Application of AHP Method for Failure Modes and Effect Analysis (FMEA) in Aerospace Industry for Aircraft Landing System

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ABSTRACT

FMEA has been used in the aerospace industry for many years; this industry has been growing rapidly, so reliability and safety guarantee have been of increasing concern within the aerospace industry.

Conventional FMEA technique still imposes many common shortages in order to compute RPN, which is product of the Severity (S), Detection (D) and Occurrence (O). Conventional FMEA considers the important of the elements S, O and D with the same weight which is not effective in practical FMEA study.

In our base article, the study was done by 4 experts using the fuzzy developed FMEA that yielded crisp RPN scores for the failure modes of the aircraft landing system used in the research, this imposes a problem when ranking the risks of those modes.

In this study, we used AHP that helps decision makers find one that best suits their goal and their understanding of the problem. It provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions.

When using the AHP method, expert's opinions and weights will be obtained and will be prioritized in a better way than FMEA weights. A pairwise comparison questionnaire was designed and distributed to 35 aerospace experts working in Jet Aviation, in Basel Switzerland, then critical selection factors were identified, consistency vector, index and rate were determined, "expert choice 11.0" was applied to compute the outcomes. FMEA components were compared in the hierarchy,

reaching the RPN and ranking its scores. RPN better values obtained showed the significant risk level attained by some FMs in the aircraft landing system that were used in our base study.

Keywords: FMEA; AHP; Failure Mode; Risk Priority Number; Decision Making

ÖZ

FMEA, hava-uzay endüstrisinde yıllardır kullanılmaktadır; bu endüstri hızla büyümektedir, bu yüzden dayanıklılığı ve güven garantisi, hava-uzay endüstrisi ile yükselişe geçmiştir.

Geleneksel FMEA tekniği, RPN hesadplamalarını bir çok sıkça rastlanan eksikliğiyle hala zorlamaktadır ki sonucu: Zorluk (Z), Tarama (T) and Oluşumu (O)'dur. Geleneksel FMEA, Z, T ve O'nun önemli elementlerini aynı ağırlıkla –ki bu, kullanışlı FMEA çalışmasını etkilemeyecek olan- birlikte göz önüne alır.

Makalemizin temeli; bu çalışma belirsiz gelişmiş olan FMEA'yı kullanan 4 bilirkişi tarafından tamamlanmıştır ve bu araştırmada, uzay-hava iniş sistemi hata modlarının, hızlı RPN skorlarından yararlanılmıştır. Bu modların riskleri en yüksek mevkide problem yaratır.

Bu çalışmada, amaçlarına en iyi uyan, karar yapıcıları bulmaya ve sorunları anlamaya yardımcı olan AHP'yi kullandık. AHP, bir karar sorunu yapısı, elementleri temsil eden ve niceliğini belirleyen, bütün bu elementlerin amaçlarının tamamıyla ilişkili olarak, etraflı ve mantıklı bir ana yapı iskeleti üretir.

AHP yöntemi kullanıldığında, bilirkişinin düşünceleri ve ağırlıkları elde edilecektir ve FMEA ağırlıklarına göre en iyi yönteme öncelik verilecektir. Bir, ikili kıyaslama anketi tasarladı ve Jet Havacılıkta, Basel-İsviçre'de, çalışan 35 uzay-hava bilirkişisine dağıtıldı sonra kritik seçim faktörleri tanımlandı, uyumluluk vektörü, dizin ve değer belirlendi, "bilirkişi seçimi 11.0" olarak sonuçların hesaplarına eklendi. FMEA bileşenleri, bir düzen içerisinde karşılaştırıldı, RPN'ye ve skorların aşamasına ulaşıldı. RPN'nin elde edilen daha iyi değerleri, hava-uzay iniş sistemlerinin bazı FM'leri tarafından, önemli risk seviyelerine ulaşıldığı gösterildi.

Anahtar Kelimeler: FMEA; AHP; Hatalı Mod; Risk Öncelik Numarası; Karar Yapıcı

DEDICATION

To my future career, future path in aviation industry

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LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
AI	Artificial Intelligence
ANP	Analytical Network Process
CIL	Critical Item List
D	Detection
DMs	Decision Makers
ER	Evidential Reasoning
FM	Failure Modes
FMADM	Fuzzy Multi Attribute Decision Making
FMEA	Failure Modes Effects Analysis
FMECA	Failure Modes Effects and Criticality Analysis
FOWGA	Fuzzy Ordered Weighted Geometric Averaging
FPSO	Floating Production, Storage and Offloading
FSUs	Floating Storage Units
FWGM	Fuzzy Weighted Geometric Means
ISO	International Organization for Standardization
JC	Joint Commission
JCAHO	Accreditation of Health Care Organization
MCDM	Multi-Criteria Decision Making
ME-MCDM	Multi-Expert MCDM
MP	Mathematical Programming
NASA	National Aeronautics and Space Administration
O	Occurrence

RPC	Risk Priority Code
MRA	Minimal Regret Approach
MAFMA	Multi-Attribute Failure Mode Analysis
PC-FMECA	Priority-Cost FMECA
GC-RPN	Green Component Risk Priority Number
TOPSIS	Technique for Order Preference by Similarity to Ideal solution
DEMATEL	Decision Making Trial and Evaluation Laboratory
MADM	Multi-Attribute Decision Making
FMAGDM	Fuzzy Multi-Attribute Group Decision Making
RPN	Risk Priority Number
S	Severity
US	United States

Chapter 1

INTRODUCTION

1.1 Overview

Failure modes and effect analysis (FMEA) is an analysis technique for identifying and removing recognized and/or possible failures, problems and errors from a design, system, process and/or service before getting to the customer. It is also stated to as Failure Modes Effects and Criticality Analysis (FMECA) when it is used for a criticality analysis (Liu et al, 2013). To define, identify and eliminate known and/or potential failures, problems, errors and so on from the system, design, process and/or service before they reach the customer we use FMEA.

This methodology has gained global acceptance and applications in numerous industries such as nuclear, aerospace, manufacturing and chemical. Analysts using FMEA can recognize known and possible FMs and their effects and causes, this method help them rank the recognized FMs and can also help them work out remedial actions for the FMs. (Feili et al., 2015).

Analytical Hierarchy Process (AHP) approach has a primary advantage, it is the relative ease with which it handles multiple criteria and performs qualitative and quantitative data (Kahraman, Cebeci, & Ruan, 2004).

1.2 Inspiration for Research

These days, safety and reliability assurance have been of increasing concern in the Aerospace industry. This is an obvious fact that a significant number of accidents happening each year are due to the failure of aircraft systems' components. To manage this risk, FMEA which is a well-known method is employed for reliability analysis in the mentioned fields. However, along all studies based on conventional FMEA technique, it still imposes many common shortages in order to compute Risk Priority Number (RPN), which is the numerical assessment of risk used to rank the failure modes.

1.3 Purpose and Objectives

1.3.1 Purpose

The purpose of this study was to extend FMEA by considering the priority of a set of alternatives and the relative importance of attributes in a multi-criteria decision-making under the Analytical Hierarchy Process (AHP) environment.

1.3.2 Objectives

a) Theoretical and practical contribution to aircraft landing system as one of the important potential FM in aerospace industry.

b) Improving the RPN calculation.

c) Generating more exact RPN values.

1.4 Study Query

a) How did FMEA evolved during the past decades?

b) What level of contribution does AHP provide in RPN calculation?

1.5 structure of Thesis

This thesis consists of five chapters; the first chapter is an introduction to our study. The second chapter consists of a literature review discussing all FMEA history and its evolution through a sequence of different methods. Chapter three describes the methodology followed for this study. In chapter four we have our data analysis and the results. The fifth chapter and the last one contains a discussed conclusion along with a future study recommendation.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Safety and reliability engineering has been developed out of the integration of a number of exercises, which were beforehand the area of the engineer. A safety innovation for optimizing risk endeavors to adjust the risk against the advantages of the exercises and the cost of further hazard decrease (Smith, 2017).

Reliability assessment of a system from its fundamental components is a standout amongst the most essential parts of reliability analysis. A system is a collection of parts whose appropriate coordinated function prompts to its proper functioning. It is important to model the relationship of the individual parts as well as the reliability of the system in a reliability analysis. There are various system modeling schemes for reliability analysis such as reliability block diagram, fault tree and success tree methods, event tree method, failure mode and effect analysis (FMEA) etc. FMEA method is inductive in nature and it is utilized in all aspects of failure analysis from idea to process development (Helvacioglu & Ozen, 2014).

FMEA was initially created as an official plan approach in the aerospace industry in the 1960s in order to reduce or eliminate risks found in a system, process or a design; has turned out to be a useful and powerful tool in assessing probable failures and avoiding them from happening (Liu et al., 2013)

FMEA has been broadly utilized in an extensive variety of industries, including aerospace, mechanical, nuclear, automotive, electronics, chemical and medical technologies industries since its startup as a backup tool for designers. (Chang & Cheng, 2011; Chin et al., 2009; Sharma et al., 2005).

2.2 Failure Modes and Effects Analysis (FMEA)

All design disciplines must be part of the product's development to ensure a solid design that meets customer's needs, designing a reliable product is in fact a simultaneous engineering procedure. FMEA, a reliability engineering approach with its tools can concentrate on the design process (Crowe and Feinberg, 2001). FMEA was officially announced in 1949 by the US Armed Forces and later accepted in the Apollo space program to relieve hazard. The usage of FMEA gained importance during the 1960s (Carlson, 2012). This method helps to improve design decisions and product quality during the operation phase. It is considered as a product development (or process analysis) tool used to suspect modes of failure and moderate potential hazard (Helvacioglu & Ozen, 2014).

In 1949, the US Armed Forces formalized FMEA that was later adopted in the Apollo space program to decrease risk. The use of FMEA gained momentum during the 1960s (Carlson, 2012).

Grumman Aircraft Corporation first developed FMEA in the 1950s, a helpful appraisal method for a safety and reliability analysis of a system, design and other reliability engineering fields (Brad, 2008; Karim, Smith, & Halgamuge, 2008). The key target of FMEA is to identify, evaluate and rank the possible FMs by using

RPNs. The risk factors occurrence (O), severity (S) and detection (D) form the product of RPN (Zhang & Chu, 2011).

FMEA is “a methodical technique for the risks analysis and rating, joined with many process or product FM (both existing and probable), ranking them for corrective action, acting on the biggest ranked items, re-evaluating those items and returning to the ranking step in a continuous cycle until minimal returns set in”. In pharmacy, its application is growing, for the development of health care risk management and production processes of pharmaceuticals, and for the methods evaluation for analytical validation (Barendset al., 2012)

FMEA is an engineering practice for identification, definition and elimination of known and/or potential failures, problems and errors from a system, process, design, and/or service before reaching the customer (Helvacioglu & Ozen, 2014).

FMEA is a systematic technique for risk analysis and their ranks associated with various products (or processes), FM (both existing and potential), prioritizing them for corrective action, focusing on the highest ranked items, re-evaluating those items and returning to the prioritization step in a incessant cycle until minimal returns set in. In order to identify possible failures before they occur with the aim of reducing their risks, we use FMEA as a consistency tool. Since FMEA method is based on finding, prioritization, and minimization of the failures, it has been utilized in numerous types of industrial areas. The use of FMEA in the area of energy is also considered recently (Feili et al, 2013).

Data for taking risk management decisions is provided by FMEA. Stamatis stated detail procedures on how to carry out an FMEA and its various applications in the different industries (Pillay & Wang, 2003).

Throughout the years, a few varieties of the conventional FMEA have been produced. The use of knowledge base system for the automation of the FMEA process has been discussed by Price (1995). Bell (1992) documented the use of a causal reasoning model for FMEA. Kara-Zaitri (1992) presented an enhanced FMEA technique using a single matrix to model the entire system and a set of indices derived from probabilistic combination to spot the importance of an event relating to the indenture under consideration and to the entire system. Using a fuzzy cognitive map, a similar approach was made to model the entire system (Pelaez & Bowles, 1995).

This needs huge data on the numerical distribution of failing modes. It also requires knowledge of dependency relations amongst parts under outer irritations and ordinary operations. (Pillay & Wang, 2003).

2.3 Objectives of FMEA

Helping analysts in identification and prevention of known and potential problems from reaching the customer is the principle objective of FMEA (Feili et al, 2015).

FMEA's fundamental goal is to recognize potential FMs, assess the circumstances and end results of various parts of FMs, figuring out what might decrease the chance of failure. The analysis results can help analysts to identify and remedy the FMs that detrimentally affect the system and enhance its execution amid the phases of plan and creation (Liu et al, 2013).

A quantitative objective for many FMEAs is to forecast the probability of happening for some types of system failing modes (Pillay & Wang, 2003).

Analysts can also use FMEA as a qualitative analysis (or a semi-quantitative analysis). It helps identifying critical components whose failure will lead to accident, injury, and/or property loss. The goal is to make systems safer or more reliable by:

- Impacts of component failures on system performance evaluation.
- Components identification that are critical to safety.
- System upgrades or managerial changes to enhance safety and/or system reliability.

FMEA main safety objectives include:

- System analysis to identify the effects of component failures on system performance and safety.
- Identification of components that are critical to safety (identifying where component failure would compromise system operation, resulting in injuries, property damage, or other losses).
- Redesigning the system to improve 'passive' reliability and safety.
- Reduce the probability of component failures by improving maintenance routines.

DFMEA is an analytical technique used in product development circles to ensure that possible problems have been considered and addressed. To study problems originating from malfunctions of military systems, reliability engineering developed it in 1950s (Rausand & Arnljot, 2004). When DFMEA is used properly, it provides many advantages. These include: [1] improved product/ process quality, reliability and safety, [2] reduced development time, [3] fewer late changes, [4] increased customer satisfaction, [5] shorter time to market, [6] early identification and elimination of potential product failure modes, [7] improved validation process, [8] reduced warranty, [9] documented evidence of due care, and [10] improved company image and competitiveness (Kolich, 2014).

FMEA is directed to provide information for making risk management decisions, it is an important method used to identify and eliminate known or potential failures to increase the reliability and safety of complex systems.

2.4 Drawbacks of traditional FMEA

The conventional FMEA is one of the most relevant early precaution actions in process, design and system that prevent failures and errors from happening. However, the conventional RPN method has been criticized broadly in the literature for a variety of reasons (Liu et al, 2013).

Traditional FMEA has certain drawbacks although it is used widely in current studies; The primary drawbacks consist of the following; (Khasha et al., 2013);

- Identical RPN value for different combinations of O, S and D; however, failure modes with an identical RPN may correspond to different risk factors.
- O, S and D are proposed to be of the same significance in traditional FMEA. However, in real cases, their importance degree may vary.
- RPN is simply calculated by multiplying the three input factors and not taking into consideration the possible indirect relationships between these factors.

The whole scope of causative variables prompting a failure mode have not been enveloped by the three parameters utilized as a part of FMEA, which leads to mix-ups, inconsistencies, instabilities and ambiguities (Dağsuyu et al., 2016).

The traditional FMEA has been a well-accepted safety analysis method, however, it experiences few mishaps. The method that the traditional FMEA utilizes to accomplish a risk positioning is one of the most critically debated setback. Ranking risk purpose is to appoint the constrained assets to the most genuine risk items. RPN is used in traditional FMEA to evaluate the risk level of a component or process. This shortens the calculation though; another scoring system done by probability transformation and then resulting the duplication of variable scores that are accepted to cause problems (Pillay & Wang, 2003).

Fuzzy logic eliminates these drawbacks, using lingual variables. It’s easier to use lingual variables than using numerical variables for describing the failure modes. Membership functions are used to fuzz the input parameters. Those parameters are evaluated by decision rules. (Dağsuyu et al., 2016).

FMEA is confirmed to be one of the most significant early preventive initiatives during the design stage of a system, product, process or service. However, for several reasons, the RPN has been extensively critiqued. (Feili et al., 2015):

- Different sets of D, O and S ratings may yield exactly the same value of RPN, but their hidden risk implications may be totally dissimilar. For example, two different events with values of 3, 2, 2 and 1, 3, 4 for O, S and D, respectively, will have the same RPN value of 12. However, because of the different severities of the failure consequence, the two events hidden risk implications may be very different. Waste of resources and time is caused by that, or in certain cases, an event of high-risk being unnoticed.

- The importance between S, D and O is not taken into attention. The three factors are supposed to have the same importance. When FMEA is practically applied, this may not be the case.
- The mathematical formulation to calculate RPN is doubtful and arguable. There is no explanation as to why O, D and S should be multiplied to produce the RPN.
- The three factors have different scores modification. For example, a linear conversion is used for O, but a nonlinear transformation is employed for D.
- RPNs are not constant and deeply distributed at the bottom of the scale from 1 to 1000. This causes problems in the meaning of the differences analysis between different RPNs. For example, is the difference between the neighboring RPNs of 2 and 3 the same or less than the difference between 800 and 900?
- Only three factors mainly in terms of safety are taken into consideration by the RPN. Other important factors such as environmental and economic aspects are ignored.
- Minor deviation in one rating may result in widely different RPN effects, depending on the other factors values. For example, if D and O are both 10, then a one-point difference in severity rating results in a 100-point difference in the RPN; if D and O are equal to one, then the same one-point difference results in only a one-point difference in the RPN; if D and O are both 4, then a one-point difference produces a 16-point difference in the RPN.

- The three factors are hard to be determined precisely. Many data in FMEA can be stated in a lingual way such as likely important or very high and so on.

The traditional FMEA methods have been reviewed by Liu et al. (2013) between1992 and 2012. The knowledge for explaining failure modes of a system is multi-attributed. Also, the attributes are based on opinions acquired from a group of experts. Yet, experts' weights for each attribute may differ. A fuzzy-based approach model may be more appropriate to overcome the fuzzy nature of risk analysis in order to analyze the problem. Wang et al. (2009) presented a wide application of fuzzy methods to FMEA (FFMEA).

Conventionally, by developing a RPN, risk assessment in FMEA is carried out. Yet, for FMEA application in real-world situations, the crisp RPN method indicates critical shortcomings. Thus, many suggestions have been stated for alternative approaches to effectively solve the mishaps of traditional RPN technique and for FMEA implementation into real life situations.

To the best of our knowledge, no review of approaches research has been conducted to enhance the FMEA performance (Liu et al, 2013).

2.5 Terminology in FMEA

Despite many variations used in FMEA, the terms used during decades has been maintained. Some common terms used in FMEA include:

- *Failure modes.* A probable failure mode portrays the method in which a systen or product might not succeed to execute its wanted task (decided design or performance requirements) as mentioned by the expectations and needs of both inner and outer customers. There are several examples of failing modes such as falls off, stripped, corroded, deformed, binding, etc.

- *Potential cause(s) of failure.* Every FM is selected by a list credible probable cause(s) of failure. The causes listed have to be brief and to the point. Common causes of failure are: corrosion, tooling marks, over stressing, bad maintenance, material impure, eccentric, etc.
- *Severity.* Severity is the effect evaluation of the probable FM on the customer.
- *Effect.* An effect is a clashing significance that the user could experience. The customer might be the next movement, successive operations, or the final user (Pillay & Wang, 2003).

2.6 FMEA procedure

In order to operate risk analysis, engineers used FMEA and it is viewed as something added rather than a substitute for risk analysis. Safety examiners can use the FMEA method in order to check that all safety critical hardware has been forwarded in the risk analyses. To design evaluation and the review process documentation, we can use FMEA as a technique. The reliable FMs and their effects on the system are determined and documented. Elements that do not match the standards are determined as dangerous parts and are placed on the CIL. For the design changes detection can be implemented in order to delete the parts from the CIL, we evaluate every entry of the CIL and parts that might not be deleted from the CIL should be accepted by the program/project, depending on the rationale for acceptance of the identified risk. The followings are the steps that the analysis follows:

- (1) Failing mode
- (2) Failing effects

- (3) Reasons
- (4) Detection
- (5) Remedial actions
- (6) Foundation for acceptance. (Pillay & Wang, 2003).

FMEA is a proactive technique done to prevent errors in a system before they happen. Three hazard determinants consisting of occurrence (O), severity (S) and detectability (D) are used in FMEA. O signifies the density of the hazards, D indicates the chance of forecasting those hazards before they happen, and S is the sincerity of the hazard to the system.

For an evaluation of a specific system or product a cross-functional group must be settled for completing FMEA first. Initial phase in FMEA is to pinpoint all probable failing mechanisms of the system or product by an efficient brainstorming. Then, detail study is functioned on these failing mechanisms considering the hazard determinants: (O), (S) and (D). The aim of FMEA is to set up the failing mechanisms of the system or product to select the restricted resources to the most severe risk elements. Almost, the prioritization of failure mechanisms for curative behavior is driven through the risk priority number (RPN), which is obtained by finding multiplying the O, S and D of a failure. Which is

$$RPN = O \times S \times D$$

Where O is the chance of the failure, S is the asperity of the failure, and D is the chance of not catching the failure. For getting the RPN of a potential disappointment mode, the three hazard elements are assessed utilizing the scale of ten-point depicted in Tables 1–3. The greater the RPN of a disappointment mode, the more noteworthy the hazard is for item/framework unwavering quality. As for the scores of RPNs, the disappointment modes can be positioned and after that appropriate moves will be specially made on high-chance failure mechanism. RPNs ought to be computed after the adjustments to see whether the dangers have decreased, and to check the productivity of the restorative activity for every failing mechanism (Liu et al, 2013).

Table 1: Rating Qualitative Scale for Occurrence (O) in FMEA

Probability of occurrence	**Rating**	**Description**
Almost never	1	Failure unlikely
Remote	2	Rare number of failures
Slight	3	Very few failures
Low	4	Few failures
Moderately low	5	Occasional number of failures
Moderate	6	Moderate number of failures
Moderately high	7	Moderately high number of failures
High	8	High number of failures
Very high	9	Very high number of failures
Almost certain	10	Failure almost certain

Table 2: Rating Qualitative Scale for Severity (S) in FMEA

Effect of severity	**Rating**	**Description**
None	1	No effect
Very slight	2	Very slight effect on product performance
Slight	3	Slight effect on product performance
Very low	4	Very low effect on product performance
Low	5	Low effect on product performance
Moderate	6	Moderate effect on product performance with minor damage
High	7	High effect on product performance with equipment damage
Very high	8	Very high effect and product inoperable
Serious	9	Serious effect and product must stop when a potential failure mode affects safe system operation with warning
Hazardous	10	Hazardous effect and safety related when a potential failure mode effects safe system operation without warning

Table 3: Rating Qualitative Scale for Detection (D) in FMEA

Detection	Rating	Description
Almost certain	1	Design control will detect potential cause/mechanism and subsequent failure mode
Very high	2	Very high chance the design control will detect potential cause/mechanism and subsequent failure mode
High	3	high chance the design control will detect potential cause/mechanism and subsequent failure mode
Moderately high	4	Moderately high chance the design control will detect potential cause/mechanism and subsequent failure mode
Moderate	5	Moderate chance the design control will detect potential cause/mechanism and subsequent failure mode
Low	6	low chance the design control will detect potential cause/mechanism and subsequent failure mode
Very low	7	Very low chance the design control will detect potential cause/mechanism and subsequent failure mode
Remote	8	Remote chance the design control will detect potential cause/mechanism and subsequent failure mode
Very remote	9	Very remote chance the design control will detect potential cause/mechanism and subsequent failure mode
Almost impossible	10	Design control cannot detect potential cause/mechanism and subsequent failure mode

(Zhang & Chu, 2011)

The yield parameter signified the RPN is the multiplication of the info parameters positioning the failure mechanisms. A 10-point scale is used to score the three info parameters. Subsequent to duplicating those parameters, the most noteworthy RPNs are centered around. These outcomes help experts to character failures and their causes. Experts allocate an edge an incentive to characterize failures, and remedial activities are required for the disappointments that are have an esteem more prominent than 100 RPN (Dağsuyu et al., 2016).

A framework, outline, process or administration may often have numerous disappointment modes or effects and causes. In this circumstance, every disappointment mode or effect needs to be evaluated and organized in terms of its risks so that high unsafe (or most hazardous) disappointment modes can be amended with beat need. FMEA utilizes past involvement of range specialists to rank disappointment methods of any framework according to three rating scales; severity(S), detection (D) and occurrence (O) (Wang et al., 2009).

These three phonetic esteems can be exchanged to fresh esteems by utilizing the related scales. Disappointment method of an issue can as a rule be ascertained by duplicating S×O×D and this esteem is eluded to risk priority number (RPN). Higher RPN esteems indicate the basic disappointment methods of the framework. Positioning the disappointment modes as indicated by RPN may not be reasonable in genuine applications. A portion of the purposes behind this, distinctive blends of S, O and D esteems may result with the same RPN; S, O and D have diverse significance weights in connection to disappointment mode and RPN can't accentuate the circumstance; likewise, relative significance of specialists can't be incorporated into traditional RPN computations (Helvacioglu & Ozen, 2014).

FMEA is a complex technique used to recognize potential FMs, failure causes, failure impacts and issue regions influencing the framework or item mission achievement, equipment and programming unwavering quality, viability, and security. It also gives an organized procedure to evaluate FMs and alleviate the impacts of those FM through remedial activities. The achievement of FMEA relies on upon joint effort between the FMEA investigator and the designers and partners (Raheja and Gullo, 2012).

Besides, FMEA method begins with dissecting the entire systems one by one, looking at framework capacities, subsystems and so on. A table can be set up to indicate framework components, a FM happens and causes a failure. These steps disclose how to create a table for a FMEA model (Helvacioglu & Ozen, 2014):

Failing modes and reasons: The way of the failure of the function, subsystem, segment or part ought to be characterized plainly. In the present work, six distinctive region specialists have been solicited to clarify FMs from yacht frameworks.

a. **Effect(s) of failure:** The result of every FM ought to be deliberately inspected and recorded.
b. **Failure detections and compensation:** All the recognized failure ought to be redressed to dispose of their engendering to the entire framework and to augment dependability.
c. **Severity classification:** For the present work seriousness ranking is developed.
d. **Remarks:** Any correlated data ought to be noted.

FMEA method was introduced and begun to be applied to many subjects in the mid-1960s. Bowles and Peláez (1995) proposed a fuzzy model as a contrasting option to the regular techniques. Then, an exceptionally review is given by Wang et al. (2009), and Liu et al. (2013).

FMEA system begins with surveying design details, showing equipment block diagram and perceiving every single possible failure, individually. After perceiving, all potential circumstances and outcomes ought to be arranged to the related FMs.

After this practice, need of failing modes because of their catastrophe impacts ought to be positioned by an RPN, which is the product of seriousness of failures (S), their probability of occurrence (O), and the likelihood of detection (D) (Puente et el., 2002).

Essentially, by calculating RPNs, specialists will be permitted to concentrate on high RPNs promptly rather than all FMs because of the biggest priority. In addition, they can keep the disaster to survey the enhancements for priority things.

Since FMEA is used in huge territories and different enterprises, including aeronautical; automotive; atomic and electro specialized, military specific styles of rating scale have been extended (Arabian-Hoseynabadi et al., 2010).

Identification of potential FMs is the first phase in executing FMEA. These FMs are recorded and then rated based on three elements of the FMs: occurrence (O), detection (D) and severity (S). Mostly, this FMEA rating is accomplished by allocating discrete esteems for each of the elements on a predefined measure, for example from 1 to 4, 1 to 7 or 1 to 10. Total scores are situated, to the point that bigger scores are connected with bigger risks and the hazard is computed as a Risk Priority Number (RPN), which is the result of the scores of O, D and S (Barends et al., 2012).

These RPN values permit a risk examination: the FMs with the most essential RPN-scores are the most critical for enhancements to decrease these risks. However, in traditional FMEA, risk prioritization that relies on the multiplication of these three definitive scores signified as RPN values, has been criticized. It suggested risk evaluation using probabilities for occurrence and detection, and expected cost as a quantitative measure for seriousness. RPN can be mishandling and that the scores utilized to compute RPN need to be examined independently. Harpster (1999). FMs Effects and Criticality Analysis (FMECA), is a method of criticality examination by which each potential FM is placed based on the effect of severity and chance of occurrence. Nonetheless these option techniques are faraway from the conventional FMEA (Barends et al., 2012).

The procedure for completing a FMEA can be partitioned into a few stages as appeared in Figure 1. These steps are quickly clarified here:

1. When the framework is working legitimately, build an excellent understanding of what it must do.

2. Categories the framework into sub-frameworks in order to "restrict" the search for items.

3. To distinguish parts and relations among segments, use blue prints, schematics and diagrams

4. Establish for each assembly a full segment list.

5. Determine environmental and operational problems that can disturb the framework. Consider how the execution of individual segments is affected by these problems.

6. Failure methods determination of each segment and the effect of FMs on the whole framework.

7. Rank the risk level of each FM.

8. Estimate the likelihood of occurrence. Without strong quantitative data, this may be completed using qualitative estimates.

9. RPN calculation: the RPN is calculated by multiplying of the record defining the probability to occur, seriousness and perceptibility.

10. Depending on the RPN, make a decision on whether action has to be made.

11. Construct suggestions to boost the framework execution. This falls into two sets:

- Preventive activities: staying away from a failure circumstance.

- Compensatory activities: decreasing losses in case of failure.

12. Compact the investigation: this can be done in a tabular form.

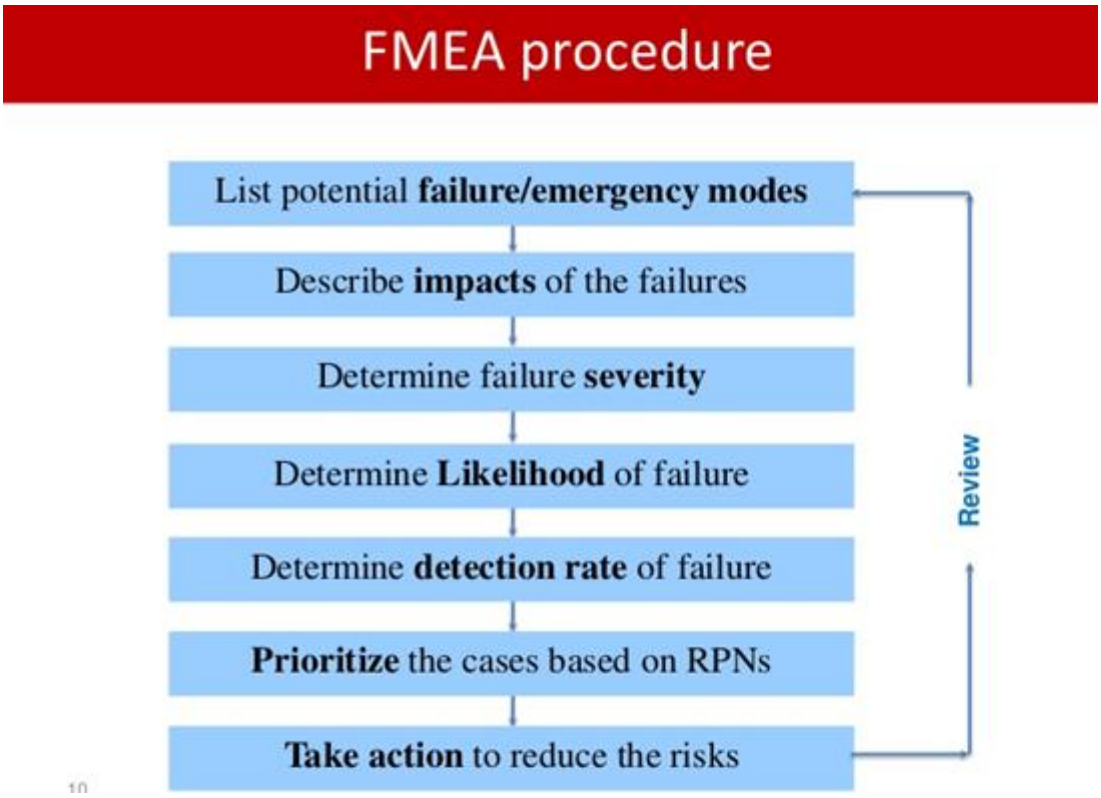

Figure 1: FMEA Procedure

In general, for each element there is a dominant row in the FMEA table. As these elements can have different FM, the dominant row is often split into sub-rows where every sub-row outcome a particular FM. The table is arranged into the coming columns:

(a) Failure Modes: pinpoint FMs and build a sub-row for every mode.

(b) Impacts (by FM): Safety and system accomplishment effects definition, coming from the failure, list specific conflicting results.

(c) Probability: in case reliable data does not exist, try using qualitative ranks.

(d) Hazard level (severity): in case of absence of experience data, try using qualitative ranks.

(e) Causes of failure mode (if known): comprises environmental and/or operational stresses which maximize the probability of the FM.

(f) Methods of detecting failure mode (if known): even if this entry does not impede a failure from happening, it is essential to detect that a failure has happened. This column is used to impede signs and symptoms which an element has been unsuccessful.

(g) Suggested interventions: hardware adjustments and/or compensative actions to reduce effects (Pillay & Wang, 2003).

2.7 Literature review on FMEA

FMEA technique has been functional in many engineering zones. Offshore assemblies are a standout amongst the most fertile zones for these applications. Wall et al. (2002) disclosed how to use FMEA to FPSO vessels and other FSUs. Wang and Trbojevic (2007) illuminated the plan for the security of marine and offshore frameworks by giving some FMECA applications for the related frameworks. Vinnem (2007), after categorizing FMEA as Qualitative Risk Valuation, provided many examples for accidents occurred offshore to acquire information from the previous experience. FMEA association with fuzzy sets and FMADM methods have been tested to offshore and marine engineering matters such as ballast water (Pam et al., 2013), maritime risk assessment (Balmat et al., 2009, 2011), fishing vessels (Pillay and Wang, 2003), explosion on board ships (Cicek and Celik, 2013) and so on.

The US Armed Forces Military Process FMEA initially announced FME(C)A in their documentation. NASA continued FMEA operations with several names for spacecrafts in the 1960s, (Baig & Prasanthi, 2013). The operation of FMEA was initially approved by the U.S. Army; then, it was mainly approved to the automotive industry and in 1990s it was initially executed within the healthcare system. In the mid-1990s, the Institute for Safe Medication Practices proposed that FMEA can be utilized to block errors that happen when delivering medications (Chioza & Ponzeti, 2009). The Joint Commission on Accreditation of Health Care Organization (JCAHO) requires all intense care hospitals to execute FMEA regularly (Standard LD 5.2 Accreditation Manual, 2001 Edition). The Technical Committee of the International Organization for Standardization (ISO) also suggested FMEA as a method for reducing high medical risks (ISO/TS 22367).

There are many analysts that use FMEA in the healthcare industry (Khasha, Sepehri, & Khatibi, 2013). Soykan et al. (2014) utilized the FMEA method to examine nine contagious diseases using risk factor frameworks such as O, D and S. They sorted the RPNs based on the three risk items and analyzed the hazards starting with the ones that had the highest RPN. Khasha et al. (2013) evaluated the risk management approach for programming surgery cancel causes. The first factor that resulted in surgery cancellation are high blood pressure, the lack of intensive care unit beds, high risk surgery, and diabetes determined from study results. Wetterneck et al. (2004) used the FMEA method for a new immersion pump and suggested recommendations. Reiling et al. (2003) tested FMEA to assure the security of patients and minimize errors and proved that FMEA was an excellent method to maximize the safety of patients. Liu, You, and You (2014) used hybrid weighted distance measures to develop the traditional FMEA. This method brings an excellent solution for environments where information is not precise and incomplete. The efficacy and success of this method was proved by application to a blood transfusion event. Lin, Wang, Lin, and Liu (2014) examined qualitative and quantitative procedures in order to evaluate medical devices. At the beginning, they analyzed the shell method named as Software, Hardware, Environment, Live-ware and Central live-ware for qualitative analysis; then, they tested the FMEA using quantitative analysis to make decision about the risk factors and improve the safety of medical devices. Although FMEA is utilized in several sectors, frequently in the health sector, it has various disadvantages.

Wide majority of risk priority models are found in the literature to raise the criticality analysis process of FMEA. Therefore, we suggest a system for ordering the inspected papers according to the failure mode prioritization techniques which have been determined. In this analysis, we split the techniques used in the literature into five major categories, which are multi-criteria decision making (MCDM), mathematical programming (MP), artificial intelligence (AI), hybrid approaches and others. Each of the five categories with their own related approaches and references are stated in Table (4) (Liu et al., 2013).

Table 4: Classification of Risk Evaluation Methods in FMEA

Categories	**Approaches**	**Literature**	**Total number**
MCDM (22.50%)	ME.MCDM	Franceschini and Galetto (2001)	1
	Evidence theory	Chin et al.(2009b). Yang et al.(2011)	2
	AHP/ANP	Braglia(2000). Carmignani (2009). Hu et al.(2009).Zammori and Gabbrielli (2011)	4

	Fuzzy TOPSIS	Braglia et al.(2003b)	1
	Grey theory	Chang et al.(1999,2001). Sharma et al.(2008b,2007d). Pillay and Wang (2003). Sharma and Sharma (in press). Geum et al.(2011)	7
	DEMATEL	Seyed.Hosseini et al.(2006)	1
	Intuitioanistic fuzzy set ranking technique	Chang et al.(2010)	1
	VIKOR	Liu et al.(2012)	1
Mathematical programming (8.75%)	Linear programming	Wang et al.(2009b). Gargama and Chaturvedi (2011). Chen and Ko(2009a,2009b)	4
	DEA/Fuzzy DEA	Garcia et al.(2005). Chang and sun (2009). Chin et al.(2009a)	3
Artificial intelligence (40.00%)	Rule-base system	Sankar and Prab hu(2011)	1
	Fuzzy rule-base system	Bowles and Peliez (1995). Moss amd Woodhouse (1999). Xu et al.(2002). Zafiropoulos and Dialynas(2005). Chin et al.(2008). Puente et al.(2002). Pillay and Wang (2003). Yang et al.(2008). Gargama and Chaturvedi (2011). Braglia and Bevilacqua (2000). Braglia et al.(2003a). Tay and Lim (2006a,2012). Guimaraes and Franklin Lapa (2004). Guimaraes and lapa(2004,2006,2007). Guimaraes et al.(2011)	29
	Fuzzy ART algorithm	Keskin and Zkan (2009)	1
	Fuzzy cognitive map	Pelaez and Bowles (1996)	1
Integrated approaches (11.25%)	Fuzzy AHP-Fuzzy rule-base system	Abdelgawad and Fayek(2010)	1

	WLSM-MOI-Partial ranking method	Zhang and chu (2011)	1
	OWGA operator-DEMATEL	Chang(2009)	1
	IPS-DEMATEL	Chang and Cheng(2010)	1
	Fuzzy OWA operator-Dematel	Chang and Cheng(2011)	1
	2-tuple-OWA operator	Chang and Wen (2010)	1
	FER-Grey theory	Liu et al.(2011)	1
	Fuzzy AHP-Fuzzy TOPSIS	Kutlu and Ekmekcioglu(2012)	1
	ISM-ANP-UPN	Chen (2007)	1
Other approaches (17.50%)	Cost based model	Gilchrist (1993). Ben-Daya and Raouf (1996). Von Ahsen(2008). Kmenta and Ishii (2004). Dong (2007).Rhee and Ishii(2003)	6
	Monte Carlo simulation	Bevilacqua et al.(2011)	1
	Minimum cut sets theory (MCS)	Xiao et al.(1995)	1
	Boolean representation method (BRM)	Wang et.al(1995)	1
	Diagraph and matrix approach	Gandhi and Agrawal (1992)	1
	Kano model	Shahin(2004)	1
	Quality functional deployment(QFD)	Braglia et al.(2007). Tan(2003)	2
	Probability theory	Sant'Anna(2012)	1

We should note that some references, like Gargama and Chaturvedi (2011) and Pillay and Wang (2003), use more than one method to solve the traditional FMEA problems.

A scale 1–10 is used in traditional FMEA for the risk levels of FMs with O, S and D evaluation. However, during FMEA decision-making process, big uncertainty may be found. In real-life cases, the precisely scale application is difficult or even impossible. Uncertainty can be detected by the fuzzy set theory and then fuzzy RPNs have been widely applied in FMEA. There are two categories defining the usual risk evaluation in FMEA; The mathematical calculation method and the rule-based inference method. A fuzzy-logic-based technique using the fuzzy lingual terms, max–min implication and defuzzification in criticality analysis for FMEA was proposed by Bowles and Peláez (1995). The Bowles's method consists of a system of fuzzy assessment by the expert expertise and knowledge for FMEA was proposed by Xu, Tang, Xie, Ho, and Zhu (2002). A new scale called risk priority ranks (RPRs) in which the ranks from 1 to 1000 are used for estimating the risks of O–S–D combinations using an ‘‘If-Then” rule reference technique was defined by Ravi Sankar and Prabhu (2001). Introducing a joined technique by merging the advantages of matrix FMEA with the method that satisfactorily quantify the aspects that contribute to risk instead of risk quantification only. Chin, Chan, and Yang (2008) incorporated a prototype system named EPDS-1 to evolve the fuzzy logic method and knowledge-based system techniques into product design. Inexperienced users can apply FMEA using this system containing 384 fuzzy If-Then rules. A new approach using grey relation theory and a fuzzy rule base was suggested by Pillay and Wang (2003). A generic fuzzy RPN method using the weighted fuzzy production rules was proposed by Tay and Lim (2006) which provides a global weight associated with each rule. Sharma, Kumar, and Kumar (2008) utilized a fuzzy rule-based inference Technique and the grey theory for prioritizing failure modes. Fuzzy lingual terms are introduced to represent the risk degree for O, S, D and RPNs in the fuzzy rule base. Not all rules in the fuzzy rule base were actually required (Tay & Lim, 2006). Rule reduction can be found in the FMEA applications as an output (Guimarães & Lapa, 2006).

The following two defects were bypassed in previous methods by using different ‘‘If-Then” rules:

(1) FMEA’s big disadvantage is that many combinations of O, S and D may prompt a similar value of RPN, however, their risk levels may be completely different. Therefore, this can impose some high-risk hidden actions.

(2) The three factors O, S and D are supposed to be equally important. Nonetheless, in the real-life applications, the relative importance weights may be different. (Zhang & Chu, 2011).

A new path is essential to tackle with the drawback, moreover, in risk factors evaluation and the final ranking of FMs using fuzzy RPNs, two other gaps must be profoundly considered (Zhang & Chu 2011):

(1) Generally, FMEA is achieved by a cross-functional crew, which requires DMs from different fields. Taking into consideration their preferences, personal backgrounds and different understanding levels to the FMs, different linguistic term sets maybe used by DMs to express their own decisions on assessing S, O, D, and importance weights of those three factors. In order to reach a better group agreement, these multi-granularity linguistic valuations must be aggregated. (Herrera, Herrera-Viedma, & Martínez, 2000).

(2) (Braglia et al., 2003) stated that the mathematical expressions are powerfully sensitive to variations in the evaluation process when calculating RPNs, which cannot ensure the ranking results to be strong against the uncertain environment.

2.8 MCDM approach

Franceschini and Galetto (2001) presented this technique to compute the RPN in FMEA, enabling them to handle the data provided by the design team, ordinarily given on subjective scales, without requiring a self-assertive and simulated numerical change. Risk factors were examined as assessment criteria in this approach, while failing modes as the other options to be chosen. Every decision making measure is considered in this strategy as a fuzzy subset over the arrangement of other options to be chosen. The failing mode was resolved with the maximum (RPC) after the collection of assessments communicated on every rule for a given option. If two or more FMs have the same RPC, a more detailed collection is made to distinguish their relative ranking.

An FMEA working with the group-based evidential reasoning (ER) approach to attract FMEA team members' opinions variety and prioritize FMs under various types of uncertainties such as deficient assessment, ignorance and intervals was proposed by Chin et al. (2009). The risk priority model was created utilizing the ER approach that contains surveying risk factors utilizing belief structures, joining singular belief structures into group belief structures, accumulating the gathered belief structures into general belief structures, changing them into expected risk scores, and positioning the normal risk scores utilizing the (MRA). A clue theory for the risk evaluation information aggregation of (ME) was also adopted by Yang, Huang, He, Zhu, and Wen (2011). Nonetheless, in the suggested model, all interval and individual assessment grades were supposed to be crisp and independent of each other. FMEA did not take into consideration the occasion where an assessment grade may represent a vague concept or standard and there may be no clear cut between the definitions of two adjacent grades (Liu et al., 2013).

MAFMA methodology based on AHP technique was expanded by Braglia (2000), considering the risk factors (S, D, O and expected cost) as decision principle, probable causes of failing as decision possible choices and the choice of cause of failing as decision goal. A three-level hierarchy formed by the target, criteria and choices; in which the pairwise comparison matrix was used for weights estimation and causes priorities in terms of the (ECA). The local priorities of the causes were assigned as initial scores for O, S and D. In order to combine the local priorities into the global priority, the weight composition technique in the AHP was utilized, based on which the possible causes of failing were ranked. In reference to Braglia (2000), (PC-FMECA) was presented by Carmignani (2009), allowing new RPN calculation and the presentation of the idea of profitability making into thought the remedial cost of action. On the other hand, for the risks of green components to hazardous substance analysis, (GC-RPN) is presented by Hu, Hsu, Kuo, and Wu (2009). Fuzzy AHP determined the risk factors related weights. Then the GCRPN was computed for each of the components for risk identification and management.

An advanced type of the FMECA was presented by Zammori and Gabbrielli (2011), called analytic network process (ANP), allowing enhancement the standard FMECA capabilities in consideration of likely interactions among the basic causes of failing in the criticality assessment. According to the ANP/RPN model, O, S and D were divided into sub-criteria and arranged in a hierarchy decision structure containing the causes of failure at its lowest level. The RPN was calculated by pairwise comparison starting from this hierarchy. A graphical instrument was also presented in the paper in order to clarify and to make evident the rational of the final results.

An alternative multi-attribute decision-making approach called fuzzy technique for TOPSIS approach for FMECA was presented by Braglia, Frosolini, and Montanari (2003), which considers the alternatives to be graded as failure reasons, the risk factors S, D and O related to a FM as criteria. The failures were prioritized based on the measurement of the Euclidean distance of an alternative from an ideal goal. The three risk factors and their corresponding weights were assessed by fuzzy TOPSIS approach using triangular fuzzy numbers instead of exact crisp numbers, easing the interpretation of final ranking for failure causes.

Grey theory and fuzzy method were used by Chang, Wei, and Lee (1999) for FMEA, where the risk factors D, S and O were evaluated by lingual fuzzy variables and the risk importance of possible causes is determined by the grey relational analysis. To implement the grey relational analysis, defuzzification of fuzzy linguistic variables as crisp values was made, standard series is the minimal levels of the three risk factors, and comparative sequence defined the evaluation data of the three risk factors for every potential cause, whose grey relational coefficient and degree of relational with the standard sequences were calculated in terms of the grey theory. A less effect of potential cause means stronger degree of relational. Hereafter, the risk priority of the potential problems to be improved was represented as the increasing order of the degrees of relational. The grey theory for FMEA was used also by Chang, Liu, and Wei (2001), in which the traditional scores 1–10 for the three risk factors was used to calculate the degrees of relational rather than fuzzy linguistic variables. In Sharma, Kumar, and Kumar (2008), Pillay and Wang (2003), grey theory and similar applications of fuzzy method for prioritization of FM in FMEA can also be found.

A systematic approach for identifying and evaluating potential failures using a service-specific FMEA and grey relational analysis was proposed by Geum, Cho, and Park (2011). The service-specific FMEA was provided at first to show the service-specific characteristics, using three dimensions and nineteen sub-dimensions to represent the service characteristics. Secondly, using grey relational analysis under this framework of service-specific FMEA, the risk priority of each FM was computed. Grey relational analysis application in this paper obtained a two-phase structure: the first for computing the risk score of each dimension: O, S and D, in the other phase, the final risk priority is calculated. A method called DEMATEL for reprioritization of FMs in a corrective actions system was proposed by Seyed-Hosseini, Safaei, and Asgharpour (2006). The failure information in FMEA was described as a weighted diagraph in this proposed methodology, where FMs or causes of failures are represented by nodes and the effects FMs by edges. The harshness of effects of one alternative on another is indicated as the connection weights. An indirect relationship is a connection that will only move in an indirect path between two alternatives meaning that a FM could be the cause of other failing mode(s). Dispatchers are alternatives more effective to another with bigger priority and those receiving more influence from another are called receivers were assumed to have lower priority. Therefore, the alternatives prioritization can be obtained in terms of the type of relationships and severity of influences of them on another.

An approach, which utilizes the intuitionistic fuzzy set ranking technique, for reprioritization of failures in a system FMECA was proposed by Cheng and Chang (2010). The experts' experiences defined the triangle intuitionistic fuzzy set for each unit fault. Chang, Chang, Liao, and Cheng (2006) proposed the vague fault tree analysis definition, in which calculation of the power of influence of each unit for the system and increasable reliability for the whole system was made. The degree of influence each unit fault finally ranked the risk of failures. VIKOR method was applied recently by Liu, Liu, Liu, and Mao (2012), a method that was developed for multi-criteria optimization for complex systems, to find the compromise priority ranking of FMs according to the risk factors in FMEA. Lingual variables, expressed in trapezoidal or triangular fuzzy numbers, were used to assess the ratings and weights for the risk factors O, S and D. In order to determine risk priorities of the FMs that have been identified, the extended VIKOR method was used.

Saaty (1980) introduced the analytic hierarchy process (AHP) to show the process of determining the priority of a set of alternatives and the relative importance of attributes in a MCDM problem (Wei, Chien, & Wang, 2005). AHP approach has a primary advantage, it is the related easiness with which it handles numerous criteria and performs quantitative and qualitative data (Kahraman, Cebeci, & Ruan, 2004). However, many criticized AHP for its incapability to effectively accommodate the characteristics of uncertainty and imprecision associated with mapping decision maker perceptions to extract number (Hu et al., 2009).

Table 5: The Major Shortcomings for FMEA

Shortcomings	Literature	Total number
The relative importance among O, S and D is not taken into consideration	Wang et al. (2009b), Chin et al. (2009a, 2009b), Liu et al. (2011, 2012), Gargama and Chaturvedi (2011), Kutlu and Ekmekçioğlu (2012), Zhang and Chu (2011), Yang et al. (2008), Braglia et al. (2003a, 2003b), Sharma et al. (2005, 2007a, 2007b, 2007c, 2007d, 2008a, 2008b, 2008c), Sharma and Sharma (2012, 2010), Chang and Cheng (2011, 2010), Chang and Wen (2010), Chang et al. (2010, 1999, 2001), Seyed-Hosseini et al. (2006), Tay and Lim (2010, 2006a), Keskin and Zkan (2009), Pillay and Wang (2003), Bowles and Peláez (1995), von Ahsen (2008), Carmignani (2009), Xiao et al. (2011), Franceschini and Galetto (2001), Nepal et al. (2008), Sankar and Prabhu (2001), Zammori and Gabbrielli (2011), Abdelgawad and Fayek (2010), Shahin (2004), Puente et al. (2002), Garcia et al. (2005), Chang and Sun (2009)	45
Different combinations of O, S and D may produce exactly the same value of RPN, but their hidden risk implications may be totally different	Wang et al. (2009b), Chin et al. (2009a, 2009b), Liu et al. (2011, 2012), Gargama and Chaturvedi (2011), Kutlu and Ekmekçioğlu (2012), Zhang and Chu (2011), Yang et al. (2008), Braglia et al. (2003b), Sharma et al. (2005, 2007a, 2007b, 2007c, 2007d, 2008a, 2008b, 2008c), Sharma and Sharma (2012, 2010), Tay and Lim (2010, 2006a), Keskin and Zkan (2009), Pillay and Wang (2003), Chen (2007), von Ahsen (2008), Carmignani (2009), Franceschini and Galetto (2001), Chang et al. (1999, 2001), Shahin (2004), Puente et al. (2002), Chang and Sun (2009)	33
The three risk factors are difficult to be precisely evaluated	Wang et al. (2009b), Chin et al. (2009a, 2009b), Liu et al. (2011, 2012), Gargama and Chaturvedi (2011), Kutlu and Ekmekçioğlu (2012), Yang et al. (2008), Braglia et al. (2003a, 2003b), Sharma et al. (2005), Chang et al. (2010), Xu et al. (2002), Braglia (2000), Yang et al. (2011), Chen and Ko (2009a, 2009b), Zammori and Gabbrielli (2011), Abdelgawad and Fayek (2010), Garcia et al. (2005)	21
The mathematical formula for calculating RPN is questionable and debatable	Chin et al. (2009a, 2009b), Liu et al. (2011, 2012), Gargama and Chaturvedi (2011), Kutlu and Ekmekçioğlu (2012), Braglia et al. (2003a, 2003b), Geum et al. (2011), Chang et al. (1999, 2001), Puente et al. (2002), Ben-Daya and Raouf (1996), Gilchrist (1993)	14
The conversion of scores is different for the three risk factors	Chin et al. (2009b), Liu et al. (2011), Braglia et al. (2003a, 2003b), Chen (2007), von Ahsen (2008), Carmignani (2009), Chang et al. (1999, 2001), Sankar and Prabhu (2001), Puente et al. (2002), Ben-Daya and Raouf (1996), Gilchrist (1993)	13
The RPN cannot be used to measure the effectiveness of corrective actions	Yang et al. (2008), Braglia et al. (2003b, 2007), Pillay and Wang (2003), Chen (2007), Carmignani (2009), Chang et al. (1999, 2001), Shahin (2004), Puente et al. (2002), Ben-Daya and Raouf (1996), Gilchrist (1993)	12
RPNs are not continuous with many holes	Liu et al. (2012), Chang and Cheng (2011, 2010), Chang et al. (2010), Chang (2009), Keskin and Zkan (2009), Carmignani (2009), Franceschini and Galetto (2001), Garcia et al. (2005), Chang and Sun (2009)	10
Interdependencies among various failure modes and effects are not taken into account	Xu et al. (2002), Chin et al. (2008), Braglia et al. (2007), von Ahsen (2008), Carmignani (2009), Nepal et al. (2008), Zammori and Gabbrielli (2011), Shahin (2004), Chang and Sun (2009), Gandhi and Agrawal (1992)	10
The mathematical form adopted for calculating the RPN is strongly sensitive to variations in risk factor evaluations	Chin et al. (2009b), Liu et al. (2011, 2012), Gargama and Chaturvedi (2011), Kutlu and Ekmekçioğlu (2012), Yang et al. (2008), Braglia et al. (2003a, 2003b), Chang (2009)	9
The RPN elements have many duplicate numbers	Gargama and Chaturvedi (2011), Chang and Cheng (2011, 2010), Chang et al. (2010), Chang (2009), Seyed-Hosseini et al. (2006), Sankar and Prabhu (2001), Garcia et al. (2005), Chang and Sun (2009)	9
The RPN considers only three risk factors mainly in terms of safety	Chin et al. (2009b), Liu et al. (2011), Yang et al. (2008), Braglia et al. (2003a, 2003b), Chang and Cheng (2010), Braglia (2000), Carmignani (2009), Zammori and Gabbrielli (2011)	9

(Liu et al., 2013)

Multi-attributed selection with group of experts whose importance level may vary impose a problem and for this reason it is very suitable for Multi-Attribute Decision Making (MADM), which is associated with problems whose number of alternatives has been predetermined. When there is more than one decision maker, the problem becomes more complex. MADM refers to selections among some courses of action in the presence of multiple, usually conflicting attributes (Chen and Hwang, 1992). MADM has many problems, Chen and Hwang (1992) suggested solution methods for those problems. Hwang and Yoon (1981) proposed one of the classical MADM methods, it is the Technique for Order of Preference by Similarity to Ideal Solution

(TOPSIS). Because it is very commonly used, easy to apply and reliable, TOPSIS was chosen for this application. This research aims to utilize FMEA for reliability analysis under fuzzy environment with regard to issues during yacht design as well as operation, in order to rank the most critical FMs of the system, which are acquired by using experience of six domain experts. After seeing the shortcomings of FMEA especially in ranking according to RPN, a new method was considered. Fuzzy Multi-Attribute Group Decision Making (FMAGDM) was chosen after reviewing the literature to utilize and compare with the existing RPN method (Helvacioglu & Ozen, 2014).

Chapter 3

METHODOLOGY

3.1 Introduction

The aim of present research was to apply analytic hierarchy process (AHP) for extending traditional FMEA. This chapter comprises the information of how the study was conducted; it also determines the setting and sampling, the instrument and the variables used in this examination. Indeed, Because of airplane landing system as a critical potential FM in aircraft industry, we designed this research with mix up FMEA and AHP approach for combining both aspects of theoretical and practical. With an engineer perspective the association of conclusions between the traditional FMEA and AHP procedure, produce a more reliable outcome.

The study carried out, as its theoretical structure in estimating the Risk Priority Number (RPN) for focusing on the risks and taking remedial actions, while the AHP method is hired to test the related elements importance: Severity (S), Detection (D) and Occurrence (O) and the FMs in the sub level are considered in typical FMEA to calculate (Figure 1).

3.2 Conceptualizing prioritization of failure modes

In order to create the decision tree, standard questionnaire of AHP was designed and then filled out by 50 respondents. The result is exposed in Appendix A.

Evaluate and rank the potential FMs was taken as the main goal of the inquiry which is the first level, by using risk priority numbers (RPNs). A RPN is a product of the risk factors occurrence (O), severity (S) and detection (D) in the second level as the criteria (Zhang & Chu, 2011)

3.3 Variables used in the Study

3.3.1 Manual calculation

Occurrence (O) is a status number related to the probability that the FM and its linked cause will be present in the item being analyzed.

Severity (S) is a ranking allied with the furthermost serious consequence for a given FM according to the factor as of a severity scale.

Detection (D) is a grade number related to the finest controller from the list of detection-type controls, according to the factor from the detection measure (Helvacioglu & Ozen, 2014).

3.3.2 Failure modes

Potential FMs are sometimes described as categories of failure. According to the expert knowledge for Aircraft landing system (Naftair Airline, 2015), Table 6 shows the potential FMs as follows:

Table 6: Definitions of Variables Used

FM1A	**Fault in raising the wheels**
FM1B	Raising wheels earlier than specified time
FM2A	Fault in coming down the wheels
FM2B	Coming down wheels earlier than specified time
FM3A	Fault on the run (automatically test)
FM3B	Wrong run (automatically test)
FM4A	Fault on the run (fault reporting system)
FM4B	Wrong run (fault reporting system)

FM5A	Fault on the run (record the result of automatically test)
FM5B	Wrong run (record the result of automatically test)

According to exposed variables for conducting an AHP analysis, a simple three-level hierarchical structure is constructed as Figure 2.

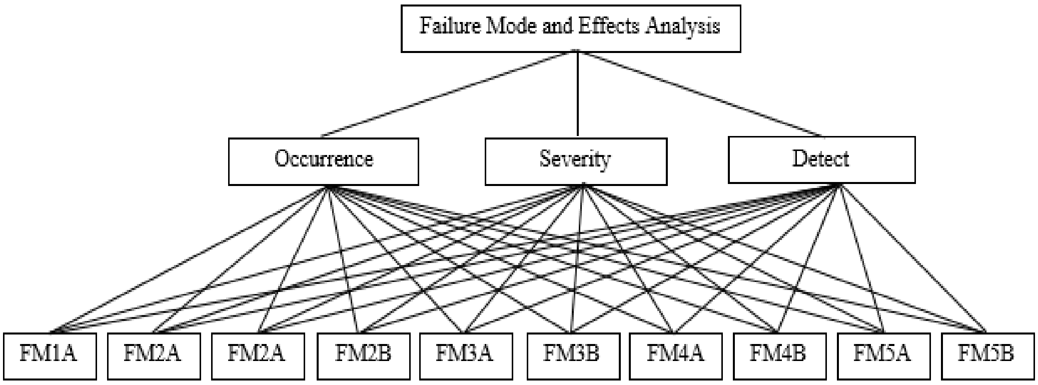

Figure 2: The hierarchy of the determinants of the decision-making process of FMEA

3.4 The Setting and Sampling

In this section, the demographics of the contributors were tested. The respondents were chosen through randomization sampling method to ensure that all types of experts (by gender, age, education and working experience) have equivalent odd of being selected. A 35-nominee sample size was done for the analysis. Questionnaires have been sent to the respondents and all were suitable entirely.

The questionnaire was dispersed to comprise the aircraft industry's experts, technicians and pilots that are defined in this study as scholars in aircraft system.

To reach the target population, the questionnaires were sent to the Mechanical Liaison Engineer 'Oana Bercea' in 'Jet Aviation' located in Basel Switzerland, Oana distributed the questionnaire to 35 respondents after explaining all the content and our purpose. According to Table 7 the demographic profile of participants are illustrated as follows:

Table 7: Demographic Characteristics of the Respondents (N = 35)

Socio-demographic variable	**Description**	**Frequency**
Gender	Male	28
	Female	7
Age (years)	Below 20	2
	21-30	10
	31-40	12
	41-50	7
	Above 50	4
Education	Diploma	5
	Bachelor	21
	Master	8
	PhD	1
Working Experience	< 5 years	8
	5-10 years	18
	> 10 years	9

Based on the AHP approach, sample with the small scale is adequate (Hussain & Malik, 2015; Cheng & Li, 2001).

The AHP works by only asking participants to compare the importance of two factors at the same time. These comparisons are called judgments.

Through comparing the importance of two factors at once which is called judgments, AHP are able to decipher the survey fatigue knot.

A two objects judgment is much simpler for the respondents to complete than comparing 20 elements of the list.

For conglomerating the feeling enlarged practically into rational thinking the judgments were applied in building paired comparisons (Ahmad & Hussain, 2017)

Additional information will be generated via pairwise comparisons which is cause of reducing the inconsistency (Saaty, 2012). Thus, the sample size of 50 respondents is considered to be satisfactory for this research (Drake, Lee, & Hussain, 2013).

3.5 Instrument Used

A standard questionnaire of AHP provided to be filled by 35 respondents to seize all FMs and a pairwise comparison questionnaire was generated from the model. The demographics of the respondents and a nine-point intensity of relative important scale were included in the questionnaire instead of the Analytical Hierarchy Process (AHP) as depicts in Table 8.

Table 8: Fundamental Scale Utilized in Standard AHP Questionnaire

Intensity of Relative Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to

		objective 1
3	Moderate importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored, and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When a compromise is needed
Reciprocal of the above nonzero numbers	Reciprocal for inverse comparison	

(Ahmad & Hussain, 2017)

Columns on the left specify a prioritization of the first element over the second, where responses on the right affirm the importance of the second element over the first. In the Saaty (1980) scale shown in Table 3, the five statements link respectively to the prominence weightings of 1,3,5,7, and 9.

3.5.1 Analytical Hierarchy Process

Saaty (1980) developed the AHP methodology and it is applied as a method multi-criteria decision-making (MCDM) broadly.

In Lee et al (2001) view, AHP has been exercised to a broad diversity of decision and human judgment progression. AHP is applied to escalation an assessment model which includes varied measures into a solitary global score for standing choice options.

There should be relocations of a unlike model issue by parsing into a multi-level hierarchy structure keeping in mind the end aim for using it (Sirikrai & Tang, 2006).

AHP vast range of usage, especially for engineering and industrial management is for its advantages. For instance, AHP has been employed for technologies assessment and selection, locations and suppliers to order performance factors, to simplify cost–benefit analyses, to design and assign resources, and for estimating (Vaidya & Kumar, 2006).

In order to distinct the substantial factor and less important ones, and rank the elements, many researches were carried out thru AHP. This approach facilitated to determine numerical weights of relative importance to each item of FMEA along with their selection criteria associated in consideration to the goal (Wong & Li, 2008).

For solving intricate decision-making issues, AHP permits both qualitative and quantitative methods (Cheng & Li, 2002).

Saaty (1990) defines how the AHP technique can appraise trade-offs between competing criteria and how it can concurrently manage both the qualitative and quantitative methods of decision-making indicators (Sirikrai & Tang, 2006).

For quantitative approach, prioritization a set of indicators shall be done through pairwise comparison to recognize the more significant attributes [45–49]. From the mail factor to the sub-factors, the criteria of one level of hierarchy given the indicator of the next higher level of hierarchy were compared pairwise (Wong & Li, 2008).

Saaty (1980) introduced AHP in five-stage as follows:

- Problem stating and objective definition
- Hierarchy expansion from top (the purpose from an overall lookout) following the midway levels (criteria and sub-criteria on following levels) to bottom (alternatives);
- pair-wise comparison matrix engagement for each of the subordinate levels;
- consistency test performance
- related weights measurements of the elements of levels.

(Wong & Li, 2008; Partovi, 1994).

The most challenging section of the decision-making procedure is constructing the hierarchy model of decision problem. It also has a significant effect on the results (Saaty, 1996). In the first level of hierarchy the main goal of a desired condition locates. Other components for decision are ordered into levels that comply for comparison on preferences of elements paired across levels individually (Sirikrai & Tang, 2006).

The hierarchy of desired goal for this study were structured in order to pairwise comparison of factors (Figure 1). The upper level was the main target, then subsequent of FMs and effects analysis criteria. The scale and the paired comparison queries are instruments for data gathering. The yield from this stage is a matrix of preferences that outcome from the pairwise comparison scores of attributes in a specified hierarchy (Wong & Li, 2008).

For data collection in AHP methodology, the participants have to choose between diverse pairs of variables. For conducting pairwise judgment a nine-point scale as depicts in Table 3 was suggested by Saaty (2012).

This factors and sub-factors related importance was valued by the 9-point scale projected, which indicated that the level of relative rank from equal, moderate, strong, very strong, to extreme level by 1, 3, 5, 7, and 9, correspondingly. The in-between values between two adjoining opinions are embodied by 2, 4, 6, and 8 (Wong & Li, 2008).

Components in each level of hierarchy are at variance with regard with their significance to the subsequent upper level. The paired correlation in the given level would be diminished to a number of square matrices when working down is started at the highest level of the hierarchical model as follows:

A = $[a_{ij}]_{nxn}$ is shown as follow:

$$\begin{pmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ . & . & . & . \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{pmatrix}$$ The matrix reciprocal belongings are:

$$a_{ji} = \frac{1}{a_{ij}}$$

For sample, if a participant perceives that the FM1A effect is moderately more important than FM2A, then the prior is valued '3' and the later as '1/3' in this judgement, so on and so forth (Ahmad & Hussain, 2017).

Regarding to the overall goal of hierarchy model, the global weights for indicators will be synthesized altogether according to the matrix algebra (Saaty, 1990). Practically, for the AHP progress computer analysis software such as Expert choice® is existing (Sirikrai & Tang, 2006).

In continue, according to the Saaty's eigenvector progress, whereas pair-wise comparison matrix was structured, we should calculate the weight vectors, w= [w_1, w_2, . . ., wn]. This calculation includes following stages:

a) Principal, paired comparison matrix, A = $[aij]_{nxn}$, is normalized with Equation (1), and

b) The weights are calculated in Equation (2).

$$a_{ji}^{*} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \qquad (1)$$

for j = 1, 2, . . ., n.

Weight Computation:

$$\bar{a}_{ji}^{*} = \frac{\sum_{i=1}^{n} a_{ij}}{n} \qquad (2)$$

for i = 1, 2, . . ., n.

Satty discussed that there is a connection between the weight vector, w, and the pairwise comparison matrix, A, as illustrated in Equation (3):

Aw = λminw (3) where "λ" is a number (element) of the consistency vector (CV)

The λmin rate is a crucial validating feature in AHP which could be utilized as a reference guide to display information via computing the consistency ratio (CR).

The expert examination of inner consistent judgement is possible through AHP. By using the consistency test as a principal feature of AHP technique, the possible inconsistency discovered in the factor weights thru the calculation of consistency level of every matrix will be removed [45].

The consistency ratio was applied to compute and validate the inconsistency in the pair-wise judgement built by the participants (Wong & Li, 2008).

By Saaty's consistency formula, the consistency can be checked through computing the Consistency Index (CI) as Equation (4):

$$CI = \frac{\lambda_{min} - n}{n-1} \qquad (4)$$

Then, based on the Equation (5) CR will be computed as follows:

$$CR = \frac{CI}{RI} \qquad (5)$$

Random pairwise comparisons have been simulated to yield average of random indices

for diverse scaled matrices. The measures of RI are specified in Table 9 (Saaty, 1990).

Table 9: Random Index

N	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.48

Where N is the number of factors

Saaty (1990) explained that if the measure of CR become lesser or equal 0.10, the inconsistency level of computation for prioritization is satisfactory.

Chapter 4

RESULTS

4.1 Demographic Profile of Respondents

The profile of the respondents illustrates that 80% of the respondents were male while 20% were female. Also, 2 of participants are below 20, 10 of the respondents are between the ages 21-30, 12 are for age group 31-40, 7 for age group 41-50 and 4 are greater than 50 as shown in Figure 6. However, 5 of the respondent's education level were diploma, whereas 28, 8 and 1 are Bachelor, Master and PhD respectively. Likewise, about organizational experience the following tables are shown 8 experts for less than 5 years, 18 for 5 to 10 years and utterly 9 of the respondents who have more than 10 years of experiences. The demographic statistics of respondents are visualized as follows in Figure (3), (4), (5), and (6):

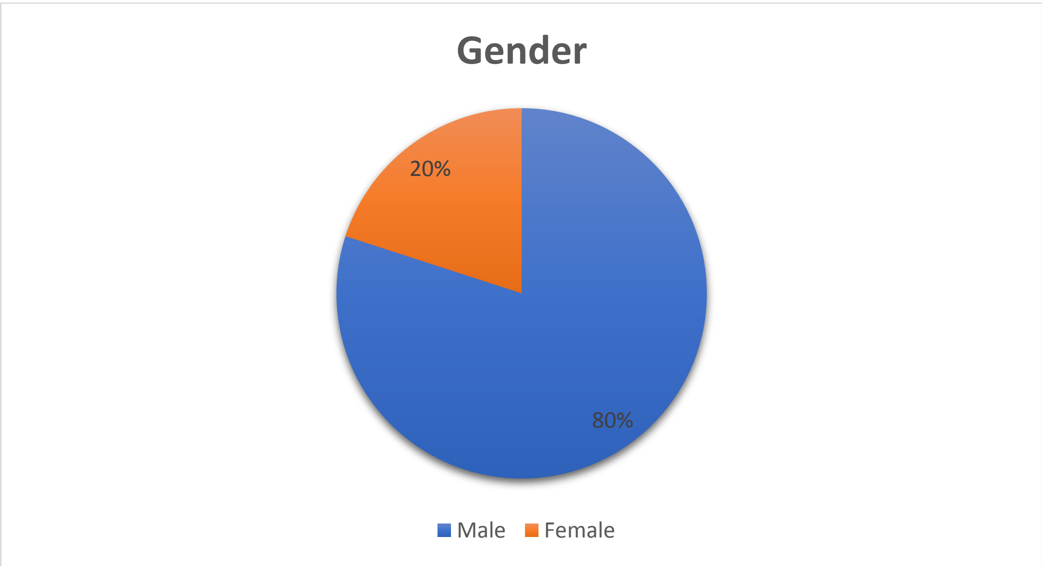

Figure 3: Distribution of the gender

The profile displays that about 80% were male and about 20% were female as exposed in above chart.

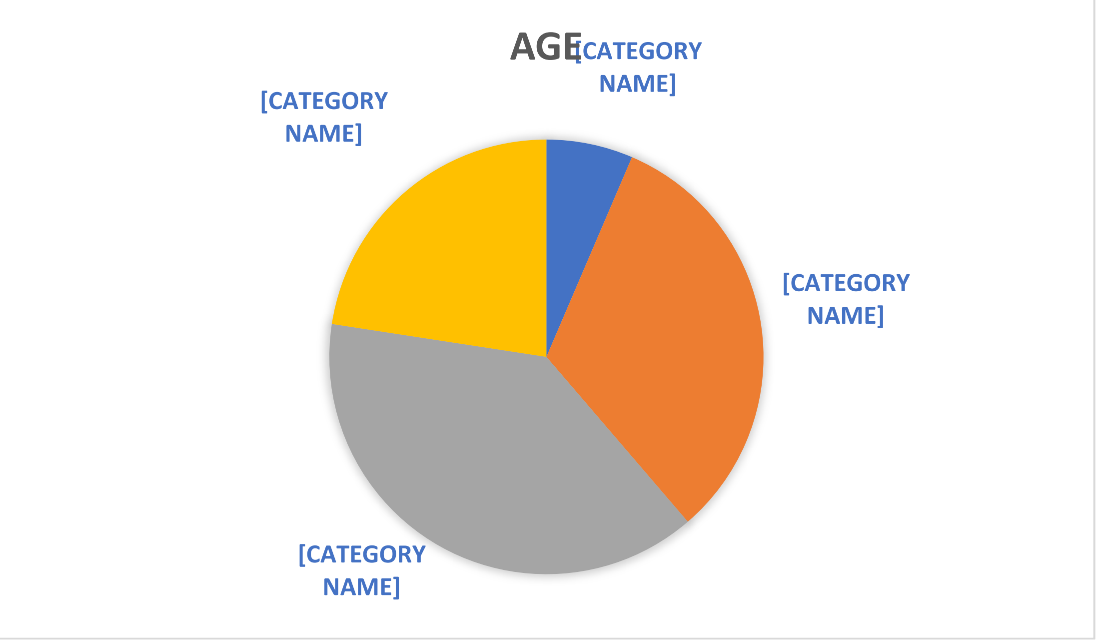

Figure 4: Distribution of the age range

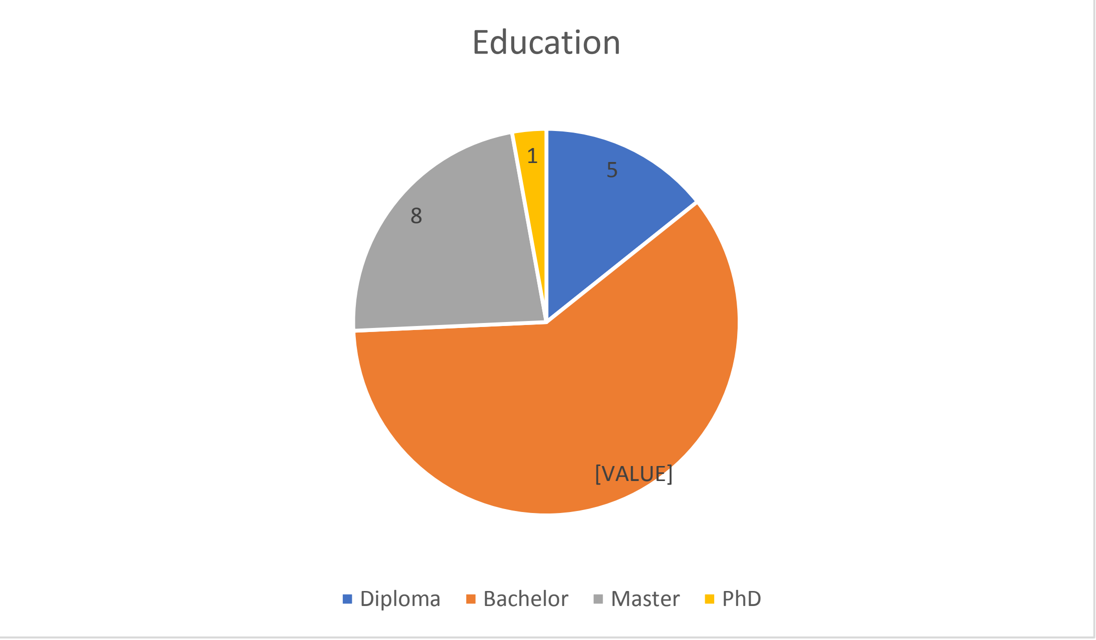

Figure 5: Distribution of the education level

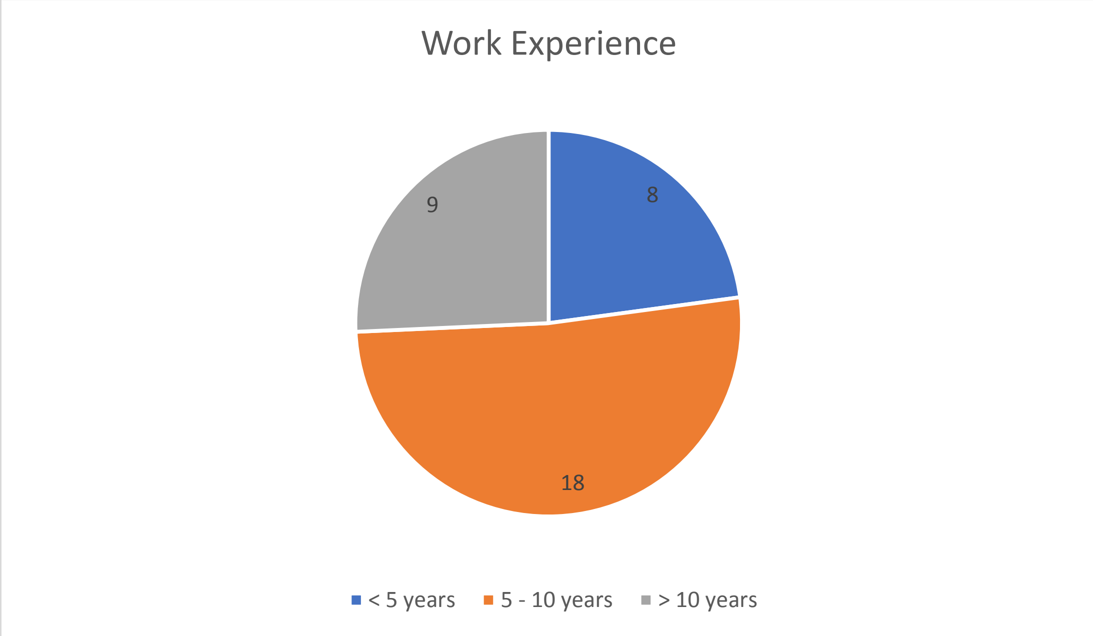

Figure 6: Distribution of the work experience

4.2 Results

4.2.1 Identification of critical selection factors

4.2.1.1 Manual calculation:

In this part, we are going to show the calculation progress of ranking the potential FMs of aircraft landing system by AHP technique as a sample for a case of occurrence sub-criteria. Therefore, weights were assigned to the factors via imputing the geometric mean measure of every pair-wise comparison corresponding to the questionnaire by the following procedure; noting that using geometric mean for this calculation is better since the bias will be removed and we can obtain the normal distribution of average.

Using the data collected from our experts as shown in this sample below:

Alternatives	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Alternatives
FM1A	7	3	2		4	2	2		7	1			1	3	2	1		FM1B

We apply the geometric mean formula as follow:

$$\sqrt[35]{\left(\frac{1}{9}\right)^7 * \left(\frac{1}{8}\right)^3 * \left(\frac{1}{7}\right)^2 * \left(\frac{1}{5}\right)^4 * \left(\frac{1}{4}\right)^2 * \left(\frac{1}{3}\right)^2 * 1^7 * 2^1 * 5^1 * 6^3 * 7^2 * 8^1}$$

Where 35 is our N (respondents), Number 9 in the first fraction represents the intensity of alternatives and the Power 7 in the first fraction represents the number of respondents choosing 9 as an intensity and so on for the rest of the equation. We continue to apply this formula for each row of our data collected in order to obtain our Geometric Mean Matrix shown below in table 10.

Table 10: Geometric means of pairwise comparison of selection criteria

	I1	**I2**	**I3**	**I4**	**I5**	**I6**	**I7**	**I8**	**I9**	**I10**
I1	1	0.51	0.85	0.52	1.26	1.07	2.03	0.49	2.32	0.62
I2	1.94	1	1.23	0.73	1.12	3.39	0.79	1.44	1.12	0.70
I3	1.18	0.81	1	1.46	2.21	3.17	0.80	3.87	0.91	3.12
I4	1.92	1.38	0.68	1	1.18	1.74	1.90	1.05	1.80	0.56
I5	0.79	0.90	0.45	0.84	1	2.01	0.49	0.85	0.92	1.96
I6	0.93	0.29	0.31	0.57	0.50	1	0.55	0.56	0.49	0.41
I7	0.49	1.27	1.25	0.53	2.04	1.82	1	0.73	0.32	0.60
I8	2.03	0.70	0.26	0.95	1.18	1.79	1.36	1	0.46	2.42
I9	0.43	0.89	1.09	0.56	1.09	2.05	3.13	2.16	1	0.37
I10	1.61	1.43	0.32	1.78	0.51	2.42	1.67	0.41	2.69	1
SUM	**12.32**	**9.18**	**7.44**	**8.94**	**12.09**	**20.46**	**13.72**	**12.56**	**12.03**	**11.76**

Where:

- I1: FM1A
- I2: FM1B

- I3: FM2A
- I4: FM2B
- I5: FM3A
- I6: FM3B
- I7: FM4A
- I8: FM4B
- I9: FM5A
- I10: FM5B

With the equation (1), we normalize the contents of Table (10):

$$a_{ji}* = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad (1)$$

According to previous Equation, Table (11) will be made for normalizing the numbers of first table which is built from the questionnaire directly. Consequently, by computing the arithmetic mean of each row of Table (11), priority vector of selected modes can be constructed as shown in Table (11) and (12) as follows:

Table 11: Normalizing the Initial Pair-Wise Comparison Matrix Components

	I1	**I2**	**I3**	**I4**	**I5**	**I6**	**I7**	**I8**	**I9**	**I10**	**Priority Vector**
I1	0.081	0.056	0.114	0.058	0.104	0.052	0.148	0.039	0.193	0.053	**0.090**
I2	0.157	0.109	0.165	0.082	0.093	0.166	0.058	0.115	0.093	0.060	**0.110**
I3	0.096	0.088	0.134	0.163	0.183	0.155	0.058	0.308	0.076	0.265	**0.153**
I4	0.156	0.150	0.091	0.112	0.098	0.085	0.138	0.084	0.150	0.048	**0.111**

I5	0.064	0.098	0.060	0.094	0.083	0.098	0.036	0.068	0.076	0.167	**0.084**
I6	0.075	0.032	0.042	0.064	0.041	0.049	0.040	0.045	0.041	0.035	**0.046**
I7	0.040	0.138	0.168	0.059	0.169	0.089	0.073	0.058	0.027	0.051	**0.087**
I8	0.165	0.076	0.035	0.106	0.098	0.087	0.099	0.080	0.038	0.206	**0.099**
I9	0.035	0.097	0.147	0.063	0.090	0.100	0.228	0.172	0.083	0.031	**0.105**
I10	0.131	0.156	0.043	0.199	0.042	0.118	0.122	0.033	0.224	0.085	**0.115**

Table 12: The final matrix prioritization criteria with AHP method

Criteria	**Weights of elements**
I3	0.1527
I10	0.1152
I4	0.1111
I2	0.1097
I9	0.1046
I8	0.0990
I1	0.0898
I7	0.0872
I5	0.0844
I6	0.0463

Thus, based on usage of the AHP approach to prioritize, importance level of the criteria are as follows:

- I3: FM2A
- I10: FM5B
- I4: FM2B
- I2: FM1B
- I9: FM5A
- I8: FM4B

- I1: FM1A
- I7: FM4A
- I5: FM3A
- I6: FM3B

In continue, consistency assessment a principal test of the AHP methodology is utilized for excluding the possible inconsistency exposed in the factor weights over the calculation of consistency level of matrices (Wong & Li, 2008; Saaty, 1980).

The procedure of consistency rate (CR) will be depicts as follows:

Weighted Sum Vector:

$$\begin{bmatrix} 1 & 0.51 & 0.85 & 0.52 & 1.26 & 1.07 & 2.03 & 0.49 & 2.32 & 0.62 \\ 1.94 & 1 & 1.23 & 0.73 & 1.12 & 3.39 & 0.79 & 1.44 & 1.12 & 0.70 \\ 1.18 & 0.81 & 1 & 1.46 & 2.21 & 3.17 & 0.80 & 3.87 & 0.91 & 3.12 \\ 1.92 & 1.38 & 0.68 & 1 & 1.18 & 1.74 & 1.90 & 1.05 & 1.80 & 0.56 \\ 0.79 & 0.90 & 0.45 & 0.84 & 1 & 2.01 & 0.49 & 0.85 & 0.92 & 1.96 \\ 0.93 & 0.29 & 0.31 & 0.57 & 0.50 & 1 & 0.55 & 0.56 & 0.49 & 0.41 \\ 0.49 & 1.27 & 1.25 & 0.53 & 2.04 & 1.82 & 1 & 0.73 & 0.32 & 0.60 \\ 2.03 & 0.70 & 0.26 & 0.95 & 1.18 & 1.79 & 1.36 & 1 & 0.46 & 2.42 \\ 0.43 & 0.89 & 1.09 & 0.56 & 1.09 & 2.05 & 3.13 & 2.16 & 1 & 0.37 \\ 1.61 & 1.43 & 0.32 & 1.78 & 0.51 & 2.42 & 1.67 & 0.41 & 2.69 & 1 \end{bmatrix} \begin{bmatrix} 0.1527 \\ 0.1152 \\ 0.1111 \\ 0.1097 \\ 0.1046 \\ 0.0990 \\ 0.0898 \\ 0.0872 \\ 0.0844 \\ 0.0463 \end{bmatrix}$$

WSV = [1.0503 1.4044 1.7202 1.3731 0.9566 0.5822 1.0200 1.1845 1.2387 1.3934]

Consistency Vector:

V1: 0.5822/0.0463= 12.5752

V2: 0.9566/0.0844= 11.3324

V3: 1.0200/0.0872= 11.7009

V4: 1.0503/0.0898= 11.6929

V5: 1.1845/0.0990= 11.9638

V6: 1.2387/0.1046= 11.8416

V7: 1.3731/0.1097= 12.5222

V8: 1.3934/0.1111= 12.5371

V9: 1.4044/0.1152= 12.1905

V10: 1.7202/0.1527= 11.2666

CV= [12.5752 11.3324 11.7009 11.6929 11.9638 11.8416 12.5222 12.5371 12.1905 11.2666]

Consistency Index:

$$CI = \frac{\lambda_{min} - n}{n - 1} = \frac{11.2666 - 10}{10 - 1} = 0.1407$$

Consistency Rate:

$$CR = \frac{CI}{RI} = \frac{0.14}{1.51} = 0.09$$

Table 13: Random Index

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

Subsequently, when the computed consistency rate value is lower or equal to 0.1, then we can say consistency is approved and paired comparisons of the models are quite significant.

4.2.2 Result by Expert Choice Software

In order to conduct the analysis to prioritize of FMs in aircraft landing system, Expert Choice 11.0 was applied to compute the outcomes.

4.2.2.1 Comparing components of FMEA in the Hierarchy

According to computing the Risk Priority Number (RPN) for FMEA in this study, with respect to 3 aspects: occurrence (O), Severity (S), and Detection (D) we made the decision to rank and calculate the weights of elements as follows:

4.2.2.2 Occurrence

In figure 7, results comparing FMs with respect to probability of occurrence, which are sub-criteria for occurrence is exposed. FM2A was prioritized over FM5B and FM5A with a weight of 0.158, 0.119and 0.114 respectively.

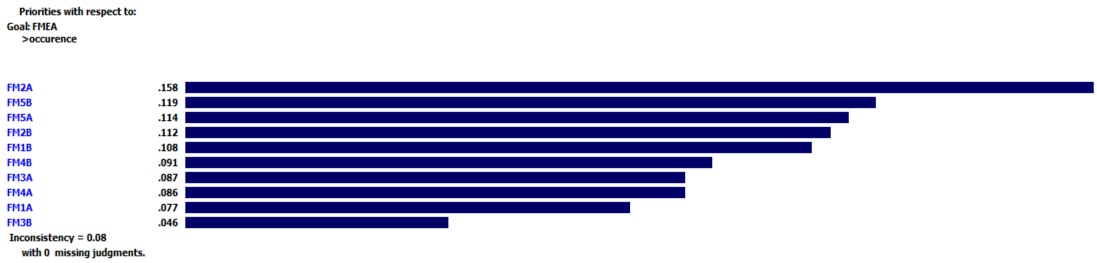

Figure 7: Software result of comparing FMs with respect to occurrence dimension

The outcomes of this part are summarized in the Table 14 as follows:

Table 14: Prioritization of FMs with respect to occurrence probability

Rank	**Failure modes**	**weights**
1	FM2A	0.158
2	FM5B	0.119
3	FM5A	0.114
4	FM2B	0.112
5	FM1B	0.108
6	FM4B	0.091
7	FM3A	0.087
8	FM4A	0.086

9	FM1A	0.077
10	FM3B	0.046

4.2.2.3 Severity

Likewise, based on the severity dimension, for the list of FMs, FM2A and FM1B were compared and as figure 8 expresses, FM2A was given preference by having a weigh of 0.132 while FM1B, 0.112.

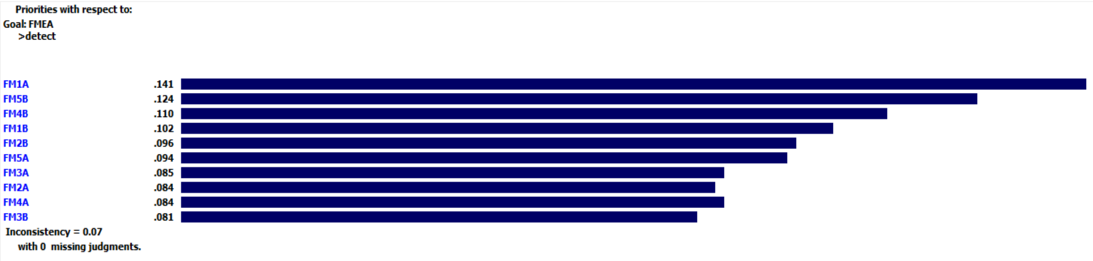

Figure 8: Software result of comparing FMs with respect to severity of effects

The ranked list of potential FMs by the AHP method is exposed in Table (15) as follows:

Table 15: Prioritization of FMs with respect to severity of effects

Rank	Failure modes	weights
1	FM2A	0.132
2	FM1B	0.112
3	FM2B	0.107
4	FM3B	0.105
5	FM3A	0.102
6	FM4A	0.101
7	FM1A	0.100
8	FM5B	0.099
9	FM5A	0.089
10	FM4B	0.054

4.2.2.4 Detection

Also, regarding to the software outcomes in Figure (9), the group of FMs under the detection in the hierarchy model were ranked that FM1A was given preference by having a weigh of 0.141 while FM5B, 0.124.

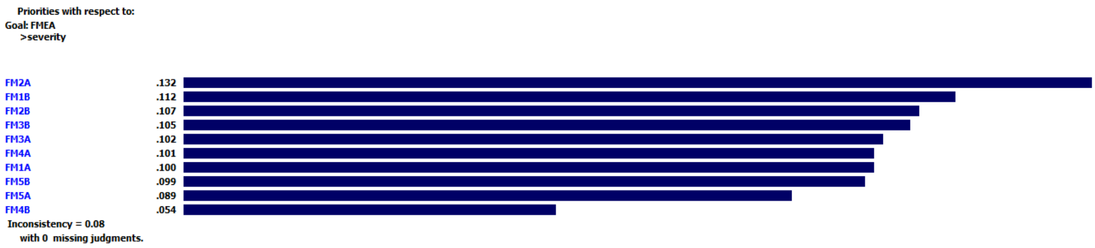

Figure 9. Software result of comparing FMs with respect to detection probability

In the following table, according to the weights of FMs, the rank of them is determined.

Table 16: Prioritization of failure modes with respect to detection of effects

Rank	**Failure modes**	**weights**
1	FM1A	0.141
2	FM5B	0.124
3	FM4B	0.110
4	FM1B	0.102
5	FM2B	0.096
6	FM5A	0.094
7	FM3A	0.085
8	FM2A	0.084
9	FM4A	0.084
10	FM3B	0.081

4.2.2.5 Dynamic Sensitivity of criteria for all aspects

The result as shown in figure 10 which is the dynamic sensitivity for the potential FMs with respect to three dimensions: Occurrence, Severity and Detection.

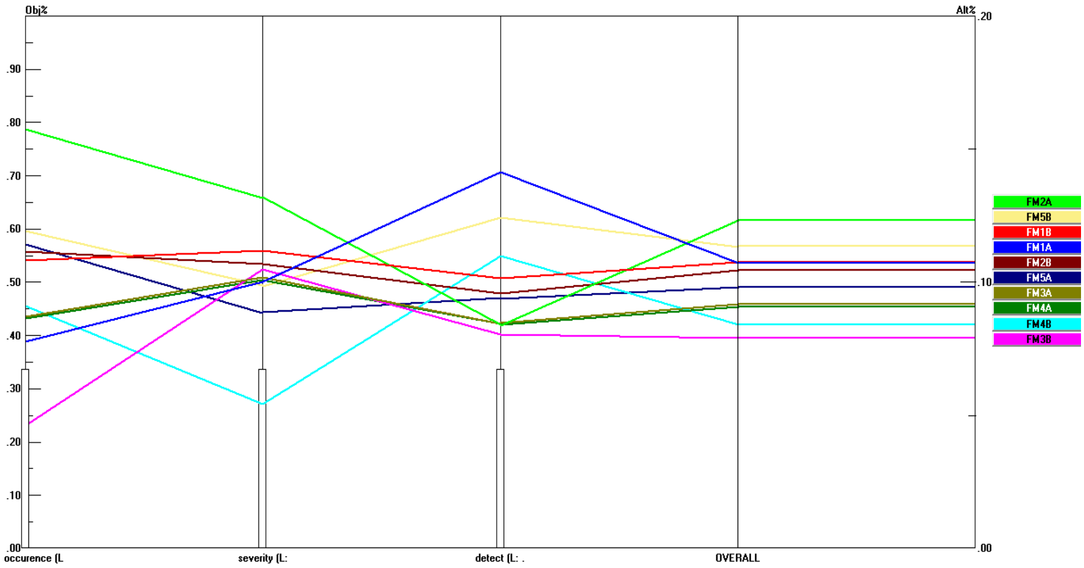

Figure 10. Dynamic Sensitivity diagram for FMEA of aircraft landing system

4.2.3 Risk priority number

As we discussed in previous chapters, an algebraic ranking progress for measuring the risk of each FM is called Risk Priority Number (RPN) which it is build up by arithmetic multiplication of three components: probability of occurrence, severity of the influence, and likelihood of reason detection. The range of RPN is between 1 to 1000 (Helvacioglu & Ozen, 2014).

To drive of cleanse the exploited declared methodology, the specifics of a numeric FM (A simplest aircraft landing systems) is chosen as a case study.

The cause of choosing aircraft landing system for this research is for the Mahan Airline’s (2015) report of lots of accidents in Iranian airlines during recent years.

As it demonstrates in Figure 9 with pushing GDnB and GupB the gear let down and up one-to-one. Switch (S1) direct a signal to computer (C) throughout raising the equipment (otherwise an error signal is shown). On the other side, while the gear is going down the switch (S2) send a signal to the computer (otherwise an error signal will be sent reported). Task switches is exploring information round the actual position of the landing gear and stopping unreliable commands. The key performances of airplane landing structures for both types of process (hardware and software) are provided as follows:

- Raising gear
- Coming down gear
- Automatic test
- error reporting system
- Record the result of automatic test

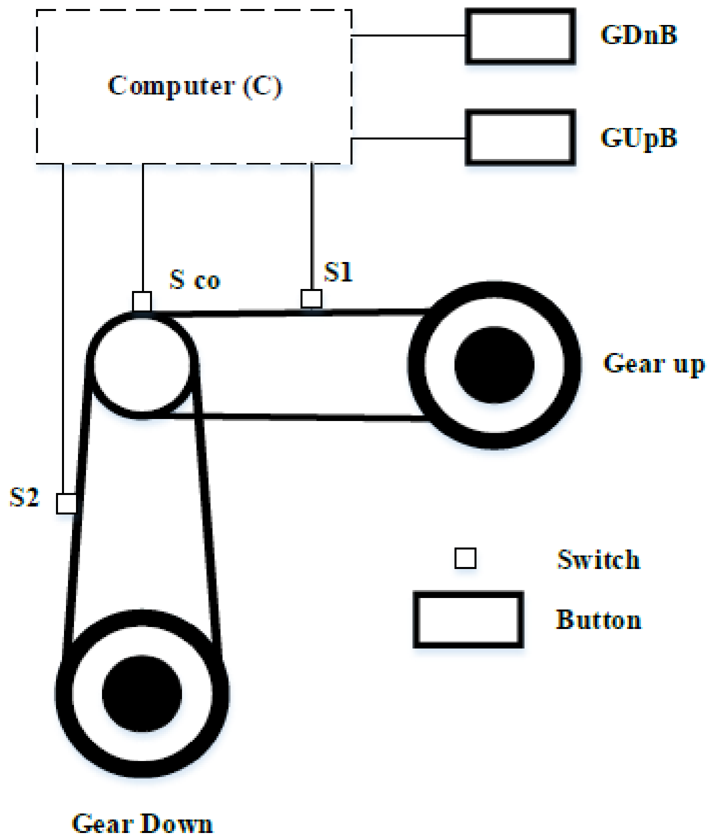

Figure 11. Simple aircraft landing system (Ericson, 2005)

According to Figure 11, the traditional FMEA table of FMs is provided on Table 17.

Table 17: FMEA of the Aircraft landing system

Process Step		**Potential Failure modes**	**Potential effect(s) of failure**	**Potential cause(s)/Failure mechanism**	**Detection Practice**
FM1A	Raising Gear	Fault in raising the wheels	Extension system damage of aircraft, taking off with open wheels	Software fault, fault in in the wiring of computer	Sensor
FM1B		Raising wheels earlier than specified time	Aircraft damaged on landing.	Software fault	Sensor
FM2A	Coming down Gear	Fault in coming down the wheels	Landing with closed wheels, Aircraft damaged on landing	Software fault, fault in in the wiring of computer	Sensor
FM2B		Coming down wheels earlier than specified time	Damage caused by the pressure and tension	Software fault	Sensor
FM3A	Automatic test	Fault on the run	Possible unsafe conditions	Software and electronic fault	None
FM3B		Wrong run	Possible unsafe conditions	Software and electronic fault	None
FM4A	Fault reporting system	Fault on the run	Fault information was not reported, Without risk	Software fault	Pilot Report
FM4B		Wrong run	Fault information was reported mistakenly, Without risk	Software fault	Pilot Report
FM5A	Record the result of automatic test	Fault on the run	Failure to register unsafe situation, Without risk	Software fault	Data analysis
FM5B		Wrong run	Register unsafe situation mistakenly, Without risk	Software fault	Data analysis

(Naftair Airline, 2015)

According to Table 18, the process steps denoted as FM1A, FM1B etc. and also RPN scores are computed as the initial effort.

Table 18: Ranking of the alternative for aircraft landing system

Process steps	Occurrence	Severity	Detection	RPN(1-1000)	Critical Level
FM1A	9	7	1	63	2
FM1B	5	2	4	40	1
FM2A	1	1	8	8	2
FM2B	4	3	5	60	1
FM3A	7	5	7	245	2
FM3B	10	4	10	400	3
FM4A	8	6	9	432	3
FM4B	6	10	3	180	2
FM5A	3	9	6	162	2
FM5B	2	8	2	32	2

As above-mentioned former the aim of this research is to combine FMEA procedure with AHP technique for aircraft landing system to generate better RPN scores. RPN comparison between base article and this study is provided below in table 19 showing the better generated RPN scores after using AHP method.

Table 19: RPN scores comparison

Failure Modes	Base-study RPN	New RPN
FM1A	48	63
FM1B	84	40
FM2A	84	8
FM2B	84	60
FM3A	180	245
FM3B	180	400
FM4A	18	432

FM4B	18	180
FM5A	12	162
FM5B	12	32

The grades of RPN rates for FMEA are provided in Table 18. To make additional understandable evaluation as well as the maximum and minimum risky RPN score could be figure out from Figure 12.

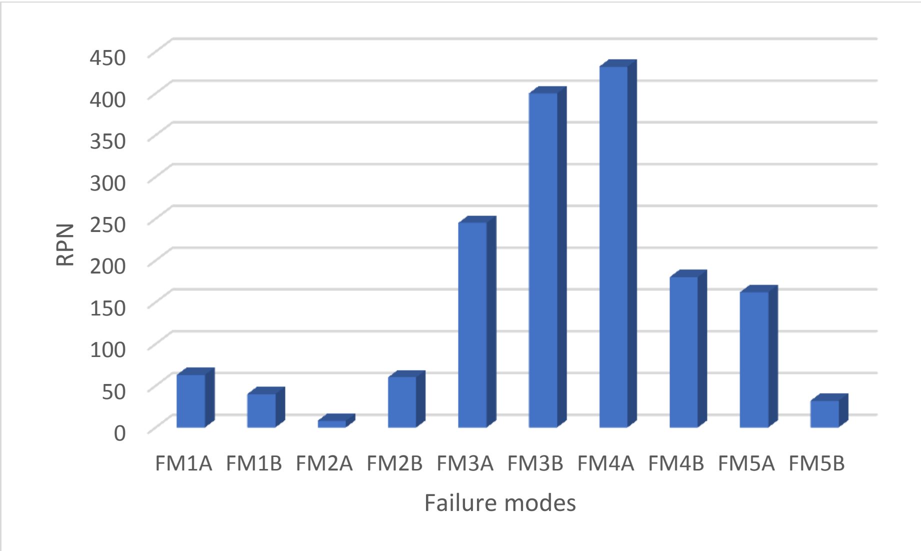

Figure 12. Ranking of RPN score

Due to the theory of FMEA, for recognizing the hazardous potential FM/cause, with respect to the number of likelihood occurrence, severity of effects, likelihood of detection, and arithmetic product computation of RPN, we can determine the level of dangerous or critical level of studied factors. In order to provide the critical level, if the number of occurrence, severity, and detection become less than 6, we should allocate critical value 1. Moreover, if one of the O, S, and D is greater than 6 but the level of RPN is not too large, level 2 would be assigned. Ultimately, if there are three elements (O, S, and D) larger than 6 altogether with the considerable number of RPN, it will be gotten critical level equal to 3. The number of RPN with the critical level of risk is visualized in Figure 13.

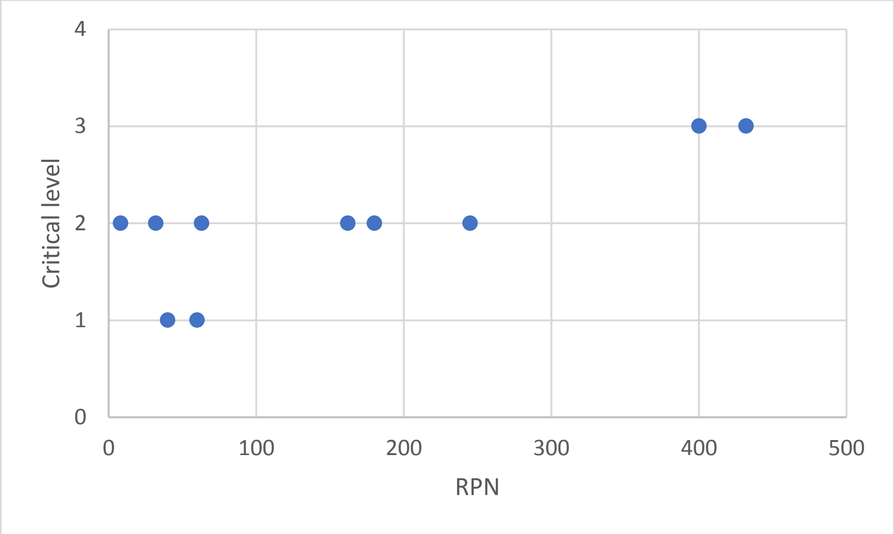

Figure 13: Risk index diagram, RPN and critical level of potential FMs

According to the Figure 13, in order to determine the acceptable level of risk in this study, after computation of RPN for all parts of systems, the first point which is placed in level 3, is the cut point of acceptable and non-acceptable will be defined which is here 40

At the end of this chapter, for better understanding the results of FMEA with AHP application methodology, Figure 14 was sketched as risk index charts for all aspects.

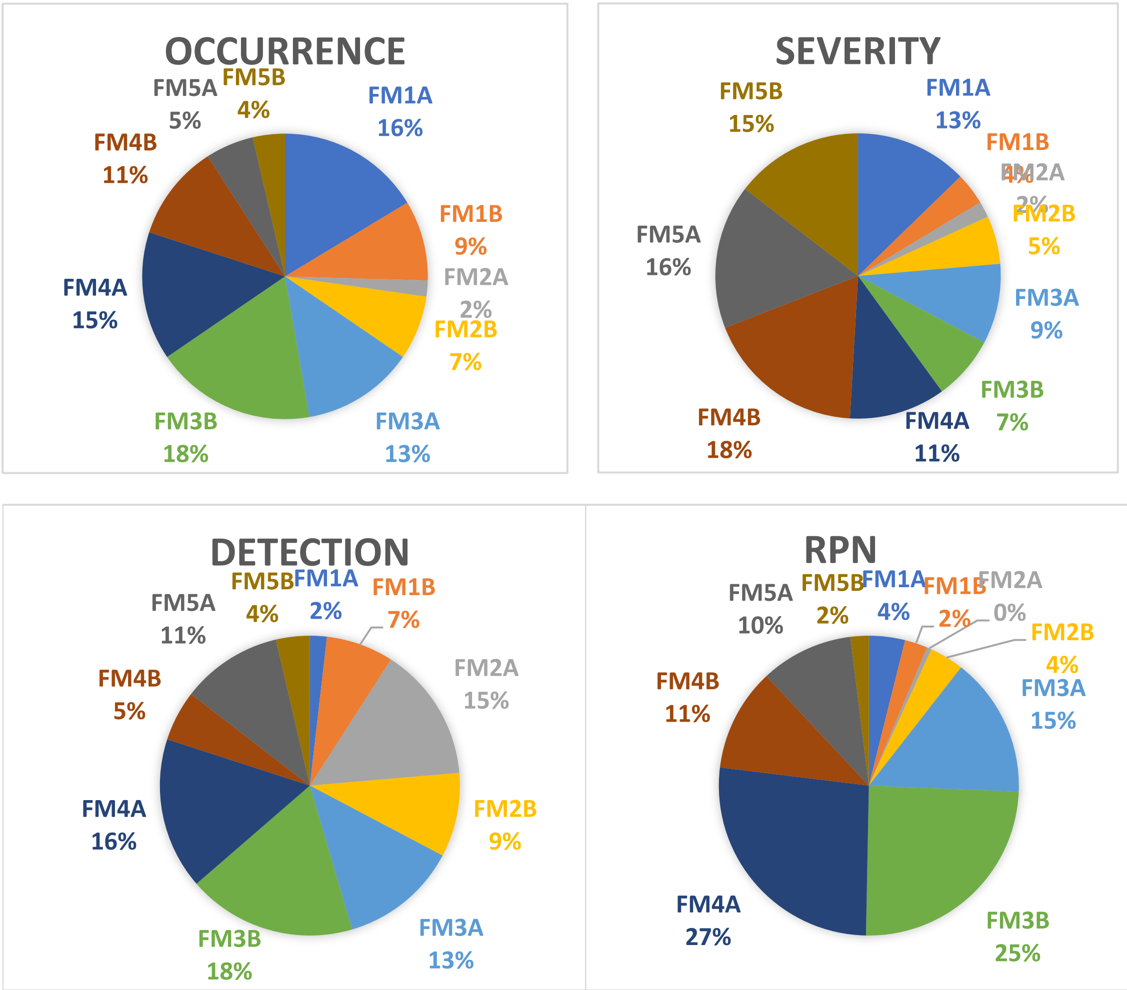

Figure 14: Risk index charts at a glance

Chapter 5

CONCLUSION

5.1 Study Outcome

In the previous chapters of this study, we showed the results of our calculations for all the FMs, obtaining data from respondents, applying AHP method for this data in order to obtain the ranking of those modes under three elements: occurrence, detection and severity. This allowed us to use the ranking obtained to find the Risk Priority Number (RPN) by the FMEA method. After applying the Analytical Hierarchy Process (AHP) on the 10 potential FMs in this study, and after obtaining the RPN for the studied factors, we observe that the risk priority number is very high for some modes.

The risk index diagram shows that the critical levels of FM4A (Fault on the run of Fault reporting system) and FM3B (wrong run of Automatic test) attained the cut point. Determining to us that those factors are at a dangerous risk level and their occurrence can cause unsafe conditions for the aircraft. Critical Level 2 was assigned to other FMs including FM1A (Fault in raising the wheels), FM2A (Fault in coming down the wheels), FM3A (Fault on the run of Automatic test), FM4B (Wrong run of Fault reporting system), FM5A and FM5B (Automatic test result record).

After analyzing our aerospace experts opinions and from the given mechanisms, we can note that the failure of those modes is mainly caused by software and electronic faults, that leaves us with the fact that the aircraft landing system used in our base study has a high probability of unacceptable failure, that will cause unsafe conditions leading to severe damage on aircraft landing. The obtained results are not the same results obtained by FMEA in our base article, this study showed us the importance of AHP method over the FMEA.

5.2 Future recommendation

The failures of the aircraft landing system studied in our case are caused by electronic and/or by software system faults. This fault can be induced either by a human factor, like the technicians working on the system and maintaining it, or by a manufacturing defect.

In the case of a maintenance cause of failure, it is recommended by the researcher the application of extensive maintenance actions, taken on ground, by increasing the number of checks and tests on the system before aircraft takeoff, maintenance supervisors can come up with better preventative maintenance tasks, well planned according to time and cost.

5.3 Further Studies

Future improvements of this study recommend to use a higher number of experts, at least 100 experts in order to reach optimality in computing the risk priority number (RPN) for the different FMs studied in this research.

Because of rare risk assessment studies done for aircraft systems, it is recommended to develop these types of study for entire aircraft systems with considering the group decision-making methods such as fuzzy hybrid weighted, Grey relational projection, VIKOR, Fuzzy hybrid TOPSIS approach or combination of them.

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APPENDIX

Appendix A: Survey Questionnaire

Dear respondent;

In light of the Analytical Hierarchy Process (AHP), this questionnaire is designed by pairwise comparison for factors and decision options in 9-point intensity of relative importance scale as follow:

9-POINT INTENSITY OF RELATIVE IMPORTANCE SCALE

Intensity of Relative Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to objective 1.
3	Moderate importance of one over another	Experience and judgment slightly favor one activity over another.
5	Essential or strong importance	Experience and judgment strongly favor one activity over another.
7	Demonstrated importance	An activity is strongly favored, and its dominance is demonstrated in practice.
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When a compromise is needed.
Reciprocals of the above nonzero numbers	Reciprocal for inverse comparison	

Definition of Terms:

FM1A	Fault in raising the wheels
FM1B	Raising wheels earlier than specified time
FM2A	Fault in coming down the wheels
FM2B	Coming down wheels earlier than specified time
FM3A	Fault on the run (automatically test)
FM3B	Wrong run (automatically test)
FM4A	Fault on the run (fault reporting system)
FM4B	Wrong run (fault reporting system)
FM5A	Fault on the run (record the result of automatically test)
FM5B	Wrong run (record the result of automatically test)

Occurrence:

Alternatives	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Alternatives
FM1A																		FM1B
FM1A																		FM2A
FM1A																		FM2B
FM1A																		FM3A
FM1A																		FM3B
FM1A																		FM4A
FM1A																		FM4B
FM1A																		FM5A
FM1A																		FM5B
FM1B																		FM2A
FM1B																		FM2B
FM1B																		FM3A
FM1B																		FM3B
FM1B																		FM4A
FM1B																		FM4B
FM1B																		FM5A
FM1B																		FM5B
FM2A																		FM2B
FM2A																		FM3A
FM2A																		FM3B
FM2A																		FM4A
FM2A																		FM4B
FM2A																		FM5A
FM2A																		FM5B
FM2B																		FM3A
FM2B																		FM3B
FM2B																		FM4A
FM2B																		FM4B
FM2B																		FM5A
FM2B																		FM5B
FM3A																		FM3B
FM3A																		FM4A
FM3A																		FM4B
FM3A																		FM5A
FM3A																		FM5B
FM3B																		FM4A
FM3B																		FM4B
FM3B																		FM5A
FM3B																		FM5B
FM4A																		FM4B
FM4A																		FM5A
FM4A																		FM5B
FM4B																		FM5A
FM4B																		FM5B
FM5A																		FM5B

Severity:

Alternatives	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Alternatives
FM1A																		FM1B
FM1A																		FM2A
FM1A																		FM2B
FM1A																		FM3A
FM1A																		FM3B
FM1A																		FM4A
FM1A																		FM4B
FM1A																		FM5A
FM1A																		FM5B
FM1B																		FM2A
FM1B																		FM2B
FM1B																		FM3A
FM1B																		FM3B
FM1B																		FM4A
FM1B																		FM4B
FM1B																		FM5A
FM1B																		FM5B
FM2A																		FM2B
FM2A																		FM3A
FM2A																		FM3B
FM2A																		FM4A
FM2A																		FM4B
FM2A																		FM5A
FM2A																		FM5B
FM2B																		FM3A
FM2B																		FM3B
FM2B																		FM4A
FM2B																		FM4B
FM2B																		FM5A
FM2B																		FM5B
FM3A																		FM3B
FM3A																		FM4A
FM3A																		FM4B
FM3A																		FM5A
FM3A																		FM5B
FM3B																		FM4A
FM3B																		FM4B
FM3B																		FM5A
FM3B																		FM5B
FM4A																		FM4B
FM4A																		FM5A
FM4A																		FM5B
FM4B																		FM5A
FM4B																		FM5B
FM5A																		FM5B

Detection:

Alternatives	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Alternatives
FM1A																		FM1B
FM1A																		FM2A
FM1A																		FM2B
FM1A																		FM3A
FM1A																		FM3B
FM1A																		FM4A
FM1A																		FM4B
FM1A																		FM5A
FM1A																		FM5B
FM1B																		FM2A
FM1B																		FM2B
FM1B																		FM3A
FM1B																		FM3B
FM1B																		FM4A
FM1B																		FM4B
FM1B																		FM5A
FM1B																		FM5B
FM2A																		FM2B
FM2A																		FM3A
FM2A																		FM3B
FM2A																		FM4A
FM2A																		FM4B
FM2A																		FM5A
FM2A																		FM5B
FM2B																		FM3A
FM2B																		FM3B
FM2B																		FM4A
FM2B																		FM4B
FM2B																		FM5A
FM2B																		FM5B
FM3A																		FM3B
FM3A																		FM4A
FM3A																		FM4B
FM3A																		FM5A
FM3A																		FM5B
FM3B																		FM4A
FM3B																		FM4B
FM3B																		FM5A
FM3B																		FM5B
FM4A																		FM4B
FM4A																		FM5A
FM4A																		FM5B
FM4B																		FM5A
FM4B																		FM5B
FM5A																		FM5B