Best-Worst Failure Mode and Effect Analysis: a novel approach to appraise the impact of safety, times and costs on engineering and construction projects

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Abstract: This research is focused on risk assessment for construction projects through Failure Mode Effect Analysis (FMEA). The aim is to develop an improved FMEA methodology by integrating in FMEA the Best Worst Method. In particular, the new approach includes a wider range of criticality factors instead of the traditional three factors, namely Occurrence, Severity and Detection. The methodology is then further enhanced with long-term risk assessment by the use of Markov Chain to overcome possible inaccurate evaluations during the first stage. The research framework and methodology have been validated by means of a case study in the construction industry. The application allowed to further improve the conventional FMEA through the introduction of a weighted risk priority number (WRPN) that has been applied to the safety assessment to certain critical failures. The research resulted in a detailed map of the possible risks distribution along the stages of project development.

Keywords: FMEA, Best Worst Method, Markov Chain, Risk analysis, WRPN

I. Introduction

Construction industry is an important economic contributor and an extensive workforce employer. Yet, because of working places and conditions, it is one of the most hazardous industry, with lags regarding safety as compared to other sectors (Hinze, 2008; Ringen et al., 2010). Likelihoods of death and injuries for the workers in this sector are three and two times, respectively compared with other industries. According to European Agency for Safety and Health at Work, more than 1,000 workers died and over 800,000 injured every year in Europe (EU-OSHA Magazine 7, 2004).

Risk management techniques in construction industry underwent significant improvements in the last decade. Yet, risks associated with a construction project and its relative supply chain have not decreased as expected. This may be mainly due to the fact that it may be very difficult to define reliable methodologies able to ensure a complete safety, reliability and risk analysis of a project. In particular, construction projects are regarded as one of the highest risk project type (Sharma, 2013). In this area, several studies have been developed to mitigate the project risks (Muriana and Vizzini, 2017).

The present study aims at developing a new risk assessment methodology considering the mutual influence between failure modes. The aim is to provide a good level of flexibility and customization for the users. In particular, the new methodology wants to overcome some of the main problems affecting traditional FMEA such as the tendency to always consider a unique cause-effect relationship.

The Best Worst FMEA (BW-FMEA) developed in this research allows to define specific criticality factors that might affect the project. Then, the methodology is further improved with the use of Markov Chain to appraise the risk level in the long-term of the project.

The remainder of the paper is organized as follows: Section 2 presents a state of art review of the recent literature. Section 3 illustrates the research objectives and framework, while Section 4 discusses the model application. Section 5 presents some critical analysis and final remarks, while Section 6 concludes the paper.

II. Literature Review

A. Construction and Risk Assessment

Risk analysis/assessment has always deserved significant importance in the field of engineering and construction (Menanno et al, 2021, Banaitiene and Banaitis, 2012). This work identified different types of risk based on the findings of questionnaire-based survey in Lithuania.

Major concern related to construction risks was due to mismanagement and improper scheduling or estimating by project managers. Risk preventive techniques – introduced before the project began – and corrective ones deliberated during the execution phase. The major risk factors identified were financial issues, sudden mishaps on the sites or defective design patterns being followed. Further, most of the risks in the implementation phase were due to the contractors' mismanagement, such as issues related to labour, subcontractors, availability of materials and machinery. The research also revealed that clients were responsible for financial constraints, design and code issues related to wrong codes assignments and contradictions in the construction documents. A study of El-Sayegh and Mansour (2015) based on similar construction projects in the UAE was presented, highlighting substantial risks in highway construction. In order to avoid risk factors on later stages these authors concluded that Project Managers should estimate and evaluate the risk factors at earlier stages. Then, a paper by Lund-Thomsen et al (2016) discussed about the corporate social responsibility in the developing countries. These authors focused on the improvement of environmental management and work circumstances of the local industrial domain.

B. *Construction Industry and FMEA*

According to a recently published research, "Construction is one of the world's biggest industrial sectors, including the building, civil engineering, demolition and maintenance industries. It is, however, one of the most dangerous industries" At least 108 thousand workers die on construction sites every year, a figure that accounts for about 30 percent of all occupational fatal injuries. Data from some industrialized countries show that construction workers are 3 to 4 times more likely than other workers to die from occupational accidents (International Labour Organization, 2015). To improve this situation, FMEA has been implemented by construction firms as it addresses budget, schedule, and technical risk at once, even though it does so based on ordinal, rather than cardinal, scales (Yu and Lee, 2012).
Most of the scientific publication in the field used the conventional FMEA for construction projects risk assessment, while some authors proposed a modified version of FMEA, which – in most of the cases – was combined with fuzzy logic.
Fayek, (2010) proposed an extension application of FMEA to risk management in construction industry. He used combination of Fuzzy Logic and Fuzzy Analytical Hierarchy process (AHP) to build the model.
Mohammadi and Tavakolan (2013) used the same concept of fuzzy-AHP based FMEA. His model considered more dimensions in the evaluation process. He presented a practical approach for construction project risk assessment based on combined Fuzzy and FMEA. AHP is utilized to assess cost and time impact, quality and safety impact, which gave this approach a more general-purpose and flexible structure considering all aspects of risk impact (Mushtaq et al., 2018).
Zang et.al, (2011) 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 et.al, (2011) proposed a complete FMECA application to enhance Building maintainability through mitigation of defects. The methodology used bottom-up, qualitative FMECA as a suitable defect-grading tool and developed criticality parameters applicable for buildings.

C. *Limitations of FMEA*

Although FMEA is one of the most important early preventative actions in the system, process, design etc., it has been extensively criticized for its many shortcomings, which lead to a high risk priority number (RPN), and thus low reliability of the risk assessment process especially for complex systems. Therefore, a significant amount of research has been carried out in order to eliminate or decrease the effect of these shortcomings. Chin et.al, (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. 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, namely i)probability of failure, ii)probability of non-detection, iii)severity, and iv)expected cost, instead of the three traditional factors proposed by conventional FMECA.
Wang et.al (2009) proposed a fuzzy risk priority number (FRPN) to prioritize the failure modes based on alpha-level sets and linear programming models.
Based on the above mentioned literature review, it can argued that there are many limitations regarding these methodologies used below. Most of the methodologies use linguistic evaluation for criticality parameters, which provides uncertainty and variety in the experts' provided information. There is not a single unified methodology that can accurately evaluate risk with 100 percent confidence. These risk evaluation methodologies have different aspects, thus we cannot assume that one single methodology is valid for the whole cases. It can also be seen that Fuzzy technique is the most common methodology. Moreover, the larger the number of rules provided by the experts, the better the prediction accuracy of the fuzzy RPN model.

III. RESEARCH FRAMEWORK

Despite the wide use of FMEA as a risk assessment tool to improve safety and reliability of a system in construction projects, the conventional FMEA may have some limitations due to the complexity of the risks existing in design, supply chain and construction phases. These limitations may further increase in case of interdependence between the different failure modes that are not considered with the conventional method, or when the assessment relates to long-term risks. To overcome this limit and to assess risk distribution, Brun et al. (2017) improved traditional FMEA integrating it with the pairwise comparison method and Markov chains. The present paper aims to apply the previous FMEA methodology to construction projects, improving it with more attention to importance of input factors such as cost, lead time and safety in risk priority number calculation. This new approach called BW-FMEA (Best-Worst FMEA) is based on the integration of Failure Mode Effect Analysis with the Best-Worst method (BWM) jointly with Markov Chains approach. The way the new methodology works is illustrated in Figure 1.

After analyzing the system with the identification of hierarchical levels, the methodology provides the calculation of a Weighted Risk Priority Number (WRPN) based on the selection of the most significant parameters that can influence the project, namely critical factors, that can vary depending on the characteristics of the project.

Then, two correction factors are used. The first one is called Reprioritization Correction Factor (RCF), based on the concept of Markov Chain, introduced to correct the possible mistakes of having inadequate information given by the experts during the first stage. RCF allows a better assessment of 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).

The second correction factor is called Interdependence Correction Factor (ICF) and has been designed to take into account the effect of the interdependency of different failures that are neglected by the conventional FMEA. ICF calculation is based on a matrix assessing the effect of each failure mode on other failure modes. In particular, experts shall assess 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 other failures.

In the first phase the methodology provides an analysis, namely Project and Process FMEA (PP-FMEA), that considers the design, supply chain and construction activities. For each activity, the failure modes and their effects on the system are recorded in a worksheet.

The four basic steps of the analysis are the following:

1. Definition of the system;
2. Mission analysis, operation and parts of the system;
3. Identification of hierarchical levels to conduct analyzes;
4. Identify each item to be analyzed.

The second phase evaluates the weighted risk priority number (WRPN). Construction project includes several significant parameters that can influence the system. In the present study the severity factor of FMEA is divided into three main factors, such as Lead time, cost and safety.

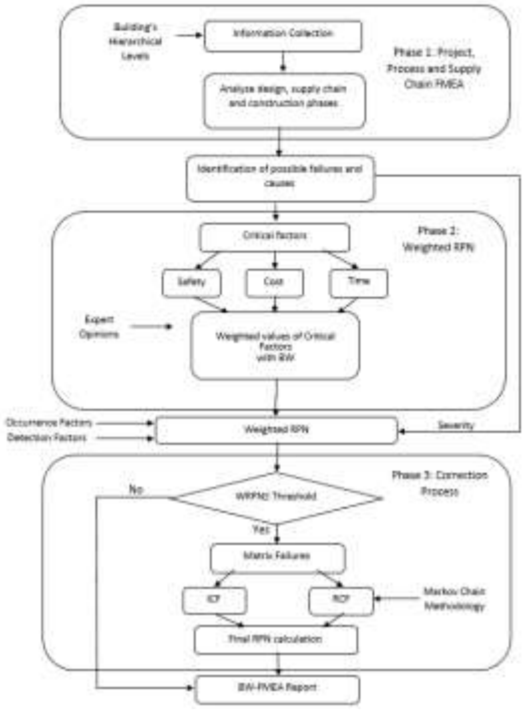

Fig 1. Flow Chart

BW-FMEA makes it possible to assess whether the severity of a failure mode is derived from a specific parameter based on the characteristics and scope of the project. Through the BW method, which compares 2n + 3 criteria in contrast to the pairwise comparison method which does n * (n + 1)/2 evaluations, weights are assigned to the critical factors related to severity. Therefore, this method may allow for a lower degree of inconsistency in expert opinions because it reduces the number of comparisons resulting faster.

The third phase carries out an analysis of failures from average to minimum failures with a threshold for WRPN set at 200, improving the probability of each risk (Braglia and Montanari, 2007; Carmignani, 2009). In this step two correction factors are introduced such as RCF and ICF.

As shown in the flow chart (Figure 1), the methodology ends with the determination of the new RPNs of the system. The final results consider the different interactions of the failure mode and the weights as regards to critical factors which can play a crucial role in construction industry.

IV. CASE STUDY

The research methodology developed in this study has been applied to the risk analysis of a residential building project. The first phase has been conducted thorough a meeting with five experts of Quality, Safety, Project Management, Design and Supply Chain. The analysis phase regarded a description of the mission, operations and parts of the system. As a result of this portion of the study, the hierarchical levels of all the elements have been identified, along with the critical elements that may cause potential failure modes. The project of the case study has been divided into eight subsystems (figure 2), in which the failure modes can be assigned to each level of this sub-system.

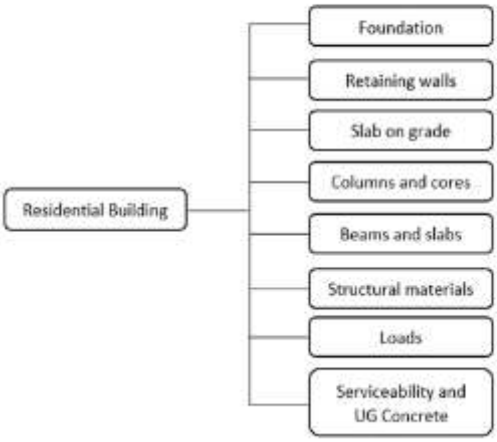

Fig. 2. Hierarchical structure of the construction project

Through the interviews, the potential failure modes have been assessed referring to three main groups of activity, namely (i) Design; (ii) Construction; (iii) Supply chain (Liu et al., 2013).

Then, the potential failures have been assessed with the relative effect on the system.

Phase 2 - Weighted Risk Priority Number (WRPN)

In this phase, the three main critical factors such as safety, costs and time are defined. These factors, combined together, will measure the severity of a failure mode and each factor has been divided into several linguistic classes in a [1-100] scale.

After selecting and defining the criticality factors, a Best Worst Method (BWM) has been used in order to define the importance of each factor in the project through the weights calculation. BWM is a decision- making method that uses two vectors of pairwise comparisons to determine the weights of criteria. After identifying the fundamental decision criteria, each of the experts is asked to evaluate the best enabler, which is the most desirable and the worst enabler, the least desirable. This technique was developed by Rezaei (2015); it allows to solve the problem of inconsistency during the comparison in pairs requiring a reduced number of comparisons compared to other techniques. BWM requires fewer comparison data, while being able to generate more consistent comparisons, allowing it to produce more reliable results according to previous analyses (Rezaei, 2015). Based on the answers of all the experts, safety is identified as the best criteria (Best-to-Others - BO) and time is identified as worst (Others-to-Worst – OW. Table I reports the comparison vectors obtained according to the experts' opinions. Furthermore the experts were asked to evaluate the preference of the best criteria with respect to all the main criteria and likewise all the other criteria with respect to the worst criteria on a scale from 1 to 9. In which the first vector is obtained by determining the preference of the best criterion according to the experts' judgment values. While in the second vector the experts' judgment value is compared to the worst one.

TABLE I
BEST-TO-OTHERS (BO) AND OTHERS-TO-WORST (OW) PAIRWISE COMPARES ON VECTORS

BO	Safety	Cost	Time
Best Criteria:	1	5	7
OW		Worst criterion: Time	
Safety		8	
Cost		5	
Time		1	

After obtaining the comparison score in pairs for all the criteria, the next step is to find the optimal weights for each of the main criteria, by formulating and solving a linear programming problem, in which the absolute differences for all j is minimized according to (1).

$$\begin{cases} \min \xi \\ \left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi \quad for\ all\ j \\ \left|\frac{w_j}{w_w} - a_{jw}\right| \leq \xi \quad for\ all\ j \\ \sum_j w_j = 1 \\ w_j \geq 0, \quad for\ all\ j \end{cases} \tag{1}$$

Where

$a_B = (a_{B1}, \dots\dots a_{Bn})$, best-to-others (BO) vector;

a_{Bj} indicates the preference of the best criterion B over criteria j and a_{BB}=1;

$a_w = (a_{1W}, \dots\dots a_{nW})^T$, others-to-worst (OW) vector;

a_{1W} indicates the preference of the criteria j over the worst criterion W and a_{WW}=1;

Solving the (1) we obtain the optimal weights for each of the criteria w*1, w*2, w*3 and the optimal value of ξ (Table II). At this step a consistency ratio is calculated to evaluate the goodness of the judgment. The comparison is fully consistent when a_{Bj} x a_{jw} = a_{Bw}, for all j, where a_{Bj}, a_{jw} and a_{Bw} are respectively the preference of the best criterion over the criterion j, the preference of criterion j over the worst one, and the preference of the best criterion over the worst one.

TABLE II
OPTIMAL WEIGHTS FOR THE CRITERIA

Criteria	Weights	ξ^*
Safety	0.731	
Cost	0.187	0.046
Time	0.082	

The judgments can be considered as acceptable if ξ^*<0.1 (Rezaei, 2015). For this case study ξ^*=0,046, thus confirming that the judgment is acceptable.

The results obtained by solving eq. (1) show that Safety has the highest priority with a weight of 73%, followed by the Cost 19% and 8% for the Time. Then, a Weighted Risk Priority Number (WRPN) has been calculated for each failure mode (Brun et al. 2017) through eq. (2).

$$\text{WRPN} = \text{Oi} \times \left(\frac{\text{F1} \times \alpha 1 + \text{F2} \times \alpha 2 + \text{F3} \times \alpha 3 + \cdots \text{Fi} \times \alpha \text{i}}{10}\right) \times \text{Di} \tag{2}$$

Where Fi is the criticality factor score; Oi is the occurrence failure; α the criticality factors weight; Di is the detection failure and i the number of critically factors.

Phase 3 Re-assessment of RPN

The last phase of the methodology consists in the re-assessment of failures with low, very low and Medium risk to select the failures that may be under a predefined threshold (Brun et al. 2017). After analysing the results obtained during the phase 2, the correction process was actuated only to those failures with WRPN less than 200 (Braglia and Montanari, 2007; Carmignani, 2009). The threshold value was chosen taking into account the number of failures that needed a new evaluation to avoid the re-examination of the High risk ones.

With this aim, the RCF is used to correct the possible errors due to inadequate information got in the first phase. The RCF considers the possible effect of failures in the long term, to check whether the risk levels may remain almost the same or they could increase over time. RCF is determined through two steps. First, we identify the initial risk vector and the transition matrixes. Then, we calculate risk probability at the steady state of the project.

TABLE III

GIVES THE OUTPUT OF THIS PHASE.

	Second stage Assessment						
	Risk level	Very low	Low	Medium	High	Very high	Total
First Stage	Very low	0.076	0.076	0.230	0.307	0.307	1
	Low	0	0.083	0.250	0.333	0.333	1
	Medium	0	0	0.384	0.307	0.307	1
	High	0	0	0.200	0.400	0.400	1
	Very High	0	0	0.200	0.400	0.400	1
	Total	0.076	0.160	1.265	1.748	1.748	

In this step of the methodology, we explored the long-term equilibrium stage, in which each risk level may remain constant. The Markov chain model is of ergodic type, that is why the risk distribution for each level remains constant after long time (Sujiao, 2009). The probabilities to find errors into a certain risk level along the steady state are described as a steady state vector evaluated with risk distribution equation. The vector resulting from this part of study is reported in Table IV.

TABLE IV

THE RISK DISTRIBUTION AT THE PROJECT STEADY STATE

	The Probability at the steady state					
	V1	V2	V3	V4	V5	
Failure	Very low	Low	Medium	High	Very high	Total
F5	0.000	0.000	0.245	0.377	0.377	1.00
F8	0.013	0.104	0.519	0.208	0.154	1.00
F9	0.119	0.671	0.170	0.018	0.018	1.00
F14	0.161	0.441	0.173	0.111	0.111	1.00
F15	0.139	0.318	0.318	0.229	0.000	1.00
F23	0.075	0.075	0.225	0.323	0.300	1.00
F24	0.000	0.071	0.232	0.330	0.359	1.00
F26	0.000	0.000	0.300	0.350	0.356	1.00
F28	0.000	0.000	0.123	0.297	0.579	1.00
F33	0.000	0.097	0.416	0.291	0.194	1.00
F35	0.000	0.021	0.244	0.402	0.326	1.00
F38	0.000	0.070	0.276	0.326	0.326	1.00
F39	0.000	0.070	0.276	0.326	0.326	1.00
F41	0.200	0.200	0.400	0.200	0.00	1.00

Then, the RCF is calculated as the sum of the probability of the failure mode to have a High or Very High risk.

V. INTERDEPENDENCE CORRECTION FACTOR (ICF)

The ICF is conceived to consider the effect of the interdependency of different failures, that is usually neglected by the conventional FMEA.

This factor is calculated through the Interdependencies Matrix (IM), that reports the effect of each failure on the other failure modes. To build the IM, the experts define the relationships between the different failure modes by identifying the probability of a certain failure to be a cause of the other failures.

The RPN needs to calculate the Failure Impact Ratio (FIR), that is defined as the ratio of number of probabilities higher than or equal to threshold and total number of failures (eq.3), where the threshold is defined through the literature and expert's estimations as 0,4.

$$\mathrm{FIR} = \frac{\text{Number of probabilities} \geq 0{,}4}{\text{Total number of failures} - 1} \quad (3)$$

At this stage, the ICF can be set on a [1-9] scale in relation to the value of the FIR. The results of FIR computing through eq. 3 are shown in table V.

Final RPN calculation

The final RPN for the failures with WRPN $\leq$200 is calculated through (4).

$$\mathrm{RPN} = \max(\mathrm{WRPN} \times \mathrm{RCF}; \mathrm{WRPN} \times \mathrm{ICF}) \leq 1000 \quad (4)$$

TABLE V

FINAL RPN VALUES

Failure	RCF	$\mathrm{RPN}_{\mathrm{RCF}}$	ICF	$\mathrm{RPN}_{\mathrm{ICF}}$	RPN
F5 – Hard rains	4	597	6	895	895
F8 - Design of grating	2	303	2	303	303
F9 - Water height	1	121	4	483	483
F14 - Loads on slab on grade	1	135	1	135	135
F15 - Contraction and expansion joints	1	106	1	106	106
F23 - Steel design for columns	3	510	1	170	510
F24 - Calculation of loads	3	484	2	323	484
F26 - Plotting of columns	3	419	1	140	419
F28 - Selection of materials	5	796	6	955	955
F33 - Type of cement	2	289	2	289	289
F35 – Information on purpose of the	4	644	7	1128	1000

structure					
F38 - Calculation of wind loads	3	475	3	475	475
F39 - Calculation of earthquake loads	3	595	3	595	595
F41 - Calculation of fire rating	1	148	1	148	148

VI. DISCUSSION

The methodology developed in this study was tested by comparing it with Conventional FMEA and the Risk Rating Matrix. The second one 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 worst-case outcome, and the Likelihood (L), that indicates chance of happening. Conventional FMEA is a little more sophisticated than the Risk Rating Matrix, as it evaluates risks by assigning a value to Occurrence, Severity and Detection of each failure according to standardized tables, such as the one proposed by Chin et.al, (2009) and Wang et.al. (2009). Then, the RPN is calculated for each failure. The results of the applications of the three methodologies is shown in figure 3. As we may see, in terms of the highest risk distribution, the BW-FMEA gives the highest value and the Risk Rating Matrix gives the lowest one. In particular, from the BW-FMEA we obtained a risk distribution close to the conventional FMEA with a low increase for those failures with Very High and Medium risk levels. We may also see a corresponding reduction in the number of failures with Low risk level. It is clear that the conventional FMEA and the newly proposed BW-FMEA give a wider range of risk levels that can help in taking more convenient corrective actions. According to the results obtained, we may argue that the added value of BW-FMEA lies in the reliability of the results, because it relies on a number of factors chosen and evaluated by the experts.

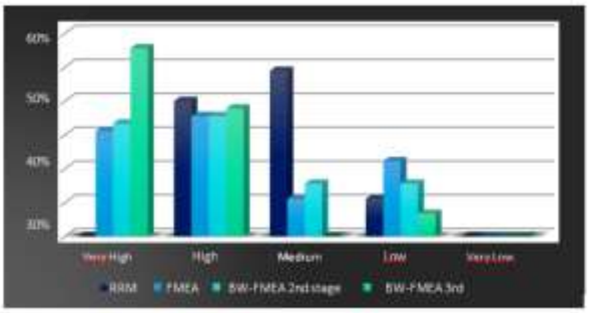

Fig. 3. Risk distribution- Residential Building Case

The correction factors effect comes from the third stage of the methodology, aiming at rectify the possible mistakes in the information given by the experts in the first stage. The two correction factors have been applied only on the failure modes with WRPN less than or equal to 200 (Brun et al, 2017), expecting that some of them may have been incorrectly evaluated in the second stage and need some adjustment.

TABLE VI
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

The correction factors have been applied on 14 failure modes with a WRPN lower than 200. As expected, 78% of said failures moved from one risk level to another. Figure 4 shows the difference in the risk distribution between BW-FMEA in the second and in the third stage.

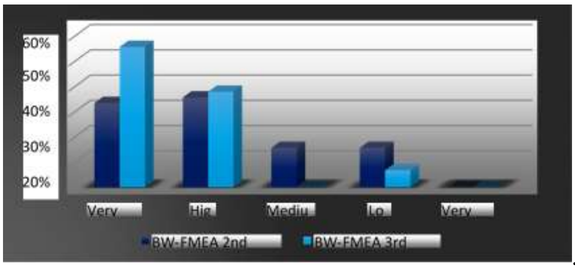

Fig. 4. Risk level changes from second to the third stage of BW-FMEA- Residential Building Case

For F5 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. For F14, F15 and F41, 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.

We may argue that one of the main goals of the proposed methodology is to consider the effect of Interdependencies between faults that conventional

FMEA does not consider, thus moderating the handicap of having inadequate information from the experts during the evaluation. Furthermore, the BW-FMEA reduces the limits of the conventional FMEA as follows:

•Reducing the number of duplicated RPN

The number of failure modes with the same RPN has been reduced by 90%, since the conventional FMEA has nine cases of similar RPN coming from different combination. In contrast, there is just only one case in the BW-FMEA approach.

• Possibility to use a variable number of criticality factors with different weights, make the results more diversified and allows to better highlight the failure having higher severity on project.

• 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 addressed, moving on with the criticality factors definition and the Pairwise Comparison, and ending up with a correction phase, makes the analysis more powerful and reliable. Our methodology can support the decision-making process in the short and long-term, allows the users to make better and more effective corrective actions.

VII. CONCLUSIONS

This work aims to provide a new methodology to assess risks in construction projects based on an improved version of FMEA. With this purpose, the proposed framework and the methodology have integrated the traditional FMEA with the BWM and Markov Chain in a comprehensive framework that provides a practical and thorough approach for assessing the risk in the construction domain. The results obtained have confirmed the capability and the usefulness of the method to produce enhanced FMEA results by addressing several shortcomings of the conventional FMEA. The BW Method has been used to consider the relative importance of the input factors in calculating the RPN, while the use of Markov chains reduced the possibility of having similar RPN values. Differently from the conventional FMEA, the methodology adopted allowed correction of the wrong information provided by the experts in the first phase through the effect of the interdependencies between the various failures. According to the results obtained, we may argue that the added value of the novel BW-FMEA approach lies in the reliability of the risk appraisal; 78% of the faults on which the correction factor was applied had a variation in the resulting risk level. Notwithstanding the improvements obtained, the methodology has shown some limitations. The most prominent limitation is that BW-FMEA risk assessment still depends on linguistic evaluation for the criticality parameters, which may let incur in a certain degree of subjectivity and uncertainty linked to the (possible) limited information available to experts. As a future research avenue, a decision support method could be developed in this regard, to reduce judgemental estimation, thus achieving a more accurate evaluation.

REFERENCES

[1] Banaitiene N., Banaitis A., (2012). "Risk management in construction projects. Risk Management–Current Issues and Challenges." In N. Banaitiene (Ed.), Risk Management–Current Issues and Challenges. 12:429-48.

[2] Braglia, M. F., and Montanari R., (2007). The house of reliability. International Journal of Quality & Reliability Management, 24(4), 42-440.

[3] Braglia, M., (2000). MAFMA: multi-attribute failure mode analysis. International Journal of Quality & Reliability Management, 17(9), 1017 - 1033.

[4] Brun A., Savino M. M., (2017) "Assessing risk through composite FMEA with pairwise matrix and Markov chains". International Journal of Quality & Reliability Management, 35(9), 1709-1733.

[5] Carmignani, G., (2009). An integrated structural framework to cost-based FMECA: The priority-cost FMECA. Reliability Engineering and Systems Safety, 94(4), 861-871.

[6] Chew, M. Y. L., Das, S., (2011). Generic Method of Grading Building Defects Using FMECA to Improve Maintainability Decisions. Journal of performance of constructed facilities, 1-12.

[7] Chin, K.S, Yang, J. B., Poon G. K., Yang, J. B., (2009). Failure mode and effects analysis using a group-based evidential reasoning approach. Computers & Operations Research, 1768-1779.

[8] El-Sayegh S. M, Mansour M. H., (2015)."Risk assessment and allocation in highway construction projects in the UAE." Journal of Management in Engineering. 23;31(6).

[9] EU-OSHA - European Agency for Safety and Health at Work, Building in Safety, Luxembourg: Publications Office of the European Union, Magazine 7, 2004.

[10] Lund-Thomsen, P., Lindgreen, A., Vanhamme, J., (2016). Industrial clusters and corporate social responsibility in developing countries: What we know, what we do not know, and what we need to know. Journal of Business Ethics, 133(1), 9-24.

[11] Menanno, M., Savino, M. M., & Ciarapica, F. E. (2021). Exploring continuous improvement for safety management systems through artificial neural networks. International Journal of Product Development, 25(3), 213-241.

[12] Mohammadi, A., Tavakolan, M., (2013). Construction project risk assessment using combined fuzzy and FMEA. Paper presented at Joint IFSA World Congress and NAFIPS Annual Meeting (IFSA/NAFIPS).

[13] Muriana C., Muzzini V., (2017). Project risk management: A deterministic quantitative technique for assessment and mitigation. International Journal of Project Management. 35(3), 320-340.

[14] Mushtaq, F., Shafiq, M., Savino, M. M., Khalid, T., Menanno, M., & Fahad, A. (2018, August). Reverse Logistics Route Selection Using AHP: A Case Study of Electronics Scrap from Pakistan. In IFIP International Conference on Advances in Production Management Systems (pp. 3-10). Springer, Cham.

[15] Rezaei, J., (2015) Best-worst multi-criteria decision-making method. Omega 53, 49-57

[16] Seyed-Hosseini, S. M., Safaei, N., Asgharpour, M. J., (2006). Reprioritization of failures in a system failure mode and effects analysis by decision making trial and evaluation laboratory technique. Reliability Engineering and System Safety, 91(8), 872-881.

[17] Sharma, K. S., (2013). Risk Management in Construction Projects Using Combined Analytic Hierarchy Process and Risk Map Framework. The IUP Journal of Operations Management, 12(4).

[18] Sujiao, Z. (2009), "Risk analysis of construction projects based on Markov chain", Information Processing, APCIP Asia-Pacific Conference, pp. 514-517.

[19] Yu, J. H., Lee, S. K., (2012). A conflict-risk assessment model for urban regeneration projects using Fuzzy-FMEA. KSCE Journal of Civil Engineering, 16(7), 1093-1103.