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OBTAINING FMEA'S INDICES FOR OCCUPATIONAL SAFETY IN CIVIL CONSTRUCTION: A THEORETICAL CONTRIBUTION

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Highlights: 1- Severity, occurrence and detection indices were obtained for specific use in construction safety; 2- Important theoretical contribution to the use of FMEA in safety of construction work; 3- Obtaining the S, O and D indices better suited to civil construction will encourage the use of FMEA in the area; 4- A quick reference table of S, O and D indexes was proposed for use by occupational safety professionals; 5- The quick reference table will allow the RPNs of the fault modes to be safely compared between different situations and different applicators.

Goal: The achievement of FMEA indices better adapted to the area of occupational safety in construction. From a quick reference table, the use of the FMEA will be facilitated by professionals in the area.

Design / Methodology / Approach: For the elaboration of this work were carried out researches in the literature available in scientific journals on the subject. To obtain the severity tables, the conversion of concepts of maintenance and reliability to concepts of accident severity was performed. For the occurrence table the Ford Handbook model was used (FORD, 2011), and as the database of accident statistics the most up-to-date social security yearbook was used (FAZENDA, 2016). For the detection table, a detection index model was proposed that was discussed based on commonly used risk management procedures and tools.

Results: Individual tables were obtained for each FMEA index. The indices were adapted to the reality of the application of FMEA in work safety in construction. From the individual tables, a quick reference table containing the three FMEA indices related to the qualitative scale of each was obtained.

Limitations of the investigation: The study limits itself to adapting the FMEA indices for work safety in construction. This study may serve as a basis for future studies on obtaining the FMEA indexes for work safety applied in other areas of activities, requiring adequate scientific sources. Regarding the validation of the indices, it is noticeable the difficulty of comparing these indices proposed in this work with indices applied subjectively and without scientific reference, relying only on the skill and previous experience of the applicator. However, it is reasonable to say that the FMEAS applied with the indices obtained in this work will have a better accuracy in representing the reality, regardless of the applicator's ability.

Practical implications: Reduce the difficulties in choosing the S, O and D indices for the application of FMEA in construction safety, reduce the inaccuracy in obtaining the risk priority number for failure modes and diffuse the use of FMEA for risk analysis and prevention occupations in construction are the main theoretical implications of this work.

Originality / Value: there are studies in the literature on the application of FMEA in various areas - maintenance and product development, for example - but there is very little research on the application of FMEA in occupational safety. In addition, FMEA application studies cite the difficulty of choosing the S, O and D indices, but there is an absence of studies seeking solutions to this imprecision. Inthis sense, this work seeks to contribute to a choice of the FMEA indexes, which is easier and more efficient due to the better adaptation of the same to the occupational safety area in civil construction.

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1. INTRODUCTION

With the growing interest of construction companies in obtaining certifications, such as ISO 9001, ISO 14001 and OHSAS 18001, there is a need to improve risk analysis and management tools (Zeng *et al.,* 2010). Civil construction is an important element for the Brazilian economy and it is essential as an instrument of public policies, since it guarantees the generation of employment and income (Mello and Amorim, 2009). The construction industry is comprised of 94% of micro and small enterprises, with low technical development and high labor turnover, leading to a low specialization in their activities (Teixeira and Carvalho, 2005). In this way, the construction industry is a fertile field for high rates of industrial accidents. In the year 2016 there were 34,786 accidents involving the removal of employees enrolled in construction activities. From the total of these accidents, the impact caused by the fall of materials and the fall of employees, among different levels, stand out as causes (Fazenda, 2016).

Working at heightsis awidely performed activity within civil construction worldwide and itoffers several risks, both for those who execute it and for who is exposed to possible falls of materials. In the North American civil construction, falls from height have the highest rate of fatalities within works, with approximately 35% of deaths recorded and reports of 49 fatalities due to falling objects (Mroszczyk, 2015).

Workplace accidents are responsible for major losses in the industry. As cost-generating instruments resulting from work-related accidents, the causes of separation within the process and the cost generated, with salary payments to workers on medical leave, first aid expenses and recovery of the injured worker are highlighted; loss of equipment, materials and repair engineering costs; and losses with downtime and compensatory overtime (Costa*et al.,* 2009). In a total of 2,857 work accidents registered in Bahia's social security system in 2000, 18% of accidents related to the construction industry were detected, with estimated costs of R$ 8.5 million (Santana *et al.,* 2006). Because of this, it is essential to assess the risks associated with the tasks in order to avoid accidents or failures, in order to guarantee the quality, deadlines, costs and safety of all that is related to the work. Risk assessment should be present at all stages of construction or reform, both in prevention within the project phase and its implementation (Cruz, 2012).

According to Stamatis(2003), the FMEA, or failure mode and effects analysis is one of the methods of fault evaluation, which correlates its causes and effects, also punctuating the means of its detection, prevention and mitigation of effects. Developed as a military procedure by the US military in the post-war 1940s (Pentti and Atte, 2002) has been widely used in engineering industries and is now used in other areas such as food safety (Scipioni *et al.*, 2002), management procedures (Milazzo*et al.,* 2009; Rhee and Ishii, 2003) and critical medicine and trauma (Duwe and Hansen-Flaschen, 2005; Day *et al.,* 2006; Derosier *et al.,* 2005).The use of the FMEA for the area of occupational safety is still not widespread, requiring scientific studies on the subject.

The FMEA allows a hierarchy of risks, prioritizing failure modes according to a coefficient called a risk priority number, or RPN. This number is a result of the multiplication of three independent indices - severity (S), occurrence (O) and detection (D) - and varies from 1 to 10, the worse its reality.

According to Mcdermott *et al.*(2009), severity is the classification that indicates the severity of a possible consequence in the potential mode of a fault. In maintenance there is a direct connection between the effects of the failure in the system or process and the severity index that will be assigned. If the effects are critical to the proper functioning of the process the severity will be high and if the effects are not critical the severity will be low.

The occurrence in FMEA is the estimation of the frequency or probability of failure mode occurring. The best method to determine its value is through the use of real data of the process; however, in the case where there are data for evaluation, qualitative scales can be assigned (Mcdermott *et al.,* 2009).For the maintenance area there are tables of quite consolidated indices of occurrence (Ford, 2011; Mcdermott *et al.,* 2009; Stamatis, 2003); however, the occupational safety area does not have studies correlating the occurrence indexes with actual data. Thus, a certain difficulty is generated to the FMEA applicators in the choice of indices in a qualitative way (Laurenti*et al.,* 2012).

Detection is the difficulty of causing the fault to be detected before the failure mode occurs. For the maintenance area, the probability of detection is conceptualized between very low and very high, relating the concepts from 1 to 10 with the probability of detection (Stamatis, 2003). The absence of failure detection histories is a complicating factor for the correct use of this index and, in many situations, obtaining the FMEA detection index is based on the experience that is reported by the collaborators making the analysis imprecise (Posso and Estorilio, 2009). Other factors that may influence are the nature of the failure, the checking procedures and the difficulty in technological detection procedures (Mcdermott *et al.,* 2009). In occupational safety, the difficulty of detecting the failure mode is great due to the lack of control procedures that generate statistical data for this, requiring studies on the subject.

The use of FMEA has a wide range of possible improvements. The studies on the application of FMEA frequently enumerate as main difficulties the imprecision of the Risk

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Priority Number (RPN) obtained to define the risk, with the same RPN representing different situations; the need for a large amount of time to apply a judicious FMEA; the dependence of the experience of the team members for the tool application (Laurenti*et al.,* 2012). The difficulty in estimating the values for the S, O and D indices is also highlighted by Laurenti *et al.,*(2012). This difficulty, in particular, is relevant to the area of occupational safety, which is absent from using the FMEA, limiting itself to using purely qualitative risk management tools.

The method of failure analysis and its effects by the FMEA may be applied within the works in conjunction with the knowledge of the current Regulatory Standards (NSs) to mitigate potential risks. Because of this, the present work seeks to contribute to the area of risk management and analysis in occupational safety by proposing a methodology to obtain the indexes that compose the RPN to facilitate the use of FMEA in the analysis and prevention of accident risks. In this way, this work seeks to contribute theoretically to the use of FMEA in occupational safety in the construction industry through a better adjustment of the concepts S, O and D for this use.

2. METHODOLOGY

For the elaboration of this work research was carried out in the literature available in scientific journals on the subject. To obtain the severity tables, the conversion of concepts of maintenance and reliability to concepts of accident severity was performed. For the occurrence table, the Ford Handbook model was used (Ford, 2011) and, as the database of accident statistics, the most up-to-date social security yearbook was used (Fazenda, 2016). For the detection table, a detection index model that was discussed based on commonly used risk management procedures and tools was proposed.

3. S, O AND D TABLES FOR OCCUPATIONAL SAFETY IN CONSTRUCTION

In view of the difficulties reported in the scientific literature, the best adaptation of the S, O and D indices for specific application in construction safety is necessary. Next, a discussion will be made on the S, O, and D indices, exposing the methods used to obtain each one.

3.1 Obtaining the severity index (S)

This classification is done using a numerical scale from 1 to 10, where the classification 1 corresponds to a zero or imperceptible severity and the classification 10 is the worst possible consequence for the failure mode analyzed. The indices that Stamatis(2003) propose are shown in table 1.

Table1. Scale of severity for processes or services.

Index	Qualitative scale	Potential consequence of failure
1	Minor / Secondary	Failure has no real impact
2 and3	Low	Almost negligible failure
4 and 6	Moderate	Failure presents some discomfort
7 and 8	High	Failure has direct effect on operation
9 and 10	Criticism	Failure with real impact on security

Source: Stamatis, 2003 (Adapted)

In table 1, the index with smaller scale represents a minor or secondary fault with no real impact as consequence and the highest index is a critical fault with a real impact on safety. This characterization of Stamatis (2003) can be translated for occupational safety.

Most construction accidents are deadly; therefore, severities must consider aspects beyond economic damage (Song *et al.,* 2007). Based on studies by the Korea Occupational Safety and Health Agency (KOSHA), Song *et al.*(2007) presents a numerical model from 1 to 6, where it considers the time of medical treatment of the consequences of the failures to define the severity. The employee's absence time with the company, together with a qualitative description of the effects of the accidents caused by the faults can be used to define the severity (Patricio *et al.,*2013). Holt (2008) presents a scoring system, from 1 to 15, of the consequences of risks in construction, where first aid is considered as low severity and multiple fatalities are regarded as critical failures. Its index also assigns a score to the number of workers exposed to risk.

These indices can be adapted to the Stamatis (2003) index presented previously, assigning a scale of 1 to 10 and correlating the qualitative scales with each other. Table 2 presents the new index proposed by the adaptation.

Failure of no real impact is one in which there are no physical sequelae on employees, thus not causing loss of working time. Irrelevant traumas are those where failure can cause slight physical sequelae, but still without causing loss of working time. The trauma requiring first aid differs from irrelevant trauma because it causes temporary disruption of activity due to the need for first aid.

Temporary disabilities are characterized as partial or absolute, the first occurring when the worker is still able to perform 50% of his abilities, even with difficulties, and the second happens when the employee is totally unable to per-

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form his professional activities (Durão *et al.,* 2012).In this sense, three types of temporary incapacities are proposed: without remoteness, with small remoteness, and with large remoteness.

Table 2. Adapted model of the severity scale

Index	Qualitative scale	Potential consequence of failure
1	Smaller	No real impact
2	Low	Irrelevant trauma
3		Trauma requiring firstaid
4	Moderate	Temporary incapacity without remoteness
5		Temporary incapacity with small remoteness
6		Temporary incapacity with large remoteness
7	High	Partial permanente disability
8		Total permanente disability
9	Criticism	Death of those involved in the process
10		Death of those not involved in the process

Source: Adapted from Stamatis, 2003; Patricio et al., 2013; Holt, 2008

Temporary incapacity without remoteness is the one in which the collaborator affected by an injury has to engage in another, simpler task until the incapacity is solved, as long as the injury does not require remoteness.

Temporary incapacity with small remoteness is the event in which the collaborator cannot be relocated to another function due to the severity of the trauma, requiring full remoteness for recovery, but not exceeding 15 days, thus excluding the necessity of social security.

Large remoteness, on the other side, is the period of more than fifteen days in which the collaborator needs social security for a complete recovery.

Permanent disability, called "permanent damage", is characterized by the loss of work capacity resulting from one or more dysfunctions or sequelae left in patients, which prevents them from performing any type of work (Durão *et al.,* 2012). However, according to the social rehabilitation professional program, people with partial permanent disability can be relocated to work functions where they can adapt (Takahashi and Iguti, 2008). In this way, partial permanent disability is one in which employees have permanent sequelae; however, there is the possibility of continuing to perform other possible job functions to adapt. The total permanent disability is the one that the sequels of the accident do not allow the worker to be reinstated in any job function.

The worst severity indexes, 9 and 10, are intended for accidents involving deaths. In this severity range, there are 9 accidents that lead to the death of employees directly involved in the process. Accidents that cause the death of the employees who are not directly involved in the function, in addition to those who execute the process, due to their magnitude, obtain the maximum index in the proposed severity scale, 10.

3.2 Obtaining the occurrence index (O)

Table 3 shows the parameters for evaluating the occurrence criterion proposed by Ford(2011). It is possible to adjust the occurrence index presented by Ford(2011) through a statistical analysis of the values obtained from studies of work accidents in civil construction. Since the occurrence index model is based on the frequency of the occurrence of the fault, the number of accidents, delimited by the causes and divided by the number of active employees, will be used for the analysis. Thus, it is possible to determine the probability of the cause of the accident for each active worker.

Table 3. Evaluation criterion of the occurrence.

Index	Qualitative Scale	Frequency	
10	Very high	≥ 1 in10	≥ 10%
9	High	1 in20	5% - 10%
8		1 in50	2% - 5%
7		1 in100	1% - 2%
6	Moderate	1 in500	0,2% - 1%
5		1 in2000	0,05% - 0,2%
4		1 in10000	0,01% - 0,05%
3	Low	1 in100000	0,001% - 0,01%
2		1 in1000000	≤ 0,0001%
1	Very low	The fault is eliminated by the control method	

Source: FORD (2011). Adapted

Guimarães *et al.*(2000) proposes in his study a statistical analysis of the distribution of accidents in civil construction according to their nature. Their results can be used to delimit the causes of accidents using the quantitative forms of the Social Security statistical forms for the year 2016, thus obtaining the relation of the accidents associated to their causes, as presented in table 4.

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Table 4. Comparative values of accidents for the year 2016.

Accident nature	Total
Impact suffered	11027
Drop with level difference	6609
Impact against	5218
Excessive or inappropriate effort	4313
Pressing or imprisonment	2748
Fall on the same level	2644
Noise exposure	870
Contact with harmful substance	591
Electric shock	417
Friction or abrasion	174
Contact with extreme temperature	174
Total	34786

Source: Interpolation between Fazenda (2016) and Guimarães *et al.*(2000)

With these values, a new interpolation is then made with the statistics of taxpayers employed in the economic sector of construction in the year 2016, presented in table 5.

Table 5. Statistics of taxpayers employed in the civil construction sector.

2012	2013	2014	2015	2016
7.489.616	7.595.995	6.156.905	5.410.627	4.232.101

Source: Fazenda (2016). (Adapted)

Thus, it is possible to determine the probability of occurrence of the cause of the failure for each employee hired in 2016. Applying this result in the generic index presented by Ford(2011), an estimate of the occurrence index of the causes of accidents in the civil construction sector is obtained.

Table 6. Percentage of the number of accidents by the number of taxpayers.

Accident nature	Value	Occurrence
Impact suffered	0,261%	6
Drop with level difference	0,156%	5
Impact against	0,123%	5
Excessive or inappropriate effort	0,102%	5
Pressing or imprisonment	0,065%	5
Fall on the same level	0,062%	5
Noise exposure	0,021%	4
Contact with harmful substance	0,014%	4
Electric shock	0,010%	4
Friction or abrasion	0,004%	3
Contact with extreme temperature	0,004%	3

Fonte: Interpolation between Fazenda (2016), Ford (2011), and Guimarães *et al.*(2000)

These values, shown in Table 6, based on occupational safety, can then be used to determine the occurrence rates (O) for the application of FMEA in the different areas of construction. At this point it is valuable to point out that the information in table 6 can be updated annually, from the new edition of the social security yearbook. The synthesis of the method of updating the occurrence index (O) starts from the proportions obtained by Guimarães *et al.*(2000),applied in the total number of work-related accidents recorded in the social security system, annually disclosed by the body, comparing the number of accidents with the total number of inscribed in the economic activity of construction and converting the percentages obtained into occurrence indexes from the table proposed by Ford (2011).

3.3 Obtaining the detection index(D)

Detection is the probability that existing control measures detect the failure mode root before it is played. This detection can be done by repeated inspection activities, by checking procedures before using the element or by automated devices. It is represented by a numerical scale where the highest value represents a very low or no chance of failure detection and the lowest value represents an immediate detection. Table 7 shows the correlation between the difficulty of detection and the scale of the detection index.

Table 7. Detection index.

Index	Qualitative scale	Criterion
1	Very high	The detection is almost certain
2 a 4	High	High probability of detection
5 a 7	Moderate	Moderate probability of detection
8 a 9	Low	Low probability of detection
10	Very low	Nearly impossible detection

Source: Stamatis, 2003

The use of qualitative scales in relation to the detection can be made from the check methods available in safety of the work. From empiric observations, some methods, as the visual inspection, were enumerated, detecting the existence or absence of safety devices, such as devices that prevent falls of people and materials in height (skirting boards, elevator pit guards, use of lanyards, etc.); manual or tactile routine inspection (checking the condition of paratrooper belts, placing of ladders, firmness in the scaffolding, etc.); procedural checklists, where several visual and tactile inspections are required in sequence prior to the execution of the task; and mechanical tests, such as loading tests on lifeline anchorages, for example; furthermore, if it is still not possible to detect the source of the fault, the detection difficulty index rises to 10. Thus, it is reasonable to correlate the safety inspection methods available with the qualitative scale proposed by Stamatis (2003). The correlation is shown in table 8.

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Table 8. Correlation of detection methods with the qualitative scale of Stamatis (2003) to obtain the detection index for FMEA.

Index	Qualitative scale	Detection methods	Criterion
1	Very high	Visual	The detection is almost certain
2 a 4	High	Tactile	High probability of detection
5 a 7	Moderate	Check list	Moderate probability of detection
8 a 9	Low	Instrumental inspection	Low probability of detection
10	Very low	Lack of methods	Nearly impossible detection

Source: Stamatis, 2003. (Adapted)

It is noticed that it is difficult to determine detection indices, even in defined areas such as maintenance, due to the lack of records; therefore, one can expect even greater difficulty in a new application in the area of occupational safety. A deeper study of the detection index is necessary, especially in an opportunity where there is a history of inspection and detection records of possible causes of accidents.

3.4 Indices S, O and D, for occupational safety in civil construction

Table 9 shows a fast access correlation between the severity (S), occurrence (O) and detection (D) indices, with their qualitative concepts, usually found in occupational safety for civil construction. For the qualification of severity, the qualitative definition of severity proposed by Stamatis (2003) was expanded with definitions of Song *et al.*(2007), Patricio *et al.*(2013), Holt (2008), and Durão *et al.*(2012). Thus, each index has a correlation with the nature of severity, starting from an index 1, where there is no real impact, up to index 10, where there are deaths of people external to the process. For the occurrence qualification (O), for each nature of the occurrence, there is a correlation with the respective index based on the probability defined by Ford (2011) and adapted with the data of Fazenda (2016) and Guimarães *et al.* (2000). For the quantification of the detection indices (D), each index was correlated with the difficulty of adapted detection of Stamatis (2003), starting from an index 1, where the primary cause of the failure can be detected with simple visual inspections, up to an index 10 where it is assumed that there are no available techniques to ensure detection. Table 9 is proposed as a tool for quick reference to the professionals who elaborate, execute and research the topic of occupational safety, in order to reduce the difficulty of using the FMEA reported by Laurenti *et al.*(2012).

It is worth to point out that, regarding the validation of the indices, it is noticeable the difficulty of comparing the indices proposed in this work with indices applied subjectively and without scientific reference, relying only on the skill and previous experience of the applicator. For that, this comparison requires a specific scientific methodology, demanding specific scientific work for this situation.

However, it is reasonable to say that the FMEAS applied with the indices obtained in this work will have a better accuracy in representing the reality, regardless of the applicator's ability. In this way, the contribution of this work is to offer a reference point so that the RPNs can be compared between FMEA applications at different times by different applicators, bringing to the tool a quantitative power that is not dependent on the applicator subjectivity, thus, nearing the reality of the FMEA in occupational safety of the FMEA in the areas of maintenance and reliability, for example.

4. CONCLUSIONS

This work sought to contribute to the area of risk analysis and management in occupational safety by obtaining indexes S, O, and D, best adapted for the use of FMEA in work safety, with emphasis on civil construction. The literature on the subject points out that the lack of clarity in the choice of S, O, and D indices generates difficulties in terms of the use of FMEA. In this sense, the creation of index tables S, O, and D, clearly and previously adapted for the use in work safety can be a mechanism that will promotes the diffusion of the use of FMEA in this area of knowledge. In this paper, it was attempted to construct a clear correlation between the S, O, and D indices with the reality of work safety in civil construction. Correlation tables of the S, O, and D indexes were obtained from the methodology described during the study. From the tables obtained, a quick reference table was constructed that includes the three indexes S, O, and D, related to their respective nature. Thus, this work sought to provide a fast and safe reference for professionals responsible for execution and research on the subject of work safety, with emphasis on construction.

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Table 9. Reference table of severity (S), occurrence (O) and detection (D) indexes, for the application of FMEA in analysis and risk prevention for occupational safety in construction

Severity (S)		Occurrence (O)		Detection (D)	
Index	**Consequence of failure**	**Index**	**Accident nature**	**Index**	**Detection methods**
1	No real impact	6	Impact suffered	1	Visual inspection
2	Irrelevant trauma	5	Drop with level difference	2	Tactile test / manual test
3	Trauma requiring first aid	5	Impact against	3	
4	Temporary incapacity without remoteness	5	Excessive or inappropriate effort	4	
5	Temporary incapacity with small remoteness	5	Pressing or imprisonment	5	check-list/sequence of tests before process
6	Temporary incapacity with large remoteness	5	Fall on the same level	6	
7	Partial permanente disability	4	Noise exposure	7	
8	Total permanente disability	4	Contact with harmful substance	8	Instrumental inspection / mechanical tests
9	Death of those involved in the process	4	Electric shock	9	
10	Death of those not involved in the process	3	Friction or abrasion	10	Lack of effective methods
		3	Contact with extreme temperature		

Source: the authors

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