

4.1. Fuzzy Risk Matrix

Fuzzy logic approach is used widely in risk assessment. Lee (2006) proposed a quantitative model to assess aviation safety risk factors by using fuzzy linguistic approach, failure mode effect and critically effect analysis (FMECA) on an empirical study. Similarly, (Feng, C.M. and Chung, C.C., 2013) assessed the risks of airside of the airports using fuzzy logic based FMECA. Skorupski (2019) assessed the risk of air traffic accidents by the simulation fuzzy method usng fuzzy risk matrices. Sharov and Vurobyov (2017) used fuzzy risk assessment for aviation events. Hadjimichael (2009) stated risk factors and interrelationships in fuzzy expert system for flight operations risk assessment system (FORAS). In his paper, FORAS is defined as a supportive tool which uses proactive approach on risk assessment for airline safety departments to examine risks factors. Rezaei and Borjalilu (2018) designed a dynamic risk assessment modeling based on fuzzy ANP for safety management systems. Risk assessment based on the fuzzy logic approaches in economics are commonly preferred. Production risk economic assessment (Sokolitsyn, Kovalenko and Zvontsov, 2017), risk management model for production supply chain (Đurić, Todorović, Dorđević and Tišma, 2019), risk assessment of residential real estate investments (Ribeiro, Ferreira, Jalali, Kavaliauskienė, 2017), Risk assessment in IT outsourcing (Samantra, Datta and Mahapatra, 2014) are only a few examples where fuzzy logic is used to assess risks in economics.

Practical application of the fuzzy risk matrix uses 5x5 dimensions and 2 inputs (probability and severity) and one output (risk). Each input is designed to have 5 membership functions. Risk is categorized under three different membership functions. MATLAB Fuzzy Interference System is used to model the fuzzy risk matrix. Symmetric and evenly spaced triangular and trapezoidal membership functions are selected based on

intuitive approach in the design. Whilst the numerical values of the membership functions are chosen between '-0.1 to 1.1', the values between '0 and 1' are used. Membership functions of probability input as follows:

- very_low, trapezoidal, -0.1, 0, 0.1, 0.2
- low, triangular, 0.1, 0.3, 0,5
- medium, triangular, 0.3, 0.5, 0.7
- high, triangular, 0.5, 0.7, 0.9
- very_high, trapezoidal, 0.8, 0.9, 1, 1.1

Numbers mentioned in membership functions are the points where geometric illustrations are drawn from on probability and severity axis. For example, medium triangular membership function's left starting point sits on 0.3, and projection of top of triangle on 0.5, and right extreme point on 0.7. As stated earlier they are defined as symmetric and evenly spaced (0.2). Similarly, severity input values are designed via symmetric and evenly spaced triangular and trapezoidal membership functions. Membership functions are given as follows:

- very_light, trapezoidal, -0.1, 0, 0.1, 0.2
- light, triangular, 0.1, 0.3, 0,5
- medium, triangular, 0.3, 0.5, 0.7
- severe, triangular, 0.5, 0.7, 0.9
- very_severe, trapezoidal, 0.8, 0.9, 1, 1.1

During fuzzy interface system design, two different methods are often used in MATLAB. These methods are called as Mamdani and Sugeno. In this study, Mamdani method is chosen for analyses. Although both systems have advantages and disadvantages relative to each other, a brief comparison of these two methods as follows:

- Mamdani Method
    - It is effective in modeling systems based on intuition.
    - Widely accepted.

- Adapted to intuitive data entry.

- Sugeno Method
  - Effective in applications that require calculations.
  - Effective in linear systems such as PID design
  - Works well with optimization and adaptive systems.
  - It allows for mathematical analysis

Illustrations of probability and severity membership functions are shown in Figure 4.3 and 4.4.

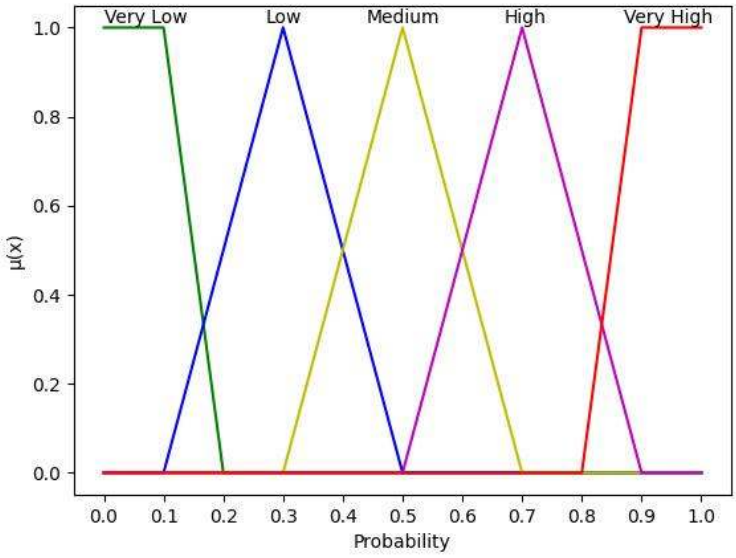


Figure 4.3. *Probability membership functions*

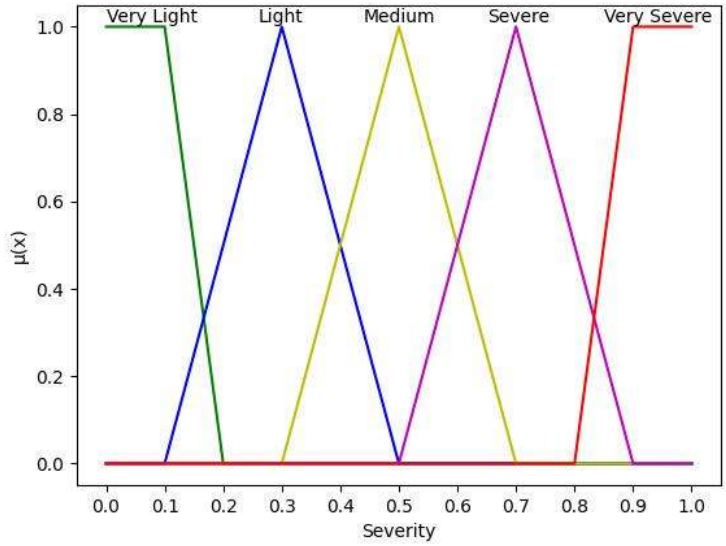


Figure 4.4. *Severity membership functions*

After defining the inputs, a rule processor is needed to produce the outputs. The basic operation in rule processor is to perform linguistic classification as 'if ... then…'. There are twenty-five outputs and one risk category for each two inputs in the database. Table 4.3 (ICAO risk classification) is used to determine the relationship in the rule processor. Database of the analysis is shown in Table 4.4.

Table 4.4. *Fuzzy risk matrix database*

Probability	Severity	Risk
Very_low	Very_light	Low Risk
Very_low	Light	Low Risk
Very_low	Medium	Low Risk
Very_low	Severe	Low_Risk
Very_low	Very_Severe	Medium_Risk
Low	Very_light	Low_Risk
Low	Light	Low_Risk
Low	Medium	Medium_Risk
Low	Severe	Medium_Risk
Low	Very_Severe	Medium_Risk
Medium	Very_light	Low_Risk

Medium	Light	Medium_Risk
Medium	Medium	Medium_Risk
Medium	Severe	Medium_Risk
Medium	Very_Severe	High_Risk
High	Very_light	Medium_Risk
High	Light	Medium_Risk
High	Medium	Medium_Risk
High	Severe	High_Risk
High	Very_Severe	High_Risk
Very_High	Very_light	Medium_Risk
Very_High	Light	Medium_Risk
Very_High	Medium	High_Risk
Very_High	Severe	High_Risk
Very_High	Very_Severe	High_Risk

Risk output is defined with symmetrical and equally spaced triangular and trapezoidal membership functions. Whilst the numerical values of the membership functions are chosen between '-0.2 to 1.2', the values between '0 and '1 are used in the analysis. Membership functions of risk output are determined as follow.

- Low_Risk, trapezoidal, -0.2, 0, 0.2, 0.4
- Medium_Risk, triangular, 0.2, 0.5, 0,8
- High_Risk, trapezoidal, 0.6, 0.8, 1, 1.2

Numbers mentioned in membership functions are the points where geometric illustrations are drawn from on risk perception axis. For example, medium risk triangular membership function's left starting point sits on 0.2 and tops on 0.5 and right extreme point on 0.8. As stated earlier they are defined as symmetric and evenly spaced (0.3). Output membership functions of risk is shown in Figure 4.5.

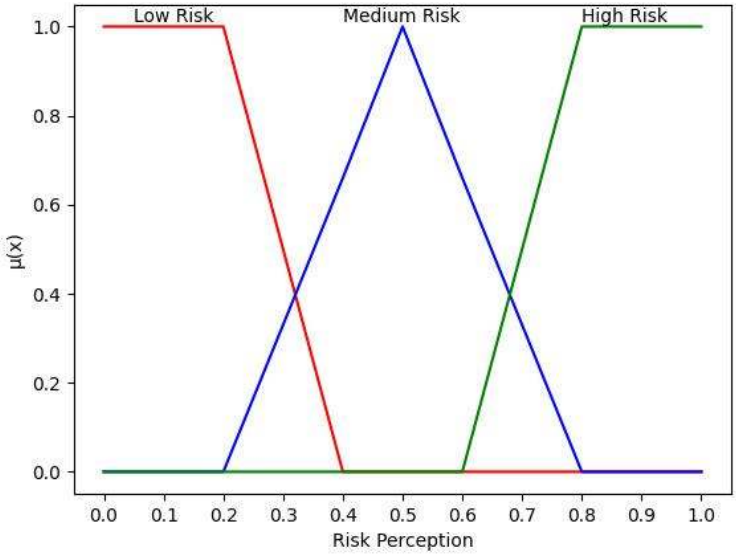


Figure 4.5. *Risk membership function*

For the classical risk matrix, it can be said that all risks are equal in a certain range of values. For example, from Table 4.2 it can be said that 2A and 4D risk groups are both classified as tolerable risk groups. There is not any importance level inside the same risk level. For that reason, 2A and 4D can be classified as equally important. Furthermore, when Table 4.3 is examined, it can be seen that there is a requirement to define bandwidth for risk classifications. In such analysis, sorting two risk level in the same group or differentiation in the same risk level cannot be determined in classical approach. On the other hand, fuzzy approach overcome these difficulties. It is easy to sort different importance levels within same risk group. Furthermore, in fuzzy approach it is possible to differentiate risk output within same risk level. Fuzzy risk outputs are given in Figure 4.6, 4.7, and 4.8.

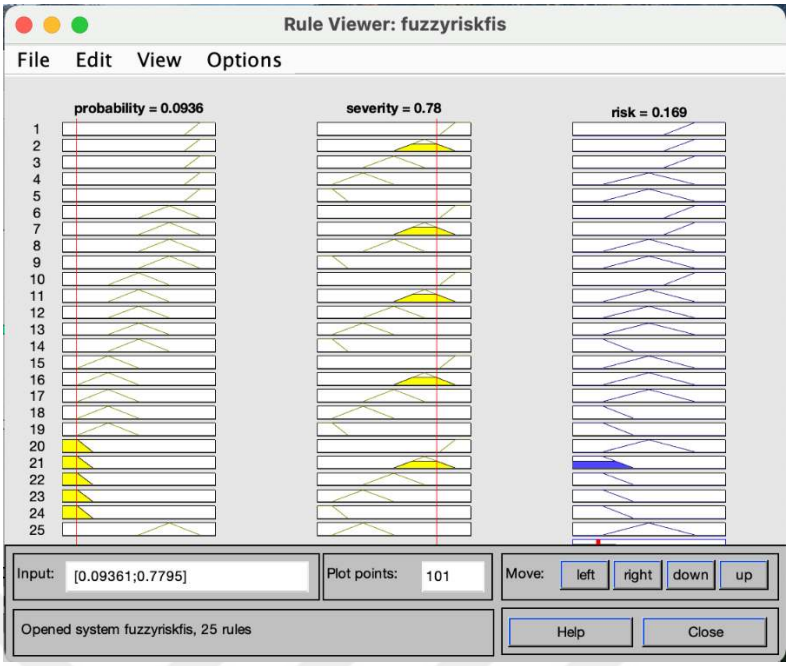


Figure 4.6. *Fuzzy risk matrix computation - 1*

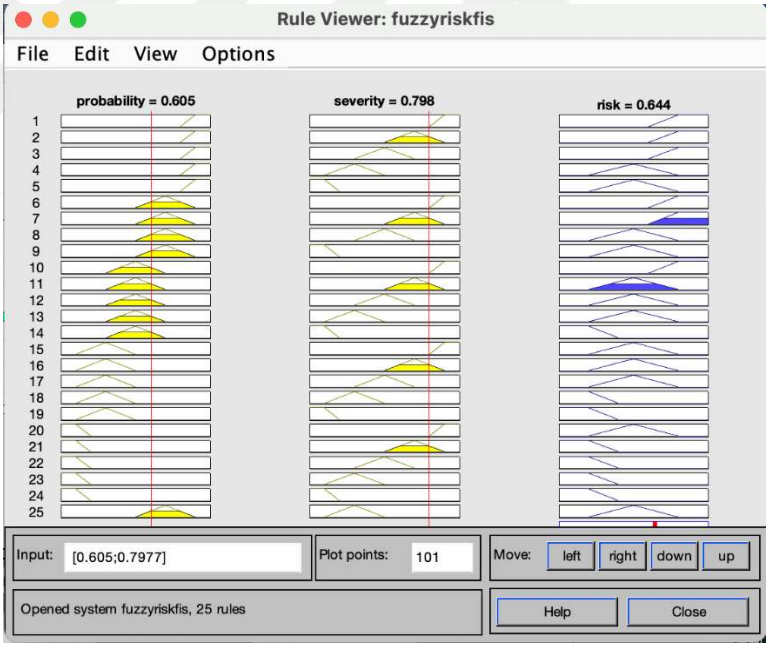


Figure 4.7. *Fuzzy risk matrix computation - 2*

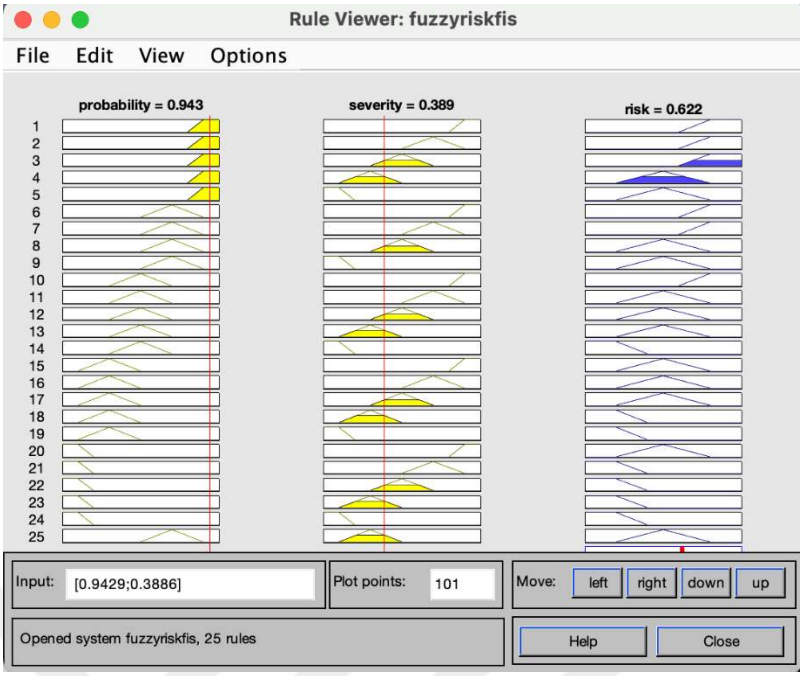


Figure 4.8. *Fuzzy risk matrix computation - 3*

In order to verify the fuzzy outputs, outputs of the classical matrix and fuzzy results must be compared. Since all membership functions are chosen symmetrically, it can be shown that probability and severity inputs reach highest value from the lowest value as a numerical value in the range of one to zero. Similarly, it can be said that the output risk value falls into a range of low, medium or high-risk groups according to its value between zero and one. If probability value is kept very low and checked from the Table 4.2, linear increase in the severity of the event from very light to very severe will not increase the risk value substantially. In this analysis the biggest risk group that can occur will be in the tolerable risk group. Figure 4.6 is an example of this situation. Similarly, if probability is chosen as medium, and severity value is increased by a serious dimension, the level of risk will reach to the high-risk group easily. Figure 4.7 shows this situation. Lastly, it is a fact that even in cases where the probability is very high, but severity is very low, the risk level will be in tolerable range. This can be seen in Figure 4.8.

Fuzzy risk matrix assessment is designed to improve discrete structure of risk assessment process. As shown in chapter 4, fuzzy risk matrix assessment process reduced discrete structure of the analysis. In classical risk matrix, risk assignment for classifications is fixed. For example, 3D risk assessment is fixed, and risk cannot be further classified in 3D group. However, a fuzzy approach eliminates this problem. In this approach, 3D risk level can also be analyzed enabling early 3D or late 3D risk levels.

Fuzzy risk assessment changes the assessment approach entirely. While the classical approach can only represent black and white situations, fuzzy logic can also represent grey areas. The fuzzy risk approach can offer a solution to reduce discrete structure of matrix assessment. Figure 4.9 shows the fuzzy risk matrix.

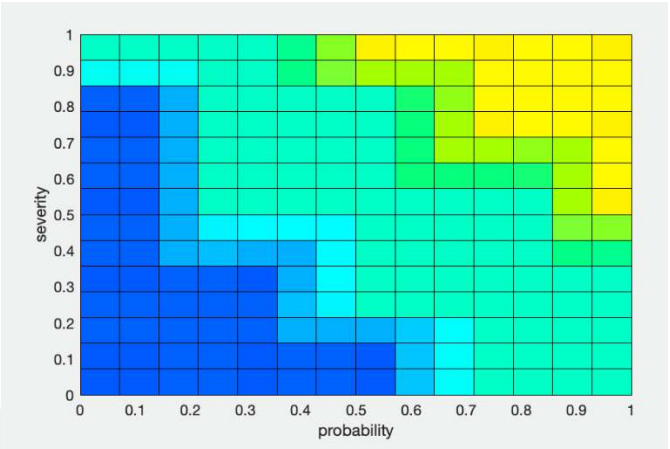


Figure 4.9. *Fuzzy risk matrix*

While the classical matrix is represented in three different colors, fuzzy risk matrix shows the transient colors. These colors indicate less discrete structure in the analysis. In other words, risk classification shows grey areas as it cannot be shown in classic matrix approach.

Risks in the same group can have different values in the fuzzy risk matrix. When fuzzy and classical analysis are compared, it is seen that risk values for fuzzy analysis are in a more continuous structure. Just before or just after a risk value can be considered in the analysis irrespective of which risk group they belong to. However, in the classical method, the risk values are represented in discrete form. For example, risk level jumps directly from 3B to 3C level and does not allow any intermediate risk level definition. However, fuzzy analysis can have different risk outputs even if they are in the same risk level. Thus, it is possible to rank the values within same level and assign a different importance level. Figure 4.10 is three-dimensional illustration of risk matrix and summarizes how fuzzy risk value is distributed according to values of probability and severity membership functions.

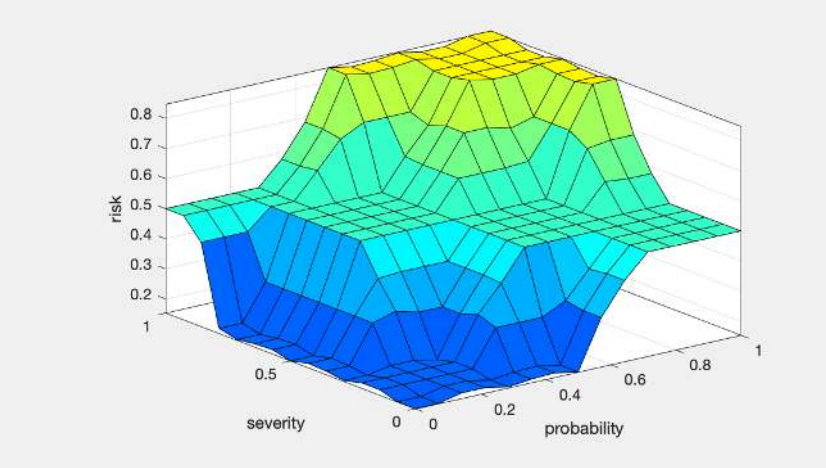


Figure 4.10. *Fuzzy risk distribution*

4.2. SPI Analysis

Flight operations SPI values use FDR data to keep track of safety of operation. Any operation beyond the defined limits is detected by the algorithm and logged for SPI. In this study permission is granted from Turkish Airline for limited number of SPIs for a certain year of 2014-2015.

In the assessment, flight operations are analyzed and combined to extract unstabilized approach SPI values. The SPI documents are published in PDF format and required to be process numerically. For that reason, PDF to excel document conversion is performed using visual basic programming language. Next step is to parse all different flight operation SPI data into one big data file. This allowed to calculate all flight operations SPI data. Lastly 2014 and 2015's unstabilized approach SPI values and their occurrence rate are calculated. Figure 4.11 shows the SPI transformation algorithm.

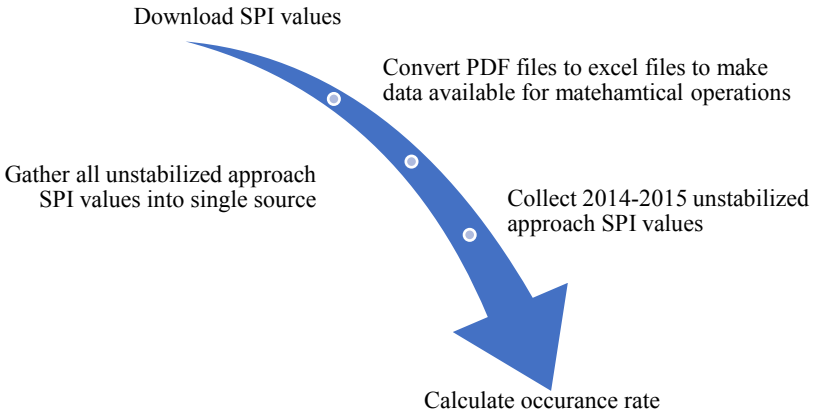


Figure 4.11. *SPI transformation algorithm*

Table 4.5 summarizes unstabilized approach SPI values. Based on this data, in two years unstabilized approaches have been encountered 64 times out of 567520 flights. Ratio of total number of undesired states over total number delivers an occurrence rate. This is also referred to as the probability of the occurrence of undesired event.

Table 4.5. *SPI summary for unstabilized approaches*

	Total number of flights: 567520	**#**	**P(R1)**
Contributing Factors	***Unstabilized Approach***	64	0,000112771
	Path High at 1000ft	971	0,001710953
	Path High at 500ft	708	0,001247533
	Speed High at 1000ft	3819	0,006729278
	Speed High at 1000ft	391	0,000688963
	Late Configuration Change	64	0,000112771
	High Vertical Speed Below 1000-100 ft	1012	0,001783197
	GPWS Sink Rate	486	0,000856357
	GPWS Glideslope	1109	0,001954116

These numbers are based on previous flights' data and can only constitute as a guide for the company after the undesired event happens. For that reason, it can be said that this approach is a reactive approach and lacking information about the event that had not occurred in the organization before. In other words, those are only numerical expression

to reflect an organization past and current conditions. For example, a catastrophic failure in an aircraft system might not yet happened for a specific airline but on the other hand another company could suffer from this failure dramatically e.g. B737 Max technical issues. In this case, just because this situation has not been observed in the company hence not in SPI does not mean that airline is safe to operate with this configuration. Therefore, SPI values are not only stand-alone tools for the safety analysis. In fact, SPI values are supportive tools for safety analysis. To overcome this problem in this study expert's opinions are used to calculate the probability of the events. Experts can take a snapshot of a specific organizations as well as whole aviation system. Therefore, any risk inducing situations can be caught even it they are not seen in the specific airline.

4.3. Fuzzy-Bayesian Bowtie Analysis of Unstabilized Approach

The development of risk insights contributes to enhance system safety and improve system performance. This approach requires the interpretation of scenario evolutions and the principal characteristics of the events that contribute to the risk (Mandelli, Yilmaz, Aldemir, Metzroth and Denning, 2013). In the study, bowtie analysis with fuzzy-bayesian method is used for risk assessment of unstabilized approaches. Scenario evolutions and principal characteristics of the event is analyzed via bowtie method and Bayesian approach. Bowtie method consists of two sub-analyses (FTA & ETA). FTA deals with possible cause of the top-event whilst ETA is related with post event analysis. Quantified Expert Opinions use fuzzy linguistic method. These inputs are used to obtain prior probabilities in the FTA. ETA is applied to obtain the impact of TE in the analysis and its possible outcomes. ETA provides posterior probabilities of the analysis. Next, bowtie model is mapped into Bayesian network equivalent to update prior and posterior probabilities (Acarbay and Kıyak, 2020). After completing bowtie analysis, SPI values are checked against prior and posterior probabilities to crosscheck the validity of the whole analysis. SPI values play vital role in the analysis since they supply past performance values of the analysis. Since BEs are described in line with SPI values, outputs of SPI and expert's opinion can be validated through the analysis. In the next step, bowtie analysis mapped into Bayesian network to have a more comprehensive perspective of relationship between basic and intermediate events. By doing so, dynamic analysis can be obtained throughout the analysis. Figure 4.12 shows in detail the algorithm of the analysis.

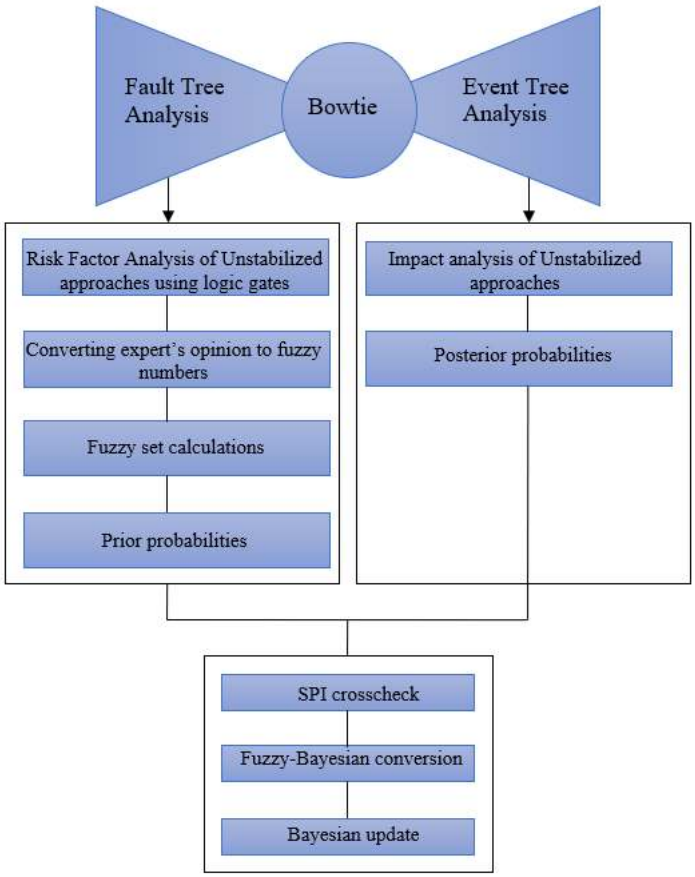


Figure 4.12. *Algorithm of the analysis*

4.3.1. Bowtie analysis of unstabilized approach

In this study, TE is the unstabilized approach. Left portion of the top-event is called as FTA. FTA consists of 8 different basic events. These basic events are chosen from SPI values to make analysis available to compare probabilistic SPI values. Basic events for analysis are as follows:

- BE1 – Path High at 1000 ft
- BE2 – Path High at 500 ft
- BE3 – Speed High at 1000 ft
- BE4 – Speed High at 500 ft
- BE5 - Late Configuration Change
- BE6 - High Rate of Descent 1000 ft
- BE7 - GPWS Glide Slope Warning

- BE8 - GPWS Sink Rate Warning
- BE9 – Lack of CRM Skills

Intermediate event 1 (IE1) is described as contributing factors for unstabilized approach. All basic events are connected to IE1 via 'OR logical gate'. By truth table given in Table 2.3 if either of the inputs of the OR gate is true, outcome will be true. In other words, all inputs should be false to have false output from an 'OR gate'. Output of the 'OR gate' is connected to the 'AND gate' via BE9. Similarly, referring Table 2.3, all inputs should be true to have 'true output or 1'. In other cases, output will be 'false or 0'. BE9 represents generic approach for the simplicity of the analysis. After constructing FTA, posterior aspect of the analysis is constructed. This part of the analysis is called as ETA. ETA aims to analyze posterior effect of the top-event. Analysis consists of safety barriers. Based on safety barrier's efficiently working condition or not, each barrier is divided into two. Safety barriers of the analysis are given below:

- SB1 – Effective Monitoring
- SB2 – Effective Communication Skills
- SB3 – Takeover Controls
- SB4 – Go Around

Probability of effective working condition of safety barrier is described as $P(SBx)$ whilst failure probability of the safety barrier is described in the analysis as $P(\overline{SBx})$. Based on the safety barriers effectiveness, two different outcomes are described in the analysis. These are safe state c(1) which is being away from any incident and accident, and unsafe state c(2) which is being away from safe outcome. These outcomes are conditionally dependent to each other and can be expressed as probabilistic manner. Equation 4.1 and 4.2 express conditionally dependence of the c1 and c2 outcome.

$$P(C1) = P(TE)P(SB1) + P(TE)P(\overline{SB1})P(SB2) + P(TE)P(\overline{SB1})P(\overline{SB2})P(SB3) + P(TE)P(\overline{SB1})P(\overline{SB2})P(\overline{SB3})P(SB4) \quad (4.1)$$

$$P(C2) = P(TE)P(\overline{SB1})P(\overline{SB2})P(\overline{SB3})P(\overline{SB4}) \quad (4.2)$$

To have a probabilistic assignment for main event, top-event's probability assignment must be known. In other words, prior probabilities of the analysis must be

known to proceed with posterior probabilities. Prior probabilities of the analysis are obtained by quantification of expert opinions to forecast primary event's effect on the unstabilized approach. Fuzzy logic is used in quantification process. Figure 4.13 shows generic bowtie analysis for unstabilized approach.

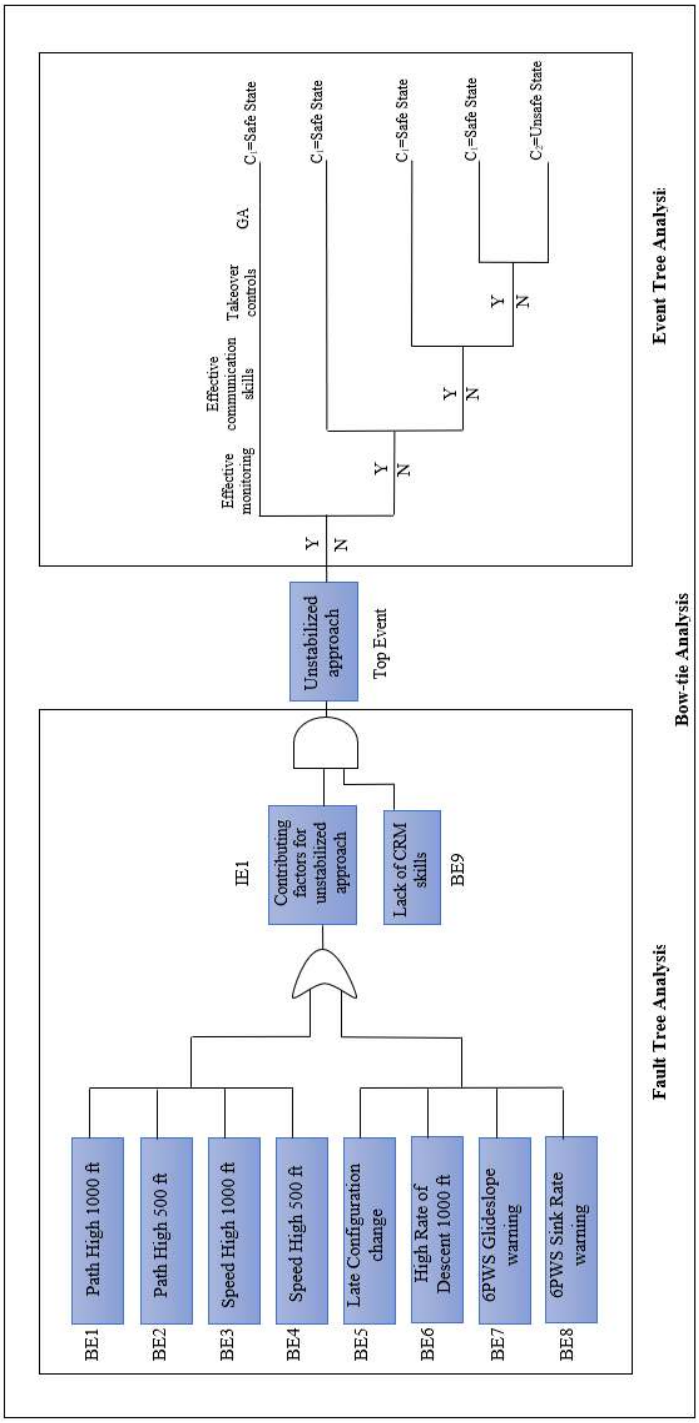


Figure 4.13. *Bowtie analysis of unstabilized approach*

4.3.2. Expert opinions

In the analysis experts were asked to assess risk level for each basic events. Their risk perception is then converted fuzzy linguistic values. Hence prior probabilities of the FTA will be created. In the study, 4 experts' opinions are considered. Basic background knowledges of the experts are given in Table 4.6. Expert's opinions are weighted by AHP. AHP analysis is carried out based on Goepel's study (Goepel, 2013).

Table 4.6. *Demographic information about experts*

Experts	Age	Experience (Years)	Occupation	Relevance to flight safety (1-5)	AHP Weights
A	32	8	Pilot	3	0.25
B	45	15	Engineer	4	0.30
C	43	10	Professor	2	0.10
D	47	15	Manager	5	0.35

Identity details of the participants are not shared in the study. Names are replaced with letters. Based on importance level of criteria and pairwise comparison, AHP values are assigned for the analysis. Next, each expert is asked to assign membership functions to basic events based on their knowledge and experience level. Each assignment is made via linguistically and converted into fuzzy set by triangular membership functions. Basic event's membership functions are defined as triangular and have nine different options. These options are Absolute Low, Very Low, Low, Medium Low, Medium, Medium Heigh, Heigh, Very High and Absolute High; AL, VL, L, ML, M, MH, H, VH, AH respectively. Experts' assignment is shown in Table 4.7.

Table 4.7. *Basic event assignment*

Event	Expert A	Expert B	Expert C	Expert D
BE1	M	MH	ML	ML
BE2	MH	MH	H	H
BE3	L	L	ML	L
BE4	MH	MH	MH	MH
BE5	M	MH	M	ML
BE6	L	L	ML	L
BE7	L	L	L	L
BE8	L	ML	ML	L
BE9	H	MH	H	MH

4.3.3. Quantification of expert opinions

Fuzzy logic method is widely used for quantification of uncertain data. It can be used in many fields to assess uncertain data and to convert linguistic variables into numerical values. Therefore, it is commonly used in engineering applications. Thanks to its flexible nature, fuzzy logic can be applied to many fields where uncertainty is a factor such as economics, medicine and risk assessment. For example, Shang and Hossen (2013) showed the application of fuzzy logic in risk assessment and decision-making processes for the field of economics. Kentel and Aral (2004) used the fuzzy probabilistic risk assessment method in medicine. Breast cancer risk assessment (Subramanian, Karmegam, Papageorgiou, Papandrianos and Vasukie, 2015), oral cancer risk assessment (Scrobotă, Băciuț, Filip, Todor, Blaga and Băciuț, 2017), parallel robot for elbow and wrist rehabilitation (Tucan, Gherman, Major, Vaida, Major, Plite and Pisla, 2020), and cardiovascular risk assessment (Casalino, Castellano, Castiello, Pasquadibisceglie and Zaza, 2019) are also a few examples of fuzzy risk assessment in medicine. There are studies realized with fuzzy risk assessment method in the fields of chemistry (Bilal, Mohammed and Brahim, 2017) and civil engineering (Cai, Hu and Zhang, 2016).

In the quantification process, each expert will choose membership functions intuitively for each basic event. Algorithm for the quantification of expert opinions is given in Figure 4.14.

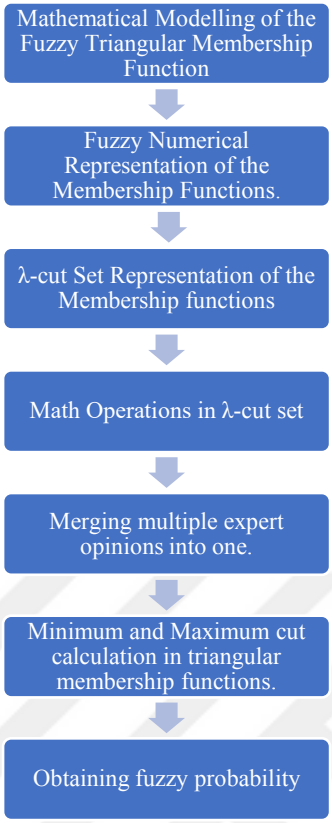


Figure 4.14. *Algorithm of the quantification process*

Mathematical expressions for these membership functions are given between equations 4.3-4.11 and graphical illustration of these membership functions are given in Figure 4.15.

$$AL = fr1(x) = \begin{cases} 1, & x < 0 \\ \frac{0{,}125 - x}{0{,}125}, & 0 < x \leq 0{,}125 \\ 0, & Other \end{cases} \tag{4.3}$$

$$VL = fr2(x) = \begin{cases} \frac{x}{0{,}125}, & 0 < x < 0.125 \\ \frac{0{,}25 - x}{0{,}125}, & 0{,}125 < x \leq 0{,}25 \\ 0, & Other \end{cases} \tag{4.4}$$

$$L = fr3(x) = \begin{cases} \frac{x - 0{,}125}{0{,}125}, & 0{,}125 < x < 0.25 \\ \frac{0{,}375 - x}{0{,}125}, & 0{,}25 < x \leq 0{,}375 \\ 0, & Other \end{cases} \tag{4.5}$$

$$ML = fr4(x) = \begin{cases} \frac{x - 0.25}{0{,}125}, & 0{,}25 < x < 0.375 \\ \frac{0.5 - x}{0.125}, & 0{,}375 < x \leq 0{,}5 \\ 0, & Other \end{cases} \tag{4.6}$$

$$M = fr5(x) = \begin{cases} \frac{x-0.375}{0.125}, & 0.375 < x < 0.5 \\ \frac{0{,}625-x}{0.125}, & 0.5 < x \leq 0.625 \\ 0, & Other \end{cases} \quad (4.7)$$

$$MH = fr6(x) = \begin{cases} \frac{x-0.5}{0{,}125}, & 0.5 < x < 0.625 \\ \frac{0.75-x}{0.125}, & 0.625 < x \leq 0.75 \\ 0, & Other \end{cases} \quad (4.8)$$

$$\mathrm{H} = \mathrm{fr7(x)} = \begin{cases} \frac{\mathrm{x}-0.625}{0{,}125}, & 0.625 < \mathrm{x} < 0.75 \\ \frac{0.875-\mathrm{x}}{0{,}125}, & 0.75 < \mathrm{x} \leq 0.875 \\ 0, & \mathrm{Other} \end{cases} \quad (4.9)$$

$$\mathrm{VH} = \mathrm{fr8(x)} = \begin{cases} \frac{\mathrm{x}-0.75}{0.125}, & 0{,}75 < \mathrm{x} < 0.875 \\ \frac{0.875-\mathrm{x}}{0.125}, & 1 < \mathrm{x} \leq 0.875 \\ 0, & \mathrm{Other} \end{cases} \quad (4.10)$$

$$\mathrm{AH} = \mathrm{fr9(x)} = \begin{cases} \frac{0{,}875-\mathrm{x}}{0{,}125}, & 0.875 < \mathrm{x} \leq 1 \\ 0, & \mathrm{Other} \end{cases} \quad (4.11)$$

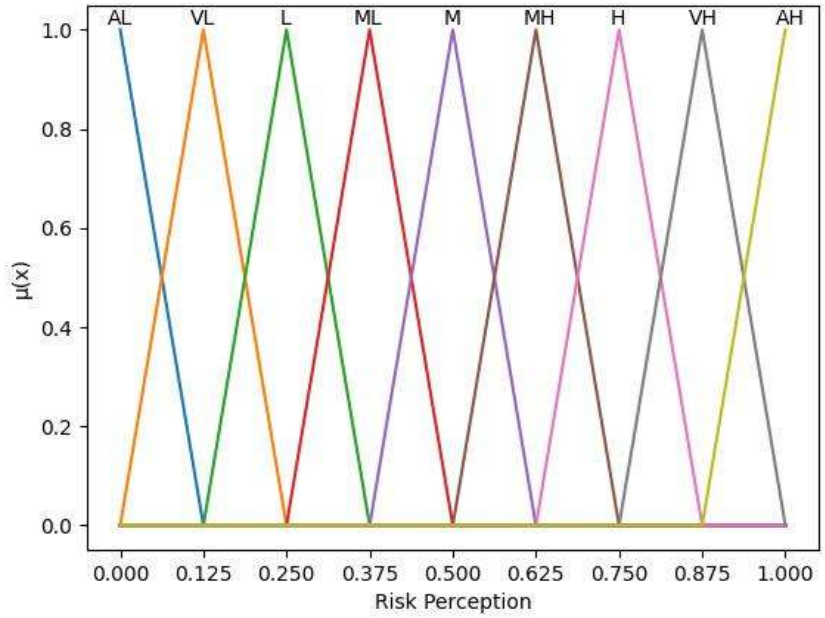


Figure 4.15. *Membership functions of basic events-1*

Membership functions can be represented as fuzzy numerical values. Fuzzy numerical representation of equations 4.3 to 4.11 are shown below.

$$AL = fr1(x) = [-0.125, 0, 0.125] \quad (4.12)$$

$$VL = fr2(x) = [0, 0.125, 0.25] \quad (4.13)$$

$$L = fr3(x) = [0.125, 0.25, 0.375\ ] \quad (4.14)$$

$$ML = fr4(x) = [0.25, 0.375, 0.5] \quad (4.15)$$

$$M = fr5(x) = [0.375, 0.5, 0.625] \quad (4.16)$$

$$MH = fr6(x) = [0.5, 0.625, 0.75] \quad (4.17)$$

$$H = fr7(x) = [0.625, 0.75, 0.875] \quad (4.18)$$

$$VH = fr8(x) = [0.75, 0.875, 1] \quad (4.19)$$

$$AH = fr9(x) = [0{,}875, 1, 1.125] \quad (4.20)$$

Opinions will be received from each expert for each basic event. Namely, four membership functions will be assigned for each key basic event between BE1 and BE9. As a result of this, there will be four membership functions for each basic event. These functions should be merged into one to represent average opinion of all experts for each basic event. For this reason, mathematical operation is required in the fuzzy set. In order to perform basic math operations in a fuzzy set, the λ-cut sets for each function must be defined.

$$f_A^{\lambda} = \{ x, x \in R, fa(x) \geq \lambda\} = [a_1^{\lambda}, b_1^{\lambda}] \quad (4.21)$$

$$f_B^{\lambda} = \{ x, x \in R, fb(x) \geq \lambda\} = [a_2^{\lambda}, b_2^{\lambda}] \quad (4.22)$$

λ-cut set equivalent of the membership functions through equations 4.12 to 4.20 can be described as follows if membership function:

$$f_{r1}^{\lambda} = [\ 0, 0.125\text{-}0.125\lambda] \quad (4.23)$$

$$f_{r2}^{\lambda} = [\ 0.125\lambda, 0.25\text{-}0.125\lambda] \quad (4.24)$$

$$f_{r3}^{\lambda} = [\ 0.125\lambda + 0.125, 0.375\text{-}0.125\lambda] \quad (4.25)$$

$$f_{r4}^{\lambda} = [\,0.125\lambda + 0.25,\ 0.5\text{-}0.125\lambda] \quad (4.26)$$

$$f_{r5}^{\lambda} = [\,0.125\lambda + 0.375,\ 0.625\text{-}0.125\lambda] \quad (4.27)$$

$$f_{r6}^{\lambda} = [\,0.125\lambda + 0.5,\ 0.75\text{-}0.125\lambda] \quad (4.28)$$

$$f_{r7}^{\lambda} = [0.125\lambda + 0.625,\ 0.875\text{-}0.125\lambda] \quad (4.29)$$

$$f_{r8}^{\lambda} = [\,0.125\lambda + 0.75,\ 1\text{-}0.125\lambda] \quad (4.30)$$

$$f_{r9}^{\lambda} = [\,0.125\lambda + 0.875,\ 1] \quad (4.31)$$

Basic mathematical operations can be performed for each λ-cut set for the equations 4.23 to 4.31. Equation 4.32 and 4.33 show the basic mathematical operations in functions defined in equation 4.21 and 4.22 for λ cut sets.

$$f_A^{\lambda} + f_B^{\lambda} = [a_1^{\lambda}, + a_2^{\lambda}, b_1^{\lambda} + b_2^{\lambda}\ ] \quad (4.32)$$

$$f_A^{\lambda} - f_B^{\lambda} = [a_1^{\lambda}, - a_2^{\lambda}, b_1^{\lambda} - b_2^{\lambda}\ ] \quad (4.33)$$

λ-cut sets from equations 4.23-4.31 can be adapted for the given membership functions. In this way, it is possible to process four fuzzy values given by four experts for a basic event into one average solution. The merging of more than one view under a single view is carried out by the linear thinking pool method proposed by Clemen and Winkler (1999). The collection of more than one opinion into one by the linear thought pool is indicated in equation 4.34:

$$f_i^{\lambda} = \left[\sum_{j=1}^{n} \omega j\, a_{ij}^{\lambda}, a_2^{\lambda}, \sum_{j=1}^{n} \omega j\, b_{ij}^{\lambda}\right], i = 1, 2, \ldots, m\ j = 1, 2, \ldots, n \quad (4.34)$$

If the weighting of four specialists is taken according to Table 4.6 and membership functions for the BE1 are taken as MH, ML, L, ML and replaced in equation 4.34, average membership function of four experts will be given in single equation as in equations 4.35 and 4.36:

$$\left[\sum_{j=1}^{4} \omega j\, a_{i1}^{\lambda} = (0.30 + 0.35) * (0.125\lambda + 0.25) + (0.10) * (0.125\lambda + 0.125) + (0.25) * (0.125\lambda + 0.5) = 0.08125\lambda + 0.1625 + 0.0125\lambda + 0.0125 + 0.03125\lambda + 0.125 = \mathbf{0.125\lambda + 0.3}\right] \quad (4.35)$$

$$\left[\sum_{j=1}^{4} \omega j\, b_{i1}^{\lambda} = (0.30 + 0.35) * (0.5 - 0.125\lambda) + (0.10) * (0.375 - 0.125\lambda) + (0.25) * (0.75 - 0.125\lambda) = 0{,}325 - 0.08125\lambda + 0.0375 - 0.00125\lambda + 0.1875 - 0.03125\lambda = \mathbf{0.55 - 0.125\lambda}\right] \quad (4.36)$$

Accordingly, merged opinion of the experts' λ-cut set is shown in equation 4.37:

$$f_{\text{result}}^{\lambda} = [\,0.125\lambda + 0.3,\ 0.55\text{-}0.125\lambda] \quad (4.37)$$

If same process is applied to all basic events, average opinion's membership functions can be obtained as follow:

$$f_{\text{BE1}}^{\lambda} = [\,0.125\lambda + 0.35625,\ 0.60625\text{-}0.125\lambda] \quad (4.38)$$

$$f_{\text{BE2}}^{\lambda} = [\,0.125\lambda + 0.55625,\ 0.84375\text{-}0.125\lambda] \quad (4.39)$$

$$f_{\text{BE3}}^{\lambda} = [\,0.125\lambda + 0.1375,\ 0.425\text{-}0.125\lambda] \quad (4.40)$$

$$f_{\text{BE4}}^{\lambda} = [\,0.125\lambda + 0.5,\ 0.75\text{-}0.125\lambda] \quad (4.41)$$

$$f_{\text{BE5}}^{\lambda} = [\,0.125\lambda + 0.36875,\ 0.58125\text{-}0.125\lambda] \quad (4.42)$$

$$f_{\text{BE6}}^{\lambda} = [\,0.125\lambda + 0.1375,\ 0.425\text{-}0.125\lambda] \quad (4.43)$$

$$f_{\text{BE7}}^{\lambda} = [\,0.125\lambda + 0.125,\ 0.375\text{-}0.125\lambda] \quad (4.44)$$

$$f_{\text{BE8}}^{\lambda} = [\,0.125\lambda + 0.175,\ 0.425\text{-}0.125\lambda] \quad (4.45)$$

$$f_{\text{BE9}}^{\lambda} = [\,0.125\lambda + 0.6125,\ 0.825\text{-}0.125\lambda] \quad (4.46)$$

Based on equations 4.38 to 4.46, all basic events' membership functions can be described as triangular three points as it is shown in throughout equation 4.12 to 4.20. Average membership functions' fuzzy numerical representation can be calculated as follows:

$$BE1 = fb1(x) = [0.35625, 0.48125,\ 0.60625] \quad (4.47)$$

$$BE2 = fb2(x) = [0.55625, 0.68125, 0.80625] \quad (4.48)$$

$$BE3 = fb3(x) = [0.1375, 0.2625, 0.3875\ ] \quad (4.49)$$

$$BE4 = fb4(x) = [0.5, 0.625, 0.75] \quad (4.50)$$

$$BE5 = fb5(x) = [0.36875, 0.49375, 0.61875] \quad (4.51)$$

$$BE6 = fb6(x) = [0.1375, 0.2625, 0.3875] \quad (4.52)$$

$$BE7 = fb7(x) = [0.125, 0.25, 0.375] \quad (4.53)$$

$$BE8 = fb8(x) = [0.175, 0.3, 0.425] \quad (4.54)$$

$$BE9 = fb9(x) = [0.54375, 0.66875, 0.79375] \quad (4.55)$$

The combined membership function of BE4 is shown in Figure 4.16. Next step in the analysis is to determine F_{mr} , $F_{ml,}$and F_m values. Based on these numbers, probability calculation will be performed.

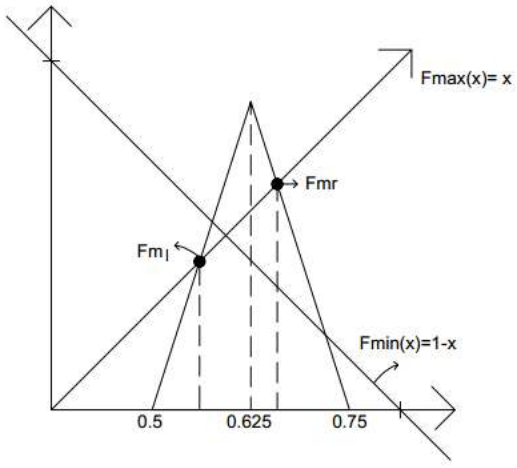


Figure 4.16. *Membership functions of basic events-2*

In the calculation of the fuzzy probabilistic values, maximum and minimum drawing method is used. By using this method fuzzy values can be converted into probabilistic values (Chen, 1985). The equations for this method are specified between equations 4.56-4.58:

$$F_m = \frac{F_{mr}+1-F_{ml}}{2} \quad (4.56)$$

$$F_{ml} = \cup [\, f_i(x) \cap f_{min}(x)] \tag{4.57}$$

$$F_{mr} = \cup [\, f_i(x) \cap f_{max}(x)] \tag{4.58}$$

In order to calculate the values of these points, fmin and fmax values specified in equations 4.59 and 4.60 must be defined:

$$f_{max}(x) = \begin{cases} x, & 0 \le x < 1 \\ 0, & \text{Other} \end{cases} \tag{4.59}$$

$$f_{min}(x) = \begin{cases} 1 - x, & 0 \le x < 1 \\ 0, & \text{Other} \end{cases} \tag{4.60}$$

If the equations between 4.56-4.60 are calculated for the membership function specified in Figure 4.15, fmr, fml, and fm values are found as 0.666667, 0.44444 and 0.61111, respectively. If the equation is applied for all basic events, fmr, fml, and fm values can be calculated as shown in Table 4.8.

Table 4.8. *F values*

Events	F_{mr}	F_{ml}	F_m
BE1	0,538889	0,572222	0,483333
BE2	0,75	0,394444	0,677778
BE3	0,377778	0,766667	0,305556
BE4	0,666667	0,444444	0,611111
BE5	0,516667	0,561111	0,477778
BE6	0,377778	0,766667	0,305556
BE7	0,333333	0,777778	0,277778
BE8	0,377778	0,733333	0,322222
BE9	0,738889	0,405556	0,666667

In the next stage, method developed by Onisawa (1990) is used to calculate the probability value of fuzzy membership functions.

$$P_{PE1} = \begin{cases} \frac{1}{10^k}, & F_m \neq 0 \\ 0, & F_m = 0 \end{cases} \tag{4.61}$$

$$k = \left(\frac{1 - F_m}{F_m}\right)^{\frac{1}{3}} * 2.301 \tag{4.62}$$

Using $F_m = 0.61111$ and k=2,352725, probability of BE1 is calculated as 0.004439 ($P_{BE1} = 0.004439$). Similarly, each k values and probability of basic events are calculated using equation 4.61, 4.62 and Table 4.8. Results are shown in Table 4.9.

Table 4.9. *K and PBE values*

Events	k	P_{BEx}
BE1	2,352725	0,004439
BE2	1,795861	0,016001
BE3	3,025281	0,000943
BE4	1,979179	0,010491
BE5	2,370244	0,004263
BE6	3,025281	0,000943
BE7	3,164033	0,000685
BE8	2,948225	0,001127
BE9	1,826305	0,014917
P_{TBE}		0,038893
P_{ME}		0,000058

In bowtie design, all basic events throughout one to eight are connected to each other via 'OR gate'. It means that total probability of the IE1 is the sum of all basic events. In this example P(IE1) is calculated as 0,038893. Main event has two inputs: IE1 and BE9. These inputs are connected to each other via 'AND gate'. Table 4.10 summarize FTA part of the bowtie analysis.

Table 4.10. *Probability calculations of FTA*

	Name	Expert A	Expert B	Expert C	Expert D	Fmr	Fml	F	K	Pr
BE1	Path High at 1000 feet	M	MH	ML	ML	0,538889	0,572222	0,483333	2,352725	0,004439
BE2	Path High at 500 feet	MH	MH	H	H	0,75	0,394444	0,677778	1,795861	0,016001
BE3	Speed High at 1000 feet	L	L	ML	L	0,377778	0,766667	0,305556	3,025281	0,000943
BE4	Speed High at 500 feet	MH	MH	MH	MH	0,666667	0,444444	0,611111	1,979179	0,010491
BE5	Late Configuration Change	M	MH	M	ML	0,516667	0,561111	0,477778	2,370244	0,004263
BE6	High Rate of Descent 1000 feet	L	L	ML	L	0,377778	0,766667	0,305556	3,025281	0,000943
BE7	GPWS Glide Slope Warning	L	L	L	L	0,333333	0,777778	0,277778	3,164033	0,000685
BE8	GPWS Sink Rate Warning	L	ML	ML	L	0,377778	0,733333	0,322222	2,948225	0,001127
BE9	Lack of CRM Skills	H	MH	H	MH	0,738889	0,405556	0,666667	1,826305	0,014917
IE1	Contrubiting factors for unstabilized approach									0,038893
TE	Unstabilized Approach									0,00058

TE's probability in this study is calculated by multiplication of IE1 by BE9 and that gives us probability of TE. In this example probability is calculated as 0,00058. The result can be compared with the SPI table given in Table 4.5. SPI value of unstabilized approaches from Table 4.5 can be seen as 0,000112771. When this probability is compared with the one originating from the quantified expert opinions (0,00058), the difference between two analysis is approximately 0,00047. Also, both probability values

start from same 4th decimal figure. Namely, difference in between two analyses can be measurable within same ten thousandths. It can be concluded that difference between both analyses is negligible and can be concluded as fuzzy probabilistic approach produce reliable output for the analysis and can be used in the operations.

4.3.4. ETA of unstabilized approach

Prior probabilities of the analysis are obtained through quantification of experts' assessment whereas posterior probabilities are assigned by each expert for each safety barriers. Figure 4.17 shows the ETA of the unstabilized approach.

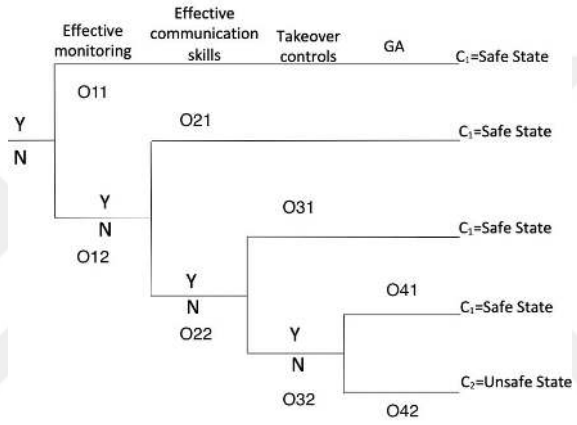


Figure 4.17. *Event tree analysis of unstabilized approach*

The ETA is aimed to mitigate negative effects of the main event occurrence. For that reason, safety barriers are introduced in the system. Each safety barrier has two different of outcome. Whereas 'Y' represents success of the safety barriers, 'N' represents failure of related barrier. Analysis consists of four layers. In other words, there is a contingency plan for failed safety barriers. For example, as illustrated in Figure 4.17, if effective monitoring barrier fails then effective communication skills safety barrier tries to mitigate overall effect of occurrence of main event and failing of effective monitoring. Based on this definition, to have an unsafe state, safety barriers of effective monitoring, effective communication skills, takeover controls and go around must fail at the same time after occurrence of main event.

Sum of the probabilities of each safety barrier's success and failures is equal to one. Based on this definition equation 4.63 can be defined.

$$P_{SBx}(Y) + P_{SBx}(N) = 1 \tag{4.63}$$

As shown in Figure 4.15, failure of the safety barrier triggers second layer safety barriers. As a result of this it can be said that overall process is an iterative process. By using equation 4.63, iterative process of second layer of safety barrier can be defined as follow.

$$P_{SBx1}(N) = P_{SBx2}(Y) + P_{SBx2}(N) \quad (4.64)$$

Similarly, third and fourth level of the barriers can be formed as follows:

$$P_{SBx2}(N) = P_{SBx3}(Y) + P_{SBx3}(N) \quad (4.65)$$

$$P_{SBx3}(N) = P_{SBx4}(Y) + P_{SBx4}(N) \quad (4.66)$$

All probabilities listed above are conditional probabilities. For that reason, overall occurrence probability of unsafe state can be formulated as equation 4.67.

$$P(C2) = P_{SBx4}(N)\, P_{SBx3}(N)\, P_{SBx2}(N) P_{SBx1}(N) \quad (4.67)$$

Occurrence probability of C1 is defined as any other situations other than occurrence of C2. The iterative formula can be simplified as equation 4.68.

$$P(C1) = 1 - P(C2) \quad (4.68)$$

4.3.5. Bayesian conversion

FTA and ETA are successful tools to assess the risk. However, these tools are not faultless due to the nature of these analysis. FTA and ETA are not appropriate for dynamic systems**.** In order to classify a system dynamic, its parameters must change by time. FTA is performed to prevent main event occurring. If system parameters have changed or main event is updated, design of the FTA must be changed to adapt and mitigate the new risk level. Although some dynamic structure can be form in ETA, it requires complex system design. Complex structure makes the dependencies between all components of the system including main event difficult to understand. Moreover, simplifying complex structures in ETA is not easy. To overcome these problems and create a dynamic environment bowtie model can be mapped into Bayesian network equivalent. Bowtie to Bayesian network conversion algorithm is shown in Figure 4.18 (Bobbio, Portinale, Minichino and Ciancamerla, 2001).

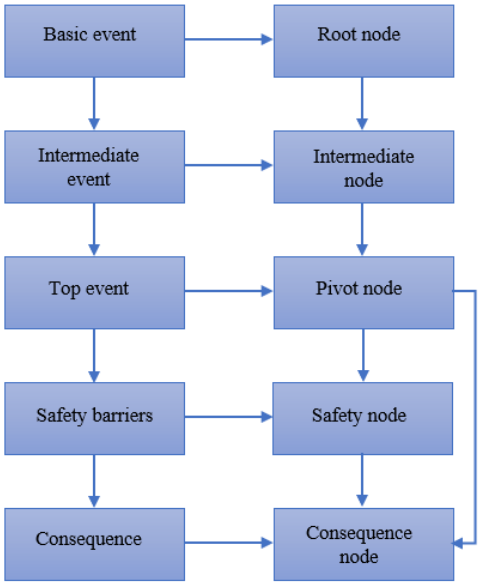


Figure 4.18. *Bowtie-bayesian network conversion*

Based on algorithm stated in Figure 4.18, Bayesian network equivalent of bowtie analysis is given in Figure 4.19. In this algorithm all basic events are called root nodes and intermediate events are converted into intermediate node or nodes. From unstabilized approach example, all basic events from 1-8 are called root nodes. These nodes come together and form intermediate node. Intermediate node and BE9 triggers main event and safety barriers tries to mitigate the effect of it. As it can be seen from Figure 4.19, main event is not shown in bayes network. The reason of this fact is to illustrate direct relationship between pre-analysis and post-analysis. Consequence node consists of two different states. These are safe state and unsafe state. In Bayesian network, analysis from basic event to the consequences can be analyzed simultaneously.

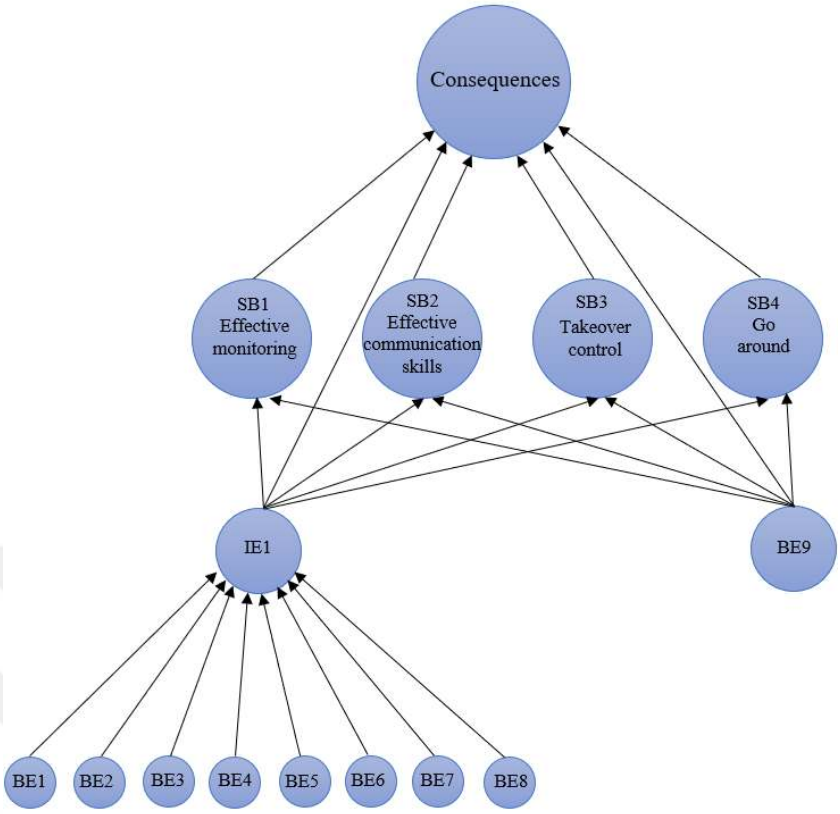


Figure 4.19. *Bayes network equivalent of the bowtie analysis*

After forming Bayesian networks, experts were asked to give their opinion about posterior analysis. In this analysis arithmetic average of experts' assessments were taken. In the analysis 'C1 safe state' represents the non-accident state of the aeroplane. On the other hand, C2 is defined as accident state of the aeroplane. The result of the analysis is shown in Table 4.11.

Table 4.11. *Posterior probabilities of bowtie analysis*

e1 = o 11	0.8
e1 = o 12	0.2
e2 = o 21	0.85
e2 = o 22	0.15
e3 = o 31	0.7
e3 = o 32	0.3
e4 = o 41	0.95
e4 = o 42	0.05

As previously mentioned, all safety barriers are connected to each other which makes the next layer of the safety barrier dependent on the previous layer. Considering this information into account, conditional probability table can be form as sown in Table 4.12. This table is designed to convert ETA into Bayesian equivalent.

Table 4.12. *Conditional probability relationship*

Effective Monitoring	o11	o12			
Effective Communication Skills		o21	o22		
Takeover Control			o31	o32	
Go Around				o41	o42
consequence = c1	1	1	1	1	0
consequence = c2	0	0	0	0	1

Based on conditional probability table, posterior probabilities of main event can be calculated. The system now hosts prior probabilities via fuzzy analysis and posterior analysis via conditional probabilities. The relationship between sub systems is described in Figure 4.19. Whenever the system is updated or probabilities of basic events are changed, these changes will be reflected to overall design and probabilities will be updated. Hence, non-dynamic environment of bowtie analysis will be eliminated.

5. CONCLUSION

Aviation is the number one transportation method in the globe that reduces travel time significantly. Thanks to its structure, aviation is the safest transportation method in the world. There is a significant amount of work behind this success. Aviation is highly regulated around the globe. Each company within this framework must fulfill national and international regulations' requirements. Safety is the main motivation for the regulations. It is the responsibility of all stakeholders to perform all operations safely within the aviation framework. In addition, management should promote safety within the organization.

Safety should be examined and practiced in a structural way. For that reason, ICAO introduced a separate annex in 2013 for the purpose of managing safety. Based on this annex, ICAO published DOC 9859 Safety Management Manual as a reference guidance. Safety management consists of four components. These are safety policy, safety assurance, safety risk management and safety promotion. This study focused on the safety risk management component of risk management. Most of the time, risk assessment process is an iterative process and prone to numerous errors. The risk assessment process used for identifying hazards and its factors that have the potential to cause a harm. By this definition, ICAO tries to mitigate risk factors in the operation by relying on risk assessors. However, the effectiveness of the risk assessment is not only depended on identifying hazards and its factors but also the reliability of assessors. Incorrectly assessed risk will never produce optimum output.

The traditional risk management approach of ICAO uses risk matrix for the risk assessment process. Matrices are practical and easy to use. This approach helps prioritize risks and focuses on certain risks among different risk classes. On the other hand, the assessment process is highly dependent on assessor. Any inexperienced or biased assessment would produce an inefficient outcome. By nature, matrix assessments are static environments, and their assignments are not continuous. The classification of risks based on severity and probability produces discrete output. For that reason, analyzed risk levels produce discrete risk output.

The aim of the study is to offer dynamic risk assessment system for airline operations. Dynamic risk assessment means a continuous process of risk identification and assessment. It also includes continuous process of risk monitoring and reviewing in

the rapidly changing aviation environment. Dynamic risk assessment helps improve the decision-making process. For that reason, dynamic risk assessment is essential in the aviation industry.

Dynamic risk assessment can be performed via either intuitive methods or using quantitative tools. In either case, an assessment should be done continuously. In order to show both solutions, the risk assessment approach uses quantification of expert opinions. Fuzzy logic was used to convert linguistic expressions into numerical probabilistic values in this study. If an assessment already has quantitative data to be analyzed, these inputs can be used directly in the analysis. However, uncertainty is present most of the time in the analysis in aviation. To cover all possibilities (quantitative data is obtained, uncertainty is present, analysis needs both quantitative data and linguistic inputs at the same time), quantification of experts' opinion was preferred. Expert opinions represent membership functions. In other words, each expert chooses linguistic terms which tied to membership functions. Next, membership functions are represented by λ-cut to use arithmetic operations in functions. Overall probability is obtained through probabilistic values.

In the bowtie analysis, basic events are chosen in the same manner where SPI tables are constructed. The main purpose of this design is to compare actual probabilistic values from SPI's with the fuzzy expert outputs. This approach helps to verify if fuzzy-Bayesian risk assessment approach results are in line with real outputs. However, it should be noted that expert opinions are subjective data whilst SPIs are objective data. Any bias during assessment may result deviating from optimum data. In order to avoid this problem, expert's accuracy on the assessment must be present.

In study, probability of top-event from fault tree analysis is calculated as 0,00058. Actual data from SPI is 0,000112771. If two data compared with each other, it can be said that analysis' probability on unstabilized approach is approximately 5.1 times more than SPI values. In other words, it can be concluded as experts have expressed more conservative opinions than actual values. The difference between two probability values is 0,00047. Both probability values are starting from ten thousandths. Namely, experts have expressed their opinions about unstabilized approach within same ten thousandths with SPI values.

Finally, this dissertation study proposes a new model to be used in the risk assessment process in airline operations. The design structure of the study enables the analysis to be used in dynamic environment. Therefore, the system can contribute to the risk management process in aviation organizations since they can be used in live operations.

Throughout the study bowtie design is kept simple and generic on purpose to compare and verify actual values of the unstabilized approaches. In real life application, bowtie analysis for the unstabilized approaches must be designed in detail to have a better analysis result. However, simple generic design in this study in line with SPI values helped to verify the model.

Future work based on this study is possible using machine learning and big data methods. Probabilistic values can be used to teach risk assessment system about risks and required mitigation strategies. From this perspective, a continuation of this study is possible. Self-learning risk assessment system applications is not present in aviation risk management applications.

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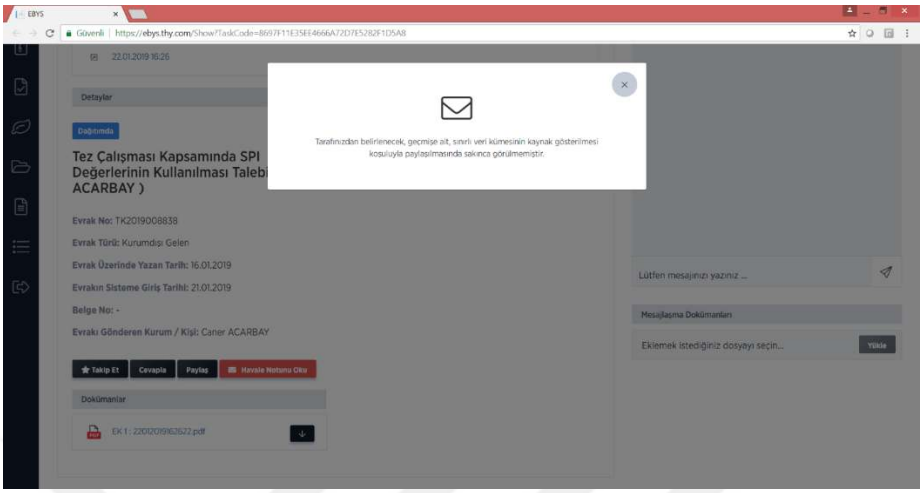
APPENDIX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Yükle

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