POLITECNICO DI MILANO
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SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING

COMPOSITE FMEA FOR RISK ASSESSMENT IN THE CONSTRUCTION PROJECTS BASED ON THE INTEGRATION OF THE CONVENTIONAL FMEA WITH THE METHOD OF PAIRWISE COMPARISON AND MARKOV CHAIN

A THESIS
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Dedication

This thesis is dedicated to the memory of a person who was cut from the same cloth and who was in fact a real brother and friend,

MOHANNAD RAGAB

There are so many great times that we have had shared together and which will never be forgotten. You are gone, but your memory will live in my heart and mind forever.

RIP My Brother.

Abstract

Purpose: The purpose of this research is to provide risk assessment tool for the construction projects by integrating three methodologies, Failure Mode and Effective Analysis (FMEA), The Method of Pairwise Comparison, and Markov Chain.

Design/ methodology/ approach: A literature of the traditional FMEA was reviewed with the aim of demonstrating its framework, highlighting the main advantages and shortcomings, and to study the application of the FMEA in the construction domain. A new methodology named Composite Failure Mode and Effective Analysis (COMP-FMEA) has been introduced aiming at addressing the limitations of the conventional FMEA that make it inconvenient for the construction projects. The integration of the three methodologies provided an improved version of FMEA that considers wider range of criticality factors instead of the traditional three factors (Occurrence (O), Severity (S) and Detection (D)). Additionally, the proposed methodology provides long-term risk assessment using Markov Chain as a correction process for the possible inadequate evaluation during the first stage. Moreover, the interdependence effect between several failures/risks has been taken into consideration for further assessment. Afterwards a case study of a residential building was presented to validate the concept of the proposed methodology.

Findings: The results obtained confirm the capability of COMP-FMEA to provide better risk assessment for the construction projects by addressing several drawbacks of the conventional FMEA. The use of the proposed approach can support the project management team with reliable information to establish effective correction action process.

Limitations: However COPM-FMEA succeed in addressing several shortcomings of the traditional FMEA and in giving better risk assessment for the construction projects, it still depends on linguistic evaluation for the criticality parameters which provides uncertainty and variety in the experts' provided information. In addition, COMP-FMEA does not include a corrective actions process, which can be a future research to be integrated with the proposed work.

Keywords: FMEA, Pairwise Comparison, Markov Chain, Construction, Risk assessment.

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For any errors or inadequacies that may remain in this work, of course, the responsibility is entirely my own.

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1 INTRODUCTION

1.1 OBJECTIVES

Although companies, project managers and risk engineers have defined many methodologies and application in order to assess project or system risk and to increase systems reliability and safety, it is very difficult to aver the existence of a complete tool or methodology that assure complete safety, reliability and riskless project or system. In particular, the construction projects considered as one of the most risky projects, therefore hundreds of studies have taken place trying to eliminate, mitigate or transfer the project risks. In addition, due to the especial nature of the construction projects, and the growing need of having innovative and complex projects, the risk assessment process has become more and more complex.

Therefore, the main research question of this study is:

What is the possibility to provide a risk assessment tool that can be convenient for the construction projects and at the same time avoids the complex calculations that come from complex and hazy methodologies?

The aim of the work is to in develop a new risk assessment methodology that can achieve the following objective:

- Ease of understanding.
- Ease of use from both managers and engineers.
- Considering a wider range of criticality factors.
- Avoiding or at least reducing the conventional FMEA shortcomings.
- Considering the mutual influence between failure modes.
- Providing a good level of flexibility and customization for the user.

Therefore, an integration between the conventional Failure Mode and Effective Analysis (FMEA), the method of Pairwise Comparison and the Markov Chain, has been used to create a Composite FMEA (COMP-FMEA).

A well-structured model has been created in order to assure the ease of use and understanding for the user, taking into consideration different level of users' mentality. Moreover, the proposed methodology not only allows the user to create his own criticality factors that might affect his project, but also provides him with a guideline of the evaluation criteria. In addition, the methodology uses the Markov Chain in order to evaluate the risk level for the failures in the long-term of the project. Moreover, it also takes into consideration the effect of interdependence between different failures, which is very important to be considered in the construction projects.

Afterwards, a case study for a residential building has been presented as a sample project of how the application of the proposed methodology can take place. It allows the user to figure out not only the potential of the proposed methodology, but also how it can provide reliable and powerful information, through a real case.

1.2 RESEARCH MOTIVATIONS

"The recent trend in the construction sites is that the buildings are becoming more skyscraperalized, complicated and large in scale; the risks of accidents in construction sites are increasing as well. Compared to general industrial accident, construction accidents are relatively more frequent, as it composes the second largest reason for industrial accidents." (Ji-Won Song, 2007). In addition, (Guikema, 2009) demonstrated that "due to the nature of the different activities involved, construction projects can be complicated and involve a number of uncertainties such as uncertainties about material delivery times and costs, task completion times and costs, and the quality of work completed by subcontractors. These uncertainties can lead to project risks and can be the cause of a construction project's failure to achieve predefined objectives."

Moreover, the Modernizing Construction (Report by the Comptroller and Auditor General, was published by the National Audit Office (NAO) on 11 January 2001) highlights that "73% of government projects were delivered over budget and 70% were late".

In addition, and according to the (International Labor Organization, 2009), "Construction is one of the world's biggest industrial sectors, including the building, civil engineering, demolition and maintenance industries. It accounts for a large proportion of GDP – 10 percent in the U.K., 17 percent in Japan, for example. In many developing countries, construction is among the fastest growing areas of the labor market, continuing to provide a traditional entry point for laborers. It is, however, one of the most dangerous industries. At least 108 thousand workers are killed on site every year, a figure that represents about 30 per cent of all occupational fatal injuries. Data from a number of industrialized countries show that construction workers are 3 to 4 times more likely than other workers to die from accidents at work. In the developing world, the risks associated with construction work may be 3 to 6 times greater. Many more workers suffer and die from occupational diseases arising from past exposure to dangerous substances, such as asbestos."

The previous challenges were the motivation to start this research looking for creating a methodology that can provide a reliable assessment for the different types of risks associated to the construction projects.

(Masera, 1999) Mentioned that, “an FMEA technique for building construction could be the most important tool in managing quality plans to obtain a suitable and adequate and subsequently more efficient system to build in conformity with specifications.”

In addition, From the conviction that a powerful tool not only should be easy to use and understand, but also should be built based on strong foundation to have the power of solving several problems in different situation and environment. We also believe that FMEA has a very strong potential to be a powerful risk assessment tool for the construction domain.

The fundamentals of FMEA allow the user to identify and assess the failure or the risk easily by breaking down the system into sub-systems and components. However, the conventional FMEA has many criticisms; it still can provide a reliable result if a sufficient modifications and enhancements provided.

Therefore, and referring to the previous challenges, this research tried to provide an improved version on FMEA that can give a promising results by considering the construction domain requirements for a risk assessment and by eliminating or at least reducing the effect of the conventional FMEA shortcomings.

2 FAILURE MODE AND EFFECTIVE ANALYSIS (FMEA)

2.1 INTRODUCTION

This chapter attempts to describe and analyze the Failure Mode and Effective Analysis tool (FMEA) in all its parts; what is FMEA, the procedures, main limitations, the different Risk evaluation methods…etc.

2.2 FMEA- FAILURE MODE AND EFFECTIVE ANALYSIS

Failure Mode and Effective Analysis (FMEA), which also referred to Failure Mode, Effects and Criticality analysis (FMECA), is a risk assessment tool that explores, identifies, analyzing root causes, and examining the potential failures in a system, process, service or design. Moreover, it also mitigates and reduces the failures by taking the advantage of the early identifications.

Historically, "Failure Mode, Effects, and Criticality Analysis (FMECA) was first developed as a formal design methodology in the 1960s by the aerospace industry with their obvious reliability and safety requirements. Since then, it has come to be used extensively to help assure the safety and reliability of products in a wide range of industries, particularly the aerospace, automotive, nuclear, and medical technologies industries" (Peldez, 1995).

Later on, it has been recommended by international standards such as MIL-STD-1629A (U.S. Department of Defense 1980).

The National Aeronautics and Space Administration (NASA) define FMEA as a forward logic (bottom-up), tabular technique that explores the ways or modes in which each system element can fail and assesses the consequences of each of these failures. Based on their point of view, FMEA is a useful tool for cost and benefit studies to implement effective risk mitigation and countermeasure.

Within the context of the traditional FMEA, there are three main objectives, identifying potential failure modes, evaluate the causes, impacts and the effects of different component failure mode, and determine the possible actions to eliminate or to reduce the effect and the impact of each failure mode.

The degree of criticality of a failure mode is determined by calculating risk priority number (RPN).

“The purpose of FMEA is to prioritize the failure modes of the product or system in order to assign the limited resources to the most serious risk items” (Hu-Chen Liu L. L., 2013).

Generally, the RPN is an index ranges from 1 to 1,000, calculated as the product of the severity (S), occurrence (O), and detection level (D) of a failure mode.

Within traditional FMEA, a numerical scale ranging from 1 and 10 is used to represent the universe of discourse for occurrence (O), severity (S), and detection (D). Based on the values assigned to these terms, the value of the RPN is calculated, that is

$$\mathrm{RPN} = \mathrm{O} \times \mathrm{S} \times \mathrm{D} \quad (1)$$

Thus, System components that are assessed to have a high RPN are assumed more critical than those with lower values.

2.2.1 Failure

The first step of implementing FMEA is to define and understand the potential failures in a system. Therefore, the definition of the failure can vary according to several factors such as, industry characteristics, the purpose of applying FMEA (design, maintenance, system development…etc.), the system type (manufacturing system or service system)…etc.

(Venky, 2003) Defined the failure as “the inability of a design or a process to perform its intended function”, (Perry, 1992) referred the failure of a project to “The lack of effective management of risk events, which often leads to overlooking of milestones and targets”. Also (Fayek, 2010) mentioned his own failure definition as “Failure is not limited to design or process weakness but can also be due to errors made during product or process use”).

On the other hand, from a project risk management perspective, failure mode refers to the “risk”, therefore, the Guide to the Project Management Body of Knowledge _PMBOK defined the risk as “an uncertain event or condition that, if it occurs, has a positive or a negative effect on at least one project objective, such as time, cost, scope or quality”

From service perspective, (Chuang, 2007) mentioned that a service failure occurs when customers' expectations are not met while (Ronald L. Hess Jr., 2003) referred the service failure to the situation when service performance falls below a customer's expectation.

2.2.2 Occurrence

The occurrence rating (O) is the frequency or the probability of the occurrence of the failure. (Ayyub, 2003) Defined the detection rating (D) as "a measure of the capability of the current controls." (Peldez, 1995) Mentioned that, occurrence "is ranked according to the failure probability, which represents the relative number of failures anticipated during the design life of the item." Table 2-1 shows the criteria used to rank the occurrence of failure effects.

Table 2-1 ***Traditional ratings for occurrence of a failure***

Rating	Probability of occurrence	Possible failure rate
10	Very high: failure is almost inevitable	≥ 1/2
9		1/3
8	High: repeated failures	1/8
7		1/20
6	Moderate: occasional failures	1/80
5		1/400
4		1/2000
3	Low: relatively few failures	1/15,000
2		1/150,000
1	Remote: failure is unlikely	1/1, 500,000

(Wang, 2003), (K.S. Chin A. C., 2008), (K.S. Chin Y. W., 2009), (S.M. Seyed-Hosseini, 2006), (Y.M. Wang, 2009)

2.2.3 Severity

The severity (S) rating is used to represent the potential effects associated with the occurrence of a failure mode. "It is ranked according to the seriousness of the failure mode effect on the next higher level assembly, the system, or the user. The effects of a failure mode are normally described by the effects on the user of the product or as they would be seen by the user. For example, some common failure effects for automobiles are excessive noise, intermittent operation, impaired control, and rough ride.” (Peldez, 1995).

Table 2-2 shows the criteria used to rank the severity of failure effects.

Table 2-2 ***Traditional ratings for severity of a failure***

Rating	Effect	Severity of effect
10	Hazardous without warning	Very High severity ranking when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulations without warning.
9	Hazardous with warning	Very High severity ranking when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulations with warning.
8	Very high	Vehicle/item inoperable, with loss of primary function.
7	High	Vehicle/item operable, but at reduced level of performance. Customer dissatisfied.
6	Moderate	Vehicle/item operable, but comfort/convenience item(s) inoperable. Customer experiences discomfort.
5	Low	Vehicle/item operable, but comfort/convenience item(s) operable at reduced level of performance. Customer experiences some Dissatisfaction.
4	Very low	Cosmetic defect in finish, fit and finish/squeak or rattle item that does not conform to specifications. Defect noticed by most customers.
3	Minor	Cosmetic defect in finish, fit and finish/squeak or rattle item that does not conform to specifications. Defect noticed by average customer.
2	Very minor	Cosmetic defect in finish, fit and finish/squeak or rattle item that does not conform to specifications. Defect noticed by discriminating customers.
1	None	No effect.

(Wang, 2003), (K.S. Chin A. C., 2008), (K.S. Chin Y. W., 2009), (S.M. Seyed-Hosseini, 2006), (Y.M. Wang, 2009)

2.2.4 Detection

The detection level (D) represents the probability of not detecting the failure. "It is an assessment of the ability of a proposed design verification program to identify a potential weakness before the part or assembly is released to production." (Peldez, 1995).

One definition of detection (D) difficulty is "'How well the organization controls the development process. Another definition relates to the detectability of failure on the product is in the hands of the customer. The former asks 'What is the chance of catching the problem before we give it to the customer?' The latter asks 'what is the chance of the customer catching the problem before the problem results in a catastrophic failure?" (Palady, 1995). "These definitions confuse the FMEA users when one tries to determine detection difficulty. Are we trying to measure how easy it is to detect where a failure has occurred or when it has occurred? On the other hand, are we trying to measure how easy or difficult it is to prevent failures?" (Ishii S. J., 2003)

Table 2-3 shows the evaluation criteria used for the rankings and the corresponding linguistic terms.

Table 2-3 ***Traditional ratings for detection of a failure***

Rating	Detection	Criteria
10	Absolutely impossible	Design control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode; or there is no design control
9	Very remote	Very remote chance the design control will detect a potential cause/mechanism and subsequent failure mode
8	Remote	Remote chance the design control will detect a potential cause/mechanism and subsequent failure mode
7	Very Low	Very Low chance the design control will detect a potential cause/mechanism and subsequent failure mode
6	Low	Low chance the design control will detect a potential cause/mechanism and subsequent failure mode

5	Moderate	Moderate chance the design control will detect a potential cause/mechanism and subsequent failure mode
4	Moderately high	Moderately high chance the design control will detect a potential cause/mechanism and subsequent failure mode
3	High	High chance the design control will detect a potential cause/mechanism and subsequent failure mode
2	Very High	Very High chance the design control will detect a potential cause/mechanism and subsequent failure mode
1	Almost certain	Design control will almost certainly detect a potential cause/mechanism and subsequent failure mode

(Wang, 2003), (K.S. Chin A. C., 2008), (K.S. Chin Y. W., 2009), (S.M. Seyed-Hosseini, 2006), (Y.M. Wang, 2009)

2.3 FMECA- FAILURE MODES EFFECTIVE AND CRITICALITY ANALYSIS

"Failure mode effects and criticality analysis (FMECA) is a widely used technique to improve products and processes safety and reliability in different contexts, such as automotive (Ford Motor Company, 1988), aviation (Bromley and Bottomley, 1994; Buzzatto, 1999), computer science (Becker and Flick, 1996), etc. The FMECA approach is based on a qualitative/quantitative analysis of a system (product or process) and its components in order to identify, by evaluating of failure mode causes and effects, the most critical elements to system operability and safety. For highly critical components, design modifications and maintenance actions have been proposed in order to prevent failure causes or to mitigate their effects." (Alessandro Brun, 2011)

The criticality number calculation described in MIL-STD-1629A (Department of Defencse- United States of America , 1980) is used mostly in the nuclear and aerospace industries.

It first categorizes the severity of the failure mode effect and then develops a criticality ranking which is, in essence, the probability of failure with that severity occurring.

The procedure consists of determining the failure-effect probability (β) (i.e., conditional probability that the failure effect will result in the identified criticality classification, given that the failure mode occurs), the failure mode ratio (α), the part failure rate (λ), and its operating time (τ). The product of these parameters gives the criticality index (I_C) for each item failure mode.

2.4 TYPES OF FMEAS AND FMEA SUCCESS FACTORS

2.4.1 Types of FMEA

According to (Carlson, 2014), there are three common types of FMEA, System FMEA, Design FMEA and Process FMEA.

“**System FMEA:** is the highest-level analysis of an entire system, made up of various subsystems. The focus is on system-related deficiencies, including system safety, system integration, interfaces or interactions between subsystems or with other systems, interactions with the surrounding environment, human interaction, service, and other issues that could cause the overall system not to work as intended. In System FMEAs, the focus is on functions and relationships that are unique to the system as a whole (i.e., do not exist at lower levels). Included are failure modes associated with interfaces and interactions, in addition to considering single point failures (where a single component failure can result in complete failure of the entire system). Some practitioners separate out human interaction and service into their own respective FMEAs.

Design FMEA: focuses on product design, typically at the subsystem or component level. The focus is on design related deficiencies, with emphasis on improving the design and ensuring product operation is safe and reliable during the useful life of the equipment. The scope of the Design FMEA includes the subsystem or component itself, as well as the interfaces between adjacent components. Design FMEA usually assumes the product will be manufactured according to specifications.

Process FMEA: focuses on the manufacturing or assembly process, emphasizing how the manufacturing process can be improved to ensure that a product is built to design requirements in a safe manner, with minimal downtime, scrap and rework. The scope of a Process FMEA can include manufacturing and assembly operations, shipping, incoming parts, transporting of materials, storage, conveyors, tool maintenance, and labeling. Process FMEAs most often assume the design is sound. Failure Mode Effects and Criticality Analysis (FMECA) is similar to FMEA, with the added step of a more formal Criticality

Analysis. This added step commonly requires objective data to support the criticality calculation. It is recommended for practitioners who are required to perform a FMECA analysis to understand the basics of FMEA first, and then to learn the FMECA procedure.

Some other types of FMEAs include:

Concept FMEA: a short version of FMEA to aid in selecting optimum concept alternatives or to determine changes to system design specifications

Maintenance FMEA: in support of Reliability Centered Maintenance projects

Hazard Analysis FMEA: This focuses on identifying and addressing potential hazards associated with the use of a product

Software FMEA: This identifies system weaknesses, and evaluates the effectiveness of the software architecture and software specifications."

2.4.2 FMEA Success Factors:

(Carlson, 2014) Has mentioned six broad success factors that are critical to uniformity of success in the application of FMEA in any company as following:

1. "Understanding the fundamentals and procedures of FMEAs, including the concepts and definitions.
2. Selecting the right FMEA projects.
3. Preparation steps for each FMEA project.
4. Applying lessons learned and quality objectives.
5. Providing excellent facilitation.
6. Implementing an effective company-wide FMEA process.
7. Implementing these FMEA success factors will help ensure FMEAs achieve safe, reliable and economical products and processes."

2.5 FMEA PROCEDURE

Referring to (Wang, 2003), the process for carrying out FMEA can be divided into several steps as shown in Fig. 2-1; these steps are briefly explained as:

1. "Develop a good understanding of what the system is supposed to do when it is operating properly.
2. Divide the system into sub-systems and/or assemblies in order to 'localize' the search for components as shown in figure 2-2
3. Use blue prints, schematics and flow charts to identify components and relations among components.
4. Develop a complete component list for each assembly.
5. Identify operational and environmental stresses that can affect the system. Consider how these stresses might affect the performance of individual components.
6. Determine failure modes of each component and the effects of failure modes on assemblies, sub-systems, and the entire system.
7. Categorize the hazard level (severity) of each failure mode (several qualitative systems have been developed for this purpose).
8. Estimate the probability. In the absence of solid quantitative statistical information, this can also be done using qualitative estimates.
9. Calculate the risk priority number (RPN): the RPN is given as the multiplication of the index representing the probability, severity and detectability.
10. Determine if action needs to be taken depending on the RPN.
11. Develop recommendations to enhance the system performance. These fall into two categories:
    - Preventive actions: avoiding a failure situation.
    - Compensatory actions: minimizing losses in the event that a failure occurs.
12. Summaries the analysis: this can be accomplished in a tabular form as shown in table 2-4

Generally, an FMEA table will have a major row for each component. As these components may have multiple failure modes, the major row is sometimes divided into sub-rows where each sub-row summarizes a specific failure mode. The table is organized into the following columns:

a) Component: create a major row for each component.
b) Failure mode(s): identify failure modes and establish a sub-row for each mode.
c) Effects (by failure mode): describe the effects on safety and system performance resulting from the failure. List specific adverse outcomes.
d) Probability: if reliability data does not exist, estimate using qualitative ranks.
e) Hazard level (severity): if experience data does not exist, estimate using qualitative ranks.
f) Causes of failure mode (if known): this includes environmental and/or operational stresses that increase the likelihood of the failure mode.
g) Methods of detecting failure mode (if known): although this entry does not prevent a failure from occurring, it is important to discover that a failure has occurred. This column is used to present signs and symptoms that a component has failed.
h) Suggested interventions: hardware modifications and/or compensatory actions to minimize effects."

Table 2-4 ***Format of an FMEA report.***

System FMEA NO.														
Subsystem **Component** **Core team**									**Page** **Prepared by** **FMEA Date (org.)**					
	Existing conditions								**Action**		**results**			
Component/ Process	Potential failure mode	Potential effects of mode	Potential causes of mode	Present control mechanisms	Severity	Occurrence	Detection	Risk priority number (RPN)	Recommend actions	Action taken	S	O	D	RPN

(Hu-Chen Liu L. L.-H.-L.-C., 2011)

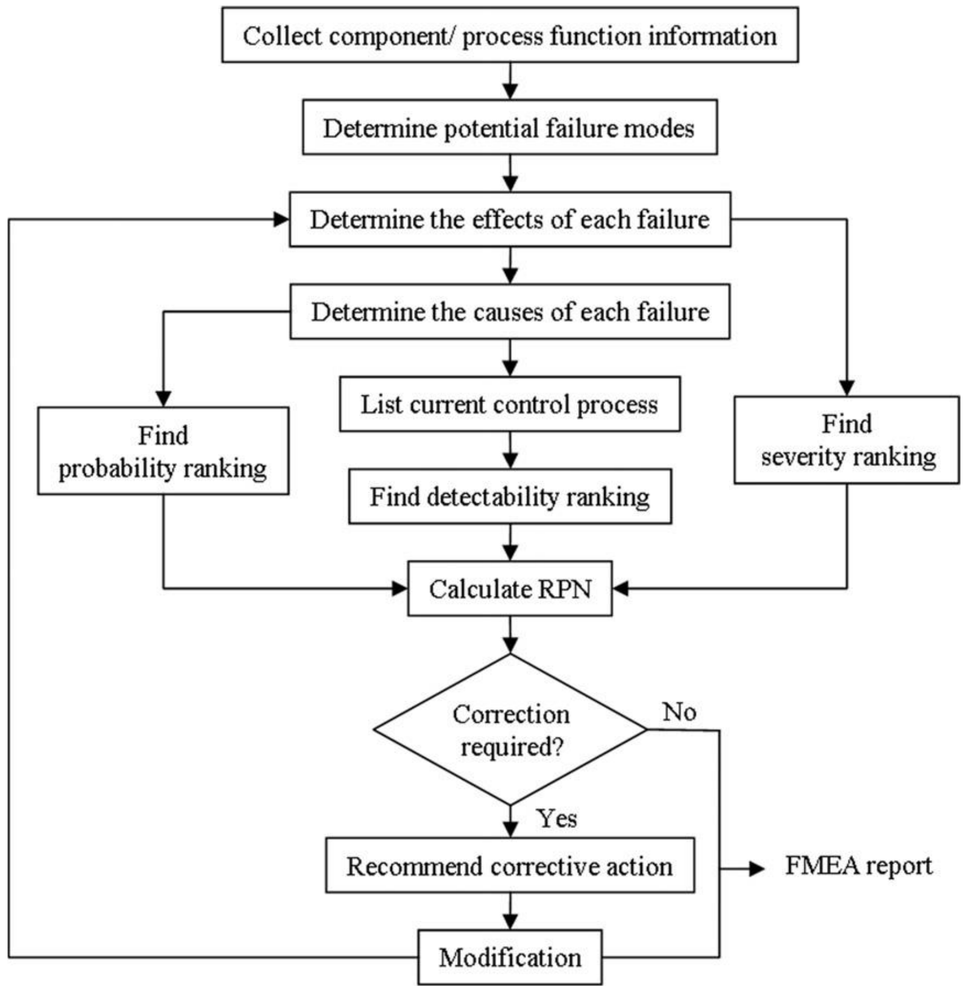

Figure 2-1 ***FMEA procedure*** *(Wang, 2003)*

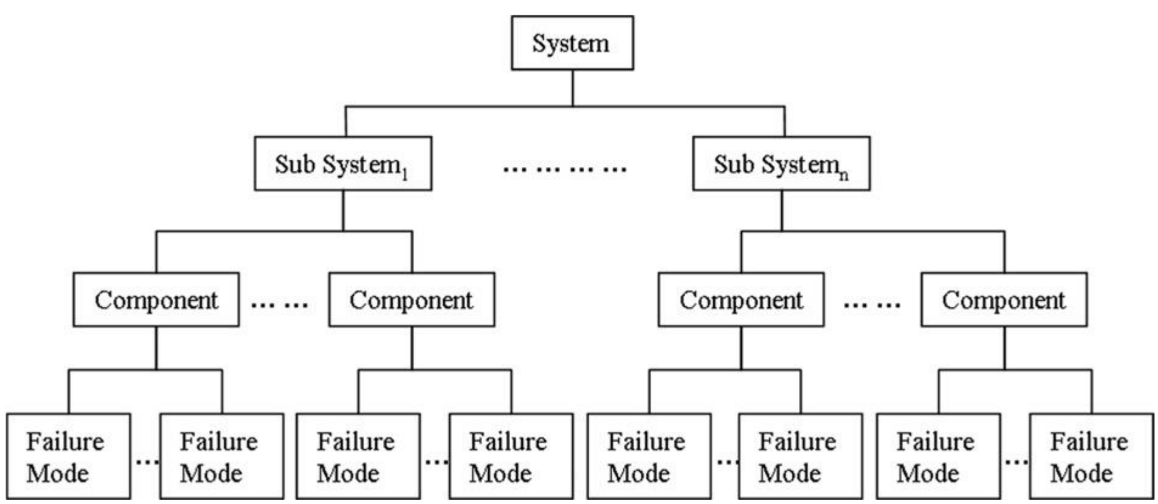

Figure 2-2 ***Hierarchical structure of a system.*** *(Hu-Chen Liu L. L.-H.-L.-C., 2011)*

2.6 FMEA IN CONSTRUCTION INDUSTRY

According to the (International Labour Organization, 2009), "Construction is one of the world's biggest industrial sectors, including the building, civil engineering, demolition and maintenance industries. It accounts for a large proportion of GDP – 10 percent in the U.K., 17 percent in Japan, for example. In many developing countries, construction is among the fastest growing areas of the labour market, continuing to provide a traditional entry point for labourers. It is, however, one of the most dangerous industries. At least 108 thousand workers are killed on site every year, a figure which represents about 30 per cent of all occupational fatal injuries. Data from a number of industrialized countries show that construction workers are 3 to 4 times more likely than other workers to die from accidents at work. In the developing world, the risks associated with construction work may be 3 to 6 times greater. Many more workers suffer and die from occupational diseases arising from past exposure to dangerous substances, such as asbestos."

Thus, to improve this situation, many systems have been implemented by construction firms such as, Occupational Health & Safety Advisory Services (OHSAS 18001) for Occupational Health and Safety (OHS) management, ISO 14001 for environmental management and ISO 9001 for quality management.

Moreover, in order to predict and hence mitigate or prevent the risks of a construction projects, "Various techniques have been developed for use in the management of risks in construction. However, these techniques are limited to addressing risks relating to only cost, schedule, or technical performance individually or at best a combination of cost and schedule risks" (William Imbeah, and Seth Guikema, 2009). These techniques are summarized in table 2-5.

In addition, (William Imbeah, and Seth Guikema, 2009) demonstrated that "The exceptions to this general conclusion are approaches based on Failure Modes and Effects Analysis (FMEA)." As "FMEA addresses budget, schedule, and technical risk together, but it does so based on ordinal, rather than cardinal, scales." However, in the other hand, he urged, "FMEA does not provide a sound basis for allocating resources to manage risk. For example, if there are sufficient funds to address either a potential failure event given a score of 10 or two potential failure events each with a score of 5, which should be addressed?

FMEA cannot answer this question because ordinal scales do not provide a sound basis for optimizing the use of scarce resources to best manage project risk."

Table 2-5 ***Some Risk Analysis Techniques and Risks Addressed***

Risk analysis technique	Addresses schedule risk	Addresses budget risk	Addresses technical risks _quality_
Computer Aided Simulation for Project Appraisal and Review (CASPAR)	Yes	Yes	No
Schedule Risk System	Yes	No	No
Judgmental Risk Analysis Process (JRAP)	Yes	No	No
Estimating Project and Activity Duration Using Network Analysis	Yes	NO	No
Data-Driven Analysis of Corporate Risk Using Historical Cost-Control Data	No	Yes	No
Estimating Using Risk Analysis (ERA)	No	Yes	No
Failure Modes and Effects Analysis (FMEA)	Yes	Yes	Yes
Utility-Functions in Engineering Performance Assessment	No	No	Yes
Program Evaluation and Review Technique—PERT	Yes	No	No

(William Imbeah, and Seth Guikema, 2009)

Despite the importance of FMEA as a risk assessment tool, still the "Studies with FMEA in construction industry are at their first step compared to the application of FMEA in manufacturing industry. Application of FMEA is also limited to reliability and influence of the types of constructions." (Ji-Won Song, 2007)

In addition, most of the authors used the conventional FMEA for the construction projects risk assessment without major modifications except some authors who proposed modified FMEA, which has been combined with a fuzzy logic in most of the cases. In the following part of this section we are presenting the major researches done regarding the applications of FMEA in the construction industry.

(Fayek, 2010), Proposed an extension application of FMEA to risk management in construction industry. They used combination of Fuzzy Logic and Fuzzy Analytical Hierarchy process (AHP) to build their model. In order to avoid the crisp evaluation of the conventional FMEA, they referred the severity (S) to impact (I) with three dimensions: Cost Impact (CI), Time Impact (TI) and Scope Impact (SI).

Although (Amir Mohammadi, 2013) used the same concept of fuzzy-AHP based FMEA but their model considered more dimensions in the evaluation process. They presented a practical approach for construction project risk assessment based on combined Fuzzy and FMEA. The proposed approach allows the project management team to use their judgment and experience in order to have a combination of Likelihood, Impact and Detection of risks. The judgment has been made using linguistic terms, which has been expressed in trapezoidal fuzzy members. This fuzzy concept has been used to address the limitation of the conventional FMEA. Moreover, AHP is utilized to engage cost impact, time impact, quality impact and safety impact, which gave this approach flexible structure since it considered all aspects of risk impact. The proposed framework has been applied in a subway construction project to investigate how this approach works.

(Ji-Won Song, 2007), proposed a model for the construction safety management using the conventional FMEA technique, that is shown in figure 2-3. The proposed model established a system for the safety management of steel-frame work by applying FMEA sheet based on the analysis of precedents.

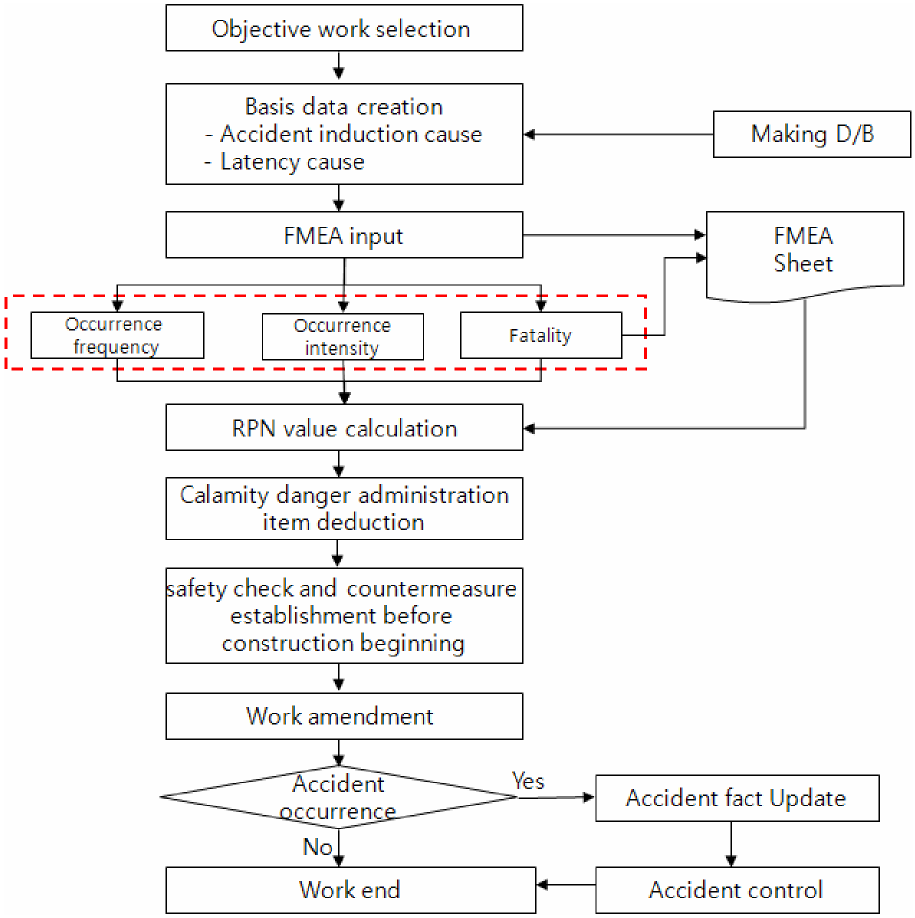

Figure 2-3 ***Administration process to inflect FMEA in a steel-frame work.*** *(Ji-Won Song, 2007)*

(Ltd, 1997): Demonstrated that although FMEA is most frequently used in in the initial design and the development phase of the project, it also has a valuable contribution in the manufacturing stage. Moreover, the author not only demonstrated the importance of FMEA in driving the most visible construction method and schedule, it also adds value in the analyses of day-to-day plant operations and maintenance activities. The paper proposed a frame-wok for applying FMEA at each project life-cycle stage, with suggested FMEA worksheets for each stage.

(Sai X. Zeng, 2010), Used FMEA technique in order to identify and evaluate twenty potential risk factors from Occupational Health and Safety (OHS), environment and quality for an industrial building construction project.

(Chew, 2011), Proposed a complete FMECA application to enhance Building maintainability through mitigation of defects. The methodology used bottom-up, qualitative failure mode effect and criticality analysis (FMECA) as a suitable defect-grading tool and develops criticality parameters applicable for buildings. The analysis has been done for two major systems, nine subsystems, and 62 components of Singapore commercial buildings as shown in figure 2-4. In addition, 319 defects were identified. Moreover, the proposed method aptly evaluated defects from both complex (mechanical and electrical) and simple (Civil and architectural) subsystems whose general characteristics matched with the identified nature of associated defects.

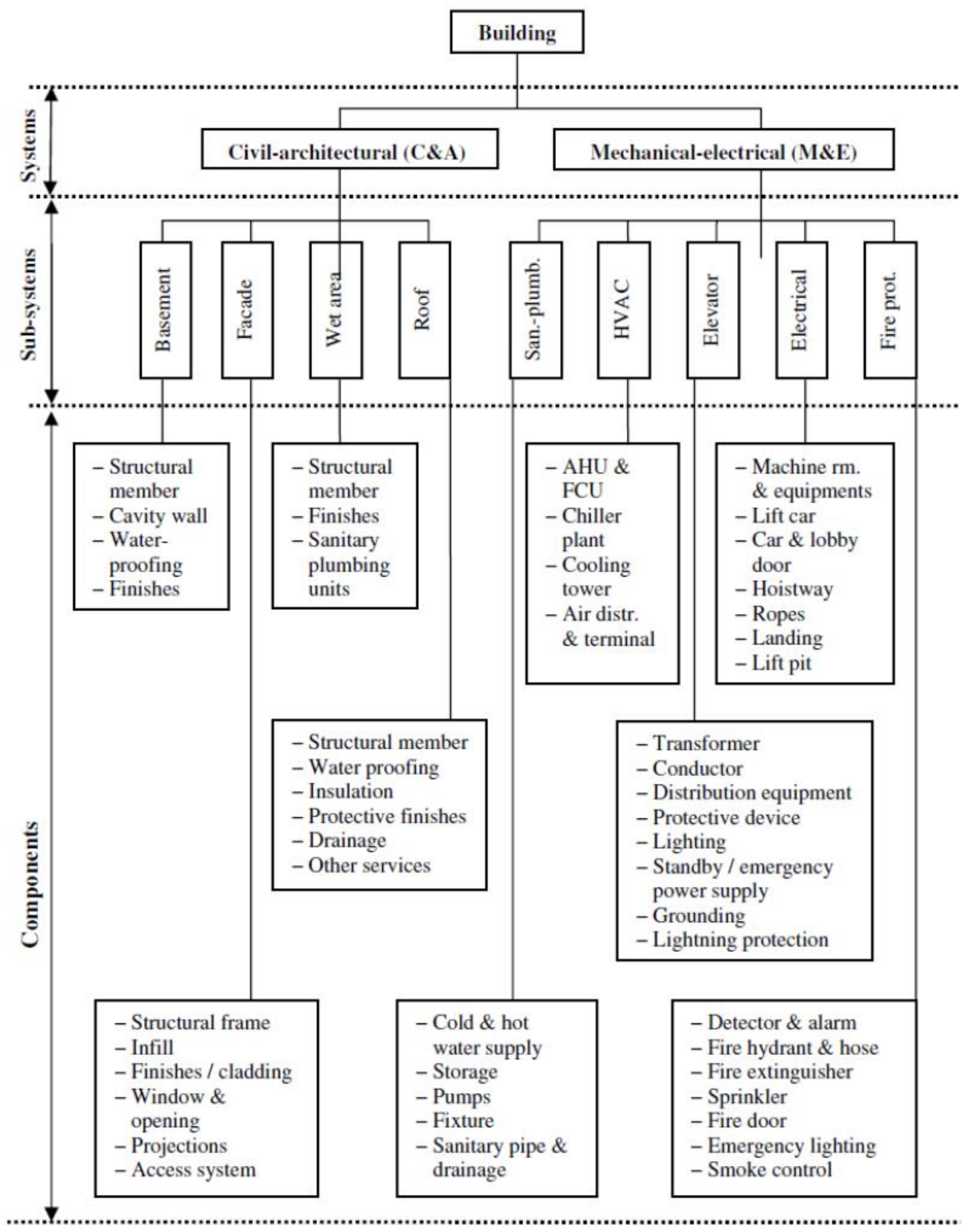

Figure 2-4 ***Elements of a building.*** *(Chew, 2011)*

3 FMEA LIMITATIONS

This chapter mainly concerns of the shortcomings of traditional FMEA, and the methodologies used to evaluate the risk. Moreover, at the end, the chapter provides a criticality analysis and future research suggestions. The analysis is based on the literature review done by (Hu-Chen Liu L. L., 2013) and other papers.

3.1 FMEA SHORTCOMINGS

However, FMEA is one of the most important tool for early preventative actions in system, process, design etc., it has been extensively criticized for having many shortcomings, which lead to crisp risk priority number (RPN) and subsequently low reliability of the FMEA process especially in the complex systems. Therefore, a lot of research has been carried out in order to come up or decrease the effect of these shortcomings. In this section we are providing the most complete classification in the best of our knowledge, which has been done by (Hu-Chen Liu L. L., 2013), Table 3-1 summarizes the eleven major shortcomings of the conventional FMEA. Moreover, The statistics made by (Hu-Chen Liu L. L., 2013) showed that the importance of doing researches in order to enhance FMEA reliability has been increased over time especially between 2007 and 2011 as shown in Figure 3-1

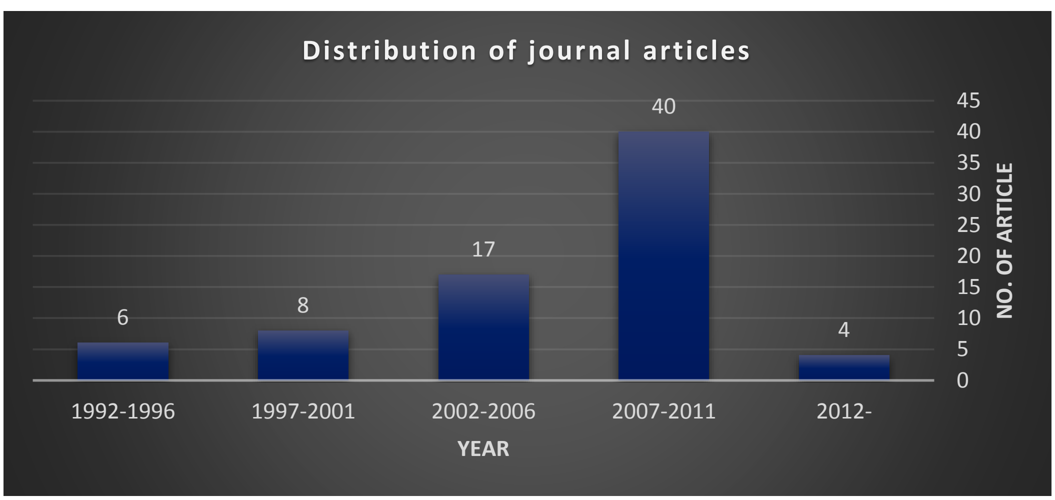

Figure 3-1 ***Distribution of the reviewed articles*** *(Hu-Chen Liu L. L., 2013)*

Table 3-1 ***The major shortcomings of FMEA***

NO.	Shortcomings	Literature
1	The relative importance among O, S and D is not taken into consideration.	(Arash, 2004) , (Ahsen, 2008), (Carmignani, 2009), (Gabbriellib, 2011), (N.C. Xiao, 2011), (S.M. Seyed-Hosseini, 2006), (C.L. Chang C. W., 1999), (C.L. Chang P. L., 2001), (Rajiv Kumar Sharma D. K., 2005), (Rajiv Kumar Sharma D. K., 2007b), (Rajiv Kumar Sharma D. K., 2007c), (R.K. Sharma, 2007d), (Rajiv Kumar Sharma D. K., 2008c), (Rajiv Kumar Sharma P. S., 2010), (Wang, 2003), (Ying-Ming Wang, 2009), (P. A. A. GARCIA, 2005), (Prabhu, 2001), (Fayek, 2010), (Zhang, 2011), (Chang K.-H. a.-C., 2010), (Kutlu, 2012), (Peldez, 1995), (Bimal P. Nepal, 2008), (Zaili Yang, 2008), (Lim, 2006a), (FIORENZO FRANCESCHINI, 2001)
2	Different combinations of O, S and D may produce exactly the same value of RPN, but their hidden risk implications may be totally different.	(Arash, 2004) , (Ahsen, 2008), (Carmignani, 2009), (Marcello Braglia M. F., 2003), (C.L. Chang C. W., 1999), (C.L. Chang P. L., 2001), (Rajiv Kumar Sharma D. K., 2005), (Rajiv Kumar Sharma D. K., 2007b), (Rajiv Kumar Sharma D. K., 2007c), (R.K. Sharma, 2007d), (Rajiv Kumar Sharma D. K., 2008c), (Rajiv Kumar Sharma P. S., 2010), (Wang, 2003), (Ying-Ming Wang, 2009), (Zhang, 2011), (Kutlu, 2012), (Chen, 2007),

		(Zaili Yang, 2008), (Lim, 2006a), (FIORENZO FRANCESCHINI, 2001)
3	The three risk factors are difficult to be precisely evaluated.	(K. Xu, 2002), (Gabbriellib, 2011), (J. Yang, 2011), (K.H. Chang, 2010), (Braglia, 2000), (Ying-Ming Wang, 2009), (Gargama, 2011), (Liang-Hsuan Chena, 2009a), (Liang-Hsuan Chen, 2009b). (P. A. A. GARCIA, 2005), (Fayek, 2010), (Kutlu, 2012), (Zaili Yang, 2008)
4	The mathematical formula for calculating RPN is questionable and debatable.	(Gilchrist, 1993) , (Raouf, 2006), (C.L. Chang C. W., 1999), (C.L. Chang P. L., 2001), (Y. Geum, 2011), (Gargama, 2011), (Kutlu, 2012), (Rajiv Kumar Sharma D. K., 2005)
5	The conversion of scores is different for the three risk factors.	(Gilchrist, 1993) , (Raouf, 2006), (Ahsen, 2008), (Carmignani, 2009), (K.S. Chin Y. W., 2009), (C.L. Chang C. W., 1999), (C.L. Chang P. L., 2001), (R.K. Sharma, 2007d), (Gargama, 2011), (Prabhu, 2001), (Hu-Chen Liu L. L.-H.-L.-C., 2011), (Chen, 2007)
6	The RPN cannot be used to measure the effectiveness of corrective actions.	(Arash, 2004) , (Gilchrist, 1993), (Raouf, 2006), (Carmignani, 2009), (C.L. Chang C. W., 1999), (C.L. Chang P. L., 2001), (R.K. Sharma, 2007d), (Wang, 2003), (Gargama, 2011), (Chen, 2007), (Zaili Yang, 2008)
7	RPNs are not continuous with many holes.	(Carmignani, 2009), (K.H. Chang, 2010), (H.C. Liu, 2012), (P. A. A. GARCIA, 2005), (Chang K.-H. ,

		2009), (FIORENZO FRANCESCHINI, 2001)
8	Interdependencies among various failure modes and effects are not taken into account.	(K. Xu, 2002), (K.S. Chin A. C., 2008), (M. Braglia, 2007), (Arash, 2004) , (Ahsen, 2008), (Carmignani, 2009) , (Carmignani, 2009), (Gabbriellib, 2011), (K.S. Chin A. C., 2008), (Bimal P. Nepal, 2008), (O.P. Gandhi, 1992)
9	The mathematical form adopted for calculating the RPN is strongly sensitive to variations in risk factor evaluations.	(K.S. Chin Y. W., 2009), (Gargama, 2011), (Chang K.-H. , 2009). (Kutlu, 2012), (Zaili Yang, 2008)
10	The RPN elements have many duplicate numbers.	(S.M. Seyed-Hosseini, 2006), (K.H. Chang, 2010), (Gargama, 2011), (P. A. A. GARCIA, 2005). (Prabhu, 2001), (Chang K.-H. , 2009)
11	The RPN considers only three risk factors mainly in terms of safety.	(Carmignani, 2009) (Gabbriellib, 2011) (K.S. Chin Y. W., 2009), (Braglia, 2000), (Hu-Chen Liu L. L.-H.-L.-C., 2011), (Zaili Yang, 2008), (Kuei-Hu Chang and Ching-Hsue Cheng, 2010)

(Hu-Chen Liu L. L., 2013)

3.2 RISK EVALUATION METHODS OF FMEA

The literature done by (Hu-Chen Liu L. L., 2013) proposed a complete classification for the different methodologies used to evaluate the risk. Therefore, our literature will follow the same structure trying to propose more criticality analysis for the most important papers that can enrich our research.

In total, this section reviewed more than seventy scientific paper covered different applications in different domains. The followed framework divides the methods into five main categories, which are multi-criteria decision-making (MCDM), mathematical programming (MP), artificial intelligence (AI), hybrid approaches and others. Each category has been divided into sub-categories as showed in table 3-3.

3.2.1 MCDM approaches

3.2.1.1 ME-MCDM

- (FIORENZO FRANCESCHINI, 2001), presented a multi-expert MCDM (ME-MCDM) technique for carrying out the calculation of the risk priority of failures in FMEA, which is able to deal with the information provided by the design team, normally given on qualitative scales, without necessitating an arbitrary and artificial numerical conversion. The method considered each decision-making criterion as a fuzzy subset over the set of alternatives to be selected. After the aggregation of evaluations expressed on each criterion for a given alternative, the failure modes were determined with the maximum risk priority code (RPC). If two or more failure modes have the same RPC a more detailed selection was provided to discriminate their relative ranking.

3.2.1.2 Evidence theory

- (K.S. Chin Y. W., 2009) **:** Proposed a new FMEA methodology using the group-based Evidential Reasoning approach in order to help in capturing the diversity, incompleteness and uncertainty of information provided by FMEA team members. This methodology allows FMEA team members to independently assess risk factors and express their opinions individually. “It also allows the risk factors to be aggregated in a rigorous yet nonlinear rather than simple addition or multiplication manner.” Moreover, it “includes assessing risk factors using belief structures, synthesizing individual belief structures into group belief structures and aggregating the group belief structures into overall belief structures, converting the overall belief structures into expected risk scores and ranking the expected risk scores using the MRA.”

- (J. Yang, 2011) : In order to integrate the multiple evaluation of the risk done by experts, the paper proposed a modified evidence theory deals which different opinions of the FEMA team and multiple failure modes. It also provides simplified discernment frames according to practical engineering application. “The fused three risk factors are regarded as the discrete random variables. Consequently, the RPN is a function of the discrete random variable. The mean value of RPN is used for the risk priority ranking of failure modes.” A case study of aircraft turbine rotor blades has been used in order to demonstrate the methodology, in which the information of eight failures were evaluated by three different expertise and have been aggregated together. As a result, the risk ranking of the failure modes were consistent with the practical engineering background.

3.2.1.3 AHP/ANP

- (Braglia, 2000) **:** Developed a Multi-attribute failure model analysis (MAFMA) using Analytic Hierarchy Process (AHP) technique in order to help the analyst to formulate more efficient and effective failure priority ranking. The proposed model integrates four factors (chance of failure, chance of non-detection, severity, and expected cost) instead of the three traditional factors proposed by the conventional FMECA.

  The process starts with defining hierarchy form for the decision criteria; the goal in the top, criteria and sub-criteria (on which subsequent levels depend in) the intermediate level and the alternatives at the lowest level. Following, a judgment matrix based on Pairwise Comparison used for weighting the criteria, sub-criteria and alternatives in terms of expected cost attribute. Later on, the overall preference rating is calculating on a scale of from 0.000 to 1.000 with which each decision alternative is likely to achieve its objective.

- (Carmignani, 2009) **:** Making reference to (Braglia, 2000), the paper proposed a priority-cost FMECA (PC-FMECA) in order to exceed some of traditional FMECA method such as; arbitrariness of attribution of the three parameters Severity, Occurrence, Detection, absence of a range of homogeneously distributed values for the RPN, and that the correlation of the RPN to economic aspects in non-safety-critical-cases.

  The proposed method is an original and innovative approach based on a new interpretation of the RPN, on the AHP technique which allowed for new calculation of RPN and the introduction of the new parameter of Profitability taking into consideration the corrective action cost. In particular, the AHP technique has been used to give different weights to traditional parameters such as Severity, Occurrence and Detection. On the other hand, profitability, which is a new parameter based on costs and potential profit to reduce the losses caused by failure occurrence, problem is easily resolvable through an automated equation solver tool and its optimal solution gives the most convenient mix of failures to be repaired compared to the available budget.

- (Allen H. Hua, 2009) **:** Presented a novel framework for a green component risk priority number (GC-RPN) to analyze the risk of green components of Hazardous Substance in compliance with the European Union (EU) the restriction. Applying the fuzzy analytic hierarchy process (FAHP), they determined the relative weightings of four risk factors (Occurrence (O), Detection (D) and Severity (S), which divided into two components, The Declaration Statement (S1) and The Frequency of Green Component Used by Project (S2)). Then the (GC-RPN) is calculated for each one of the components to identify and manage the risks derived from them.

- (Gabbriellib, 2011) **:** The paper urged that (M. Braglia, 2007) HOR model captures only the immediate dependency between two causes and neglected the existence of higher order domino effects, however it was the only approach that tackled the criticism of the interdependency and correlation between the failures in the conventional FMEA. Therefore, the paper proposed ANP/RPN model, which is more comprehensive risk assessment procedure combining FMEA, and ANP. This model enhanced the capability of the conventional FMEA taking into account the possible relationship among the causes of failure. Furthermore, a Pairwise Comparison has been used in order to calculate the RPN. Finally, the paper presented a graphical tool to clarify the results.

3.2.1.4 Fuzzy TOPSIS

- (Marcello Braglia M. F., 2003) **:** proposed a new approach to calculate the risk priority number based on fuzzy version of the technique for order preference by similarity to ideal solution (TOPSIS). They have adopted this technique in order to simplify and enhance the risk assessment procedures in traditional FMECA, taking advantage of the basic idea of TOPSIS that allows measurement of the Euclidean distance of an alternative from an ideal goal. In addition, in order to eliminate the possible errors and uncertainty by directly evaluate the crisp linguistic assessment of FMECA three factors (O, S, D); a fuzzy logic version of TOPSIS has been developed. The benefits of this approach as mentioned in the conclusion are;
  "Introducing a potentially larger number of failure criteria; giving different degrees of importance to the criteria themselves; and making the analysis easier to carry out, due to the possibility of using imprecise data in the form of fuzzy numbers."
  At the end, the paper demonstrated the capability of the methodology to manage a criticality analysis easily through case study, which also confirmed that the proposed approach gave reasonable and robust results using the sensitivity analysis of the fuzzy weights.

3.2.1.5 Grey theory

- (C.L. Chang C. W., 1999) **:** Proposed an approach for RPN calculation using combination of the Fuzzy Method and the Grey Theory. They used the Fuzzy Logic in order to evaluate the FMEA factor levels using linguistic measures, while the Grey used to determine the risk priority of the failures. The conclusion demonstrated three main advantages of this approach as following:

- “The linguistic terms such as ``high'', ``low'' and ``moderate'' can be used to evaluate the degree of occurrence, undetection and severity; this is believed to increase the applicability of FMEA.”
- “The grey relational analysis is capable of assigning relative weight to the decision factors; therefore, the rationality of FMEA can be improved. This is the first attempt to consider the relative importance of factors.”
- “The grey theory can prioritize the potential risks of product or process failures without any utility function, this is also a breakthrough.”

- (Rajiv Kumar Sharma D. K., 2008c) **:** proposed a structured framework that helps in analyzing the system behavior for a maintenance project using fuzzy logic. In addition, the proposed framework included various reliability parameters such as repair time, failure rate, availability, mean time between failures, and expected number of failures. The author concluded that,
  “The application of fuzzy methodology in system failure engineering in general will help the system/reliability analysts to deal with the notion of uncertainty and imprecision related with subjective, imprecise and incomplete information.”

- (Wang, 2003) **:** Proposed methodology for enhancing the conventional FMEA using the Fuzzy Set theory. The proposed methodology has been divided into two main steps. The first step uses fuzzy rule base (without the weighting factors of the linguistic variables) to perform the first step of the formal safety assessment (FSA) process by determining the risk level of failures. Second, The grey theory has been used (with the weighting factors of the linguistic variables) for the second step of the (FSA) process by providing more detailed analysis for each failure in order to provide ranking order determines the allocation of the limited resources.

- (Y. Geum, 2011) **:** Proposed a systematic approach for identifying and evaluating potential service failures using service-specific failure mode and effect analysis (service-specific FMEA) and grey relational analysis. This approach is divided into two main stages; the first one is to construct the service-specific FEMA by identifying the three dimensions: severity, occurrence, and detection. For each dimension, they identify 19 service-specific elements (sub-dimensions) required to evaluate the service system. The aim of this framework is to have a holistic view of the service system and to provide the appropriate decision criteria required to evaluate the failure modes. Following, a calculation for the risk priority number for each failure takes place using grey relational analysis characterized by the multiple criteria decision making in a complicated interrelated situation. The overall framework is shown in figure 3-2

The advantage and the contribution of this paper has been summarized as following: "The contribution of this paper can be summarized in two ways. Firstly, this study incorporates the various service characteristics to the service by introducing the service-specific FMEA, incorporating 3 dimensions and 19 sub-dimensions to represent the service characteristics, thus modifying the traditional FMEA to a more concrete and systematic one. The criteria included in this paper, however, are by no means exhaustive or fixed, but can be customized depending on the context according to the firm. The criteria can be selectively used or aggregated according to the judgment of a firm. Using the service-specific dimensions, managers in practice can get an insight to identify as well as evaluate failure modes. It is also expected to be a guideline for managing service failure in practice. Secondly, from the methodological perspective, this paper contributes to the field in that it combines FMEA and grey relational analysis, addressing the limitations of previous calculations of risk priority, which are too simple to apply in a practical setting. In addition, two-phase grey relational analysis is applied to reflect the multilateral perspective of service, providing the aggregated risk score of each dimension, together with the overall score. Since the service-specific FMEA consists of many inter-related different dimensions, the use of grey relational analysis fits the service-specific FMEA by providing a simple, straightforward, but flexible approach."

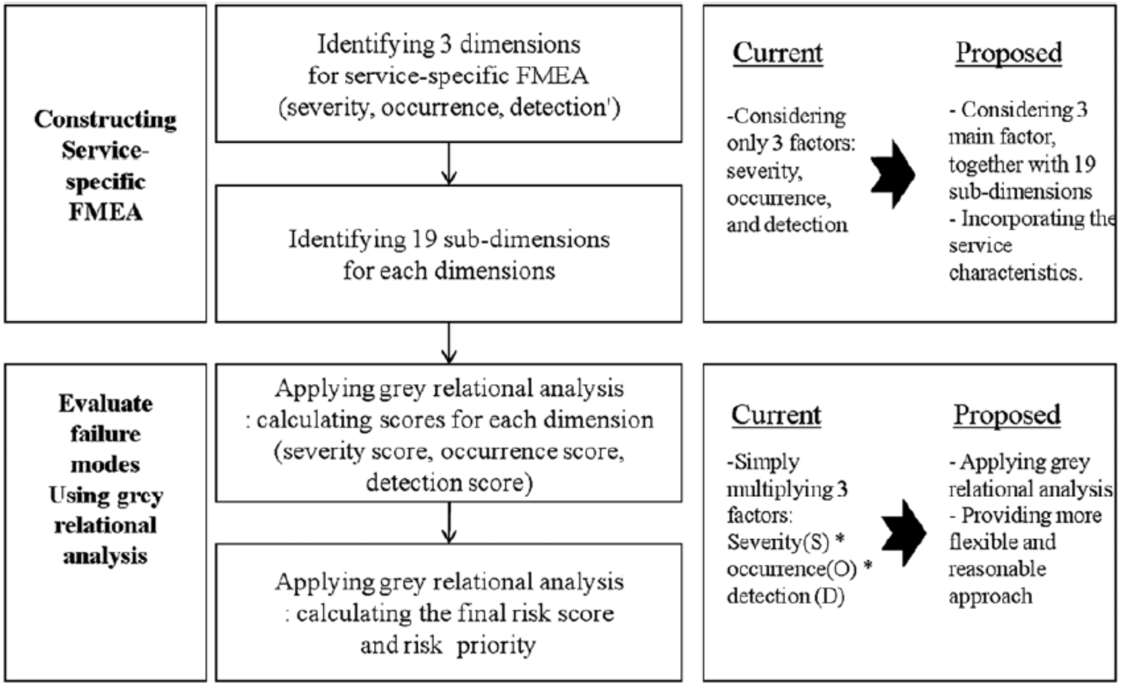

Figure 3-2 ***Service-specific FMEA and grey relational analysis.*** *(Y. Geum, 2011)*

3.2.1.6 DEMATEL

- (S.M. Seyed-Hosseini, 2006) **:** proposed a novel technique named Decision Making Trial and Evaluation Laboratory (DEMATEL) as an effective approach to reprioritize the failure modes by analyzing the relation between system components in respect to its type (direct or indirect) and the severity of effect or influence. To distinguish between the direct and the indirect relation they demonstrated the indirect relation, as

  "A failure mode (that is under effect of a cause of failure) can be cause of other failure mode (s)."

  There are four main advantages of this technique; the consideration of indirect relationships during the analysis, the ability of grouping alternatives in large systems with many failure modes, allocating as possible as a unique rank number to each alternative and the ability to determine the severity relation between an alternative and others.

3.2.1.7 Intuitionistic fuzzy set ranking technique

- (K.H. Chang, 2010) **:** Proposed a new methodology to reprioritization of failure modes in FMECA based on an intuitionistic fuzzy set ranking technique. The main goal of this technique is to reduce the duplicate in the RPN numbers, which make the results more reliable. This technique is very helpful during the design phase of a project as it allows the designer to identify high-risk areas and attain explicit levels of safety through a systematic approach by identifying and implementing ways to reduce failures occurrence and the extent of the respective consequences. By applying the technique in a saline supply system they came up with the following advantages
  - Reduction of duplicate RPN numbers.
  - More flexible and realistic failures information.
  - More accurate and effective information that support decision-making process.
  - An evaluation of redundancy place allows the designer to make correct decisions and to have safer and reliable product design.

3.2.1.8 VIKOR

- (H.C. Liu, 2012) **:** "In this paper an extension of the VIKOR, a recently introduced MCDM method, in fuzzy environment is used to deal with the risk factors and identify the most serious failure modes for corrective actions. The VIKOR method focuses on ranking and selecting from a set of alternatives in the presence of conflicting criteria. It determines a compromise solution that could be accepted by the decision makers. Therefore, a new fuzzy FMEA based on fuzzy set theory and VIKOR method."

3.2.2 *Mathematical programing approaches*

3.2.2.1 Linear programming

- (Ying-Ming Wang, 2009) : Proposed a fuzzy risk priority number (FRPN) to prioritize the failure modes based on alpha-level sets and linear programming models. In addition, the defuzzification procedures used a new centroid formula based on alpha-level sets.

- (Gargama, 2011) **:** Proposed two modified FMEA models to prioritize the failure modes. The first one fuzzy risk priority number (FRPN) has been calculated based on alpha-level sets and the fuzzy extension principles. Instead of the linear programming approach proposed in (Ying-Ming Wang, 2009), they introduced the benchmark adjustment search algorithm to obtain alpha-level sets for FRPN. The second model introduced an approach based on the degree of match and fuzzy rule-base, which will be mentioned later in the literature of the Fuzzy Rule-Based system.

- (Liang-Hsuan Chena, 2009a) and (Liang-Hsuan Chen, 2009b)**:** They urged that however, the determination of the fulfillment levels of design requirements (DRs) and parts characteristics (PCs) in the first two phases of the typical Quality Function Deployment (QFD) process is an important issue, but the existing literature focuses mainly on the design of requirement (DRs). Therefore, the proposed fuzzy nonlinear programming models based on Kano's concept to determine the fulfillment levels of PCs with the aim of achieving the determined contribution levels of DRs in phase 1 for customer satisfaction. In addition, they used Fuzzy FMEA in QFD phase 2 model in order to reduce the design risk and for the risk analysis of (DRs).

3.2.2.2 DEA /Fuzzy DEA

- (P. A. A. GARCIA, 2005) **:** Proposed Data Evolvement Analysis approach (DEA) to rank the failures modes by using the fuzzy set to model the conventional FMEA parameters.

- (Sun, 2009) **:** Also applied (DEA) approach to enhance the FMEA risk assessment capability using the conventional crisp FMEA values (from 1 to 10) instead of fuzzy sets.

- (Kwai-Sang China, 2009) **:** Urged that the model proposed by (P. A. A. GARCIA, 2005) is very complicated and incomplete. Therefore, they proposed an FMEA based on (DEA), which is simpler. The proposed model measures the maximum and the minimum risks of the failures, and the overall risk is measured by the geometric average. Subsequently these averages are used for prioritizing the failure modes. Moreover, the model takes into account the relative importance weights of the risk parameters with a weight restriction on the ratio of maximum weight to minimum weight to avoid the relative importance of any risk factors from being under- or overestimated.

3.2.3 Artificial intelligence approaches

3.2.3.1 Rule-base system

- (Prabhu, 2001) : Proposed modified FMEA with a new technique that prioritize the failure modes. This technique is based on the Risk Priority Ranks (RPRs), which is used to represent the 1000 possible severity-occurrence-detection combination through a rank from 1 to 1000. The failures having higher ranks are given higher priority. The characterization of this system is based on expert knowledge. Therefore, the 1000 possible combinations are tabulated by an expert in order of increasing risk and can be represented in the form of “if-then rules”.

3.2.3.2 Fuzzy rule-base system

- (Peldez, 1995) : Described a new technique based on fuzzy logic to prioritize failures for corrective actions in a FMECA. The technique has two perspectives to assess criticality, first one is based on the conventional numerical raking in FMECA to calculate the RPN using crisp inputs gathered from the user or extracted from a reliability analysis. The second one has been designed for the early design process when less detailed information is available; it allows fuzzy inputs also illustrates the direct use of the linguistic rankings defined for the RPN calculations. The overall process has been described in figure 3-3.

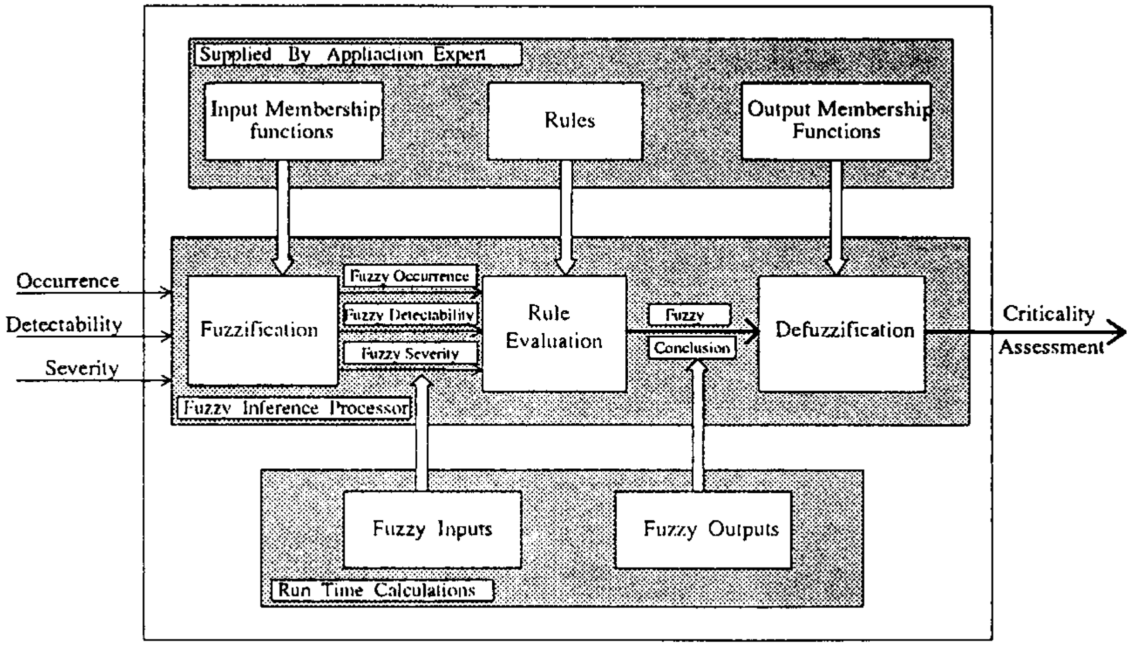

Figure 3-3 ***Overall view of the fuzzy criticality assessment system.*** *(Peldez, 1995)*

- (K. Xu, 2002) **:** The author demonstrated the difficulty to incorporate the interdependencies among various failure modes with uncertain and imprecise information for failure analysis when performing FMEA analysis for quality assurance and reliability improvement. Therefore, they proposed a fuzzy-logic-based method for FMEA to address this issue. They integrated a platform for a fuzzy expert assessment with the proposed system to overcome the potential difficulty in sharing information among experts from various disciplines.

  The general assessment system they used included three main modules based on the fuzzy logic toolbox platform of MATlab. It also includes an expert knowledge-based module and user input/output interference module. This architecture is shown in figure 3-4

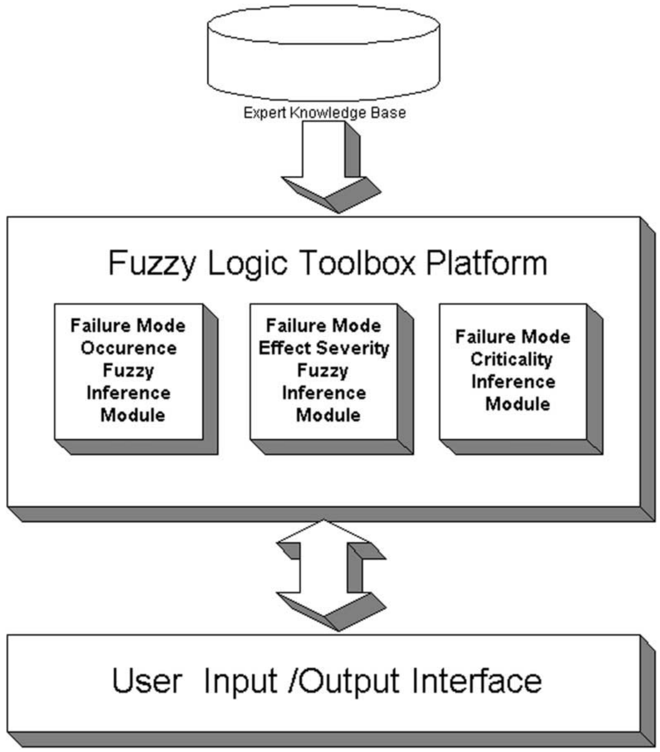

Figure 3-4 ***General assessment system architecture.*** *(K. Xu, 2002)*

A case study of a mechanical diesel engine is used and they concluded with the following advantages:

- As the failure information in FMEA is being described as fuzzy variables, these results are in more realistic and flexible reflection of the real situation.
- The interdependencies among various failure modes and effects can be explored.

- (Dialynas, 2005) **:** Proposed a methodology that applies FMECA based on fuzzy logic for the reliability and prediction of electronic devices. The priority to the criticality of components for the system operations has been defined through a fuzzy failure mode risk index, while a knowledge base is developed to identify the rules governing the fuzzy inputs and output. In addition, they used Madmani fuzzy inference module that uses the min-max implication-aggregation. Moreover, the paper emphasized the importance of farther research efforts for the application of fuzzy modeling techniques in the area of reliability assessment of electronic devices.

- (K.S. Chin A. C., 2008)**:** Demonstrated the contribution of the fuzzy logic and knowledge-based systems in producing products with high quality, low cost and short development time. Therefore, they introduced a framework based on fuzzy FMEA named as the Expert Product Development System (EPDS) as an evaluation approach for a new product concept. The aim of the proposed model is to automate the planning and evaluation intelligently, by integrating multiple domains.

- (Bimal P. Nepal, 2008) **:** Mentioned the importance of taking the system interaction failures emphasized it as the most important gap between the FMEA teamwork and the current FMEA practice, particularly in a complex product like an airplane or an automobile. Therefore, they introduced a framework for interaction FMEA. The aim of the proposed model is to capture interaction failures between various components or modules of product architect. Moreover, the framework consists of three main process modules supported by a database module as shown in figure 3-5. The three main process modules are PA developer, system-level failure modes examiner, and failure modes analyzer; in addition, a database module (SFC) supports the three processes.

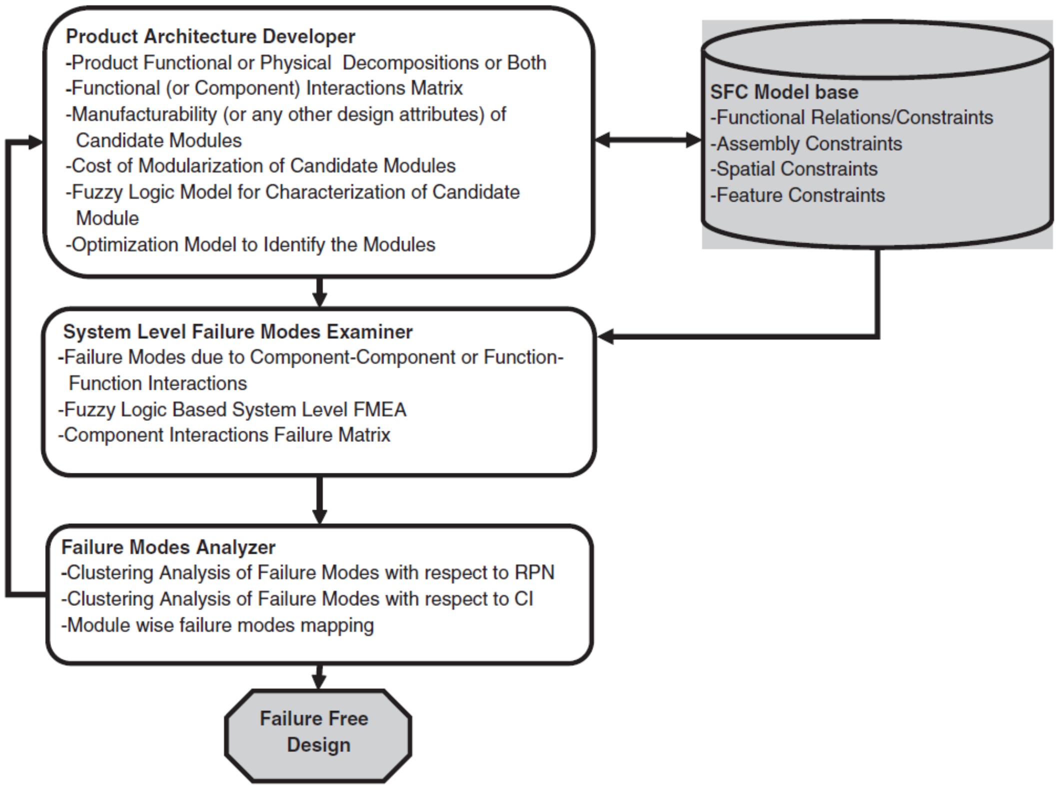

Figure 3-5 ***Proposed product architecture-based framework for failure modes and effects analysis.*** *(Bimal P. Nepal, 2008)*

- (Zaili Yang, 2008) **:** Proposed a novel fuzzy rule-based Bayesian reasoning (FuRBaR) for prioritizing FMEA in order to deal with some of the limitations of the conventional fuzzy logic. The approach assigned subjective belief degrees the consequent part of the rules to model the incompleteness encountered in establishing the knowledge base. Moreover, they aggregated the all-relevant rules for assessing and prioritizing potential failure modes using Bayesian reasoning mechanism.

- (Marcello Braglia M. F., 2003) **:** Proposed a fuzzy based FMECA to support the maintenance activities with a fuzzy criticality assessment model easy to implement and design by using a triangular approach as crisp inputs in fuzzy models to evaluate the different opinions of the maintenance staff. (Lim, 2006a) Proposed a generic method to simplify the fuzzy logic-based FMEA. The author urged that not all the rules are required in the determination of the RPN, therefore, they introduced a guided rules reduction system (GRRS) to regulate the number of rules required during the fuzzy RPN modeling process. As a result, the total number of rules needed have been reduced hence; the fuzzy based FMEA process has been simplified.

- (Wang, 2003)**,** (Rajiv Kumar Sharma D. K., 2005)**,** (Rajiv Kumar Sharma D. K., 2007b)**,** (Rajiv Kumar Sharma D. K., 2007c)**,** (R.K. Sharma, 2007d)**,** (Rajiv Kumar Sharma D. K., 2008c)**,** (Rajiv Kumar Sharma P. S., 2010)**,** (Antonio C.F. Guimarães, 2004_1)**,** (Antonio C.F. Guimarães, 2004_2)**,** (Antonio C.F. Guimarães, 2006)**,** (Antonio C.F. Guimarães, 2007)**,** and (Antonio C.F. Guimarães, 2011)**,** also applied the methodology of Rule Reduction to reduce the total number of roles.

3.2.3.3 Fuzzy ART algorithm

- (Özkan, 2009) : "Applied the fuzzy adaptive resonance theory (Fuzzy ART) neural networks to evaluate RPN in FMEA. In the study, occurrence, severity and detection values constituting RPN value were evaluated separately for each input. RPN values composed inputs and each input in its own was presented as O, S and D to the system. In each case, an input composed of three data (O, S and D) was presented to the system by efficient parameter results obtained from application of FMEA on test problems and similar inputs were clustered according to the three parameters. Finally, arithmetic mean of the input values in each obtained failure class was used for prioritization." (Hu-Chen Liu L. L., 2013)

3.2.3.4 Fuzzy cognitive map

- (C.E. Pela´ez, 1996) : "Applied fuzzy cognitive maps (FCMs) to model the behavior of a system for FMEA. The FCM was a diagram to represent the causality of failures with failure node and causal relation path. The path was described by using linguistic variables such as 'some, always, often' and relative scales were assigned for each term. Then min–max inference approach was used to evaluate the net causal effect on any given node and weighted mean of maximum method was used as defuzzification technique to extract the resulting confidence values on linguistic variables." (Hu-Chen Liu L. L., 2013)

3.2.4 *Integrated approaches*

3.2.4.1 Fuzzy AHP-Fuzzy rule-base system

- (Fayek, 2010) **:** Proposed an extension application of FMEA to risk management in construction industry. They used combination of Fuzzy Logic and Fuzzy Analytical Hierarchy process (AHP) to build their model. In order to avoid the crisp evaluation of the conventional FMEA, they referred the severity (S) to impact (I) with three dimensions: Cost Impact (CI), Time Impact (TI) and Scope Impact (SI). The proposed model as shown in figure 3-6 consists of two main phases. The first phase is concerned with developing the Fuzzy FMEA expert system. As in the conventional FMEA, they used linguistic definitions in order to define the probability of Occurrence (O), Impact (I), the detection level (D), Risk criticality number (RCN). In addition, according to the definitions they define Membership Functions (MFs) for the impact (I), probability of occurrence (O) and for the detection level (D). Later on, they integrated the three dimensions of Severity (S) using Fuzzy Analytical Hierarchy Process (Fuzzy AHP) into a single variable named Aggregated Impact (AI).

  The second phase used to analyze the risks and to provide correction actions. In this phase, they used Work Breakdown Structure Technique (WBS) to breakdown the project into its components and each package analyzed to identify different risk events, and then they defined the level of impact (I) of each risk event on each work package. By defining the root cause of each risk event, they define the probability of occurrence (O) and the detection level (D). Finally, RCN is calculated using the fuzzy expert system. Moreover, the paper introduced a software system entitled "Risk Criticality Analyzer" (RCA) to implement the proposed model.

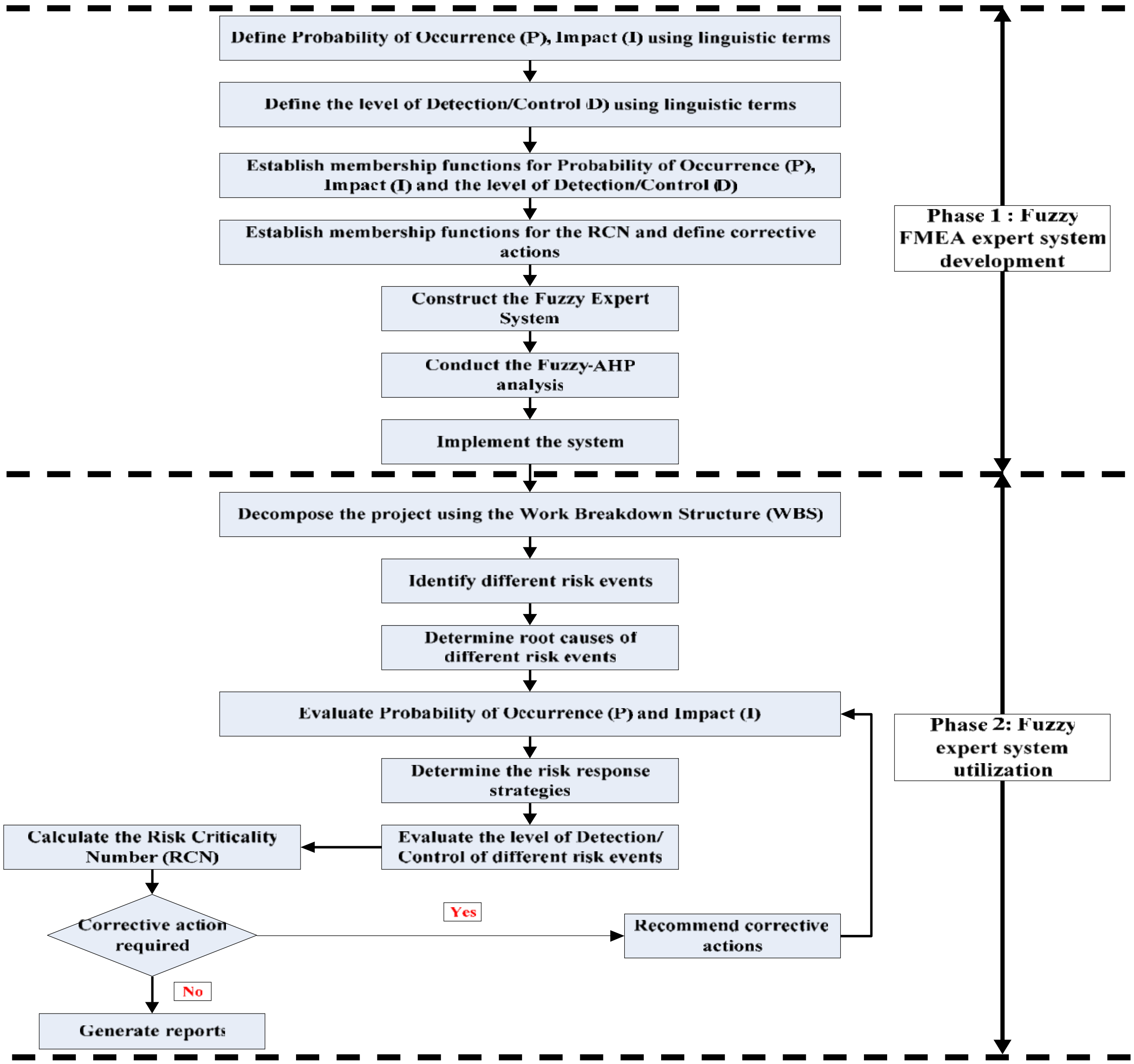

Figure 3-6 ***Framework for applying FMEA in construction using combination of Fuzzy Logic and Fuzzy (AHP)*** *(Fayek, 2010)*

3.2.4.2 WLSM-MOI-Partial ranking method

- (Zhang, 2011) **:** Introduced a new fuzzy RPNs approach for FMEA under uncertainty based on integration between three methods, the first method is the fuzzy weighted least squares model (WLSM) which used to avoid the subjectivity in determining the transformation function by aggregating the decision makers' opinions in multi-granularity linguistic numbers. Secondly, the method of imprecision (MOI) has been incorporated with a nonlinear programming model to fully consider the compensation level among Occurrence (O), Severity (S) and Detection (D) and to perform their calculations. Finally, for the final ranking of the failure modes, a partial order method based on fuzzy preference relations is used in order to enhance the robustness of ranking results.

3.2.4.3 OWGA operator-DEMATEL

- (Chang K.-H. , 2009) **:** Urged that most current FMEA use the traditional RPN however, the conventional methodology does not consider the situation parameter and the relationship between components of a system with respect to its type (direct/indirect) and severity. Therefore, they used more general RPN methodology based on combination of The Ordered Weighted Geometric Averaging (OWGA) operator and The Decision-Making Trial and Evaluation Laboratory (DEMATEL) approach for prioritization of failures in a product FMEA.

3.2.4.4 IFS-DEMATEL

- (Kuei-Hu Chang and Ching-Hsue Cheng, 2010) : Presented a technique combining the intuitionistic fuzzy set (IFS) and DEMATEL approach to evaluate the risk of failure that gave more flexible structure for combining severity, occurrence and detection parameters.

3.2.4.5 Fuzzy OWA operator-DEMATEL

- (Cheng, 2011) **:** Proposed a simplified algorithm to evaluate the failure modes' risks orders. The proposed methodology can utilize fuzzy Ordered Weighted Averaging (OWA) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) approach to rank the risk of failure. This technique provides more flexible combination of FMEA parameters (O, S and D). In addition, the method is to more convenient to differentiate the risk representations among the failure modes that have the same RPN, it is more accurate and more reasonable for helping decision makers find the most critical causes of failure modes and assign limited resources to the most serious risk items.

3.2.4.6 2-tuple-OWA operator

- (Chang K.-H. a.-C., 2010) **:** In order to assess the risk of Color Super Twisted Nematic (CSTN), the paper also proposed a novel technique that combining 2-tuple and the Ordered Weighted Averaging (OWA) operator for prioritization of failures in a product Design Failure Mode Effects Analysis (DFMEA). The purpose of the provided technique is to solve the problem that the conventional RPN does not consider all the information provided by the experts, as there is possibility to lose some of them. The role of the (OWA) operator was to consider the ordered weight that is not considered by the conventional FMEA.

3.2.4.7 FER-Grey theory

- (Hu-Chen Liu L. L.-H.-L.-C., 2011) **:** Demonstrated that the acquirement of FMEA team members' diversity opinions and the determination of risk priorities of the failure modes that have been identified is the most important issue during performing FMEA. This problem refers to the cross-functional and multidisciplinary nature of the provided information. In addition, the other cites the difficulty of incorporating such information either by traditional FMEA or by the Fuzzy logic approach. Moreover, they also demonstrated the problem of the inaccurate RPN of the traditional FME. Therefore, they proposed an FMEA based on Fuzzy Evidential Reasoning approach (FER) and grey theory to solve the two problems.

3.2.4.8 Fuzzy AHP-fuzzy TOPSIS

- (Kutlu, 2012) **:** Proposed a fuzzy approach allows the experts to use linguistic variables to determine the Occurrence (O), Severity (S) and detection (D) by applying fuzzy technique for order preference by similarity to ideal solution (TOPSIS) integrated with fuzzy (AHP). Frist they used the (AHP) method to determine the weight vector of the three risk parameters (O, S and D), and then they utilized a Fuzzy (TOPSIS) in order to obtain the score of the failure modes.

3.2.4.9 ISM-ANP-UPN

- (Chen, 2007) : cited the importance of involving the corrective actions beside the risks measurement while performing FMEA. The author demonstrated this importance by showing up that the corrective actions might be interdependent. Taking advantage of this potential interdependency feature, he explained,

  "If the implementation of these corrective actions is in proper order, selection may maximize the improvement effect, bring favorable results in the shortest times, and provide the lowest cost."

  Therefore, he implemented a new methodology to improve the priority order of FMEA aiming at evaluating the structure of hierarchy and interdependence of corrective action by Interpretive Structural Model (ISM) and then to calculate the weight of a corrective action through the analytic network process (ANP). Finally, he combined the utility of corrective actions and made a decision on improvement priority order of FMEA by utility priority number (UPN).

3.2.5 Other approaches

3.2.5.1 Cost based

- (Gilchrist, 1993) : In this paper the researcher demonstrated the question "Why we should multiply the three main parameters of RPN, (O, S and D), however the *O* and *D* relate to probability in different ways, so there is no logic in either multiplying or adding. The paper mentioned that the score *O* related to probability in a form which is not linear and in fact looks more like 10^{O}. If *D* had a similar relation, the rules for multiplying probabilities would give 10^{O} x 10^{D} = 10^{O+D}.

  The other aspect analyzed by the paper is the RPN ignores the number of items, which are to be produced; it is used to compare the risk to the customer form one item only. Therefore, the paper modified the conventional criticality assessment of FMEA by proposing an expected cost model. The idea was to calculate the expected cost (EC) by knowing the cost of failure (C), the annual production quantity (n), the probability of failure (P_f) and the probability of not detecting the failure (P_d) at the end the criticality assessment index based on cos analyses or the expected cost can be calculated through the formula $EC = C \cdot n \cdot P_f \cdot P_d$.

- (Raouf, 2006) **:** The paper criticized the model proposed by (Gilchrist, 1993) in four points that, the model completely ignores the severity, the probabilities (Pf) and (Pd) are not always independent, it is very difficult to estimate such probabilities and that there is a lot of expertise that goes into the classical FMEA methodology that the new model does not make use of. Therefore, they proposed an improved FMEA model to address the (Gilchrist, 1993) criticisms by giving more importance to the occurrence as it affects the likelihood of a fault reaching the customer. The way they used in order to increase the importance of the occurrence over the detection is taking ratings for the likelihood of the occurrence in a large interval. Moreover, they combined their improved FMEA model with the expected cost model proposed by (Gilchrist, 1993) to provide quality improvement scheme for the production phases of a product or service.

- (Ahsen, 2008) **:** Due to the wrong decisions in terms of company's financial objectives that could be taken by using the conventional FMEA, the authors proposed a cost oriented FMEA in order to prioritizing failures within the procedure of the FMEA. He argued that (Gilchrist, 1993) took into account only two possible cost situations, that the customer detects the fault on delivery of the product and return it under warranty or the customer doesn't spot the failure but will have an accident and sue the company. However, wider range of consequences into account such as faults may entail the cost of repairing or replacing of defective items, decreased profits (if the client does not accept replacement), disruption owing to defective material, and losses of potential future clients and so on. In addition, different customers may react in a variety of ways will be more reliable. Therefore the paper proposed the following model to estimate the cost of faults not detected before delivery:

  $E[C^e] = \sum_r^1 \sum_s^1 P_{rs} \cdot C_{rs}^e$

  Where:

  $\sum_{r=1}^n P_{rs} = 1 \qquad \forall s, with\ s = 1, \ldots, m$

  C^e = Cost of external faults (equivalent to the severity of faults to customers);

E [] = expected value;

C_{rs}^{e} = Cost as consequence of reaction r by customer s;

r = customer reactions because of a fault, with $r = 1, \dots, n$

s = customers, with $s = 1, \dots, m$

P_{rs} = Probability of reaction r by customer s.

Then by multiplying $E[C^e]$ by the product of probability of occurrence and probability of not detecting it before delivery, we obtain a cost-oriented RPN (RPNC^e):

$$\text{RPN}C^e = P(O) \cdot P(\bar{D}|O) \cdot \ E[C^e]$$

Whit: P (O) = probability of occurrence;

$P(\bar{D}|O)$ = Conditional probability of not detecting a fault before delivery.

However, this model calculating a cost-oriented RPN uses an estimation of costs associated with detected external faults to evaluate the severity, but still important proportion of the cost remains neglected that the paper showed in Figure 3-7.

The authors argued that neither conventional FMEA nor (Gilchrist, 1993) took into consideration that internally detected faults may also lead to very substantial failure costs "for example, those of scrapping defective product-waste, the time taken to repair faulty products, material costs to replace defects, disassembling of products, repacking costs and so on". To deal with this problem they proposed a cost oriented FMEA takes into consideration both external and internal cost of faults as following:

$$RPN_c = P(O) \cdot \{P(\bar{D}|O) \cdot E[C^e] + P(D|O) \cdot E\left[C^i\right]\} + P(\bar{O}) \cdot (D|\bar{O}) \cdot E(C^c)$$

Where:

RPN_c= Risk priority number based on cost of detected internal and external faults;

C^e = Cost of externally detected faults.

C^i = Cost of internally detected faults.

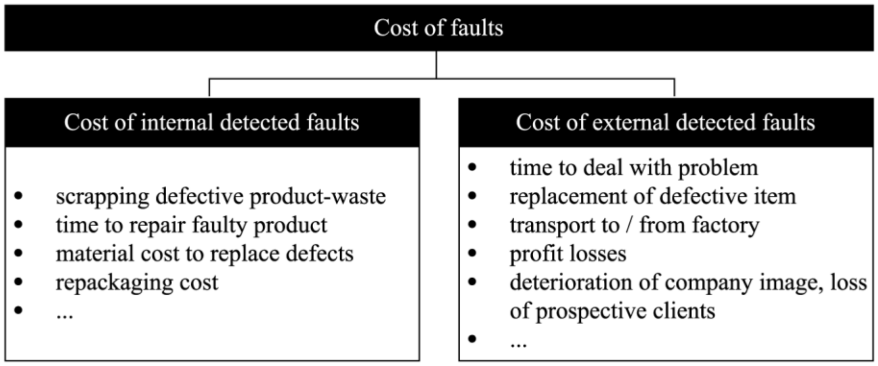

Figure 3-7 ***Cost of faults.*** *(Ahsen, 2008)*

- (Ishii S. K., 2004) **:** one of the roles of conventional FMEA as mentioned by the authors is driving the engineers to improve the reliability of high-risk areas, however this This reliability-centric strategy often adds cost to the system by introducing higher quality components, employing functional redundancy, etc. However, using FMEA allows the team to reduce the operating cost, but still the conventional FMEA practice does not estimate the cost benefit of reliability measures. Moreover, the paper mentioned another cost reduction strategy, which is the design of service, or "serviceability design" which assumes that some failures are unavoidable, so engineers should reduce the cost of service by lessening the cost required for frequent or high-cost service operations.

  Therefore, they used Scenario-based FMEA technique that uses expected failure cost to make decision about whether to make reliability or serviceability investments. The difference between the three strategies, the design improvement strategies of traditional FMEA, serviceability design, and scenario-based FMEA is shown in table 3-2

Table 3-2 ***Comparison of risk-reduction techniques***

Method	Strategy	Failure probability	Cost of Failure	Product Cost	Total cost
Traditional FMEA	Increase reliability	Reduce	No change	Same or increase	?
Design of service	Reduce service and main cost	No change	Reduce	Same or increase	?
Scenario based FMEA	Reduce total cost (failure and product cost)	Cost-based decision	Cost based decision	Cost based decision	Same or lower

(Ishii S. K., 2004)

- (Chensong Dong, 2007) **:** Provide a cost effective failure mode and effects analysis tool to overcome the disadvantages of the traditional FMEA that the cost due to failure is not defined. They used the fuzzy utility theory fuzzy membership functions as a method for this approach for the assessment of severity, occurrence, and detection. It showed through two case studies that the advantage of this approach is that it can take the cost due to failure into account when prioritizing failure modes. The author mentioned that, since the ultimate goal of FMEA is to reduce the cost due to failure, the cost due to failure modes should be the objective for decision-making. The expected cost E(C) due to a failure mode can be expressed as:

$$E(C) = C_{fm}P_{fm}(1 - P_d)$$

Where C_{fm} is the cost due to a failure mode, P_{fm} is the probability of this failure mode and P_d is the probability that this failure will be detected. The previous equation indicates that the expected cost due to failure increases when the failure mode has severer effects, occur more frequently and less possibly to be detected. He considered the severity, occurrence and detection of a failure mode as cost drivers in the utility theory since they determine the failure cost.

- (Ishii S. J., 2003) **:** The paper has been introduced in order to addresses two main shortcomings of the conventional FMEA as mentioned

  "Measuring severity and detection difficulty is very subjective and with no universal scale, RPN is also a product of ordinal variables, which is not meaningful as a proper measure".

  Therefore, they introduce a new methodology, Life Cost-Based FMEA, which measures risk in terms of cost. The usefulness of this methodology is to compare and select design alternatives that can reduce the overall life cycle cost of a particular system. Moreover, they applied a Monte Carlo simulation to the Cost-Based FMEA to account for the uncertainties in: detection time, fixing time, occurrence, delay time, down time, and model complex scenarios.

3.2.5.2 Monte Carlo Simulation

- (Maurizio Bevilacqua, 2000) **:** the aim of this paper is to presents a new tool for failure mode and effect analysis developed for a new Integrated Gasification and Combined Cycle plant in an important Italian oil refinery. In order to choose the best maintenance policy for each planet in the project, integration between a modified Failure Mode Effective and Criticality analysis (FMECA) and Monte Carlo simulation as a method for testing the weights assigned to the measure of the risk priority numbers (RPNs).

  Regarding to the complexity of the electrical power plant based on Integrated Gasification and Combined Cycle (IGCC) technology.

  The RPN proposed consists of a weighted sum of six parameters (safety, machine importance for the process, maintenance costs, failure frequency, downtime length, and operating conditions) multiplied by a seventh factor (the machine access difficulty). These parameters have been chosen as the most important factors from the all-relevant parameters that can contribute to the machine criticality.

  In order to calculate the relative importance of the weight of the six attributes, a Pairwise Comparison has been executed. Later, a Monte Carlo simulation adopted to obtain simultaneous changes of the weights and to generate final RPN ranking results that can be easily analyzed statistically. At the end the benefit of this model as mentioned in the analyzed paper is that, "The random weight model is useful in that it helps the decision maker focus on the best alternative, regardless of the relative importance attached to the attributes. By using the importance rank order and the weight simulation, we are able to identify a subset of critical machines that are consistently (and statistically) ranked above the other facilities."

3.2.5.3 Minimum cut sets theory (MCS

- (N.C. Xiao, 2011) **:** The purpose of this paper is to extend the work done by (Karsten Pickard, 2005) which provided model assesses the impact of multiple failure modes. The idea of the proposed method of (Karsten Pickard, 2005) was to evaluate the system reliability taking into account multiple failure modes simultaneously, which is out of conventional FMEA scope. (N.C. Xiao, 2011) Urged that (Karsten Pickard, 2005) only described how to combine multiple failure modes into a single mode without details about which multiple failures should be combined, moreover the unclear overflow during the combination as well. Therefore, (N.C. Xiao, 2011) proposed a method named the linear interval mapping to resolve the overflow problem. Furthermore, they introduced minimum cut sets and WRPN to characterize the importance of the failure causes or components by multiplying a weight parameter.

3.2.5.4 Boolean representation method (BRM)

- (J. Wang, 1995) **:** The proposed model combines Failure Mode, Effective and criticality analysis (FMECA) and the Boolean Representation Method (BRM) using an inductive bottom-up risk identification and estimation methodology. The methodology is useful where the failure modes analysis is associated to multiple state variables and feedback loops are involved.

3.2.5.5 Digraph and matrix approach

- (O.P. Gandhi, 1992): presented a method for FMEA of mechanical and hydraulic systems based on a digraph and matrix approach. A failure mode and effects digraph, derived from the structure of the system, was used to model the effects of failure modes of the system and, for efficient computer processing, matrices were defined to represent the digraph. A function characteristic of the system failure mode and effects was obtained from the matrix, which aids in the detailed analysis leading to the identification of various structural components of failure mode and effects. An index of failure mode and effects of the system was also obtained.

3.2.5.6 Kano model

- (Arash, 2004) **:** The main purpose of this paper is to provide a novel approach to overcome one of the major limitations of traditional FMEA that, severity rates are determined only with respect to organization's point of view, not according to its customers. Therefore, Kano model has been used as an advanced evaluation technique for customer satisfaction/dissatisfaction and it has been integrated with FMEA to make it customer oriented aimed at enhancing FMEA capabilities.

  The paper classified the severities according to customers' perceptions to evolve the current approaches for determination of severity and "risk priority number" (RPN), which supports the nonlinear relationship between frequency and severity of failure. In addition, the paper proposed a new index called "correction ratio" (Cr) to assess the corrective actions in FMEA.

  In addition, the case study in the paper highlighted the gap between managers and customers in prioritizing a set of failures and the difference between RPN and Cr prioritizations, caused by target failure frequencies. The proposed approach enables managers/designers to prevent failures at early stages of design, based on customers who have not experienced their products/services yet.

  Moreover, the new integrated approach is critical to the success of FMEA. FMEA is a live document and should always be modified in the light of new information or changes. Besides the time-consuming limitation of the Kano questionnaire, one of the benefits the new approach will provide is the dynamic mechanism of the Kano model, based on its moving styles and changing quality categories over time.

3.2.5.7 Quality functional deployment (QFD)

- (M. Braglia, 2007) **:** This paper proposed a novel structure methodology for performing build-in reliability (BIR) investigation during a new product development cycle. It represents an extension of the Quality Functional Deployment/House of Quality (QFD/HoQ) concepts to reliability studies. Moreover, it is able to translate the reliability requisites of customers into functional requirements for the product in a structured manner based on a Failure Mode and Effect Analysis (FMEA). A completely new operative tool named House of Reliability (HoR) has been designed to enhance standard analysis, introduce the most significant correlations among failure modes.

  The tool formally follows formally follows the structure and shape of the well known "house of quality" with rooms and roof, however its goals are deeply different. The goal was developing a new, self-standing and operative tool able to bring both the voice of customer and the voice of engineer closer together during a full product development program.

  The authors concluded that this tool enables users to finely analyses failure modes by splitting severity according to the product typology and the importance of each Severity criterion according to laws or international standards. In addition, the methodology is able to consider the "domino effects" and so to estimate the impact of the correlation between the causes of failure.

- (Tan, 2003) **:** Has also integrated QFD and FMEA.

3.2.5.8 Probability theory

- (Sant'Anna, 2012) **:** proposed a method, derived from numerical evaluations on the criteria of security, frequency and detectability, of Failure Modes and Effects Analysis (FMEA), a probabilistic priority measure for potential failures; and to evaluate the use of this method when combined with subjective evaluations to decide on improvement actions. The proposed method is based on treating the numerical initial measurements as estimates of location parameters of probability distributions, which, allows for objectively taking into account the uncertainty inherent in such measurements and to compute probabilities of each potential failure being the most important according to each criterion. These probabilities are then combined into a global quality measure, which can be interpreted as a joint probability of choice of the potential failure.

According to the case study, the author concluded that the changed proposed were stable, also the thresholds levels proposed for the discretization of the probabilistic scores shown to be able to allow for an efficient combination with experts' evaluations.

Table 3-3 ***classification of the risk evaluation methods in FMEA***

NO.	Categories	Approach	Literature	Total No.
1	MCDM (22.50%)	ME-MCDM	(FIORENZO FRANCESCHINI, 2001)	1
		Evidence theory	(K.S. Chin Y. W., 2009), (J. Yang, 2011)	2
		AHP/ANP	(Braglia, 2000), (Carmignani, 2009), (Allen H. Hua, 2009) (Gabbriellib, 2011)	4
		Fuzzy TOPSIS	(Marcello Braglia M. F., 2003)	1
		Grey theory	(C.L. Chang C. W., 1999), (C.L. Chang P. L., 2001) (Rajiv Kumar Sharma D. K., 2008c), (R.K. Sharma, 2007d), (Wang, 2003), (Y. Geum, 2011)	6
		DEMATEL	(S.M. Seyed-Hosseini, 2006)	1
		Intuitionistic fuzzy set ranking technique	(K.H. Chang, 2010)	1
		VIKOR	(H.C. Liu, 2012)	1
2	Mathematical programming (8.75%)	Linear programming	(Ying-Ming Wang, 2009), (Gargama, 2011), (Liang-Hsuan Chena, 2009a), (Liang-Hsuan Chen, 2009b)	4
		DEA /Fuzzy DEA	(P. A. A. GARCIA, 2005), (Sun, 2009), (Kwai-Sang China, 2009)	3
3	Artificial intelligence (40.00%)	Rule-base system	(Prabhu, 2001)	1
		Fuzzy rule-base system	(Peldez, 1995), (K. Xu, 2002), (Dialynas, 2005), (K.S. Chin A. C., 2008), (Bimal P.	

			Nepal, 2008), (Wang, 2003), (Zaili Yang, 2008), (Gargama, 2011), (Marcello Braglia M. F., 2003), (Lim, 2006a), (Rajiv Kumar Sharma D. K., 2005), (Rajiv Kumar Sharma D. K., 2007b), (Rajiv Kumar Sharma D. K., 2007c), (R.K. Sharma, 2007d), (Rajiv Kumar Sharma D. K., 2008c), (Rajiv Kumar Sharma P. S., 2010), (Antonio C.F. Guimarães, Effects analysis fuzzy inference system in nuclear problems using approximate reasoning, 2004_1), (Antonio C.F. Guimarães, 2004_2), (Antonio C.F. Guimarães, 2006), (Antonio C.F. Guimarães, 2007), (Antonio C.F. Guimarães, Fuzzy methodology applied to Probabilistic Safety Assessment for digital system in nuclear power plants, 2011)	26
		Fuzzy ART algorithm	(Özkan, 2009)	1
		Fuzzy cognitive map	(C.E. Pela´ez, 1996)	1
4	Integrated approaches (11.25%)	Fuzzy AHP-Fuzzy rule-base system	(Fayek, 2010)	1
		WLSM-MOI-Partial ranking method	(Zhang, 2011)	1
		OWGA operator-DEMATEL	(Chang K.-H. , 2009)	1
		IFS-DEMATEL	(Kuei-Hu Chang and Ching-Hsue Cheng, 2010)	1

		Fuzzy OWA operator-DEMATEL	(Cheng, 2011)	1
		2-tuple-OWA operator	(Chang K.-H. a.-C., 2010)	1
		FER-Grey theory	(Hu-Chen Liu L. L.-H.-L.-C., 2011)	1
		Fuzzy AHP-fuzzy TOPSIS	(Kutlu, 2012)	1
		ISM-ANP-UPN	(Chen, 2007)	1
5	Other approaches (17.50%)	Cost based model	(Gilchrist, 1993) , (Raouf, 2006), (Ahsen, 2008), (Ishii S. K., 2004), (Chensong Dong, 2007), (Ishii S. J., 2003)	6
		Monte Carlo simulation	(Maurizio Bevilacqua, 2000)	1
		Minimum cut sets theory (MCS)	(N.C. Xiao, 2011)	1
		Boolean representation method (BRM)	(J. Wang, 1995)	
		Digraph and matrix Approach	(O.P. Gandhi, 1992)	1
		Kano model	(Arash, 2004)	1
		Quality functional deployment (QFD)	(M. Braglia, 2007), (Tan, 2003)	2
		Probability theory	(Sant'Anna, 2012)	1

(Hu-Chen Liu L. L., 2013)

3.3 CRITICALITY ANALYSIS AND FINDINGS:

In this paper, ninety-three journal articles, conference proceedings, and other sources, which were proposed in the period between 1980 and 2014 discussing FMEA methodology from different aspects have been analyzed in order to:

- Present the purpose, the importance, the types, and the procedures of the conventional FMEA.
- Analyze the use of FMEA in the construction industry; importance, different methodologies used and possibility of implementation.
- Highlight the major shortcomings of the conventional FMEA.
- Identify the different methodologies and approaches used to tackle the traditional FMEA problems.

Observations and findings: based on the previous literature, some observations are highlighted in the following subsection.

3.3.1 Construction industry

Due to the complexity of the construction projects in terms of (system, subsystem, components, cost, time…etc.) and subsequently the complexity of the risk assessment, many systems (OHSAS 18001, OHS, ISO 14001, ISO 9001…etc.) and tools (CASPAR, PERET, JRAP…etc.) have been implemented in order to assess risk and assure safety.

Although FMEA has not been invented to assess the risk in the construction, it has been used in some construction project as a risk assessment tool, but in a small scale. On the contrary of the manufacturing authors, who used several approach to modify FMEA in order to tackle the conventional criticisms, the majority of the construction authors used the conventional FMEA in their projects without major modification. However, some other construction authors, such as (Fayek, 2010), (Amir Mohammadi, 2013), (Marcello Braglia M. F., 2003), (Rajiv Kumar Sharma D. K., 2008c), used the fuzzy logic to for a modified FMEA framework. Also (Maurizio Bevilacqua, 2000) used Monte Carlo Simulation to Integrated Gasification and Combined Cycle plant.

This lack of research can be dedicated to the difficulties of applying FMEA in the construction domain. (Fayek, 2010) Demonstrated these difficulties as following:

- "In order to implement an effective FMEA at each stage of the project life cycle, the up-front allocation of resources is required, which is not always feasible in the construction industry.
- The identification of the potential risk events at each stage in the project life cycle is another challenge, since many root causes may interact to cause the risk event to occur."

In the other hand (Fayek, 2010) provided some suggestions in order to overcome such difficulties:

- "Organizations need to create a risk-based culture in each functional area within the organization.
- The life cycle cost analysis can be used to demonstrate the potential cost savings that can be gained by applying FMEA to the risk assessment of an organization's projects. Buy-in to the benefits of applying FMEA by top management is crucial to the successful implementation of this technique."

Therefore, an advanced and serious future research should take place in order to enhance the application of FMEA in the construction industry in a proper way.

3.3.2 The most used risk evaluation methods

Regarding the proposed literature and as mentioned in the study of (Hu-Chen Liu L. L., 2013), the category of method most frequently applied to tackle the criticisms of the conventional FMEA is the Artificial Intelligence category which almost represents 40.0% of the reviewed papers. The next one is the MCDM category that represents (22.50%), then the Other Approaches by (17.50%), then the Integrated Approaches by (11.25%) and finally the Mathematical Programming by (8.75%). Figure 3- shows this statistics. Moreover, Fuzzy rule-base system is the most frequently used methodology (around 26 papers) followed by grey theory (6 papers), cost based model (6papers), AHP/ANP (4 papers) and linear programming (4 papers).

In fact, using Fuzzy rule-based system in a high frequency is not an arbitrary choice; this approach has many advantages that have been summarized by (Hu-Chen Liu L. L., 2013) as following:

- "Ambiguous, qualitative or imprecise information, as well as quantitative data can be used in criticality/risk assessment and they are handled in a consistent manner.
- It permits to combine the occurrence, severity and detectability of failure modes in a more flexible and realistic manner.
- It allows the failure risk evaluation function to be customized based on the nature of a process or a product.
- The fuzzy knowledge-based system can fully incorporate engineers' knowledge and expertise in the FMEA analysis and substantial cost savings can thus be realized."

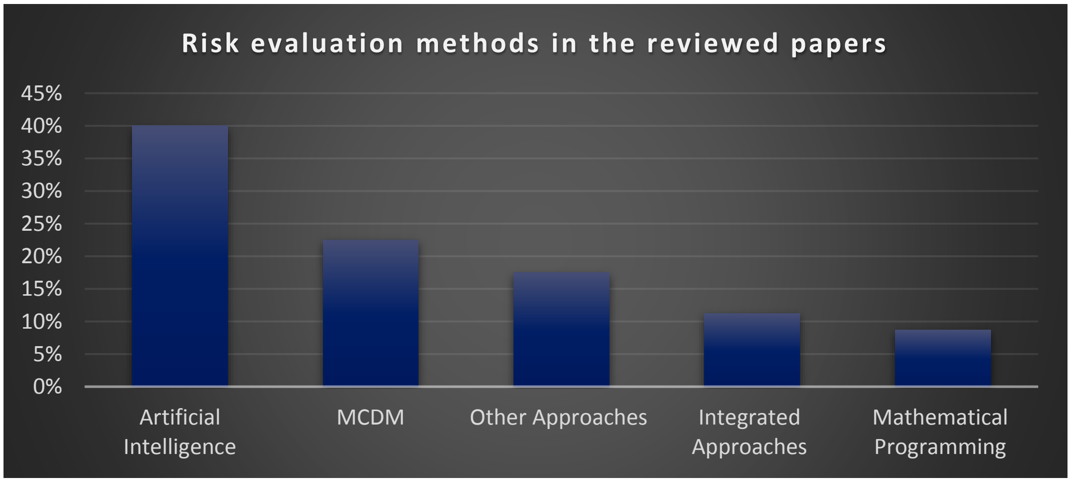

Figure 3-8 ***Risk evaluation methods in the reviewed papers.*** *(Hu-Chen Liu L. L., 2013)*

3.3.3 Limitations of approaches

Despite the advantages of the reviewed methodologies, still there are many limitations regarding them as following:

- Most of the methodologies use linguistic evaluation for the criticality parameters, which provide uncertainty and variety in the experts' provided information.
- There is no complete methodology that can precisely evaluate the risk with 100 percent confidence.
- The proposed methodologies have different aspects, thus we cannot assume that one single methodology is valid for the whole cases.

- Most of the methodologies lake the simplicity of the conventional FMEA, some methodologies are very complex and need huge effort and collaboration.

As mentioned in the above subsection, the Fuzzy role based is the most common methodology; therefore, it is important to specifically mention its limitations as proposed by (Hu-Chen Liu L. L., 2013):

- "It suffers from the combinatorial rule explosion problem, which causes the fuzzy RPN model often has a large number of rules.
- The larger the number of rules provided by the experts, the better the prediction accuracy of the fuzzy RPN model.
- The construction of a fuzzy if-then rule base is not an easy task, which requires experts to make a vast number of judgments and will be highly costly and time-consuming.
- The fuzzy if-then rules with the same consequence but different antecedents are unable to be distinguished from one another.
- As a result, the failure modes characterized by these fuzzy if-then rules will be unable to be prioritized or ranked.
- It is difficult to deal with complex calculations for producing "precise" risk results without losing too much information in the process of fuzzy inference.
- It is difficult to design appropriate software packages to realize the instant communication between risk input and output, and failure priority ranking."

3.3.4 Suggestions for future researches

Finally yet importantly, based on the reviewed literature, to mention some suggestions for future researches from our point of view, which also considered as our research motivation to implement our new methodology:

- The most visible limitation of the conventional FMEA is using only three criticality factors in order to evaluate a failure mode; therefore, it is more reliable to use criticality factors in the evaluation process. This will broaden the effectiveness of FMEA.

- In order to reduce the occurrence of duplicate RPN numbers, using different weights for the criticality factors is very important.
- The future researches should take into account the relationship among failure modes; this will play an essential role in identifying better corrective actions.
- It is crucial to consider the long-term aspect when analyzing the failure mode behavior.
- Using simple methodologies instead of complex ones will protect one of the main advantages of the conventional FMEA, the easy use.

4 COMPOSITE FMEA FOR RISK ASSESSMENT IN THE CONSTRUCTION PROJECTS

4.1 INTRODUCTION

Despite the wide use of FMEA as a risk assessment tool aiming at improving the safety and the reliability of a system, process, service...etc., the conventional FMEA cannot precisely assess the risk complexity in construction projects. The traditional approach of FMEA takes into consideration only three factors (Occurrence, Severity and Detection) in order to calculate the criticality of a failure mode through the Risk Priority Number, which is the product of the multiplication of the three factors.

This simple assessment is not enough for construction projects, which can be affected by huge number of factors such as cost, scope, time, material availability, reliability…etc. In addition, the conventional FMEA does not take into consideration the interdependency effect of the failures, which is crucial in construction domain.

Therefore, and based on the above objectives and research motivation, we are introducing a new approach named Composite FMEA (COMP-FMEA) based on the integration of the Failure Mode and Effective Analysis with the Method of Pairwise Comparison and Markov Chain methodology. The proposed methodology consists of three main stages. First, understanding the system, mission, scope and operations. Also in this stage, the hierarchical level at which the analysis take place is identified. Second, the calculation of a Weighted Risk Priority Number (WRPN) based on selection of the most significant parameters that may affect the project (Criticality Factors) which, together combined to create the severity. These criticality factors vary according to the project characteristics and importance.

Third, two correction factors are introduced, the first one named Reprioritization Correction Factor (RCF), which has been designed based on the concept of Markov Chain to correct the possible mistakes of having inadequate information given by the experts during the first stage. It gives the user possibility to identify the risk level of each failure mode in the steady state of the project (Equilibrium Stage). The second one named Interdependence Correction Factor (ICF), which has been designed to identify the effect of the interdependence among different failure modes or risks in different system levels. Figure 4-1 shows the framework of the proposed methodology.

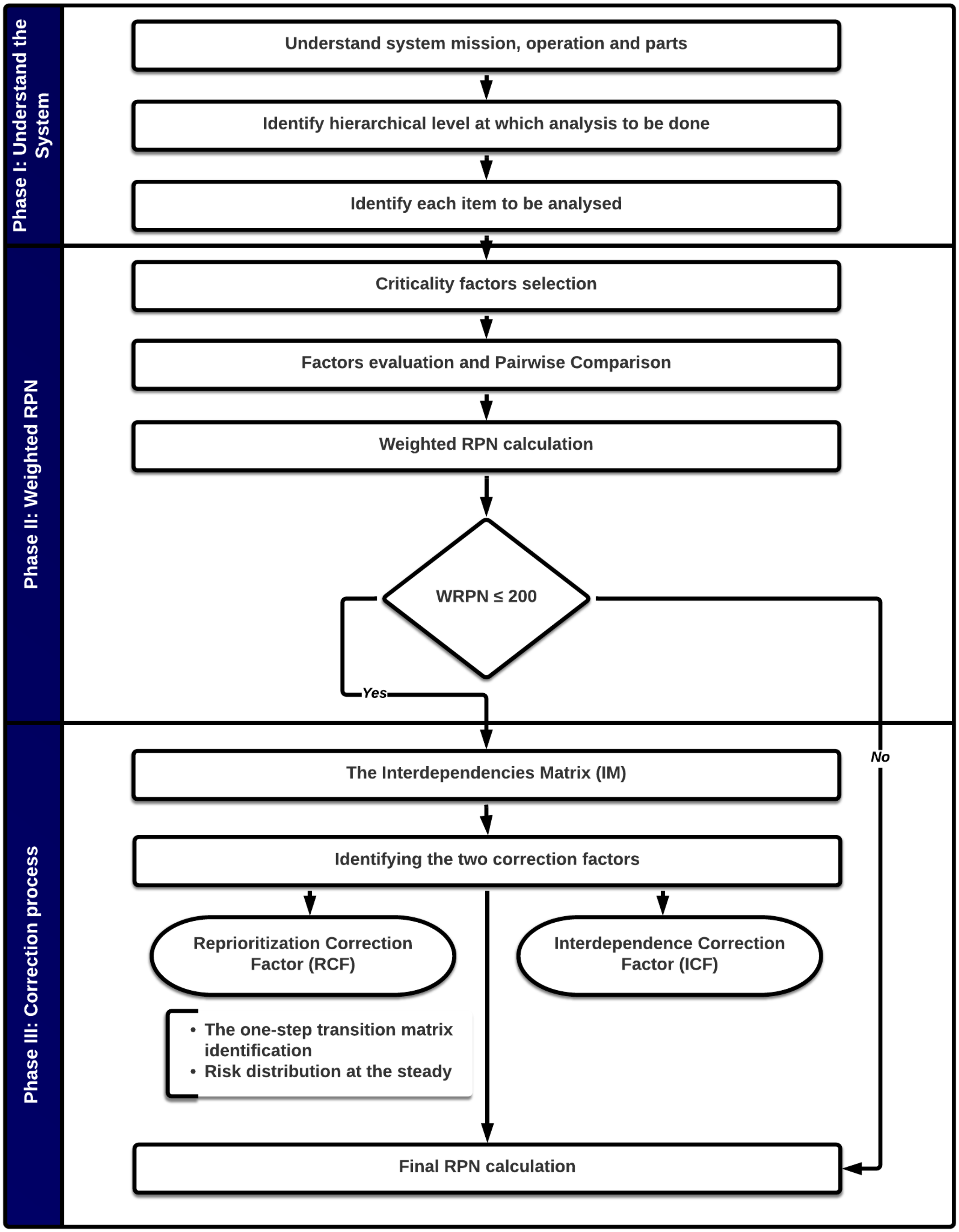

Figure 4-1 ***Composite FMEA framework***

4.2 THE USED METHODOLOGIES

Before demonstrating our proposed Composite FMEA framework, it is important to highlight the used methodologies. The proposed methodology integrates three main methodologies; the conventional FMEA, the Pairwise Comparison and Markov Chain process. The second chapter has demonstrated the conventional FMEA in details being the core of the proposed research. Therefore, the following two sub-sections will provide short review on the Pairwise Comparison and Markov Chain.

4.2.1 Pairwise Comparison

The method of Pairwise Comparison has proposed by Marie Jean Antoine Nicolas de Caritat, Marquisde Condorcet (1743/1794). The Methodology was explicitly designed to satisfy the fairness criterion called the Condorcet Criterion. The Condorcet Criterion addresses the fairness of declaring a candidate the winner even though some other candidate won all possible head-to-head matchups. With the Method of Pairwise Comparisons, any candidate who wins all possible head-to-head matchups always has a higher point total than any other candidate and thus is declared the winner.

It is a kind of divide-and-conquer problem-solving method. It allows one to determine the relative order (ranking) of a group of items. Generally refers to any process of comparing entities in pairs to judge which of each entity is preferred, or has a greater amount of some quantitative property. The method of Pairwise Comparison is used in the scientific study of preferences, attitudes, voting systems, social choice, public choice…etc.

The usefulness of this methodology in the proposed research is the possibility of evaluating a certain project based on several factors; this can give COMP-FMEA methodology a customized and flexible characteristic, which is required for the fluctuated nature of the construction projects.

Section 4.4.3.1 gives a brief explanation of how to use the method of the Pairwise Comparison in the proposed Composite FMEA.

4.2.2 Markov Chain

Markov Chain was introduced by Andrei Andreyevich Markov and was named in his honor. A Markov process is a sequence of stochastic events (based on probabilities instead of certainties) where the current state of a variable or system is independent of all past states, except the current (present) state. Movements of stock/share prices, and growth or decline in a firm's market share, are examples of Markov Chains.

Markov Chain can be described as the follows: We have a set of states, S = [S_1, S_2… S_T. The process starts in one of these states and moves successively from one state to another. Each move is called a step. If the chain is currently in state S_i, then it moves to state S_j at the next step with a probability denoted by P_{ij}, and this probability does not depend upon which states the chain was in before the current state.

The probabilities P_{ij} are called transition probabilities. The process can remain in the state it is in, and this occurs with probability P_{ii}.

An initial probability distribution, defined on S, specifies the starting state. Usually this is done by specifying a particular state as the starting state.

The tool is very useful in COMP-FMEA methodology as it gives the user the possibility of calculating the future probabilities of a certain failure to move from a specific risk status to another using the transition matrix.

Further details of how to use Markov Chain in the Composite FMEA are specified at section 4.5.

4.3 Phase (I): Understand the system

The first phase in the proposed model is the same as any conventional FMEA application. It is very important and crucial to understanding the system and the scope before using the methodology.

There are four fundamental steps in order to understand the system as follows:

- **Understanding the application scope:** the most important step in the proposed methodology, as well as the conventional FMEA, is to define the scope of the application. It is very important for the team to decide from which perspective the tool will be used (Design, Safety, Maintenance, etc.)

- **Understanding the system's mission, operation and parts:** this step has to give the teamwork clear and complete idea about the mission, the sequence and the structure of the operations and the different parts and components of the system or the project.

  The teamwork should consist of experts from several aspects in order to remove the possible conflicts among different subsystems or activities.

- **Identify hierarchical level at which analyses to be done:** it is important to choose the type of the FMEA whither, system, process, or design FMEA; this makes the decomposition process easier and reliable. In the other hand, this step aims at better understanding of the entire system; obviously, the decomposition of the system into its basic parts will make it easier to identify the possible parts that can cause failures for a specific part or for the whole part of the system. Fig 4-2 shows and example of the system decomposition.

- **Identify each item to be analyzed:** after the complete understand of the system, the teamwork has to decide which critical items have a potential to be a risk or a failure cause, thence, the teamwork has to analyze these items in order to identify the potential risks or failure modes.

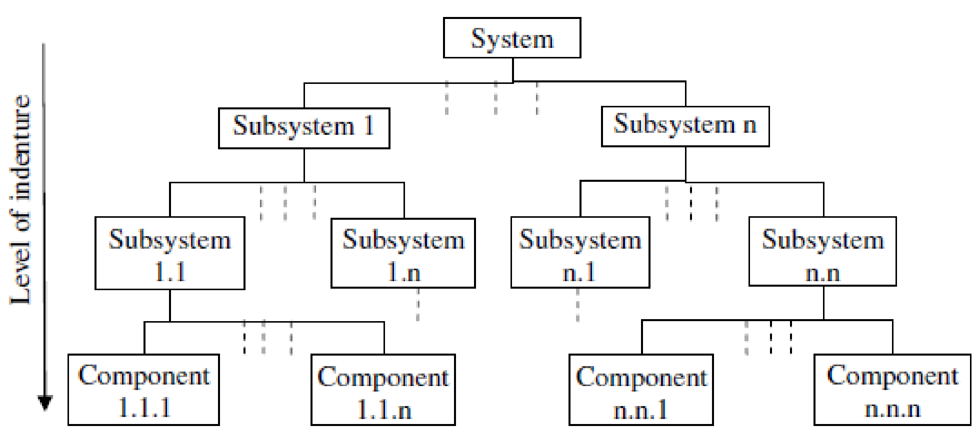

Figure 4-2 ***Typical example of FMEA hierarchy.*** *(Chew, 2011)*

4.4 Phase (II): The Weighted Risk Priority Number (WRPN)

4.4.1 Criticality factors selection

As mentioned in the introduction, the parameters affect construction project cannot be limited into only three parameters. Therefore, it is more reliable to split the conventional FMEA's severity factor into several factors. This can clearly describe whether the severity of a failure mode coms from cost, time, safety, scope, etc. depending on the project characteristics and scope. In addition, these factors should have different importance weights, which will be defined later on using the method of Pairwise Comparison.

Based on that, the project team should identify a list of the criticality factors that are significant for the project and at the same time, describe the severity. This list can vary from project to another according to its characteristics and importance, obviously having the same parameters for a nuclear plant and residential house is not logical.

4.4.2 Guideline for choosing and evaluating the criticality factors

The user can define the criticality factors and subsequently the evaluation criteria, depending on the project nature, scope, and goal. Once the criticality factors list has been defined, and by using the same logic of the conventional FMEA, each factor should be divided into several linguistic classes (Very High, High, Moderate, Low and Very Low) that follow scale of (from 1 to 100) showing the different criticality levels. This evaluation must be done by experts and should be described through tables.

Table 4-1, 4-2, 4-3, and4-5 provide a guideline for the evaluation criteria for four main criticality factors the Safety, the Time, the Cost and the Scope.

Table 4-1 **The safety factor evaluation guideline.**

Safety		
Rating	**Effect**	**Severity of effect**
100	Hazardous without warning	Very High severity ranking when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulations without warning

90	Hazardous with warning	Very High severity ranking when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulations with warning
80	Very high	Vehicle/item inoperable, with loss of primary function
70	High	Vehicle/item operable, but at reduced level of performance. Customer dissatisfied
60	Moderate	Vehicle/item operable, but comfort/convenience item(s) inoperable. Customer experiences discomfort
50	Low	Vehicle/item operable, but comfort/convenience item(s) operable at reduced level of performance. Customer experiences some Dissatisfaction
40	Very low	Cosmetic defect in finish, fit and finish/squeak or rattle item that does not conform to specifications. Defect noticed by most customers
30	Minor	Cosmetic defect in finish, fit and finish/squeak or rattle item that does not conform to specifications. Defect noticed by average customer
20	Very minor	Cosmetic defect in finish, fit and finish/squeak or rattle item that does not conform to specifications. Defect noticed by discriminating customers
10	None	No effect

(Wang, 2003), (K.S. Chin A. C., 2008), (K.S. Chin Y. W., 2009), (S.M. Seyed-Hosseini, 2006), (Y.M. Wang, 2009)

Table 4-2 **The cost factor evaluation guideline.**

Cost		
Rating	**Effect**	**Severity of effect**
90-100	Very high	≥ 10% of project cost.
70-90	High	Cost increase is ≥ 7% and < 10% of project cost.
50-70	Moderate	Cost increase is ≥ 4% and < 7% of project cost.
30-50	Low	Cost increase is ≥ 1% and < 4% of project cost.
10-30	Very low	< 1% of project cost.

(Fayek, 2010)

Table 4-3 **The time factor evaluation guideline.**

Time		
Rating	**Effect**	**Severity of effect**
90-100	Very high	In service date delayed ≥ 10% of project duration.
70-90	High	In service date delayed ≥ 7% and < 10% of project duration.
50-70	Moderate	In service date delayed ≥ 4% and < 7% of project duration.
30-50	Low	In service date delayed ≥ 1% and < 4% of project duration.
10-30	Very low	Insignificant schedule slippage.

(Fayek, 2010)

Table 4-4 **The scope factor evaluation guideline.**

Scope		
Rating	**Effect**	**Severity of effect**
90-100	Very high	Project scope or quality does not meet business expectations.
70-90	High	Scope changes or quality are unacceptable to project sponsor.
50-70	Moderate	Major areas of scope or quality are affected.
30-50	Low	Few areas of scope or quality are affected.
10-30	Very low	Scope change is not noticeable/quality degradation is not noticeable.

(Fayek, 2010)

4.4.3 Pairwise Comparison and Weighted RPN

In order to determine the criticality factors weight (α), which indicate its influence in the overall project; a simple Pairwise Comparison (two factors at one time) has been adopted. A relative scale (from 1 to 9) is used to define the relative attribute importance as shown in figure 4-3

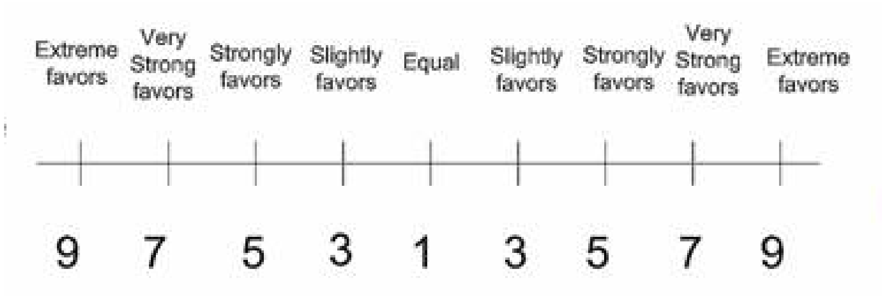

Figure 4-3 ***Relative scale to determine the criticality factors weight (α)***

The next step is to develop a comparison matrix shown in table 4-1. In this matrix, the diagonal members are always equal to one. To fill the other square of the matrix we start with the upper triangular matrix that has to be filled as following:

- If the judgment value is on the left side of figure 4-3, we put the actual judgment value.
- If the judgment value is on the right side of figure 4-3, we put the reciprocal value.

The below comparison triangular matrix should be filled by the reciprocal values of the upper diagonal.

Table 4-5 ***Comparison matrix***

	F_1	F_2	F_3	F_i	Priority	Rank
F_1						
F_2						
F_3						
F_i						

After the comparison matrix has been developed, a priority vector is calculated, which is the normalized components of the right eigenvector of the final matrix corresponding to the maximum eigenvalue of the same matrix. Then, based on the priority vector the rank can be assigned to the criticality factors.

Finally, in order to evaluate the goodness of the judgment, inconsistency ratio (I_R) should be defined as shown by (Saaty, 1990) as following:

$$I_R = \frac{CI}{RI} \quad (2)$$

Where: $CI = Consistency\ Index\ for\ an\ n\ x\ n\ matrix$

$RI = The\ corresponding\ average\ random$

$$\text{CI} = \frac{\lambda_{max} - n}{n - 1} \quad (3)$$

Where: λ_{max} = *the maximum eigenvalue of the matrix.*

n= Number of comparisons

RI Is defined by (Saaty, 1990) as shown in table 4-6, and judgments can be considered acceptable if $I_R \leq 0.1$, if the value is > 0.1 the inconsistent matrix is immediately repeated.

Table 4-6 **The corresponding average random**

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	1.49

At this moment, a Weighted RPN can be calculated through the following formula:

$$WRPN = O_i \times ((F_1 \times \alpha_1 + F_2 \times \alpha_2 + F_3 \times \alpha_3 + \cdots F_i \times \alpha_i)/10) \times D_i \quad (4)$$

Where: $O_i = Failure\ occurrence$

$F = Criticality\ Factor\ Score$

$i = Number\ of\ Criticality\ factors$

$\alpha = Criticality\ Factor\ Weigh$

$D_i = Detection$

The Occurrence and Detection follow the conventional FMEA scale presented in tables 2-1 and 2-3.

4.5 PHASE (III): CORRECTION PROCESS:

4.5.1 Reprioritization correction factor (RCF)

The Reprioritization Correction Factor (RCF) has been designed in order to correct the possible mistakes of having inadequate information given by the experts during the first phase. It assists the failure or the risk in the long term by determining the risk level of each failure mode/risk in the steady state of the project (Equilibrium Stage).

There are two steps to determine (RCF) as follows.

4.5.1.1 Identifying the One-step Transition Matrixes:

At this step, the failure modes are grouped based on the WRPN into five main risk groups regarding table 4-7.

Table 4-7 ***Failure modes grouping***

MRPN	Group	Legend
0<RPN≤50	Very low risk	
50<RPN≤150	Low risk	
150<RPN≤200	Medium risk	
200<RPN≤300	High risk	
RPN> 300	Very high risk	

Then, a re-evaluation process takes place for failures with WRPN less than or equal to (200) by identifying the probability of each risk to move from one risk level in the first stage (Pre-construction stage) to another one in the second stage (Early construction stage) of the project, respectively. The results should be set in the table 4-8.

Table 4-8 ***The Failure Risk Matrix***

		Second Stage assessment (Early stage)					
First stage assessment (Pre-construction stage)	Risk level	Very low	Low	Medium	High	Very high	TOTAL
	Very low	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{IT}
	Low	P_{21}	P_{22}	P_{23}	P_{24}	P_{25}	P_{2T}
	Medium	P_{31}	P_{32}	P_{33}	P_{34}	P_{35}	P_{3T}
	High	P_{41}	P_{42}	P_{43}	P_{44}	P_{45}	P_{4T}
	Very High	P_{51}	P_{52}	P_{53}	P_{54}	P_{55}	P_{5T}
	TOTAL						

Hence, the one-step transition probability can be defined as P Matrix.

$$P = \begin{bmatrix} \frac{P_{11}}{P_{1T}} & \frac{P_{12}}{P_{1T}} & \frac{P_{13}}{P_{1T}} & \frac{P_{14}}{P_{1T}} & \frac{P_{15}}{P_{1T}} \\ \frac{P_{21}}{P_{2T}} & \frac{P_{22}}{P_{2T}} & \frac{P_{23}}{P_{2T}} & \frac{P_{24}}{P_{2T}} & \frac{P_{25}}{P_{2T}} \\ \frac{P_{31}}{P_{3T}} & \frac{P_{32}}{P_{3T}} & \frac{P_{33}}{P_{3T}} & \frac{P_{34}}{P_{3T}} & \frac{P_{35}}{P_{3T}} \\ \frac{P_{41}}{P_{4T}} & \frac{P_{42}}{P_{4T}} & \frac{P_{43}}{P_{4T}} & \frac{P_{44}}{P_{4T}} & \frac{P_{45}}{P_{4T}} \\ \frac{P_{51}}{P_{5T}} & \frac{P_{52}}{P_{5T}} & \frac{P_{53}}{P_{5T}} & \frac{P_{54}}{P_{5T}} & \frac{P_{55}}{P_{5T}} \end{bmatrix} \qquad (2)$$

4.5.1.2 Risk probability at the steady state:

"Suppose the Markov Chain model of project risks is ergodic. Namely, the risk distribution at each risk level remains constant after a long enough time." (Sujiao, 2009).

The probabilities of the failures to be in a certain risk level (risk distribution) in the steady state of the project are described as a steady state vector, which can be defined as follows: Let the risk distribution at the steady state $\mathbf{V^{(SS)} = (V_1, V_2, V_3, V_4, V_5)}$, since the project risks are modeled by an ergodic Markov Chain, we obtain

$$V^{ss} = V^{ss} \times P \qquad (3)$$

Hence, by solving the previous equation using a MATlab model or an spreadsheet we can come up with steady state vector **V** $^{(SS)}$ which gives probabilities of a certain failure mode to be very low, low, medium, high or very high risky in the steady state of the project (the risk distribution).

Since we are looking for the failures with high or very high-risk level in the steady state of the project, the RCF will depend on the summation of the probability of being high and very high in the steady state.

$$P_{H,VH} = V_4 + V_5 \quad (4)$$

Based on the probability of the failure to be High or Very High in the steady state of the project ($P_{H,VH}$), the Reprioritization Correction Factor (RCF) can be set as in table 4-9.

Table 4-9 ***Reprioritization correction factor (RCF)***

$P_{RH,VH}$	RCF
< 30 %	1
30 % < P < 50%	2
50%-70%	3
70%-90%	4
90%-100%	5

4.5.2 Interdependence Correction Factor (ICF)

The Interdependence Correction Factor (ICF) has been designed to take into account the effect of the interdependency of different failures that is neglected by the conventional FMEA. It is also dedicated to the failures with WRPN less than or equal to (200). The research assumptions assumed that the effect of the interdependency might be more significant in the case when a certain failure has a probability higher than 40% to be a cause of another failure, thus if the probability is less than 40%, the interdependency effect shall be neglected. However, the 40% probability is not a rigid value and it could be redefined after getting results from the real application of COMP-FMEA in several projects.

The first step of determining the Interdependence Correction Factor (ICF) is to define the Interdependencies Matrix (IM). The aim of this matrix is to define the effect of each failure mode on the other failure modes. Therefore, the experts shall define the relationships between the different failure modes in different levels (subsystems, or components) by identifying the probability of a certain failure to be a cause of the other failures. Figure 4-4 shows the Interdependencies Matrix.

	The probability of a certain failure to be a cause of the other failures					
Failure	**F_1**	**F_2**	**F_3**	**F_4**	**…**	**F_i**
F_1	0	P_{12}	P_{13}	P_{14}	…	P_{1i}
F_2	P_{21}	0	P_{23}	P_{24}	…	P_{2i}
F_3	P_{31}	P_{32}	0	P_{34}	…	P_{3i}
F_4	P_{41}	P_{42}	P_{43}	0	…	P_{4i}
…	…	…	…	…	0	…
F_i	P_{i1}	P_{i2}	P_{i3}	P_{i4}	…	0

Figure 4-4 ***the Interdependencies Matrix***

Hence, for each failure the ratio between the number of the probabilities higher than or equal 40 % and the total number of failures, which is the Failure Impact Ratio (FIR), can be calculated. This ratio represents the effect of each failure on the other failures (the network of interdependencies effect). Hence, a second correction factor can be set as in table 4-11.

$$FIR = \frac{\text{No. of probabilities } \geq 40\%}{Total \text{ No. of failures} - 1} \tag{8}$$

Table 4-10 ***Interdependence Correction Factor (ICF)***

FIR	ICF
0-10 %	1
10-20%	2
20-30%	3
30-40%	4
40-50 %	5
50-60 %	6
60-70 %	7
80-90 %	8
90-100 %	9

Finally, a final RPN calculated as follows:

$$RPN = \max(WRPN \times CF_1; WRPN \times CF_2) \ \leq 1000 \qquad (9)$$

It is also important to mentions that the values of the proposed correction factors shown in tables 4-9 and 4-10, have been defined based on the prediction of the outcomes, and in order to clarify that concept a very simple example is presented as follows:

Suppose a certain failure has a WRPN equal to 50, $P_{RH,VH} = 60\%$ and FIR equal to 80%, the correction process should move it from being very low risky failure to higher risk category as follows:

- The $P_{RH,VH}$ shows that this certain failure has 60% probability to become high and very high risky failure. Therefore, the WRPN should be multiplied by a value that give a reasonable final RPN in order to move this failure to higher risk category, table 4-9 suggested this value to be 3 and hence the final RPN equal to 150, which indicates medium risky failure.
- Using the same logic, the FIR shows that this failure would be a cause of 80% of the other failures with a probability higher than 40%, which means that because of its possible effect on the other failures, it has to be moved to higher risk category as well. Table 4-10 suggested that the WRPN shall be multiplied by 8 to have a final RPN equal to 400, which indicates very high risky failure.

However, the values presented in tables 4-9 and 4-10 could be redefined based on the best practice and the results coming from real application in several projects.

5 CASE STUDY

5.1 INTRODUCTION

This Chapter provides the criticality analysis and results of a residential building case study used to validate the proposed methodology.

5.2 RESIDENTIAL BUILDING CASE STUDY

5.2.1 Introduction

In order to validate the proposed methodology in an easy and understandable way, a simple residential building, which is the basic case for a construction project has been chosen.

The starting point was a meeting conducted with a group of five experts at the participating organization in order to choose a suitable system. Due to the lack of time, the group has chosen a simple residential building, which will be analyzed from a civil engineering perspective. Therefore, most of the proposed failure modes are structural failures.

The strategy of the work was to analyze the case using three methodologies as follows

- The Risk Rating Matrix Methodology, which is the most common methodology in the similar projects.
- The Conventional FMEA.
- The Composite FMEA.

Subsequently a result criticality analysis and comparison took place by the author.

5.2.2 System identification

As a starting point for the three methodologies, the team has defined the system as a simple residential building that can be broken-down into the following eight subsystems, noted that there is no need to divide the subsystems into components as the failure modes can be assigned to the subsystems level.

1. Foundation.
2. Retaining wall.
3. Slab on grade.

4. Columns and cores.
5. Beams and slabs
6. Structural materials
7. Loads.
8. Serviceability and UG Concrete.

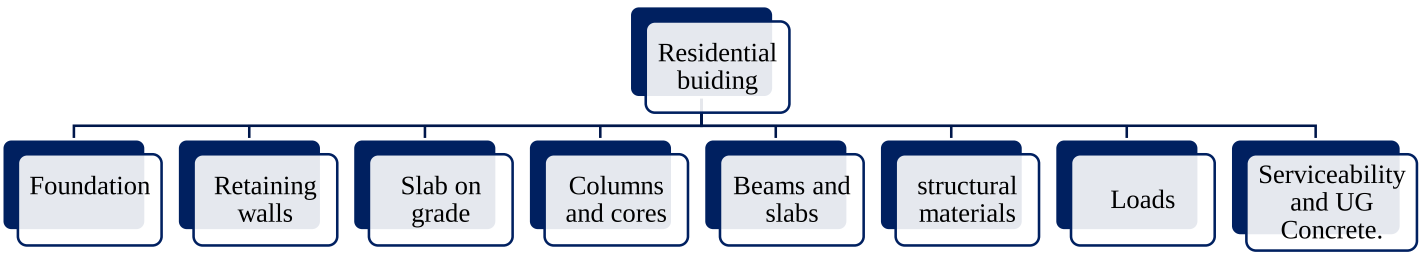

Figure 5-1 ***Residential building case hierarchical structure***

5.2.3 Failure modes identifications

In total, forty-five failure modes have been defined for the entire case. The experts have divided the proposed failure modes into two groups, failures due to design stage and failures due to construction stage. Moreover, and for each failure, a failures description and a potential risk have been defined to understand the effect of each failure mode on the overall system. Table 5-1 shows the defined failure modes assigned to the different subsystems.

Table 5-1 ***The defined failure modes- Residential Building Case.***

S-S	No.	Ref.	Description	Failure	Stage
Foundation	F1	F 1.1	Insufficient Investigation of soil	Foundation Failure	Design
	F2	F 1.2	Faulty foundation	Failure of structure	Construction
	F3	F 1.3	Inadequate foundation	Excessive deformation and settlements in Building	Construction
	F4	F 1.4	Improper bearing capacity	Foundation failure	Construction
	F5	F 1.5	Hard rains, wrong assessment bearing capacity, defective design	Ground settlement	Construction
	F6	F 1.6	Unforeseen ground conditions (extent, type)	Foundation fail	Construction
	F7	F 1.7	Subsidence at surface	Soil arch eventually collapses	Construction
	F8	F 1.8	Improper design of grating (water network)	Structure damage/collapse	Design
	F9	F 1.9	Improper water height considerations	Water tank wall cracks	Design
Retain Walls	F10	F 2.1	Improper soil investigation	Excessive deformations and proper failure	Concept
	F11	F 2.2	Improper design for stability (e.g.: Sliding, overturning)	Excessive deformations and proper failure	Design

	F12	F 2.3	Inadequate information of water table	Retaining wall failure	Design
	F13	F 2.4	Insufficient steel used in retaining walls	Shear / flexural crack	Construction
Slab on Grade	F14	F 3.1	Improper calculation of design loads on slab on grade	Excessive deformation and apparent cracks	Design
	F15	F 3.2	Improper selection of contraction and expansion joints	Excessive deformation and apparent cracks	Construction
Beams & Slabs	F16	F 4.1	Improper limits of design	Slab collapse	Design
	F17	F 4.2	Slab collapse	Injury	Construction
	F18	F 4.3	Improper steel binding & shortage of steel	Slab collapse	Construction
	F19	F 4.4	Improper selection & proportion of materials required	Slab collapse	Design
	F20	F 4.5	Improper supports required to hold the slab while casting	Slab collapse	Construction
	F21	F 4.6	Improper workman ship	Slab collapse	Construction
	F22	F 4.7	Inadequate calculation of Deflection criteria, Gravity Deflection & Wind Drift	Excessive deformations that affects serviceability	Design
Columns and Cores	F23	F 5.1	Improper steel design for columns	Columns failure	Design
	F24	F 5.2	Improper calculation of design loads	Columns failure	Design

	F25	F 5.3	Improper calculation of columns dimensions	Columns failure	Design
	F26	F 5.4	Improper plotting of columns	Conflict with architectural and remedial works should take place	Construction
	F27	F 5.5	Inadequate design of load bearing elements and lateral stability of the structure against the lateral loads such as wind loads.	Structure collapse	Design
Structural Materials	F28	F 6.1	Improper selection of materials to be used in construction	Structure collapse	Construction
	F29	F 6.2	Improper grade of design	Structural elements failure	Design
	F30	F 6.3	Improper selection & proportion of materials required	Structural elements failure	Design
	F31	F 6.4	Improper execution as per design & materials standards	Structural elements failure	Construction
	F32	F 6.5	Inadequate selection of Concrete Classes	Structural elements failure	Design
	F33	F 6.6	Inadequate type of cement selection	Structural elements failure	Design
	F34	F 6.7	Inadequate selection of reinforcement	Structure collapse	Construction
Loads	F35	F 7.1	Inadequate information in terms of the purpose of the structure, as well as the scope and complexity of the project	Structure collapse	Construction
	F36	F 7.2	Improper calculation of design loads	Structure collapse	Design

	F37	F 7.3	Improper design of gravity and lateral loads	Structure collapse	Design
	F38	F 7.4	Inadequate calculation of wind loads	Structure collapse/injury	Design
	F39	F 7.5	Inadequate calculation of earthquake loads	Structure collapse/injury	Design
	F40	F 7.6	Inadequate calculation of strength requirements	Structure collapse/injury	Design
	F41	F 7.7	Inadequate calculation of fire rating	Structure collapse/injury	Design
Serviceability & UG Concrete	F42	F 8.1	Inadequate calculation of Deflection criteria, Gravity Deflection & Wind Drift	Excessive deformations that affects serviceability	Design
	F43	F 8.2	Unforeseen ground conditions (extent, type)	Foundation fail	Construction
	F44	F 8.3	Water seepages or improper water proofing standards	Structure damage/collapse	Construction
	F45	F 8.4	Inadequate information of water table	Structure damage/collapse	Design

Legend:

S-S: Sub-System.

5.2.4 The application of the Risk Rating Matrix

The Risk Rating Matrix is considered as the most common risk assessment tool in the construction projects because of its easiness and simplicity. The evaluation criteria in the Risk Rating Matrix simply depends on two factors; the Risk (R), which presents the chance of happening and the Likelihood (L), that presents the worst case outcome. Table 5-2 and Fig 5-2 show the evaluation criteria for this methodology.

Table 5-2 ***Risk Rating Matrix-Residential Building Case.***

RISK (chance of happening) R	LIKELIHOOD (worst case outcome) L
1. Minor (no first aid required).	1. Improbable (unlikely to happen).
2. Harmful (minor first aid).	2. Remote (small chance happening).
3. Critical (lost time injury, damage).	3. Occasional (likely to happen).
4. Severe (serious injury, damage).	4. Probable (certain to happen).
5. Catastrophic (fatality, explosion).	5. Frequent (will happen).

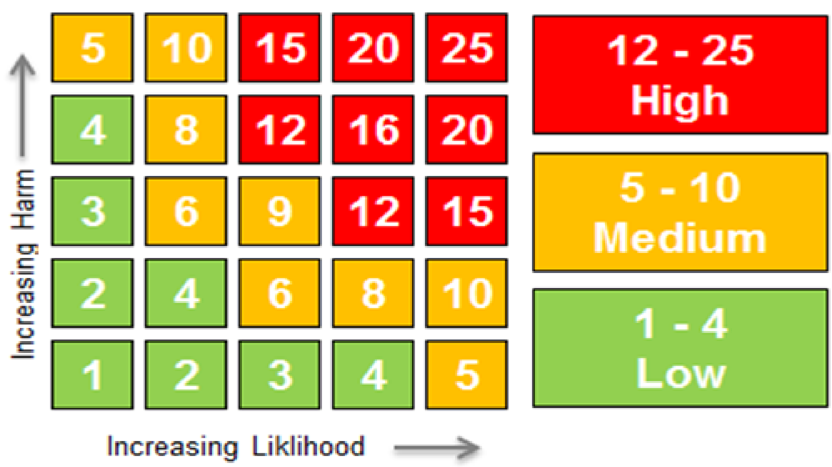

Figure 5-2 ***Risk Rating Matrix***

5.2.5 The application of the conventional FMEA

The main purpose of applying the conventional FMEA in this case, is to compare the results with the other two methodologies also it gives a clear idea on how crisp are the results coming out from applying the conventional FMEA in a construction project.

The evaluation followed the conventional FMEA framework by defining the Occurrence, Severity and the Detection of each failure using Tables 2-1, 2-2, and 2-3. Subsequently the RPN has been calculated for each failure. Table 5-3 shows the used risk grouping criteria in the conventional FMEA application.

Table 5-3 ***Conventional FEMA failures grouping-Residential Building Case.***

RPN	Group	Legend
0<RPN≤50	Very low risk	
50<RPN≤150	Low risk	
150<RPN≤200	Medium risk	
200<RPN≤300	High risk	
RPN> 300	Very high risk	

The results of the application of the two methodologies are shown in table 5-4

Table 5-4 ***Results from Risk Rating Matrix and Conventional FMEA-Residential Building Case***

						Conventional FMEA				Risk Rating Matrix		
S-S	**No.**	**Ref.**	**Description**	**Failure**	**Stage**	**O**	**S**	**D**	**RPN**	**R**	**L**	**RN**
Foundation	F1	F 1.1	Insufficient Investigation of soil	Foundation Failure	Design	6	8	7	336	4	3	12
	F2	F 1.2	Faulty foundation	Failure of structure	Construction	6	10	7	420	5	3	15
	F3	F 1.3	Inadequate foundation	Excessive deformation and settlements in Building	Construction	6	8	7	336	4	3	12
	F4	F 1.4	Improper bearing capacity	Foundation failure	Construction	8	6	6	288	3	4	12
	F5	F 1.5	Hard rains, wrong assessment bearing capacity, defective design	Ground settlement	Construction	6	6	4	144	3	3	9
	F6	F 1.6	Unforeseen ground conditions (extent, type)	Foundation fail	Construction	6	6	7	252	3	3	9
	F7	F 1.7	Subsidence at surface	Soil arch eventually collapses	Construction	6	6	7	252	3	3	9

	F8	F 1.8	Improper design of grating (water network)	Structure damage/collapse	Design	4	6	6	144	3	2	6
	F9	F 1.9	Improper water height considerations	Water tank wall cracks	Design	2	6	10	120	3	1	3
Retain Walls	F10	F 2.1	Improper soil investigation	Excessive deformations and proper failure	Concept	6	6	7	252	3	3	9
	F11	F 2.2	Improper design for stability (e.g. Sliding, overturning)	Excessive deformations and proper failure	Design	6	6	7	252	3	3	9
	F12	F 2.3	Inadequate information of water table	Retaining wall failure	Design	6	6	7	252	3	3	9
	F13	F 2.4	Insufficient steel used in retaining walls	Shear / flexural crack	Construction	8	6	7	336	3	4	12
Slab on Grade	F14	F 3.1	Improper calculation of design loads on slab on grade	Excessive deformation and apparent cracks	Design	2	8	10	160	4	1	4
	F15	F 3.2	Improper selection of contraction and expansion joints	Excessive deformation and apparent cracks	Construction	2	6	10	120	3	1	3
Beams & Slabs	F16	F 4.1	Improper limits of design	Slab collapse	Design	6	8	7	336	4	3	12
	F17	F 4.2	Slab collapse	Injury	Construction	6	8	7	336	4	3	12

	F18	F 4.3	Improper steel binding & shortage of steel	Slab collapse	Construction	6	8	7	336	4	3	12
	F19	F 4.4	Improper selection & proportion of materials required	Slab collapse	Design	6	8	7	336	4	3	12
	F20	F 4.5	Improper supports required to hold the slab while casting	Slab collapse	Construction	6	10	7	420	5	3	15
	F21	F 4.6	Improper workman ship	Slab collapse	Construction	4	10	6	240	5	2	10
	F22	F 4.7	Inadequate calculation of Deflection criteria, Gravity Deflection & Wind Drift	Excessive deformations that affects serviceability	Design	4	10	6	240	5	2	10
Columns and Cores	F23	F 5.1	Improper steel design for columns	Columns failure	Design	4	6	6	144	3	2	6
	F24	F 5.2	Improper calculation of design loads	Columns failure	Design	4	6	6	144	3	2	6
	F25	F 5.3	Improper calculation of columns dimensions	Columns failure	Design	6	6	7	252	3	3	9
	F26	F 5.4	Improper plotting of columns	Conflict with architectural and remedial works should take place	Construction	4	6	6	144	3	2	6

	F27	F 5.5	Inadequate design of load bearing elements and lateral stability of the structure against the lateral loads such as wind loads.	Structure collapse	Design	6	6	7	252	3	3	9
Structural Materials	F28	F 6.1	Improper selection of materials to be used in construction	Structure collapse	Construction	2	8	10	160	4	1	4
	F29	F 6.2	Improper grade of design	Structural elements failure	Design	6	8	7	336	4	3	12
	F30	F 6.3	Improper selection & proportion of materials required	Structural elements failure	Design	8	6	6	288	3	4	12
	F31	F 6.4	Improper execution as per design & materials standards	Structural elements failure	Construction	6	10	4	240	5	3	15
	F32	F 6.5	Inadequate selection of Concrete Classes	Structural elements failure	Design	6	8	7	336	4	3	12
	F33	F 6.6	Inadequate type of cement selection	Structural elements failure	Design	4	6	6	144	3	2	6
	F34	F 6.7	Inadequate selection of reinforcement	Structure collapse	Construction	4	8	6	192	4	2	8

Loads	F35	F 7.1	Inadequate information in terms of the purpose of the structure, as well as the scope and complexity of the project	Structure collapse	Construction	2	8	10	160	4	1	4
	F36	F 7.2	Improper calculation of design loads	Structure collapse	Design	6	8	7	336	4	3	12
	F37	F 7.3	Improper design of gravity and lateral loads	Structure collapse	Design	6	8	7	336	4	3	12
	F38	F 7.4	Inadequate calculation of wind loads	Structure collapse/injury	Design	4	6	6	144	3	2	6
	F39	F 7.5	Inadequate calculation of earthquake loads	Structure collapse/injury	Design	4	8	6	192	4	2	8
	F40	F 7.6	Inadequate calculation of strength requirements	Structure collapse/injury	Design	6	8	7	336	4	3	12
	F41	F 7.7	Inadequate calculation of fire rating	Structure collapse/injury	Design	4	6	6	144	3	2	6
Serviceability & UG Concrete	F42	F 8.1	Inadequate calculation of Deflection criteria, Gravity Deflection & Wind Drift	Excessive deformations that affects serviceability	Design	4	10	6	240	5	2	10
	F43	F 8.2	Unforeseen ground conditions (extent, type)	Foundation fail	Construction	6	6	7	252	3	3	9

	F44	F 8.3	Water seepages or improper water proofing standards	Structure damage/collapse	Construction	8	6	6	288	3	4	12
	F45	F 8.4	Inadequate information of water table	Structure damage/collapse	Design	6	6	7	252	3	3	9

Legend:

S-S: Sub-System.

O: Occurrence.

S: Severity.

D: Detection.

R: Risk (chance of happening).

L: Likelihood.

RPN: Risk Priority Number.

RN: Risk Number.

5.2.6 Composite FME Application

Using the proposed framework showed in Fig 4-1, the COMP-FMEA application followed the following three phases.

5.2.6.1 Phase I: Understanding the system

- **Understanding the application scope:** identifying the structural design and construction failures/risks from a civil engineering perspective.
- **System mission, operation and parts:** A simple residential building that can be broken-down into eight subsystems shown in Fig 5-1.
- **Hierarchical level at which the analysis can be done:** The failure modes have been assigned to the sub-systems level, based on the experts vision, there was no need to breakdown the sub-systems into components.
- **The items to be analyzed:** The analysis has been done on the eight sub-systems, with the distinction between the failures due to design stage and the failures due to construction stage.

5.2.6.2 Phase II: The Weighted Risk Priority Number (WRPN)

5.2.6.2.1 CRITICALITY FACTORS SELECTION

The teamwork has defined the Safety, Cost and Time as the three main criticality factors, which if combined together will present the severity of a failure mode. The evaluation criteria of the selected critical factors followed tables 5-4, 5-5, and 5-6.

Table 5-5 ***Safety evaluation criteria-Residential Building Case.***

Safety		
Rating	**Effect**	**Severity of effect**
100	Hazardous without warning	Very High severity ranking when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulations without warning

90	Hazardous with warning	Very High severity ranking when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulations with warning
80	Very high	Vehicle/item inoperable, with loss of primary function
70	High	Vehicle/item operable, but at reduced level of performance. Customer dissatisfied
60	Moderate	Vehicle/item operable, but comfort/convenience item(s) inoperable. Customer experiences discomfort
50	Low	Vehicle/item operable, but comfort/convenience item(s) operable at reduced level of performance. Customer experiences some Dissatisfaction
40	Very low	Cosmetic defect in finish, fit and finish/squeak or rattle item that does not conform to specifications. Defect noticed by most customers
30	Minor	Cosmetic defect in finish, fit and finish/squeak or rattle item that does not conform to specifications. Defect noticed by average customer
20	Very minor	Cosmetic defect in finish, fit and finish/squeak or rattle item that does not conform to specifications. Defect noticed by discriminating customers
10	None	No effect

Table 5-6 ***Cost evaluation criteria-Residential Building Case.***

Cost		
Rating	**Effect**	**Severity of effect**
90-100	Very high	≥ 10% of project cost.
70-90	High	Cost increase is ≥ 7% and < 10% of project cost.
50-70	Moderate	Cost increase is ≥ 4% and < 7% of project cost.
30-50	Low	Cost increase is ≥ 1% and < 4% of project cost.
10-30	Very low	< 1% of project cost.

Table 5-7 ***Time evaluation criteria-Residential Building Case.***

Time		
Rating	**Effect**	**Severity of effect**
90-100	Very high	In service date delayed ≥ 10% of project duration.
70-90	High	In service date delayed ≥ 7% and < 10% of project duration.
50-70	Moderate	In service date delayed ≥ 4% and < 7% of project duration.
30-50	Low	In service date delayed ≥ 1% and < 4% of project duration.
10-30	Very low	Insignificant schedule slippage.

5.2.6.2.2 PAIRWISE COMPARISON TO DETERMINE THE CRITICALITY FACTORS WEIGHT (α)

After selecting and defining the criticality factors, a Pairwise Comparison has taken place in order to define the importance of each factor in the project through the weights calculation.

Using the framework in section 4.4.3.1, the results are shown in table 5-8

Table 5-8 ***The Pairwise Comparison-Residential Building Case.***

Factor	**Safety**	**Cost**	**Time**	Weight (α)
Safety	1.00	5.00	7.00	0.730645
Cost	0.20	1.00	3.00	0.188394
Time	0.14	0.33	1.00	0.080961
Total				1.00

The maximum eigenvalue of the matrix $\lambda_{max} = 3.18277$

The number of comparison $n = 3$

The Consistency Index for the matrix $CI = 0.0324438$

The Corresponding Average Random $RI = 0.58$

The Inconsistency Ration $I_R = 0.055938$ <0.1

The results show that the judgment is acceptable and we can proceed to the next step using the outcome weights. Moreover, the results show that the experts gave the Safety the highest priority with 73% weight, followed by the Cost 19% and 8% to the cost.

The previous weights can vary from project to another depending on the scope and the conditions of the project even though the same criticality factors have been used.

Subsequently, a Weighted Risk Priority Number (WRPN) has been calculated for each failure mode using the formulas No.4 presented in section 4.4.3. Table 5-9 shows the results.

Table 5-9 ***WRPN Results-Residential Building Case.***

S-S	No.	Ref.	Description	Failure	Stage	O	SF	C	T	D	WRPN
Foundation	F1	F 1.1	Insufficient Investigation of soil	Foundation Failure	Design	6	80	100	95	7	357
	F2	F 1.2	Faulty foundation	Failure of structure	Construction	6	100	100	95	7	418
	F3	F 1.3	Inadequate foundation	Excessive deformation and settlements in Building	Construction	6	80	85	90	7	343
	F4	F 1.4	Improper bearing capacity	Foundation failure	Construction	8	60	100	90	6	336
	F5	F 1.5	Hard rains, wrong assessment bearing capacity, defective design	Ground settlement	Construction	6	60	65	75	4	149
	F6	F 1.6	Unforeseen ground conditions (extent, type)	Foundation fail	Construction	6	60	85	75	7	277
	F7	F 1.7	Subsidence at surface	Soil arch eventually collapses	Construction	6	60	80	75	7	273
	F8	F 1.8	Improper design of grating (water network)	Structure damage/collapse	Design	4	60	70	75	6	151

	F9	F 1.9	Improper water height considerations	Water tank wall cracks	Design	2	60	60	65	10	121
Retain Walls	F10	F 2.1	Improper soil investigation	Excessive deformations and proper failure	Concept	6	60	75	70	7	267
	F11	F 2.2	Improper design for stability (e.g.: Sliding, overturning)	Excessive deformations and proper failure	Design	6	60	65	65	7	258
	F12	F 2.3	Inadequate information of water table	Retaining wall failure	Design	6	60	75	50	7	260
	F13	F 2.4	Insufficient steel used in retaining walls	Shear / flexural crack	Construction	8	60	70	50	7	342
Slab on Grade	F14	F 3.1	Improper calculation of design loads on slab on grade	Excessive deformation and apparent cracks	Design	2	80	35	30	10	135
	F15	F 3.2	Improper selection of contraction and expansion joints	Excessive deformation and apparent cracks	Construction	2	60	35	30	10	106
Beams & Slabs	F16	F 4.1	Improper limits of design	Slab collapse	Design	6	80	60	60	7	313
	F17	F 4.2	Slab collapse	Injury	Construction	6	80	70	45	7	316

	F18	F 4.3	Improper steel binding & shortage of steel	Slab collapse	Construction	6	80	75	55	7	324
	F19	F 4.4	Improper selection & proportion of materials required	Slab collapse	Design	6	80	75	60	7	325
	F20	F 4.5	Improper supports required to hold the slab while casting	Slab collapse	Construction	6	100	70	60	7	383
	F21	F 4.6	Improper workman ship	Slab collapse	Construction	4	100	60	50	6	212
	F22	F 4.7	Inadequate calculation of Deflection criteria, Gravity Deflection & Wind Drift	Excessive deformations that affects serviceability	Design	4	100	50	35	6	205
Columns and Cores	F23	F 5.1	Improper steel design for columns	Columns failure	Design	4	60	100	100	6	170
	F24	F 5.2	Improper calculation of design loads	Columns failure	Design	4	60	90	80	6	161
	F25	F 5.3	Improper calculation of columns dimensions	Columns failure	Design	6	60	100	100	7	297
	F26	F 5.4	Improper plotting of columns	Conflict with architectural and	Construction	4	60	55	50	6	140

				remedial works should take place							
	F27	F 5.5	Inadequate design of load bearing elements and lateral stability of the structure against the lateral loads such as wind loads.	Structure collapse	Design	6	60	90	80	7	283
Structural Materials	F28	F 6.1	Improper selection of materials to be used in construction	Structure collapse	Construction	2	80	80	75	10	159
	F29	F 6.2	Improper grade of design	Structural elements failure	Design	6	80	75	70	7	329
	F30	F 6.3	Improper selection & proportion of materials required	Structural elements failure	Design	8	60	60	45	6	282
	F31	F 6.4	Improper execution as per design & materials standards	Structural elements failure	Construction	6	100	60	45	4	211
	F32	F 6.5	Inadequate selection of Concrete Classes	Structural elements failure	Design	6	80	60	45	7	308

	F33	F 6.6	Inadequate type of cement selection	Structural elements failure	Design	4	60	65	50	6	144
	F34	F 6.7	Inadequate selection of reinforcement	Structure collapse	Construction	4	80	100	90	6	203
Loads	F35	F 7.1	Inadequate information in terms of the purpose of the structure, as well as the scope and complexity of the project	Structure collapse	Construction	2	80	85	75	10	161
	F36	F 7.2	Improper calculation of design loads	Structure collapse	Design	6	80	100	90	7	355
	F37	F 7.3	Improper design of gravity and lateral loads	Structure collapse	Design	6	80	90	85	7	346
	F38	F 7.4	Inadequate calculation of wind loads	Structure collapse/injury	Design	4	60	85	75	6	158
	F39	F 7.5	Inadequate calculation of earthquake loads	Structure collapse/injury	Design	4	80	90	90	6	198
	F40	F 7.6	Inadequate calculation of strength requirements	Structure collapse/injury	Design	6	80	90	90	7	347
	F41	F 7.7	Inadequate calculation of fire rating	Structure collapse/injury	Design	4	60	70	55	6	148

Serviceability & UG Concrete	F42	F 8.1	Inadequate calculation of Deflection criteria, Gravity Deflection & Wind Drift	Excessive deformations that affects serviceability	Design	4	100	60	40	6	210
	F43	F 8.2	Unforeseen ground conditions (extent, type)	Foundation fail	Construction	6	60	85	75	7	277
	F44	F 8.3	Water seepages or improper water proofing standards	Structure damage/collapse	Construction	8	60	45	40	6	267
	F45	F 8.4	Inadequate information of water table	Structure damage/collapse	Design	6	60	65	90	7	266

Legend:

S-S: Sub-System.

O: Occurrence.

SF: Safety.

C: Cost.

T: Time.

D: Detection.

WRPN: Weighted Risk Priority Number.

5.2.6.3 Phase III Correction process

The correction process has been applied on the failures with Medium, Low and Very Low risk (WRPN ≤200) showed in table 5-10. In our case, which means that this process has been applied in 31% of the total failures. The correction follows the following steps.

*Table 5-10 **Failures having (WRPN ≤200) - Residential Building Case.***

	Occurrence	Safety	Cost	Time	D	WRPN
F5	6	60	65	75	4	149
F8	4	60	70	75	6	151
F9	2	60	60	65	10	121
F14	2	80	35	30	10	135
F15	2	60	35	30	10	106
F23	4	60	100	100	6	170
F24	4	60	90	80	6	161
F26	4	60	55	50	6	140
F28	2	80	80	75	10	159
F33	4	60	65	50	6	144
F35	2	80	85	75	10	161
F38	4	60	85	75	6	158
F39	4	80	90	90	6	198
F41	4	60	70	55	6	148

5.2.6.3.1 REPRIORITIZATION CORRECTION FACTOR (RCF)

As refer to section 4.5.1, and for each failure has WRPN ≤200 (Medium, Low, and Very Low risks), a Reprioritization Correction Factor (RCF) has been calculated in order to correct the possible mistakes of having inadequate information given by the experts during the first phase. This correction factor takes into consideration the possible effect of these failures in the long term in order to check whether it will maintain the same risk level or it will be more risky.

5.2.6.3.1.1 IDENTIFYING THE INITIAL RISK VECTOR AND THE TRANSITION MATRIXES

The first step to calculate (RCF) is to identify the One-Step Transition Matrix following the guideline proposed in section 4.5.1.1.

The input of this step is the Failure risk matrix, which shows the risk assessment for each failure mode at the first stage (Pre-construction stage) and the second stage (Early-construction stage) provided by the experts. The output is the One-Step Transition Matrix.

Inputs: (The Failure Risk Matrices)

Table 5-11 ***The failure risk matrix (F5) - Residential building Case.***

F5	Hard rains, wrong assessment bearing capacity, defective design					
	Second stage assessment					
First stage assessment	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	1	1	3	4	4	13
	Low	0	1	3	4	4	12
	Medium	0	0	5	4	4	13
	High	0	0	2	4	4	10
	Very high	0	0	2	4	4	10
	Total	1	2	15	20	20	58

Table 5-12 ***The failure risk matrix (F8) - Residential building Case.***

F8	Improper design of grating (water network)						
	Second stage assessment						
First stage assessment	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0	2	3	1	0	6
	Low	1	2	3	1	1	8
	Medium	0	1	4	1	1	7
	High	0	0	3	1	1	5
	Very high	0	0	2	3	1	6
	Total	1	5	15	7	4	32

Table 5-13 ***The failure risk matrix (F9) - Residential building Case.***

F9	Improper water height considerations					
First stage assessment	Second stage assessment					
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	1	3	1	0	0	5
	Low	1	5	1	0	0	7
	Medium	0	5	2	1	1	9
	High	0	4	2	0	0	6
	Very high	0	4	2	0	0	6
	Total	2	21	8	1	1	33

Table 5-14 ***The failure risk matrix (F14) - Residential building Case.***

F14	Improper calculation of design loads on slab on grade						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	1	4	2	0	0	7
	Low	1	5	2	0	0	8
	Medium	2	3	1	0	0	6
	High	2	3	1	0	0	6
	Very high	2	3	1	0	0	6
	Total	8	18	7	0	0	33

Table 5-15 ***The failure risk matrix (F15) - Residential building Case.***

F15	Improper selection of contraction and expansion joints						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	1	3	3	2	0	9
	Low	1	3	3	2	0	9
	Medium	1	2	2	2	0	7
	High	1	2	2	1	0	6
	Very high	1	2	2	1	0	6
	Total	5	12	12	8	0	37

Table 5-16 ***The failure risk matrix (F23) - Residential building Case.***

F23	Improper steel design for columns						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	1	1	3	4	4	13
	Low	1	1	3	4	4	13
	Medium	1	1	3	4	4	13
	High	1	1	3	5	4	14
	Very high	1	1	3	4	4	13
	Total	5	5	15	21	20	66

Table 5-17 ***The failure risk matrix (F24) - Residential building Case.***

F24	Improper calculation of design loads					
First stage assessment	Second stage assessment					
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0	1	2	4	5	12
	Low	0	1	3	4	5	13
	Medium	0	1	4	4	5	14
	High	0	1	3	5	5	14
	Very high	0	1	3	5	5	14
	Total	0	5	15	22	25	67

Table 5-18 ***The failure risk matrix (F26) - Residential building Case.***

F26	Improper plotting of columns						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	1	1	3	4	4	13
	Low	0	1	3	4	4	12
	Medium	0	0	4	4	4	12
	High	0	0	4	5	5	14
	Very high	0	0	4	5	5	14
	Total	1	2	18	22	22	65

Table 5-19 ***The failure risk matrix (F28) - Residential building Case.***

F28	Improper selection of materials to be used in construction						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	1	1	2	3	5	12
	Low	0	1	2	3	5	11
	Medium	0	0	1	3	5	9
	High	0	0	1	3	4	8
	Very high	0	0	1	2	5	8
	Total	1	2	7	14	24	48

Table 5-20 ***The failure risk matrix (F33) - Residential building Case.***

F33	Inadequate type of cement selection						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	1	1	3	3	2	10
	Low	0	1	3	3	2	9
	Medium	0	1	5	3	2	11
	High	0	1	4	3	2	10
	Very high	0	1	4	3	2	10
	Total	1	5	19	15	10	50

Table 5-21 ***The failure risk matrix (F35) - Residential building Case.***

F35	Inadequate information in terms of the purpose of the structure, as well as the scope and complexity of the project						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	1	2	3	5	4	15
	Low	0	2	3	5	4	14
	Medium	0	1	3	5	4	13
	High	0	0	3	5	4	12
	Very high	0	0	3	5	4	12
	Total	1	5	15	25	20	66

Table 5-22 ***The failure risk matrix (F38) - Residential building Case.***

F38	Inadequate calculation of wind loads						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0	1	3	4	4	12
	Low	0	1	3	4	4	12
	Medium	0	1	4	4	4	13
	High	0	1	4	5	5	15
	Very high	0	1	4	5	5	15
	Total	0	5	18	22	22	67

Table 5-23 ***The failure risk matrix (F39) - Residential building Case.***

F39	Inadequate calculation of earthquake loads						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0	1	3	4	4	12
	Low	0	1	3	4	4	12
	Medium	0	1	4	4	4	13
	High	0	1	4	5	5	15
	Very high	0	1	4	5	5	15
	Total	0	5	18	22	22	67

Table 5-24 ***The failure risk matrix (F41) - Residential building Case.***

F41	Inadequate calculation of fire rating						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	1	1	2	1	0	5
	Low	1	1	2	1	0	5
	Medium	1	1	2	1	0	5
	High	1	1	2	1	0	5
	Very high	1	1	2	1	0	5
	Total	5	5	10	5	0	25

Outputs: (The One-Step Transition Matrices)

Table 5-25 ***The One-Step Transition Matrix (F5) - Residential building Case.***

F5	Hard rains, wrong assessment bearing capacity, defective design						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0.076923	0.076923	0.230769	0.307692	0.307692	1
	Low	0	0.083333	0.25	0.333333	0.333333	1
	Medium	0	0	0.384615	0.307692	0.307692	1
	High	0	0	0.2	0.4	0.4	1
	Very high	0	0	0.2	0.4	0.4	1
	Total	0.076923	0.160256	1.265385	1.748718	1.748718	

Table 5-26 ***The One-Step Transition Matrix (F8) - Residential building Case.***

F8	Improper design of grating (water network)						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0	0.333333	0.5	0.166667	0	1
	Low	0.125	0.25	0.375	0.125	0.125	1
	Medium	0	0.142857	0.571429	0.142857	0.142857	1
	High	0	0	0.6	0.2	0.2	1
	Very high	0	0	0.333333	0.5	0.166667	1
	Total	0.125	0.72619	2.379762	1.134524	0.634524	

Table 5-27 ***The One-Step Transition Matrix (F9) - Residential building Case.***

F9	Improper water height considerations						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0.2	0.6	0.2	0	0	1
	Low	0.142857	0.714286	0.142857	0	0	1
	Medium	0	0.555556	0.222222	0.111111	0.111111	1
	High	0	0.666667	0.333333	0	0	1
	Very high	0	0.666667	0.333333	0	0	1
	Total	0.342857	3.203175	1.231746	0.111111	0.111111	

Table 5-28 ***The One-Step Transition Matrix (F14) - Residential building Case.***

F14	Improper calculation of design loads on slab on grade						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0.142857	0.571429	0.285714	0	0	1
	Low	0.125	0.625	0.25	0	0	1
	Medium	0.333333	0.5	0.166667	0	0	1
	High	0.333333	0.5	0.166667	0	0	1
	Very high	0.333333	0.5	0.166667	0	0	1
	Total	1.267857	2.696429	1.035714	0	0	

Table 5-29 ***The One-Step Transition Matrix (F15) - Residential building Case.***

F15	Improper selection of contraction and expansion joints						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0.111111	0.333333	0.333333	0.222222	0	1
	Low	0.111111	0.333333	0.333333	0.222222	0	1
	Medium	0.142857	0.285714	0.285714	0.285714	0	1
	High	0.166667	0.333333	0.333333	0.166667	0	1
	Very high	0.166667	0.333333	0.333333	0.166667	0	1
	Total	0.698413	1.619048	1.619048	1.063492	0	

Table 5-30 ***The One-Step Transition Matrix (F23) - Residential building Case.***

F23	Improper steel design for columns						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0.076923	0.076923	0.230769	0.307692	0.307692	1
	Low	0.076923	0.076923	0.230769	0.307692	0.307692	1
	Medium	0.076923	0.076923	0.230769	0.307692	0.307692	1
	High	0.071429	0.071429	0.214286	0.357143	0.285714	1
	Very high	0.076923	0.076923	0.230769	0.307692	0.307692	1
	Total	0.379121	0.379121	1.137363	1.587912	1.516484	

Table 5-31 ***The One-Step Transition Matrix (F24) - Residential building Case.***

F24	Improper calculation of design loads						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0	0.083333	0.166667	0.333333	0.416667	1
	Low	0	0.076923	0.230769	0.307692	0.384615	1
	Medium	0	0.071429	0.285714	0.285714	0.357143	1
	High	0	0.071429	0.214286	0.357143	0.357143	1
	Very high	0	0.071429	0.214286	0.357143	0.357143	1
	Total	0	0.374542	1.111722	1.641026	1.872711	

Table 5-32 ***The One-Step Transition Matrix (F26) - Residential building Case.***

F26	Improper plotting of columns						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0.076923	0.076923	0.230769	0.307692	0.307692	1
	Low	0	0.083333	0.25	0.333333	0.333333	1
	Medium	0	0	0.333333	0.333333	0.333333	1
	High	0	0	0.285714	0.357143	0.357143	1
	Very high	0	0	0.285714	0.357143	0.357143	1
	Total	0.076923	0.160256	1.385531	1.688645	1.688645	

Table 5-33 ***The One-Step Transition Matrix (F28) - Residential building Case.***

F28	Improper selection of materials to be used in construction						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0.083333	0.083333	0.166667	0.25	0.416667	1
	Low	0	0.090909	0.181818	0.272727	0.454545	1
	Medium	0	0	0.111111	0.333333	0.555556	1
	High	0	0	0.125	0.375	0.5	1
	Very high	0	0	0.125	0.25	0.625	1
	Total	0.083333	0.174242	0.709596	1.481061	2.551768	

Table 5-34 ***The One-Step Transition Matrix (F33) - Residential building Case.***

F33	Inadequate type of cement selection						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0.1	0.1	0.3	0.3	0.2	1
	Low	0	0.111111	0.333333	0.333333	0.222222	1
	Medium	0	0.090909	0.454545	0.272727	0.181818	1
	High	0	0.1	0.4	0.3	0.2	1
	Very high	0	0.1	0.4	0.3	0.2	1
	Total	0.1	0.50202	1.887879	1.506061	1.00404	

Table 5-35 ***The One-Step Transition Matrix (F35) - Residential building Case.***

F35	Inadequate information in terms of the purpose of the structure, as well as the scope and complexity of the project						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0.066667	0.133333	0.2	0.333333	0.266667	1
	Low	0	0.142857	0.214286	0.357143	0.285714	1
	Medium	0	0.076923	0.230769	0.384615	0.307692	1
	High	0	0	0.25	0.416667	0.333333	1
	Very high	0	0	0.25	0.416667	0.333333	1
	Total	0.066667	0.353114	1.145055	1.908425	1.52674	

Table 5-36 ***The One-Step Transition Matrix (F38) - Residential building Case.***

F38	Inadequate calculation of wind loads						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0	0.083333	0.25	0.333333	0.333333	1
	Low	0	0.083333	0.25	0.333333	0.333333	1
	Medium	0	0.076923	0.307692	0.307692	0.307692	1
	High	0	0.066667	0.266667	0.333333	0.333333	1
	Very high	0	0.066667	0.266667	0.333333	0.333333	1
	Total	0	0.376923	1.341026	1.641026	1.641026	

Table 5-37 ***The One-Step Transition Matrix (F39) - Residential building Case.***

F39	Inadequate calculation of earthquake loads						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0	0.083333	0.25	0.333333	0.333333	1
	Low	0	0.083333	0.25	0.333333	0.333333	1
	Medium	0	0.076923	0.307692	0.307692	0.307692	1
	High	0	0.066667	0.266667	0.333333	0.333333	1
	Very high	0	0.066667	0.266667	0.333333	0.333333	1
	Total	0	0.376923	1.341026	1.641026	1.641026	

Table 5-38 ***The One-Step Transition Matrix (F41) - Residential building Case.***

F41	Inadequate calculation of fire rating						
First stage assessment	Second stage assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
	Very low	0.2	0.2	0.4	0.2	0	1
	Low	0.2	0.2	0.4	0.2	0	1
	Medium	0.2	0.2	0.4	0.2	0	1
	High	0.2	0.2	0.4	0.2	0	1
	Very high	0.2	0.2	0.4	0.2	0	1
	Total	1	1	2	1	0	

5.2.6.3.1.2 ***RISK PROBABILITY AT THE STEADY STATE***

At this step and as mentioned in section 4.5.1.2, we are interesting in the risk distribution in the steady state, (equilibrium stage) in which each risk level remains constant. This gives us the long-term probability of each failure/risk to be in a certain risk level. Subsequently the Reprioritization Correction Factor (RCF) calculated for the fourteen failure modes (F5, F8, F9, F14, F15, F23, F24, F26, F28, F33, F35F38, F39, and F41) following the guideline proposed in table 4-9.

A MATlab model has been used to solve the steady state equation $V^{ss} = V^{ss} \times P$ for those failures where:

V $^{(SS)}$ is the risk distribution vector at the steady state **= (V$_1$, V$_2$, V$_3$, V$_4$, V$_5$)**,

The results showed in table 5.39

Table 5-39 ***The risk distribution at the project Steady State- Residential Building Case.***

	The Probability at the steady state					
	V1	V2	V3	V4	V5	
Failure	Very low	Low	Medium	High	Very high	Total
F5	0.00000	0.00000	0.24528	0.37736	0.37736	1.00000
F8	0.01309	0.10468	0.51905	0.20847	0.15471	1.00000
F9	0.11995	0.67172	0.17045	0.01894	0.01894	1.00000
F14	0.16138	0.44138	0.17379	0.11172	0.11172	1.00000
F15	0.13397	0.31818	0.31818	0.22967	0.00000	1.00000
F23	0.07514	0.075154	0.22543	0.32370	0.30058	1.00000
F24	0.00000	0.07182	0.23204	0.33702	0.35912	1.00000
F26	0.00000	0.00000	0.30000	0.35000	0.35000	1.00000
F28	0.00000	0.00000	0.12329	0.29746	0.57926	1.00000
F33	0.00000	0.09730	0.41622	0.29189	0.19459	1.00000
F35	0.00000	0.02194	0.24451	0.40752	0.32602	1.00000
F38	0.00000	0.07068	0.27685	0.32623	0.32623	1.00000
F39	0.00000	0.07068	0.27685	0.32623	0.32623	1.00000
F41	0.20000	0.20000	0.40000	0.20000	0.00000	1.00000

Later on, the ICF has been calculated by defining the probability of the failure mode to be high or very high risky $P_{H, VH,}$ where, $P_{H,VH} = V_4 + V_5$. Table 5-40 shows the result.

Table 5-40 ***RCF for the failures having (WRPN≤200) - Residential Building Case.***

Failure	$P_{H, VH}$	RCF
F5	75.47%	4
F8	36.32%	2
F9	3.79%	1
F14	22.34%	1
F15	22.97%	1
F23	62.43%	3
F24	69.61%	3
F26	70.00%	3
F28	87.67%	5
F33	48.65%	2
F35	73.35%	4
F38	65.25%	3
F39	65.25%	3
F41	20.00%	1

5.2.6.3.2 INTERDEPENDENCE CORRECTION FACTOR (ICF)

As mentioned in section 4.52, the Interdependence Correction Factor (ICF) has been designed to take into account the effect of the interdependency of different failures that is neglected by the conventional FMEA. It is also dedicated to the failures with WRPN less than or equal to (200).

In order to determine the ICF for the failures with WRPN ≤200, the Interdependencies Matrix (IM) has been developed showing the effect of each the failures (F5, F8, F9, F14, F15, F23, F24, F26, F28, F33, F35F38, F39, and F41) on the other failure modes. Obviously, the experts have defined the probability of each failure to be a cause for the others. Table 5-41 shows these results.

Table 5-41 ***The relationship between the failures with WRPN ≤200 and the other failures-Residential Building Case.***

	The probability of a certain failure to be a cause of the other failures.													
Failure	**F5**	**F8**	**F9**	**F14**	**F15**	**F23**	**F24**	**F26**	**F28**	**F33**	**F35**	**F38**	**F39**	**F41**
F1	50	0	80	0	0	0	0	0	20	80	40	0	0	0
F2	60	30	50	0	30	0	0	0	80	80	40	0	0	0
F3	60	30	50	0	30	0	0	0	80	0	40	60	60	0
F4	100	0	40	0	0	0	0	0	20	0	0	0	0	0
F5	0	0	50	0	0	0	0	0	40	0	0	0	0	0
F6	50	50	50	0	40	0	0	0	40	0	0	0	0	0
F7	50	40	50	0	10	0	0	0	30	0	0	0	0	0
F8	20	0	30	0	10	0	0	0	50	0	40	0	0	0
F9	20	40	100	0	0	0	0	0	0	0	0	0	0	0
F10	50	0	100	0	0	0	0	0	0	0	40	0	0	0
F11	50	30	80	0	40	0	0	0	40	0	0	0	0	0
F12	0	30	100	0	0	0	0	0	0	0	0	0	0	0
F13	50	0	80	0	20	0	0	0	80	0	0	0	0	0
F14	50	0	100	0	40	0	0	0	80	0	40	0	0	0
F15	20	0	30	50	0	0	0	0	0	0	40	0	0	0

F16	20	0	0	0	10	0	0	0	80	0	80	0	0	0
F17	40	0	0	0	10	60	60	40	80	40	50	0	0	0
F18	0	0	0	0	10	0	0	0	80	0	50	0	0	0
F19	0	0	0	0	10	0	0	0	80	0	30	0	0	0
F20	0	0	0	0	0	0	0	0	60	0	0	0	0	0
F21	0	0	0	0	10	0	0	0	0	0	10	0	0	0
F22	0	0	0	0	10	0	0	0	40	70	40	0	0	0
F23	0	0	0	0	0	0	100	0	20	50	50	70	70	0
F24	50	0	0	0	10	0	0	0	60	0	50	70	70	0
F25	0	0	0	0	10	0	100	0	60	50	50	70	70	0
F26	0	0	0	0	10	0	0	0	0	0	10	0	0	0
F27	40	0	0	0	10	0	100	0	60	0	50	70	70	0
F28	40	0	0	0	10	0	0	0	0	0	40	40	40	0
F29	0	0	0	0	10	0	0	0	50	0	40	0	0	0
F30	40	0	0	0	10	0	0	0	50	0	40	0	0	0
F31	0	0	0	0	10	0	0	40	50	0	40	0	0	0
F32	40	0	0	0	10	0	0	0	0	0	40	40	40	0
F33	40	0	0	0	10	0	0	0	0	0	40	40	40	0

F34	40	0	0	0	10	100	70	0	20	0	40	70	70	0
F35	60	0	20	20	0	0	0	30	20	0	0	0	0	0
F36	50	0	20	20	0	0	0	60	0	0	40	0	0	0
F37	40	0	20	20	0	0	0	0	0	0	40	60	60	0
F38	30	0	0	0	0	0	0	0	0	0	40	0	0	0
F39	70	0	0	0	0	0	0	0	0	0	40	0	0	0
F40	0	0	20	20	0	100	100	0	100	60	80	60	60	0
F41	40	0	0	0	0	0	0	0	10	0	50	0	0	0
F42	40	0	0	0	0	0	0	0	40	70	50	0	0	0
F43	20	50	30	50	0	0	0	0	40	0	40	0	0	0
F44	20	80	70	50	0	0	0	0	40	0	40	0	0	0
F45	0	30	100	0	0	0	0	0	0	0	0	0	0	0

The next step is to calculate the Failure Impact Ratio (FIR) for the five Failure modes (F09, F14, F15, F28, and F36) following the guideline in section 4.5.2. The results shown in table 5-42

$$FIR = \frac{\text{No. of probabilities } \geq 40\%}{Total \ \text{ No. of failures} - 1}$$

Table 5-42 ***FIR and ICF for the failures having (WRPN≤200) - Residential Building Case.***

Failure	FIR	ICF
F5	54.55%	6
F8	11.36%	2
F9	34.09%	4
F14	6.82%	1
F15	6.82%	1
F23	6.82%	1
F24	13.64%	2
F26	6.82%	1
F28	54.55%	6
F33	18.18%	2
F35	70.45%	7
F38	25.00%	3
F39	25.00%	3
F41	0.00%	1

5.2.6.4 Final RPN calculation

The final RPN for the failures with WRPN ≤200 is the result of formula (9) mentioned in section 4.5.2 and the results are shown in table 5-25.

$$RPN = \max(WRPN \times RCF; WRPN \times ICF) \leq 1000$$

Table 5-43***The final RPN for the failures having (WRPN≤200) - Residential Building Case.***

Failure	RCF	RPN_{RCF}	ICF	RPN_{ICF}	RPN
F5	4	597	6	895	895
F8	2	303	2	303	303
F9	1	121	4	483	483
F14	1	135	1	135	135
F15	1	106	1	106	106
F23	3	510	1	170	510
F24	3	484	2	323	484
F26	3	419	1	140	419
F28	5	796	6	955	955
F33	2	289	2	289	289
F35	4	644	7	1128	1000
F38	3	475	3	475	475
F39	3	595	3	595	595
F41	1	148	1	148	148

Table 5-44 ***the Final RPN- Residential Building Case.***

S-S	No.	Ref.	Description	Failure	Stage	Final RPN		
						RRM	FMEA	COMP-FMEA
Foundation	F1	F 1.1	Insufficient Investigation of soil	Foundation Failure	Design	12	336	357
	F2	F 1.2	Faulty foundation	Failure of structure	Construction	15	420	418
	F3	F 1.3	Inadequate foundation	Excessive deformation and settlements in Building	Construction	12	336	343
	F4	F 1.4	Improper bearing capacity	Foundation failure	Construction	12	288	336
	F5	F 1.5	Hard rains, wrong assessment bearing capacity, defective design	Ground settlement	Construction	9	144	895
	F6	F 1.6	Unforeseen ground conditions (extent, type)	Foundation fail	Construction	9	252	277
	F7	F 1.7	Subsidence at surface	Soil arch eventually collapses	Construction	9	252	273
	F8	F 1.8	Improper design of grating (water network)	Structure damage/collapse	Design	6	144	303
	F9	F 1.9	Improper water height considerations	Water tank wall cracks	Design	3	120	483

Retain Walls	F10	F 2.1	Improper soil investigation	Excessive deformations and proper failure	Concept	9	252	267
	F11	F 2.2	Improper design for stability (e.g. Sliding, overturning)	Excessive deformations and proper failure	Design	9	252	258
	F12	F 2.3	Inadequate information of water table	Retaining wall failure	Design	9	252	260
	F13	F 2.4	Insufficient steel used in retaining walls	Shear / flexural crack	Construction	12	336	342
Slab on Grade	F14	F 3.1	Improper calculation of design loads on slab on grade	Excessive deformation and apparent cracks	Design	4	160	135
	F15	F 3.2	Improper selection of contraction and expansion joints	Excessive deformation and apparent cracks	Construction	3	120	106
Beams & Slabs	F16	F 4.1	Improper limits of design	Slab collapse	Design	12	336	313
	F17	F 4.2	Slab collapse	Injury	Construction	12	336	316
	F18	F 4.3	Improper steel binding & shortage of steel	Slab collapse	Construction	12	336	324
	F19	F 4.4	Improper selection & proportion of materials required	Slab collapse	Design	12	336	325
	F20	F 4.5	Improper supports required to hold the slab while casting	Slab collapse	Construction	15	420	383

	F21	F 4.6	Improper workman ship	Slab collapse	Construction	10	240	212
	F22	F 4.7	Inadequate calculation of Deflection criteria, Gravity Deflection & Wind Drift	Excessive deformations that affects serviceability	Design	10	240	205
Columns and Cores	F23	F 5.1	Improper steel design for columns	Columns failure	Design	6	144	510
	F24	F 5.2	Improper calculation of design loads	Columns failure	Design	6	144	484
	F25	F 5.3	Improper calculation of columns dimensions	Columns failure	Design	9	252	297
	F26	F 5.4	Improper plotting of columns	Conflict with architectural and remedial works should take place	Construction	6	144	419
	F27	F 5.5	Inadequate design of load bearing elements and lateral stability of the structure against the lateral loads such as wind loads.	Structure collapse	Design	9	252	283
Structural Materials	F28	F 6.1	Improper selection of materials to be used in construction	Structure collapse	Construction	4	160	955
	F29	F 6.2	Improper grade of design	Structural elements failure	Design	12	336	329

	F30	F 6.3	Improper selection & proportion of materials required	Structural elements failure	Design	12	288	282
	F31	F 6.4	Improper execution as per design & materials standards	Structural elements failure	Construction	15	240	211
	F32	F 6.5	Inadequate selection of Concrete Classes	Structural elements failure	Design	12	336	308
	F33	F 6.6	Inadequate type of cement selection	Structural elements failure	Design	6	144	289
	F34	F 6.7	Inadequate selection of reinforcement	Structure collapse	Construction	8	192	203
Loads	F35	F 7.1	Inadequate information in terms of the purpose of the structure, as well as the scope and complexity of the project	Structure collapse	Construction	4	160	1000
	F36	F 7.2	Improper calculation of design loads	Structure collapse	Design	12	336	355
	F37	F 7.3	Improper design of gravity and lateral loads	Structure collapse	Design	12	336	346
	F38	F 7.4	Inadequate calculation of wind loads	Structure collapse/injury	Design	6	144	475
	F39	F 7.5	Inadequate calculation of earthquake loads	Structure collapse/injury	Design	8	192	595

	F40	F 7.6	Inadequate calculation of strength requirements	Structure collapse/injury	Design	12	336	347
	F41	F 7.7	Inadequate calculation of fire rating	Structure collapse/injury	Design	6	144	148
Serviceability & UG Concrete	F42	F 8.1	Inadequate calculation of Deflection criteria, Gravity Deflection & Wind Drift	Excessive deformations that affects serviceability	Design	10	240	210
	F43	F 8.2	Unforeseen ground conditions (extent, type)	Foundation fail	Construction	9	252	277
	F44	F 8.3	Water seepages or improper water proofing standards	Structure damage/collapse	Construction	12	288	267
	F45	F 8.4	Inadequate information of water table	Structure damage/collapse	Design	9	252	266

Legend:

S-S: Sub-System.

RRM: Risk Rating Matrix

5.2.7 Criticality analysis and results

5.2.7.1 The risk distribution and the criticality factors effect

Starting from the risk distribution for the three methodologies (Risk Rating Matrix, Conventional FMEA, and COMP-FMEA) showed in fig. 5-3 it is seen that in terms of the high risk, the COMP-FMEA gives the highest distribution and the Risk Rating Matrix gives the lowest.

- **Composite FMEA:** in the First stage of COMP-FMEA where the severity divided into several factors (Safety, Cost and time), we obtained a risk distribution close to the conventional FMEA with a slightly increase in the failures having Very High and Medium risk levels, and obvious reduction in the number of failures with Low risk level. The results shows that in the second stage of COMP-FMEA, 33% of the failures were Very high risky, 36% with High-risk level, 16% Medium risk level, 16% with Low risk level and 0% for the very low risk level. While the conventional FMEA gave 31%, 36%, 11%, 22%, and 0% for the Very High, High, Medium, Low and Very Low respectively.
- **Risk Raiting Matrix:** on the other hand, the distribution in the Risk Rating Matrix was different, the experts mentioned that they prefer to have a risk level scale with only three levels, and the results gives 40%, 49%, and 11% for the High, Medium, and Low risk level respectively.

It is cleare that the conventional FMEA and COMP-FMEA give more wider range of risk levels that can help in taking more convenient corrective actions. In addition, COMP-FMEA gives more reliable results as it depends on several factors which have been chosen and evaluated by the experts.

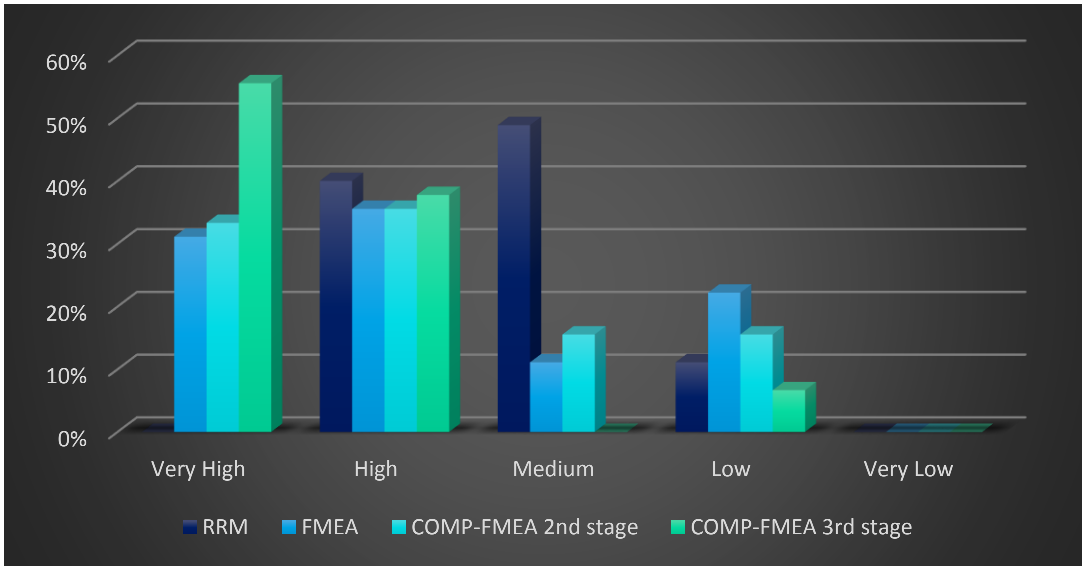

Figure 5-3 ***Risk distribution- Residential Building Case***

5.2.7.2 The correction factors effect

This effect comes from the third stage of COMP-FMEA. It aims at correcting the possible mistakes in the information given by the experts in the first stage. As mentioned before, this stage depends on two correction factors; the first one takes into consideration the long-term effect of the failure on the overall project. It gives the risk distribution of each failure in the steady state of the project (Equilibrium Stage). The second one has been designed to take into consideration the effect of each failure on the other failures, which called the effect of interdependence. Since the experts will give more attentions for the failure modes with Very High or High-risk level, thinking that these are the only failures badly affect the project and normally neglect the effect of the other failures. The two correction factors have been applied only on the failure modes with WRPN less than or equal 200, expecting that some of them has been wrongly evaluated in the second stage and needs some correction to make sure whether it has been settled in the real risk level or not.

The correction factors have been applied on fourteen failure modes having WRPN less than 200. Moreover, and as expected, 78% of the failures on which the correction factors have been applied, have moved from one risk level to another. Fig5-4 shows the difference in the risk distribution between COMP-FMEA in the second and third stage. Moreover, the results in table 5-42 show that, six failures have been transferred from the Medium risk level to the Very High, two from the Low risk level into the Very High, and one from the Low risk level to the High one. The analysis of this effect is shown as follows:

- **F5 (Hard rains, wrong assessment bearing capacity, defective design)**

  The Risk Rating Matrix showed that this is a Medium risky failure, while the conventional FMEA and the second stage of COMP-FMEA have evaluated this failure to be a low risky failure. The reason why it had low risk level in the second stage of COMP-FMEA was the low probability of occurrence and the detectability level of four. Despite this, after applying the third stage (the correction factors stage), the experts showed that F5 has a 75% probability to be High or Very High risky in the steady state of the project, and it could be a cause for 55% of the other failure mode with a probability higher than 40%. Therefore, the final evaluation of this failure was Very High risky failure mode.

- **F8 (Improper design of grating (water network))**

  The Risk Rating Matrix showed that it is a Medium risky failure, while the conventional FMEA grouped it a s a Low risky failure, and the second stage of COMP-FMEA have evaluated this failure to be a Medium risky failure. The second stage of COMP-FMEA showed that it has low probability of occurrence, Very low impact on the safety. While after considering the long-term effect and the effect of interdependence, the failure has been moved to the very high risky level as it has 36% probability to be a very high or high risk, and it could be a cause for 11% of the other failure modes with a probability higher than 40%.

- **F9 (Improper water height considerations)**

  The three methodologies have evaluated this failure to be a Low risky Failure. Despite, it has only 4% probability to be high risk in the long-term; it could be a cause of 34% of the other failures with a probability higher than 40%. Therefore, the third stage of COMP-FMEA suggested considering this failure mode to be a very high risk.

- **F23 (Improper steel design for columns)**

  It has been evaluated as a low risky failure by the conventional FMEA and as a medium risky failure from both the Risk Rating Matrix and the second stage of COMP-FMEA. However, after the correction process in the third phase of COMP-FMEA it has been moved to the very high-risk level. The reason behind that movement is the high probability for this failure mode to be high or very high risk in the equilibrium stage of the project (62%).

- **F24 (Improper calculation of design loads for the columns and cores)**

  The Risk Rating Matrix and the second stage of COMP-FMEA suggested that it is a medium risk, while the conventional FMEA has evaluated this failure to be a low risk as it has low probability of occurrence, moderate severity and low detection level. While, applying the third stage of COMP-FMEA showed that it has 70% probability to be a very high or high risk in the long-term, in addition, it could cause 14% of the other failure modes with a probability higher than 40%. Therefore, the final evaluation given by COMP-FMEA is a very high risk.

- **F28 (Improper selection of materials to be used in construction)**

  Sometimes, the evaluators forget the concept of the cost of poor quality. Therefore, the Risk Rating Matrix grouped this failure within the low risk group, and both the conventional FMEA and the second stage of COMP-FMEA have evaluated it to be a medium risk, simply because it has low probability of occurrence. This is one of the most shortcomings of not only the conventional FMEA but also COMP-FMEA if we applied only its second stage, that one factor (occurrence) could significantly affect the final evaluation. Therefore, the third stage of COMP-FMEA has been introduced. Which, showed that this failure has almost 88% probability to be high or very high risk in the long term (in terms of safety, cost and time as a criticality factors for our case) and could be a cause of 55% of the other failures with a probability higher than 40%, that finally converts it into a very high risk.

- **<u>F33 (Inadequate type of cement selection)</u>**

  For the same reason, not considering the cost of poor quality, the risk Rating Matrix considered inadequate type of cement selection as a medium risk, while the conventional FMEA and the second stage of COMP-FMEA, considered it as a low risk. Having 49% probability to be a high or very high risk in the steady state of the project, and having the possibility of being a cause for 18% of the other failure modes with a probability higher than 40%, gave it a final evaluation of high risk after applying the third stage of COMP-FMEA.

- **<u>F35 (Inadequate information in terms of the purpose of the structure, as well as the scope and complexity of the project)</u>**

  Because of the low likelihood, it has been evaluated as low risk from the Risk Rating Matrix and as a medium risk from both, the conventional FMEA and the second stage of COMP-FMEA. While after using the correction factors introduced in the third stage of COMP-FMEA, it is seen that it is the most risky failure mode ad it has been given the highest final RPN. Simply because it has 75% probability of being high or very high risk in the steady state of the project, and at the same time, it could be a cause for 71% of the other failures with a probability higher than 40%.

- **<u>F38 (Inadequate calculation of wind loads) and F39 (Inadequate calculation of earthquake loads)</u>**

  The two failure modes have the same evaluation of being a medium risk from the three methodologies (Risk Rating Matrix, conventional FMEA, and the second stage of COMP-FMEA). While the result came from applying the third stage of COMP-FMEA considered them as a very high risks, as they have a probability of 65% to be high or very high risk in the steady state of the project, and they could be a cause of 25% of the other failures with a probability higher than 40%.

- **F14, F15 and F41**

  Since they do not have a high probability of being high or very high risks in the steady state of the project (22%, 23% and 20%) respectively. Moreover, they do not have a significant impact on the other failures (7%, 7%, and 0%) respectively, the evaluation of the third stage of COMP-FMEA remains the same as the second stage. In addition, the evaluation is almost close to the evaluation of the other two methodologies.

Table 5-45 ***The correction factors effect- Residential Building Case.***

Failure	WRPN	RPN_{RCF}	RPN_{ICF}	RPN
F5	149	597	895	895
F8	151	303	303	303
F9	121	121	483	483
F14	135	135	135	135
F15	106	106	106	106
F23	170	510	170	510
F24	161	484	323	484
F26	140	419	140	419
F28	159	796	955	955
F33	144	289	289	289
F35	161	644	1128	1000
F38	158	475	475	475
F39	198	595	595	595
F41	148	148	148	148

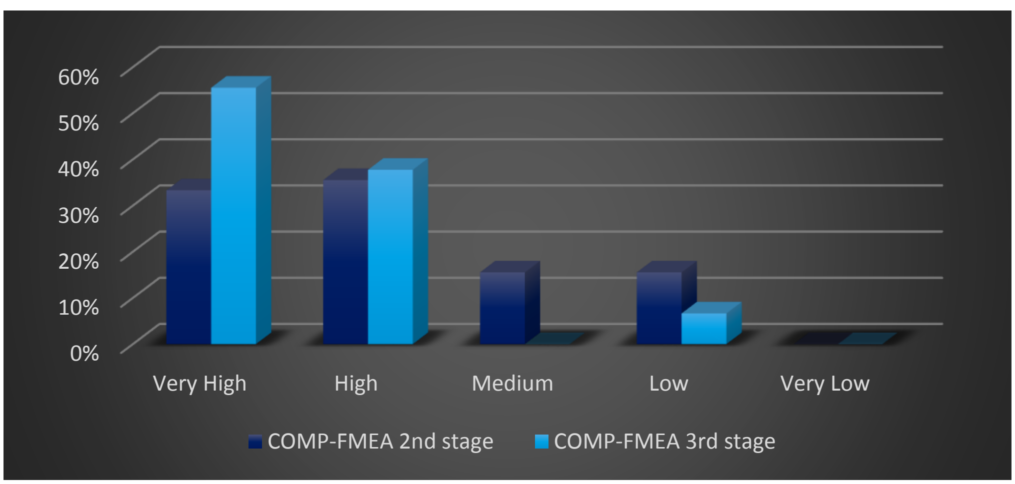

Figure 5-4 ***Risk level changes from second to the third stage of COMP-FMEA- Residential Building Case.***

5.2.7.3 The advantages of the proposed methodology

However, one of the main goals of the proposed methodology is to take into consideration the effect of Interdependencies among various failures that the conventional FMEA does not consider, and to reduce the effect of having inadequate information from the experts during the evaluation. It also succeeded in solving or at least reducing the effect of several limitations of the conventional FMEA such as:

- **The proposed methodology succeeded in reducing the number of duplicated RPN.**

  In the proposed case study, the number of failure modes having the same RPN has been reduced by 90%, since the conventional FMEA has nine cases of similar RPN coming from different combination, however only one case in the COMP-FMEA application.

- **The proposed methodology considers several criticality factors and there weights instead of using only three factors in the conventional FMEA.**

  As demonstrated before, dividing the severity into several factors with different weights makes the results more reliable. This allows the experts to identify the effect of each failure on the overall project more precisely.

- **This methodology provides Reprioritization Correction Factor (RCF), which reduce the effect of having inadequate information.**

  Introducing the first correction factor (RCF), which depends on the Markov Chain, allows the users to identify the risk distribution for the failure mode in the steady state of the project. Tis give a clear long-term vision on how the failure will affect the project.

- **The proposed method is an effective procedure to analyze structure and relationships between components of a system.**

  Using the second correction factor (ICF), allow the evaluators to take into account the effect of each failure on the others, this step has a significant effect on the final RPN.

- **The proposed method provides more accurate and effective information to assist the decision-making process.**

  Starting from the system analysis and identifying the scope, System mission, operation and parts and items to be analyzed identifications, passing through the criticality factors definition and the Pairwise Comparison, and ending up by the correction phase, makes the analysis more powerful and reliable. This can support the decision-making process in the short and long-term and allows the users to take better and more effective corrective actions.

6 CONCLUSION

This chapter represents the conclusion of the research. It starts with a discussion of the proposed research and ends with the advantages and limitations of the proposed methodology.

It is needless to speak again about the importance and the power of the Failure Mode and Effective Analysis (FMEA) as risk assessment and early preventative action tool and its potential for risk assessment on the construction projects. This has been discussed in detail in the given research. Nevertheless, it is very important to emphasize that due to the complexity and unique nature of the construction projects, it is inconvenient to apply conventional version of FMEA directly to a construction project.

Several improvements and modifications should take place in order to make FMEA convenient for the construction projects. Moreover, risk assessment for a construction project does not need a rigid tool; therefore, a customized and flexible tool that gives each project a unique risk assessment would assure more effective and reliable results.

The work has been started with the aim of providing a new methodology to assess the risk in the construction projects using the FMEA as a baseline. To fulfill this objective, the first step in the work was to review the traditional FMEA, trying to identify its advantages, limitations, risk evaluation methodologies used to improve the conventional FMEA and the possible application in the construction projects. The literature review shows that FMEA is one of the most important early preventative action tools in the system, process, design etc.; however, it has been extensively criticized for having many shortcomings, which lead to crisp risk priority numbers (RPNs) and subsequently low reliability of the FMEA process especially in complex systems.

Therefore, hundreds of researches have been carried out in order to address the conventional FMEA limitations. The majority of these researches used very complex methodologies such as fuzzy logic and Multiple-Criteria Decision Analysis to improve the conventional FMEA, however, other methods such as Monte Carlo simulation, Minimum cut sets theory, as well as Linear programming have been used and eventually provided good results.

The limitations of the Conventional FMEA and the complexity of the methodologies used to address these limitations, made it difficult to be used by different mentalities. Consequently, it led to limited use of the FMEA in the construction domain. Therefore, the applications of FMEA in the construction industry are still at their first step compared to its application in the manufacturing industry. Moreover, most of the authors who applied FMEA in the construction domain, have applied the conventional version without any major modifications. However, some of them have modified the conventional FMEA using the fuzzy logic in order to apply it in the construction domain in order to get more reliable results.

Despite that, FMEA has a strong potential to be a very effective tool for risk assessment in the construction projects. The second step in the research was to find a way to address the conventional FMEA limitations that made it incompatible with the construction projects. Therefore, the model presented in this thesis integrates the traditional FMEA with both The Method of Pairwise Comparison and Markov Chain in a comprehensive framework that provides a practical and thorough approach for assessing the risk in the construction domain.

A case study of a residential building was used to validate the concept of the proposed methodology based on the evaluation provided by a group of five experts. Forty-five failure modes were defined, and assigned to different sub- systems as the first step. Later on, an application of three methodologies (The Risk Rating Matrix, The traditional FMEA and COMP-FMEA) took place in order to check the capability of the proposed methodology through result comparison.

Benefits

The results obtained confirmed the capability and the usefulness of the method to produce enhanced FMEA results by addressing several conventional FMEA shortcomings.

As mentioned above, the framework of the conventional FMEA, which use only three main factors to evaluate each failure mode, Occurrence, Severity and Detection was the baseline for the proposed methodology; however, a significant improvement has been applied in the severity factor as the complex nature of a construction project makes it very difficult to have a general severity factor. Therefore, the methodology suggested that the user should define several criticality factors that together indicate the severity of a failure mode. These criticality factors vary from one project to another according to its nature, scope and final goal. (Three criticality factors have been used in the presented case study; Safety, Cost, and Time).

The Method of Pairwise Comparison was used for taking into account the relative importance of the input factors in calculating the RPN. The role of this methodology is to provide a Weighted Risk Priority Number (WRPN) by assigning different weights for the criticality factors defined by the user according to importance and impact on the project, which addressed one of the conventional FMEA Limitations that the relative importance among O, S and D is not taken into consideration.

Additionally, the proposed methodology has the ability to dramatically reduce the possibility of having similar values of RPN by using different combination of O, S, and D in the conventional FMEA (90% reduction as a final result in the proposed case study).

In order to avoid the possibility of having inadequate information provided by the experts during the early evaluation and to take into account the long-term effect of the different failure modes in the overall system, a further evaluation has been applied using Markov Chain for the failures having WRPN less than or equal to 200. This evaluation gives the possible risk distribution of a failure mode in the steady state or in the equilibrium stage of the project. Later on, this evaluation has been translated into a correction factor named Reprioritization Correction Factor.

Moreover, in order to address another limitation of the conventional FMEA concerning that the Interdependencies among various failure modes and effects are not taken into account, further correction process has been applied on the failure modes having WRPN less than or equal 200 by defining the probability of each failure to be a cause for the other failures.

Limits and suggestions for further researches:

Despite these improvements, the methodology developed has shown some limitations that could be a starting point for future studies in this research area.

The proposed methodology still depends on linguistic evaluation for the criticality parameters, which provide uncertainty and variety of the information provided by experts. However, a correction process could be developed to reduce this effect, such as a further improvement using fuzzy sets in order to provide more precise evaluation.

The methodology used Markov Chain for the long-term risk assessment using only one-step as a reference for the steady state risk distribution vector. However, this might not be very effective in the short duration projects.

The values of the proposed correction factors are not highly accurate; instead, they depend on the user perspective, and thus could be more or less conservative. Therefore, a future work needs to be oriented towards identifying the most suitable correction factors values.

COMP-FMEA does not include a corrective action process. Therefore, what can be suggested is a future work that aims at developing a database of recommended corrective actions that are suitable for each specific risk in the different project stages, partially based on historical data and lessons learned. Moreover, this database is suggested to contain the actual probability of each failure to move from a certain risk level in a certain project stage to a different risk level in different project stage, which will allow having more reliable and accurate results from the use of Markov Chain.

Furthermore, another future research could be also a continuous application of FMEA at each stage of the project life cycle. This challenge requires a risk-based culture within the organization and a collaborative risk assessment performed by each function of the organization.

The following tables 6-1 and 6-2 summarizes the addressed/non-addressed conventional FMEA shortcomings, the limitations of proposed methodology and the suggested future works.

Table 6-1 ***The addressed conventional FMEA shortcomings using COMP-FMEA.***

FMEA Shortcomings	Status	Proposed solution
The relative importance among O, S and D is not taken into consideration.	Addressed	The use of the Method of Pairwise Comparison has addressed this limitation by introducing different weights for the different criticality factors.
Different combinations of O, S and D may produce exactly the same value of RPN, but their hidden risk implications may be totally different.	Addressed	The use of the Method of Pairwise Comparison in the second phase of the proposed methodology reduced the number of duplicated RPNS, moreover, the correction process in the third phase helped to give further long-term assessment in order to avoid the hidden risk effect.
The three risk factors are difficult to be precisely evaluated.	Partially addressed	The user involvement in the criticality factors identification process that gives several criticality factors instead of only three factors, which also vary from project to another and the proposed correction process helped to give more precise evaluation.
The mathematical formula for calculating RPN is questionable and debatable.	Not addressed	
The conversion of scores is different for the three risk factors.	Not addressed	
The RPN cannot be used to measure the effectiveness of corrective actions.	Not addressed	
RPNs are not continuous with many holes.	Not addressed	

Interdependencies among various failure modes and effects are not taken into account.	Addressed	Introducing the interdependence correction factor helped to address this limitation.
The mathematical form adopted for calculating the RPN is strongly sensitive to variations in risk factor evaluations.	Partially addressed	This limitation has been partially addressed using several criticality factors and the correction process.
The RPN elements have many duplicate numbers.	Addressed	The Pairwise Comparison which gives different weights to the criticality factors, also the correction process succeeded to reduce the number of the duplicated RPN (90% reduction in the introduced case study).
The RPN considers only three risk factors mainly in terms of safety.	Addressed	The proposed methodology gives the user the possibility to choose several criticality factors and to design the evaluation criteria.

Table 6-2 ***COMP-FMEA Limitations and the possible future work.***

COMP-FMEA Limitations	Possible future work
The proposed methodology still depends on linguistic evaluation.	Using a fuzzy sets in order to improve the evaluation process.
Using only one-step assessment in the Markov Chain application.	Database based on historical data and lessons learned the to provide more accurate assessment.
The values of the proposed correction factors are not highly accurate.	Using database followed by a fuzzy set application could provide more accurate correction factors values.
The COMP-FMEA does not include a corrective action process.	Database of recommended corrective actions that are suitable for each specific risk in the different project stages, partially based on historical data and lessons learned.

Possible applications for COMP-FMEA:

Although COMP-FMEA has been designed in order to assess risk in the construction projects, it has a strong potential to be applied on several domains such as manufacturing, maintenance, Pharmaceutical industry...etc. Furthermore, different applications of COMP-FMEA in different industries with the aim of gathering information about industries different behavior would be a starting point for developing a software for the proposed methodology. This software should contain database for each industry that presents the possible failures, criticality factors, corrective actions based on historical projects and lessons learned, which would provide very effective and structured assessment that helps in providing project integrated risk assessment for different domains.

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8 APPENDIX

The MATLAB Script

```
p_5 = [ 1 1 3 4 4;
0 1 3 4 4;
0 0 5 4 4;
0 0 2 4 4;
0 0 2 4 4];
p_5 = pro(p_5)
p_5 = check(p_5);
[Final_RV_5, p_ss_5] = Final_Risk_State( p_5, IRV_5)


p_8 = [ 0 2 3 1 0;
1 2 3 1 1;
0 1 4 1 1;
0 0 3 1 1;
0 0 2 3 1];
p_8 = pro(p_8)
p_8 = check(p_8);
[Final_RV_8, p_ss_8] = Final_Risk_State( p_8, IRV_5)

p_9 = [ 1 3 1 0 0;
1 5 1 0 0;
0 5 2 1 1;
0 4 2 0 0;
0 4 2 0 0];
p_9 = pro(p_9)
p_9 = check(p_9);
[Final_RV_9, p_ss_9] = Final_Risk_State( p_9, IRV_5)

p_14 = [ 1 4 2 0 0;
1 5 2 0 0;
2 3 1 0 0;
2 3 1 0 0;
2 3 1 0 0];
p_14 = pro(p_14)
p_14 = check(p_14);
[Final_RV_14, p_ss_14] = Final_Risk_State( p_14, IRV_5)

p_15 = [ 1 3 3 2 0;
1 3 3 2 0;
1 2 2 2 0;
1 2 2 1 0;
1 2 2 1 0];
p_15 = pro(p_15)
p_15 = check(p_15);
[Final_RV_15, p_ss_15] = Final_Risk_State( p_15, IRV_5)

p_23 = [ 1 1 3 4 4;
1 1 3 4 4;
1 1 3 4 4;
1 1 3 5 4;
1 1 3 4 4];
p_23 = pro(p_23)
p_23 = check(p_23);
```

```
[Final_RV_23, p_ss_23] = Final_Risk_State( p_23, IRV_5)

p_24 = [ 0 1 2 4 5;
0 1 3 4 5;
0 1 4 4 5;
0 1 3 5 5;
0 1 3 5 5];
p_24 = pro(p_24)
p_24 = check(p_24);
[Final_RV_24, p_ss_24] = Final_Risk_State( p_24, IRV_5)

p_26 = [ 1 1 3 4 4;
0 1 3 4 4;
0 0 4 4 4;
0 0 4 5 5;
0 0 4 5 5];
p_26 = pro(p_26)
p_26 = check(p_26);
[Final_RV_26, p_ss_26] = Final_Risk_State( p_26, IRV_5)

p_28 = [ 1 1 2 3 5;
0 1 2 3 5;
0 0 1 3 5;
0 0 1 3 4;
0 0 1 2 5];
p_28 = pro(p_28)
p_28 = check(p_28);
[Final_RV_28, p_ss_28] = Final_Risk_State( p_28, IRV_5)

p_33 = [ 1 1 3 3 2;
0 1 3 3 2;
0 1 5 3 2;
0 1 4 3 2;
0 1 4 3 2];
p_33 = pro(p_33)
p_33 = check(p_33);
[Final_RV_33, p_ss_33] = Final_Risk_State( p_33, IRV_5)

p_35 = [ 1 2 3 5 4;
0 2 3 5 4;
0 1 3 5 4;
0 0 3 5 4;
0 0 3 5 4];
p_35 = pro(p_35)
p_35 = check(p_35);
[Final_RV_35, p_ss_35] = Final_Risk_State( p_35, IRV_5)

p_38 = [ 0 1 3 4 4;
0 1 3 4 4;
0 1 4 4 4;
0 1 4 5 5;
0 1 4 5 5];
p_38 = pro(p_38)
p_38 = check(p_38);
[Final_RV_38, p_ss_38] = Final_Risk_State( p_38, IRV_5)

p_39 = [ 0 1 3 4 4;
0 1 3 4 4;
```

```
0 1 4 4 4;
0 1 4 5 5;
0 1 4 5 5];
p_39 = pro(p_39)
p_39 = check(p_39);
[Final_RV_39, p_ss_39] = Final_Risk_State( p_39, IRV_5)

p_41 = [ 1 1 2 1 0;
1 1 2 1 0;
1 1 2 1 0;
1 1 2 1 0;
1 1 2 1 0];
p_41 = pro(p_41)
p_41 = check(p_41);
[Final_RV_41, p_ss_41] = Final_Risk_State( p_41, IRV_5)
```