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HAZARDS IDENTIFICATION AND RISK ASSESSMENT IN A STUDENT MECHANICAL WORKSHOP

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Abstract. *This paper aims to determine the potential risks present in an automotive mechanic workshop oriented to the development of the student projects Formula and Baja, proposed by the Society of Automotive Engineers (SAE). So, a preliminary analysis was performed based on the workshop's floor plan in parallel to inspection in the work environment, in order to determine the main causes of present risks, as well as the generalization of such risks in classes. The study followed with a specific assessment of the environment carried out with the aim of assessing risks in technical systems with high energy on board. The effects and significance of the risks are then determined, as well as the respective affected population. Then an application of a series of analysis tools was performed, such as Failure Modes, Effects and Criticality Analysis (FMECA), Fault Tree Analysis (FTA) and Causal Network Event Analysis (CNEA) in high energy systems. The results suggest many adjustments with the national regulatory norms (NR) applicable to the mechanical workshop, this way the study seeks to identify barriers that can be applied to avoid unwanted events, as well as recommend a series of actions and procedures.*

Keywords*: Risk Analysis, Mechanical Workshop, Regulatory Norms*

1. INTRODUCTION

The large amount of energy related to the systems used in automotive mechanic workshops increases the risk of the manufacturing process. In addition, the lack of technical familiarity and lack of student procedures potentially amplify that variable. In the context Kumamoto and Henley (2000) define the risk through five components which describe the probability of occurrence (L_i), effect (O_i), utility or significance (U_i), causal scenario (CS_i), and population affected (PO_i). The terms L_i and O_i are commonly analyzed concomitantly in order to determine the overall risk profile or, in other words, a probability distribution (discrete or continuous) of the predicted behavior of a given system. Significance represents a value related to gain or loss for each optimal solution, which its inverse is defined as utility. The term CS_i explains the causes of the respective results, as well as the propagation events of each of these. Finally, PO_i determines the size of the affected population as an important aspect of the risk. In the Eq. (1), the value of "n" represents the number of potential outcomes of an uncertain future.

$$Risk = \left[(L_i, O_i, U_i, CS_i, PO_i) \mid i = 1,..., n\right] \tag{1}$$

Apostolaki (2004) affirms that in a conventional risk analysis the probabilities of occurrence are not quantified starting from the identification of the failures and their consequences. Therefore, in this scenario, decision-making aims to reduce such probability or mitigate its consequences, often using redundant elements. The author adds that quantitative risk assessment (QRA) has recently been employed in engineering problems, highlighting an initial

aversion to the method in its initial phase of application. In a second step the user begins to use the method to identify failure modes, or the "negative" parts of the project.

The relevance of risk control is evidence from the analysis of the national regulatory norms, which consist of a series of requirements and compliance procedures according to the Consolidation of Labor Laws (CLT). Regarding the working environment of mechanical workshops, NR's provide for control measures in the areas of Machinery and Equipment (NR 12), Combustible and Flammable Liquids (NR 20), Personal Protection Equipment (NR 06), among other scenarios.

2. THEORETICAL REFERENCE

The probability of occurrence of a given event can be treated subjectively, which is an interesting approach in environments in which statistical control of occurrences is not sufficient for reliable predictions. In addition, the results can be divided according to the type of loss. As mentioned, the main objective of the study is to assess the risk in the work environment, that is, the derivation of the risk profile in the proposed scenarios. Nevertheless, alternatives to higher potential risks will be discussed in order to determine active and passive control solutions.

The Management Oversight and Risk Tree (MORT) is defined as an analytical procedure of causes and factors that contribute to the consequences where the existence of an incident is dependent on the combination of a dangerous condition and a trigger event. Its logical execution diagram (Fig.1) enables the creation of propagation barriers that mitigate the probability of occurrence or mitigate the consequences if a given incident occurs.

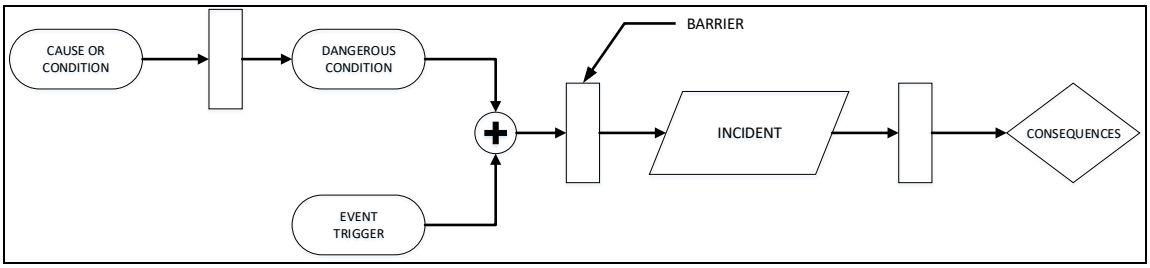

Figure 1. Management Oversight and Risk Tree – MORT (Source: Authors - adapted from Dias, *et al.*, 2004)

According to Dias, *et al.*, (2011), the importance of having a risk management methodology is closely linked to the fact that every technical system has hazards and depending on conditions any system can register an incident. Thus, such methodology must consist of a set of procedures and organized techniques, whose purpose is to manage technical, human and environmental systems, with a view to developing process of analysis, treatment, acceptance and communication of risk.

Therefore, such methodology aims to identify the causes or conditions of risk that constitute the causal chain. Dias, *et al.*, (2011) proposes a methodology of risk management that is constituted by the design, implementation, utilization, revision and deactivation stages, which present their respective general objectives according to Fig. 2.

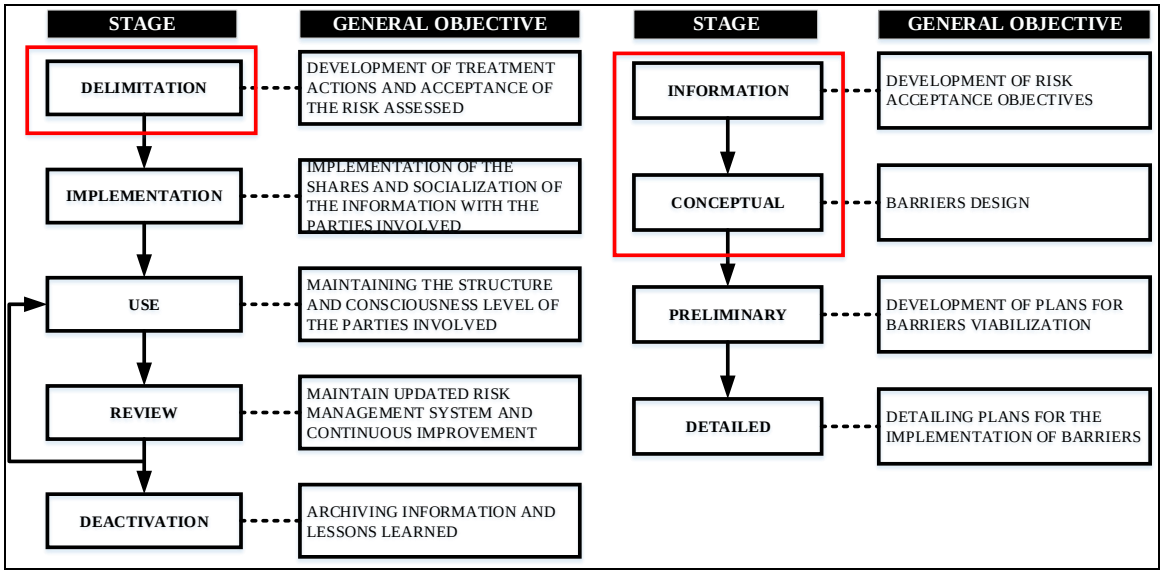

Figure 2. Stages and phases of the risk management methodology (Source: Calil, 2009 apud Dias, *et al.*, 2011)

Thus, with the risk management methodology, coupled with appropriate techniques for each situation, it presents scenarios of consequences and actions to monitor, eliminate, mitigate or accept the consequences. After, are some commonly used techniques to aid a risk management methodology.

2.1 Failure modes, effects and criticality analysis

The technique of Failure Modes, Effects and Criticality Analysis (FMECA) is a very efficient tool to identify and evaluate how potential failures can affect the performance of the process or technical system (Bertolini, *et al.*, 2006). According to Carmignani (2009), FMECA is a method that uses a bottom-up approach, which during the design phase of the system is confronted with the evaluation and clarification of all possible failure modes, all the causes of failures, effects produced by failures and also possible solutions. The same author states that method is based on its ability to quantify certain important characteristics and parameters. The combination of these parameters allows to identify the critical elements and defining certain intervention priorities.

The FMECA takes into account three parameters, which are evaluated through easily interpreted linguistic expressions, each correlated with a score (minimum of 1 and maximum of 10). The first parameter is "severity", which indicates the severity of the effects of the failure, which affects the system or the user of the system. The "occurrence" parameter indicates the probability of the failure occurring. The "detection" parameter measures the visibility of the fault, that is, the ease with which the failure mode is identified (Carmignani, 2009). Finally, with the multiplication of these three factors, the risk priority number (RPN) is obtained, thus the failure mode with the highest RPN certainly has a higher associated risk, and in this way, it must be examined with greater priority.

According to Dias, *et al.*, (2011), the FMECA can be driven by two different approaches: functional and structural. The functional approach is centered in the functions of the technical system, that is, in the operation of the item, being more used in the initial phases of the system design. In addition, that approach can also be used in the analysis of a process, when it is desired to implement an equipment maintenance management. In the second approach, the failure mode is usually associated with more specific aspects of the components, elements of the system being evaluated, being more appropriate for "deeper" analyzes (when the item is treated as the component or part of a component, for example).

2.2 Fault tree analysis

The Fault Tree Analysis (FTA) technique was introduced in 1961, and has become one of the main techniques for assessing system reliability. It is widely used in all industrial sectors where reliability is fundamental to a safe and efficient operation (Simões Filho, 2006). The same author states that the fundamental concept of FTA is the representation of a physical system in a structured logic diagram (fault tree), in which certain specific causes lead to a top event of interest. Dias, *et al.*, (2011) defines the FTA as a deductive (reverse thinking) technique, where from an initial event (top event), which will be analyzed, the intermediate events resulting from the logical association of root causes or roots are identified, which generated the top event. The authors further add that for the development of the fault tree are considered any relevant causes leading to the top event, such as equipment failure, human error or software error.

According to Simões Filho (2006), for the construction of the tree, proper nomenclature and symbols are used, which is formed by two main types of symbols: the events and the logical gates. Events are divided into three main groups: primary, intermediate, and transfer events. The primary events are events that are not developed, and the probability is given by the analyst. Intermediate events occur because one or more antecedent causes act through the logic gates. Transfer events are used to indicate that the analysis of the event in question continues in another part of the tree. The gates have two main types: "OR" gate and "AND" gate. The "OR" gate indicates that the exit event occurs only if one or more input events occur, whereas gate "AND" indicates that the output event only occurs if all incoming events occur.

In the FTA, according Dias, *et al.*, (2011), the analysis starts from an undesired event or effect (top event) and investigates the logical association of causes (root causes) that results in the undesired event, that is, a top-down approach.

2.3 Causal network event analysis

According to Dias, *et al.*, (2011), the causal network event analysis (CNEA) technique structures the risk analysis by means of representation of links between the analyzed event, centralized in the diagram, causes, that are disposed to the left, effects (to the right) and the barriers that act in the causal chain. According to the same authors, this technique is used to analyze events, causes, effects and barriers to be interposed to reduce the chances of the causes triggering the central event.

The CNEA is also related to techniques such as FTA and FMECA. When used in conjunction with the FTA technique, the top event of the FTA becomes the incident in CNEA and the root causes and intermediate events are arranged on the left side of the diagram (Dias, *et al.*, 2011).

3. MATERIALS AND METHODS

In the present paper, the risk management methodology proposed by Dias, *et al.*, (2011) was employed. However due to perceived lack of adequate procedures to monitor, eliminate, mitigate or even accept the risks within the workshop under study, the work was restricted to the design phase. In addition, the project is also limited to the initial phases of this stage, constituting the outline of risk acceptance objectives and barriers, as highlighted in Fig. 2.

The place to be analyzed is the student projects workshop (Baja and Formula SAE), which is located at the Federal University of Santa Catarina. This choice is justified by the number of machines and equipment operated in a place of intense circulation of people, mostly engineering students. The workshop is still surrounded by other laboratories.

After that, it was sought to observe the place in search of the main technical systems that has energy on board that evidences some type of dangerous condition in the place. Among the systems with the highest risk potential were listed a conventional lathe, a universal milling machine and welding equipment. Other equipment was verified as grinders, drills and bending machines. In addition, some objects, such as trestles, antique chassis and chairs, that obstruct the passage of people have been identified to be removed, in case there be a need to evacuate the laboratory. It was also observed the absence of panic doors; as well as the presence of lamp support; tires stored in suspended cabinets that also store gravitational potential energy. It shows an element to be considered in the analysis, since the fall of this support may come to generate physical damages to the system present in the environment and to those involved.

It is important to point out that a detailed analysis of the whole workshop would result in a very extensive work, so the study presented here will focus on the risks associated with welding equipment and fuel tanks, which are verified as the main energy carriers. Also, due to the competitive nature of the projects, which involves confidentiality of information, images of the analyzed environment will not be disclosed here.

4. RESULTS AND DISCUSSIONS

4.1 Environmental analysis

Preliminarily, all the types of energy present in the place were located, and based on recommendations foreseen in national ordinance 25/1994, the risk map of the place was construct (Fig. 3). This is a graphical where is possible to identify and measure the types of risks present in the environment. The classification of energy types varies in color of the markers, and the intensity is verified with the variation of markers size.

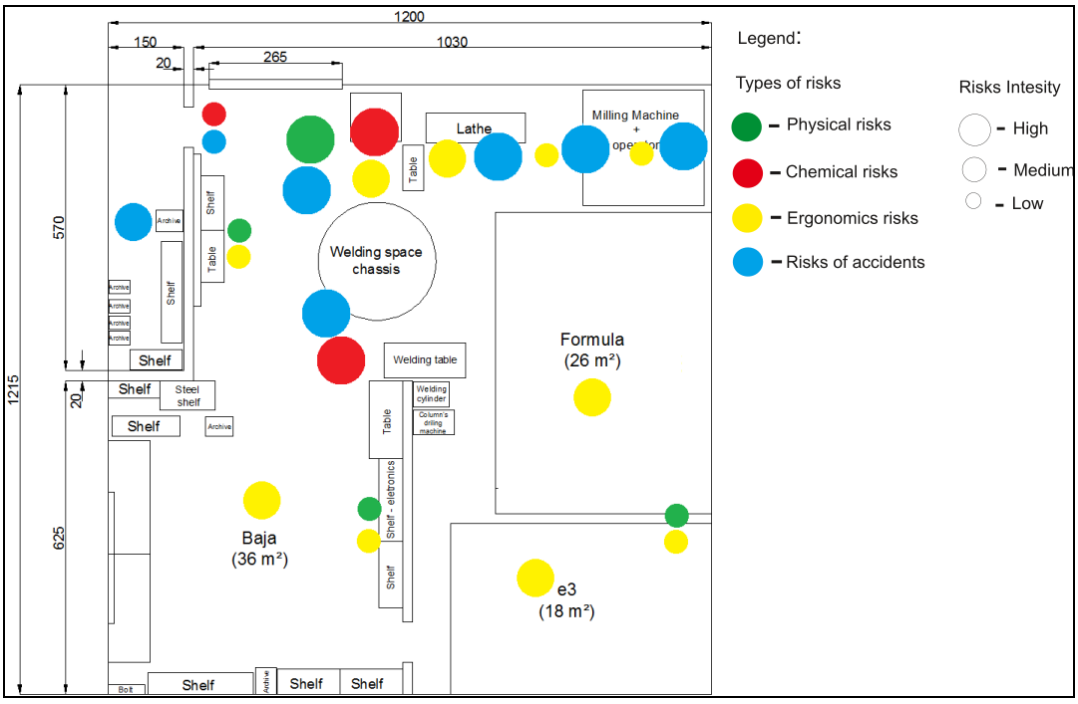

Figure 3. Classification of the main occupational risks in groups according to their nature in the mechanical workshop where the prototypes are manufactured (Source: Authors)

4.2 Risk analysis for welding systems

The workshop has an area dedicated to the fusion welding operation, in which it is possible to use two processes: GMAW (Gas Metal Arc Welding) and GTAW (Gas-Shielded Tungsten Arc Welding). This operation is considered highly dangerous, especially as it is an activity involving high concentrations of energy, where the operator, and often third parties, are exposed to chemical and physical hazards such as welding fumes, visible and invisible radiation, electrical shock, and explosions. For this reason, it is of fundamental importance for the safety of all concerned that the risks are identified and treated.

Thus, using FMECA and FTA techniques sought to better understand the main failure modes, as well as their respective causes and control actions. So that, from this, it becomes possible to propose improvements to eliminate, mitigate or even accept the risks that involve that operation when executed in an automotive workshop.

In order to construct FMECA for welding process (Table 1), data were collected regarding the workshop and the conditions of use, based on the Regulatory Norms: NR 6 - Personal Protective Equipment; NR 10 - Operations Involving Electricity; NR 11 - Transport, Storage and Material Handling, NR 12 Machinery and Equipment and NR 18 - Conditions and Working Environment.

Table 1. FMECA for welding process (Source: Authors)

Item	Function	Failure mode	Failure effect	Sev	Causes	Oco	Controls	Det	RPN	Recomended actions
1	Handling of cylinders and heavy machinery parts	Intense physical exertion	Muscle distention; Physical fatigue	4	Ergonomically incorrect postures or excessive weight	4	Adopt ergonomically correct postures in operations	3	48	Staff Training to Adopt Appropriate Positions
		Exposure to sharp / puncture parts	Short-blunt wound	6	Absence of adequate PPE	5	Use of shaving gloves and long sleeved shirts	3	90	Distribution of suitable gloves and clothing
		Fall during operation	Fall trauma	5	Slippery or uneven surfaces	5	Clean and level circulation ways; Safety boot in good condition	4	100	Regular cleaning and renewal of safety boots every 2 years
3	Stacking of metal profiles	Falling of metal profiles	Trauma	5	Excessive or incorrect stacking	5	Metal profiles duly studded on stakes or walls	3	75	Make sure that the profiles are properly anchored regularly; Do not stack profiles too much
4	Handling tools	Inappropriate and unsafe handling	Trauma	5	Defective tools	4	Tools Preview	3	60	Train staff to report cases of damaged tools; Periodically maintain tools according to ISO procedure No. IT 009
5	Welding Execution	Fire and explosions	Burns; Trauma	9	Welding operations close to flammable or explosive materials	5	Carrying operations at a safe distance from flammable materials	5	225	Keep welding location free of flammable materials
		Exposure to welding lights	Eye lesions	8	Absence of protection, or use of inadequate protection masks	8	Use of suitable protective masks	5	320	Training; Checking the protective masks
		Electric shock	Burns; Cardiac arrest	9	Direct or indirect contact of metal profiles with energized conductor	5	Disconnection or isolation of energized lines near the welding areas	7	315	Make personnel aware of welding site preparation measures with emphasis on electricity
		Inhalation of gases and metal fumes	Asphyxia, Intoxication	9	Improper operator positioning; Absence of exhaust gas system	5	Proper positioning of the operator; Exhaust gases	4	180	Exhaust Fan Installation; Operator Training
		Direct contact with weld spatter	Burns	7	Absence of PPE	8	Correct use of PPE	2	112	Training and Surveillance
		Direct contact with welded parts	Burns	7	Inadequate signaling; access by unauthorized persons	8	Signaling and / or insulation of newly welded parts.	3	168	Manufacture of warning signs and Surveillance

The FMECA contemplates five functions within the welding activity, four of which do not involve the execution, preparation and maintenance of the machinery. The main effects observed in the first four failure modes were trauma, cuts, bruises and physical fatigue. However, it is observed that the RPN attributed to these failure modes are relatively low when compared to the failure modes related to the execution of the welding, which shows the greatest risks, which is justifiable since the energy released during the process is quite high and difficult to contain. Thus, an FTA was

performed (Fig. 4) involving the main failure modes of this function so that knowing the causes and effects in detail, it is possible to propose barriers to make the welding operation in the environment safer.

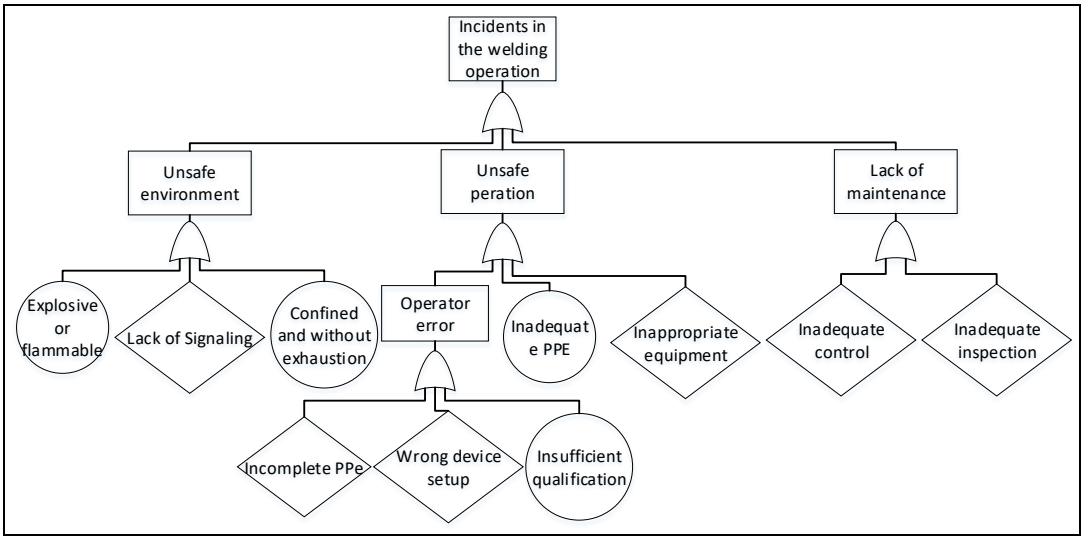

Figure 4. FTA of welding operations incident (Source: Authors)

The FTA demonstrates that incidents during welding operation are consequence of three possible (isolated or combined) causes related to unsafe environment, unsafe operation or lack of maintenance. Therefore, the main barriers to avoid its occurrence are efficient operator training, availability of quality PPE's and periodic maintenance of equipment. No research was done to verify the existence of incidents in the years prior to this analysis activity.

4.3 Fire propagation risk analysis

The FMECA was applied in order to identify recurring failure modes in the fuel tank system. The analysis was divided in two main functions: cover/sealing and container. And its functional failures, failure modes, failure mode effects, failure mode causes and severity, occurrence and detection parameters are shown in Table 2.

Table 2. FMECA for fuel tank (Source: Authors)

Item	Component	Function	Functional failure	Failure mode	Failure Mode Effect	Sev	Causes of failure mode	Ocu	Det	RPN
1	Gasket	Prevent leakage of gases and leakage of liquid fuel	Do not avoid the escape of gases or leakage of liquid fuel.	Damaged lid	Leakage of gases Leak of liquids	9	Handling and misuse	7	4	252
				Worn thread	Leakage of gases Leak of liquids	9	Handling and misuse	7	4	252
	Container	Protect and hermetically protect the fuel	Do not protect or contain hermetically	Damaged walls	Leakage of gases Leak of liquids	9	Handling and misuse	6	3	162
				Corrosion of walls	Loss of tightness	9	Inappropriate use	2	8	144
				Clogging of the pressure relief device	Increased pressure	9	Maintenance failure	6	8	432

Similarly, to the previous technical system, a series of recommended actions was developed. However, these are based on NR 20, which addresses safety and health at work with flammable and fuels. In addition, it is important to highlight that most failure modes refer to improper handling and operation. Therefore, is highlighted the operators' lack of preparation, knowledge and care as potential risk factors, as shown in Table 2.

The FTA related to the mechanical workshop was based on the potential factors that could result in a fire principle. For physical reasons, an "AND" logic gate was introduced, linking fuel-related factors to events that could potentially increase the environment or systems temperature and pressure. This two FTA branches are shown in Fig. 5.

In the first tree branch, which refers to fuels exposure, the use of inadequate reservoirs, a practice observed in the visits to the environment, meets the resulting recommendations from the FMECA due to factors such as the absence of relief valves and non-hermetic walls. Failure to execute workshop procedures, such as improperly position the fuel reservoirs and lack of expertise to close the lid are foreseen. Finally, the use of inadequate sealing and gas exhaust components stands out as potential events that can lead to failure.

The second tree branch is related to factors that lead to an increase of temperature and pressure in the fuels. In this case, the arrangement of equipment and fuel reservoirs stands out, as well as the spark generation resulting from processes, leakage current and electrical installations problems.

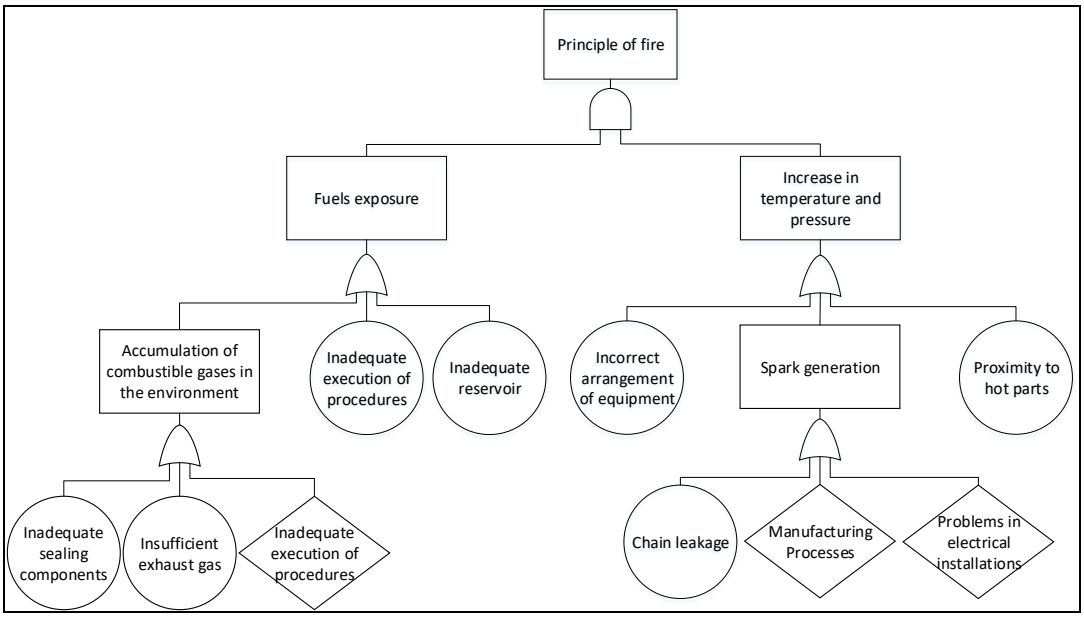

Figure 5. FTA of fire principle (Source: Authors)

Considering a scenario in which the fire principle took place, the FTA top events becomes the fire proliferation, as shown in Fig. 6. In this case, two intermediate events may be responsible for such proliferation. The first one is the failure of fire extinguishing systems, and the second are problems related to the environment layout.

The first tree branch is related to fire protection systems failures, which concerns fire extinguisher malfunction or the misuse of extinguishers (e.g. fire extinguishers not suitable for the procedure). For this reason, is highlighted the operator's qualification as a factor that potentially contribute to the event non-containment. In the second branch, there is an incorrect disposition of materials, such as Styrofoam (a highly inflammable material) molds used to manufacture the vehicle fairing, as well as obstruction of access to fire extinguishers.

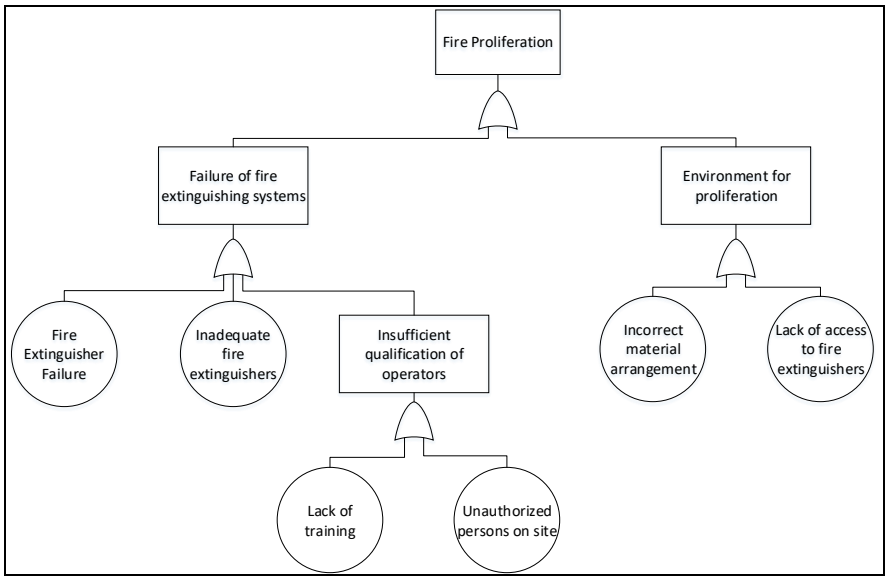

Figure 6. FTA of fire propagation (Source: Authors)

According to the FTA results, the following CNEA was developed aiming to prevent the propagation of undesirable events. Regarding the incident, the top event was considered the fire principle. The proposed barriers are shown in Fig. 7.

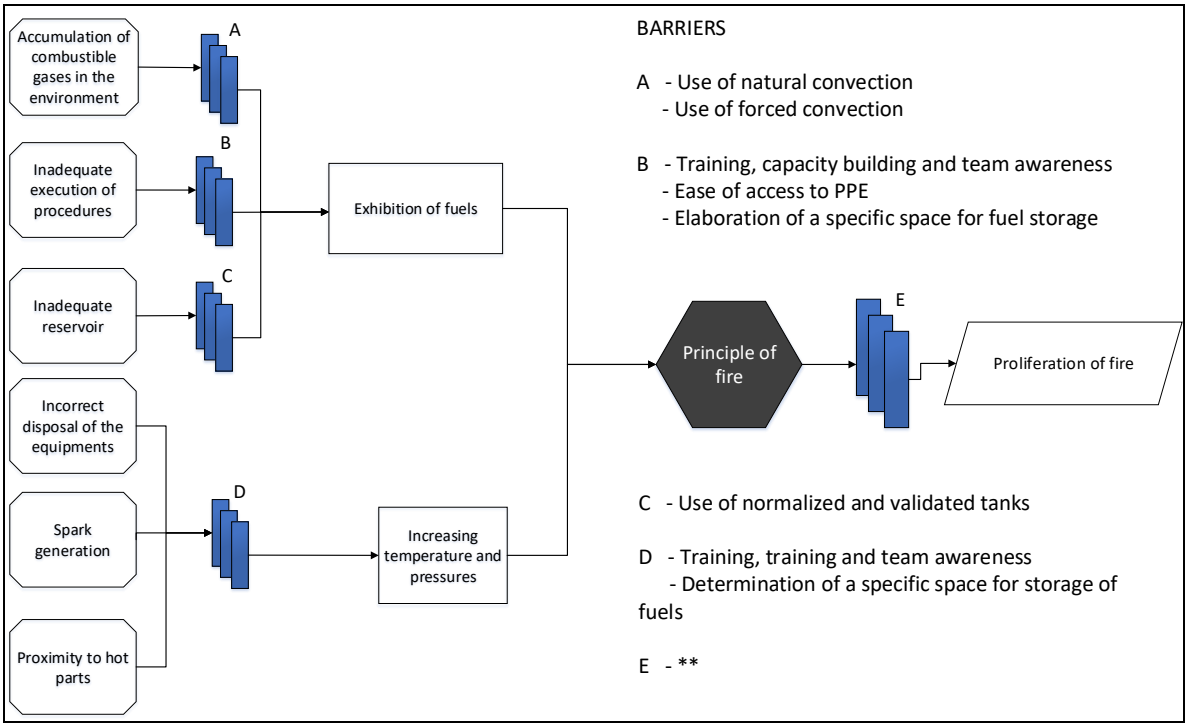

Figure 7. CNEA of fire principle (Source: Authors)

According to the most frequent effect from the failures modes in the FMECA, it was developed a specific analysis for the possible scenarios that can be triggered from fire principle. In order to analyze these scenarios, the ETA technique was applied (Fig. 8).

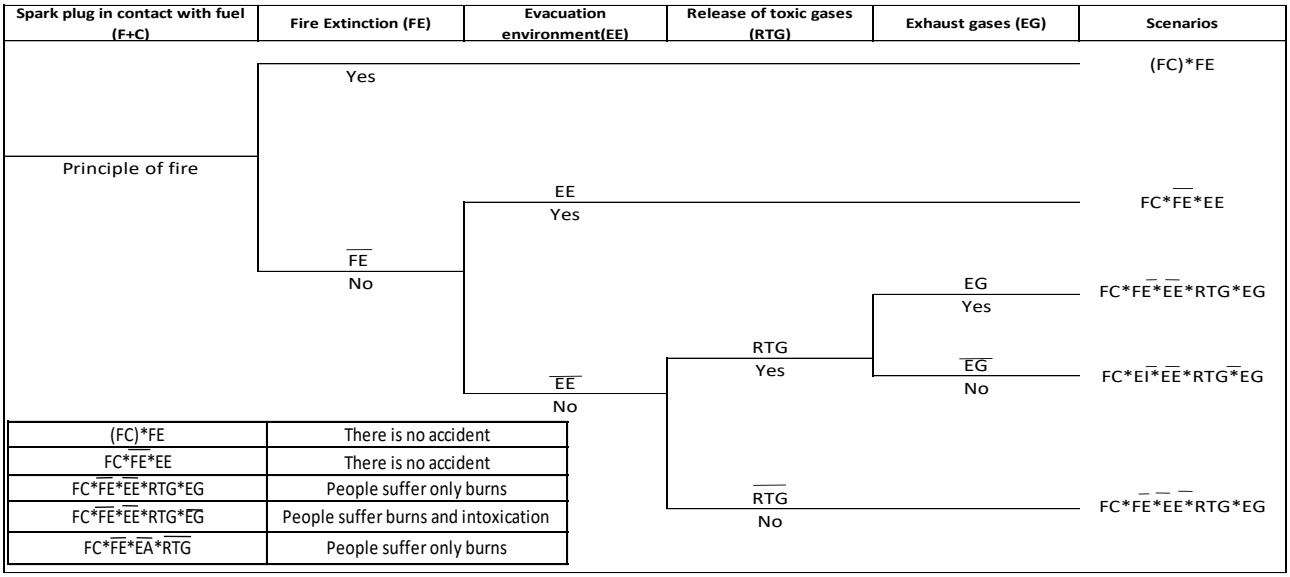

Figure 8. Event tree analysis for fire principle (Source: authors)

As shown in the Fig. 8, the possible scenarios resulting from the initiating event "fire principle" are: no incidents; people suffer only burns; people suffer burns and intoxication. Due the fact that the fire extinction (barrier 1) is not always possible (because it depends on the speed of fire propagation), the environment evacuation in sufficient time is mandatory to avoid physical damage. For this reason, the FTA shown in Fig. 9 was developed aiming to identify the root causes that could trigger the environment non-evacuation.

The root causes that can preclude the building evacuation are related to lack of maintenance, and failure or absence of an emergency exit signaling system. In addition, this event may be associated with improper emergency exit doors, or even the lack of employees training. Exit path obstruction interferes on the time required for evacuation, and thus, it was considered as an intermediate cause that may be associated with several factors.

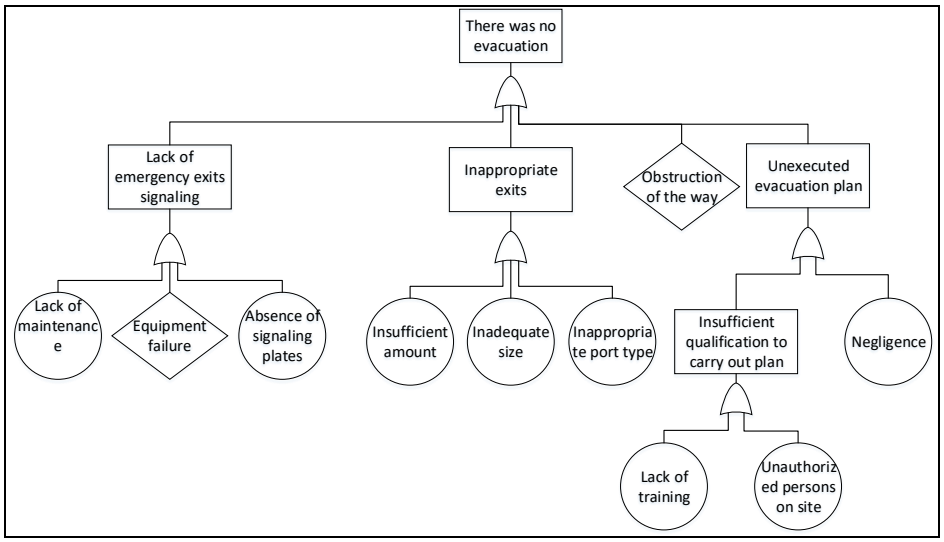

Figure 9. FTA of building evacuation (Source: Authors)

After the FTA, the CNEA was developed aiming to identify and propose barriers to prevent the incident occurrence, and to mitigate its consequences. For this analysis, the incident "there was no evacuation of the building" was considered the top event, and the barriers are regulatory compliance. Finally, after the incident occurrence, the implementation of exhaust gas systems can prevent employee's intoxication.

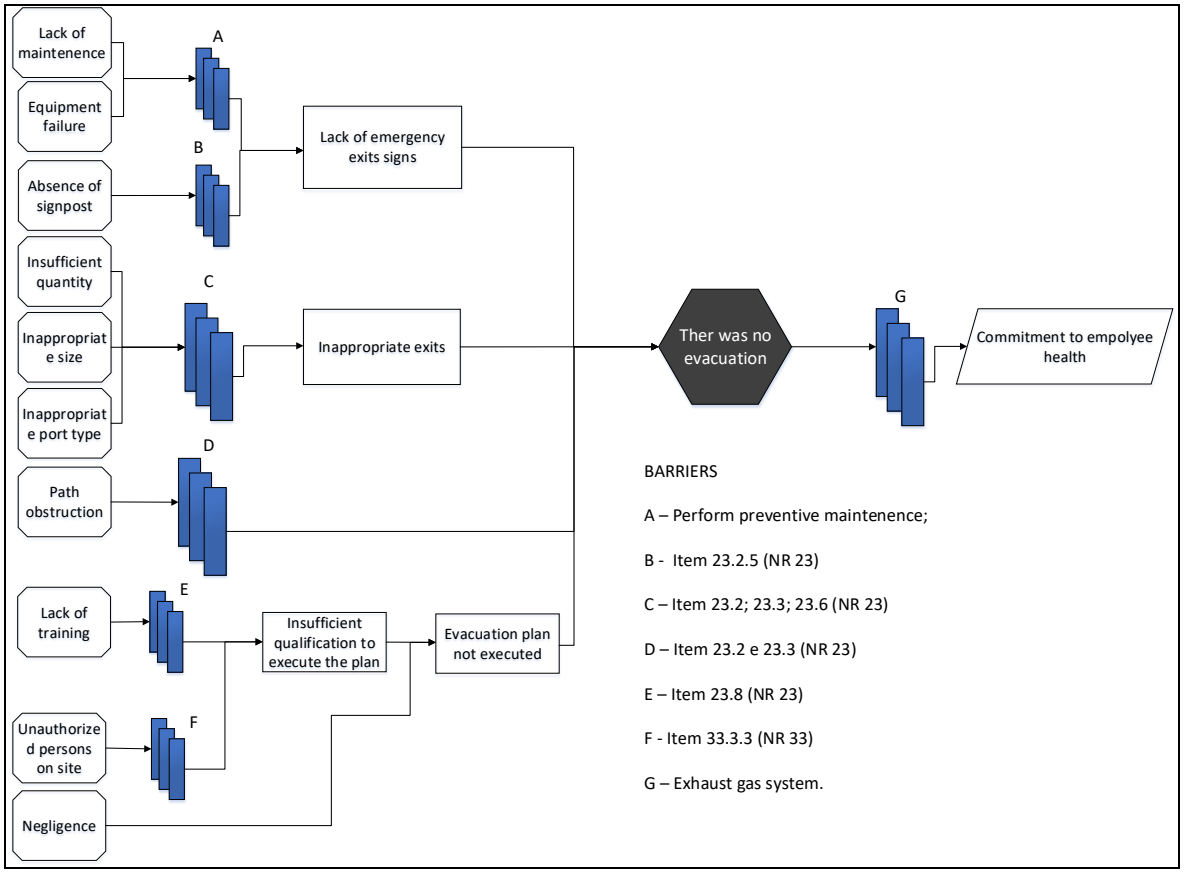

Figure 10. CNEA of building evacuation (Source: Authors)

5. CONCLUSION

The risk analysis of the SAE team's design workshops and construction process was based on risk analysis and management tools to determine potential scenarios and root causes, allowing the development of barriers and suggestions for improvements. Among the applied tools are highlighted the use of FMECA to identify the failure modes of systems and processes, the FTA to determine the root causes of each causal scenario, and the CNEA to elaborate event barriers.

There are two systems with high energy associated in the mechanical workshop: welding machines and fuel tanks. In the first two technical systems, the importance of operator training and awareness is evident, as well as the need to adapt the laboratory to national regulatory norms, such as RS 11, related to transportation, handling, storage of materials, and RS 12, concerning safety in machinery and work equipment safety. The proposed improvements are based on the national regulatory norms applicable to the environment, as highlighted in the recommended actions of each FMECA and CNEA's barriers.

In conclusions, there is an excessive number of potential risks in the environment, and therefore the compliance with the national regulatory norms, such as users training, environmental suitability and supply of PPE's is indispensable. In addition to the existing and analyzed risks, it is worth noting that the analyzed workplace is a teaching laboratory, so it is important that the students have training in this area of knowledge, so that they can adapt their work environment, when they are doing the activities professional.

Finally, as highlighted in item 3, the present work is limited to the conceptual and informational stage according to the risk management methodology proposed by Acires, *et al.*, (2011). For future researches, it is suggested a further study on detailing the barriers and implementation plans, allowing the project implementation validation.

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