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FUZZY RULE-BASED HIERARCHICAL OVERALL RISK ANALYSIS OF BATTERY TESTING LABORATORIES

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Abstract. In this paper, a fuzzy rule based preliminary risk analysis process is proposed for lithium-ion battery test laboratories. The suggested fuzzy model (Hierarchical Overall Risk Analysis-HORA) is suited for secondary lithium-ion battery testing laboratories, but it is applicable for other engineering testing facilities as well with the modification of the defined rating catalogues. The presented fuzzy model completes and merges existing risk analysis methods with taking more non-crisp factors into consideration. During practical work, a simple explosion and fire safety focused approach does not count for all of those aspects, which influence the possible test outcomes, and the traditional Failure Mode and Effect Analysis method is only applicable with significant shortcomings. The proposed model is based on a hierarchical fuzzy inference system that takes three main aspect groups into consideration that influence the consequences of testing procedures: the risks of the product, the risks of the abuse testing process, and system-related risks.

Key words: fuzzy rule-based risk assessment; preliminary risk analysis; test laboratory; hierarchical fuzzy risk assessment.

1. INTRODUCTION

The main activities of lithium-ion battery testing facilities are transport safety [1] and product safety [2] tests. Batteries are tested under abuse conditions, where so-called technical events (e.g. explosion) happen quite often. Therefore, for the operation of testing facilities fire and explosion safety analyses are needed. However, the currently available techniques do not fully cover the complexity of operational safety. Even the widely used traditional Failure Mode and Effects Analysis (FMEA) types do not give a full solution for this task. Here the main question is: when will a battery-related technical event happen? A risk analysis method that relies only on severity, occurrence, and detection like FMEA is not fully appropriate for laboratory-related risk analysis. Process-FMEA is not enough to cover the risks as the examined processes are abuse tests, and there is a high uncertainty related to Design-FMEAs, as they are often missing from manufacturer documentation or they are not carried out at all by the manufacturer.

The aim of the proposed Hierarchical Overall Risk Analysis (HORA) model is to establish a new method that fits the purposes of practical battery testing activities and to handle with the usage of fuzzy logic the inherent vagueness in the opinions of the experts regarding the evaluation of some risk factors. The purpose of the proposed model is not to replace explosion and fire safety risk analyses but to provide a practical, quick, and accurate tool for test engineers to predict the effects of secondary Li-ion battery abuse tests. The proposed model introduces Protection, Controllability, Occurrence, Effectiveness, and System/Cost as new factors taken into consideration.

The rest of this paper is organized as follows. Section 2 contains a short overview of the related literature. Section 3 introduces the proposed HORA model, the research findings and future activity plans are summarized in Section 4.

2. RELATED LITERATURE

Although FMEA is a straightforward and easy to apply analysis method and is considered as a quasi-standard requirement in several fields it suffers from some shortcomings that have been pointed out by several researchers and practical users. Spreafico et al. [3] identified four different categories of FMEA shortcomings: (a) issues with applicability (e.g. subjectivity, time-consuming nature of analysis activities, lack of integration, and high expenses); (b) issues with cause and effects connections (e.g. difficulties in finding the logical connections in the failure net); (c) issues with risk analysis results (e.g. inconsistent risk evaluation causes inconsistent decision making); and (d) difficulties in problem solving (e.g. lack of information about measure implementations). To overcome some specific shortcomings of the methods several modifications and extensions have been proposed.

Ványi and Pokorádi [4] introduced a hierarchic FMEA (H-FMEA) approach. Their method is based on the hierarchic structuring of FMEA with the usage of multidisciplinary elements (hardware-software-mechanical aspects). Their model aims to provide a general understanding of system modelling with the proposal of specific system elements. At the highest level of analysis, the system elements are taken into consideration and they are connected to lower-level design elements. The proposed model is based on the automotive R&D approaches, and uses special characteristics to define specific factors with high importance (e.g. safety critical components). Their approach aims to minimize risks of a certain automotive product.

Di Bona et al. [5] proposed an extension of the traditional FMEA method by using an increased number of influencing factors, namely Severity, Occurrence, Detection, Prevention, Effectiveness, and Cost. They combined the complex Safety Improve Risk Assessment (SIRA) method with the Failure Mode, Effect and Criticality Analysis (FMECA) method and the Association Internationale de la Sècuritè Sociale (AISS) method.

Zlateva et al. [6] created a three level fuzzy approach for social risk estimation from natural hazards in Bulgaria. The problem was defined as a multi-criterial task and the model evaluated several input variables, such as indicators for natural hazards and social vulnerability. These factors were considered as either system- or process related ones.

Takács [7] described a hierarchic fuzzy approach for risk and disaster management with the usage of a hierarchical structure. The proposed risk management model is based on hierarchical risk factors, actions and directions.

Soares et al. [8] dealt with the risk analysis perspective to Li-ion batteries in case of power system applications. They focused on the hazardous nature of lithium-ion cells. According to Soares et al., lithium-ion battery related risk analysis has the following steps: risk identification, risk evaluation, recommended mitigation measures, and risk re-evaluation.

Fantham and Galdwin [9] collected the possible failure modes during lithium-ion battery testing. In case of failures of system component cell, the failure modes are related to the test process itself and the failure effect comes from product side. In case of failures of Battery Management System (BMS) and Bi-directional power supply the failure modes and effects are related to the test process. Fantham and Gladwin identified as safety relevant system components the Battery Management System (BMS), the contactor, and the fire enclosure. Their battery level test setup relies on the fact that the test samples are equipped with BMS, and the information about it is available. However, their approach is not always applicable because not all batteries are equipped with BMS.

3. HIERARCHICAL OVERALL RISK ANALYSIS

Hierarchical Overall Risk Analysis (HORA) intends to help test engineers to define the probable risks of battery test processes. In practice, the prioritization of test processes is done according to their effects. HORA is fit for the needs of professionals to fasten and simplify decision-making based on available information. Due to the diversity of lithium-ion batteries and the lack of information provided by the battery manufacturers there is always a high level of uncertainty in case of battery testing. The fuzzy inference system helps to analyse test projects based on available information and it is applicable in cases when there is available only a low amount of product-related information (missing cell construction details, missing Battery Management System related information, and/or missing Product-FMEA).

HORA is based on the consideration that all levels of the traditional Failure Mode and Effects Analysis need to be involved, albeit in a different manner. The proposed model is based on a hierarchical fuzzy inference system that takes into consideration three main aspect groups that influence the consequences of testing procedures: the risks of the product (represented by Controllability and Occurrence factors), the risks of the abuse testing process (represented by Protection and Effectiveness factors), and system-related risks (represented by the combined System/Cost factor). The model assumes that no test engineer-related failures occur. The aim of the model is not to improve the existing test setup or to define mitigation measures but to provide a simple preliminary risk analysis tool for decision making purposes that is applicable in an environment with high uncertainty level.

3.1. Description of the method

The Hierarchical Overall Risk Analysis model aims to analyse the risks of the Li-ion battery related abuse testing processes. The model assumes the existence and availability of the mandatory fire and explosion safety analysis. The causes of battery-related technical events are analysed on levels: product level, process level and system level. Product level is considered as the cause level, process is considered as the failure mode level and system level as the effect level of the hierarchical system.

HORA combines the advantages of design level and process level analysis as the used factors are derived from different structural levels. The model uses five factors: Controllability (C), Occurrence (O), Protection (P), Effectiveness (E), and System/Cost (S/C). Severity and Cost factors are related to the battery-related technical event impacts. These two factors are interpreted together as every severity case has its cost-related effect as well. The basic concept of HORA is presented in Fig. 1.

The first fuzzy subsystem provides the causes which are related to product behavior and construction. Its first input factor (C) scales the risks of built-in product controls. These product features help to protect the battery from potential hazardous behaviour during abuse tests. The built-in control measures are as follows: low level controls (e.g. cell level protection), medium level controls (e.g. fuses, thermal fuses and safety vents) and high level controls (e.g. Battery Management System, Battery Thermal Management System). The second input factor is O, which has three levels: low, medium and high. The output is $Risk_{product}$ that summarizes and merges product level hazards and risks.

The second fuzzy subsystem uses $Risk_{product}$, P and E as inputs. Protection and Effectiveness are related to the standardized abuse testing processes (e.g. [1] [2]) that are carried out in the test laboratory. This subsystem analyses the risks of the product and the process at once. The output of the second subsystem is called $Risk_{process}$.

The third fuzzy subsystem takes product, process and system related aspects into account, as the inputs are $Risk_{process}$ and S/C. The outcome of HORA is numerical and can be defined as the acceptance criteria of the system.

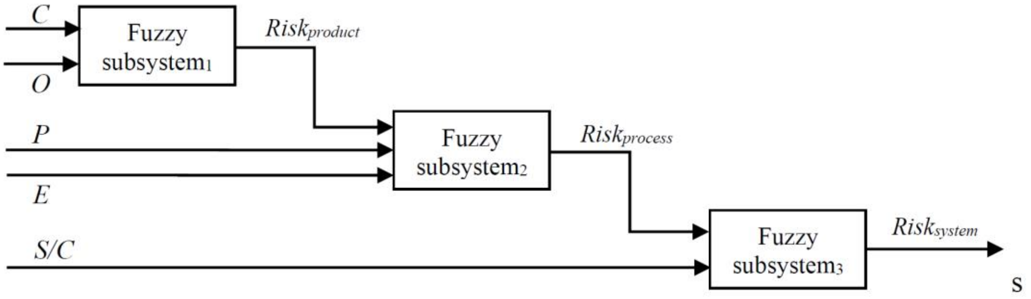


Fig. 1 – HORA model.

3.2. Evaluation of controllability and occurrence

The factors C and O refer to product level, as the first subsystem evaluates the present control solution. Controllability represents the product level control of dangerous Li-ion battery events. It might have the following three evaluation levels: high (the ‘safest’ battery system constructions, e.g. BMS or BTMS included), medium (simple safety solutions are represented in the sample, e.g. thermal fuse/fuse or safety vent) and low (in this case only cell level safety is present in the sample). Occurrence represents the possibility of hazardous effects based on the type of the lithium-ion cells used. Here the suggested three levels are identified as: high (if three or more tests result in technical events), medium (if two tests out of ten result in technical events) and low (if one or no tests result in technical events out of ten). The rating catalogue of controllability and occurrence factors are presented in Table 1. Supposing triangle shaped membership functions the parameters of the sets associated to the individual levels are given as well.

Table 1

Controllability and Occurrence rating catalogue

Fuzzy s.	Parameters	Controllability (*C*)	Occurrence (*O*)
L	{1.00, 1.00, 5.50}	Low product level control, e.g. or only cell level protection.	Occurrence is considered as low, if one or no test results in technical events out of ten occasions (in case of similar battery constructions).
M	{1.00, 5.50, 10.00}	Medium product level control, e.g. Thermal fuse/fuse or safety vent in sample.	Occurrence is considered as medium, if two tests result in technical events out of ten occasions (in case of similar battery constructions).
H	{5.50, 10.00, 10.00}	High product level control, e.g. Battery Thermal Management System (BTMS) in sample and/or Battery Management System (BMS) in sample.	Occurrence is considered as high, if three or more test result in technical events out of ten occasions (in case of similar battery constructions).

3.3. Evaluation of protection and effectiveness

The *P* and *E* factors refer to the process level, as they analyse the test process outcome. Protection stands for the existing laboratory safety solutions that are prepared to avoid battery related events, while effectiveness stands for the laboratory safety solution effectiveness. For both factors a three-level scaling was defined in Table 4. Supposing triangle shaped membership functions the parameters of the sets associated to the individual levels are given as well.

Table 2

Protection and Effectiveness rating catalogue

Fuzzy s.	Parameters	Protection (*P*)	Effectiveness (*E*)
L	{1.00, 1.00, 5.50}	No/few preventive actions/measures or protective devices exist	Laboratory related risks are unknown, no proven effective protection devices are available
M	{1.00, 5.50, 10.00}	Some preventive actions/measures exist (e.g.: extinguishing system, gas detector sensors, etc.)	Unknown phenomenon can occur, preventive action/measures are existing, without proven result
H	{5.50, 10.00, 10.00}	Several preventive action/measures exist (e.g.: explosion proof chamber, etc.)	Risks are clear and understood, proven effective protection devices are available

3.4. Evaluation of severity/cost

In this section, the recommended severity/cost criteria (rating catalogues) will be introduced. First, let us overview the risk sources. In this research, the two standardized test sequences described in [1] and [2] were taken into consideration.

The two test standards identify the following steps: electrical tests (external short circuit, abnormal charge and forced discharge test), mechanical tests (crush, impact, shock, vibration, low pressure and drop test) and thermal tests (heating, temperature cycling and projectile test). The basic test setups are the same, only the test parameters differ in some cases.

During these tests the laboratory personnel is subjected to hazardous environmental circumstances. For example, batteries are prone to catch fire or even to explode in a worst-case-scenario. These scenarios are mainly due to the thermal runaway phenomenon (a complex electrochemical effect). Thermal runaway is the result of electrical, mechanical and thermal abuse conditions.

The suggested approach for severity and cost rating is presented in Table 3. Supposing triangle shaped membership functions the parameters of the sets associated to the individual levels are given as well. In case of this catalogue three aspects have to be considered together because probable accidents have consequences in three different aspects: (a) laboratory environment related effects due to standardized tests ($S_{laboratory}$); (b) laboratory personnel related effects ($S_{personnel}$); and (c) the cost of damages (*Cost*). The combined S/C catalogue can be adjusted based on the existing laboratory setup and safety solutions.

Table 3

Severity/Cost catalogue

Fuzzy s.	Parameters	$S_{laboratory}$	$S_{personnel}$	*Cost*
NE	{1.00, 1.00, 2.29}	No effect in the testing environment	No effect in the testing environment, no health effect	No effect in the testing environment, no costs occur
VL	{1.00, 2.29, 3.57}	Melted plastic parts in chamber, cleaning necessary	Potential effects on respiration, health hazards	Chamber cleaning required, cleaning costs occur
L	{2.29, 3.57, 4.86}	Release of excessive internal pressure from a cell or battery in a manner intended by design to preclude rupture or explosion; excessive amount of melted plastic parts in chamber, cleaning necessary	Effects on respiration, heat hazards	Chamber cleaning required, cleaning costs occur, service downtime
ML	{3.57, 4.86, 6.14}	Unplanned, visible escape of liquid electrolyte; minor gas leakage in the environment; smoke in the test environment	Long-term effects on respiration, heat hazards	Cleaning of test environment is required, service downtime
M	{4.86, 6.14, 7.43}	Major gas leakage in the environment; smoke in the test environment	Long-term effects on respiration, effects on vision, heat hazards	Cleaning of test environment is required, possible damaged test equipment in the room, excessive service downtime
MH	{6.14, 7.43, 8.71}	Mechanical failure of a cell container or battery case induced by an internal or external cause, resulting in exposure or spillage but not ejection of materials; fire in the test environment	Potential burn hazard	Possible damaged test equipment in the room, dust accumulation, excessive service downtime
H	{7.43, 8.71, 10.00}	Emission of flames from a cell or battery; fire, flying parts in the test environment	Burn hazard, cut injuries	Damaged test equipment in the room, dust accumulation, excessive service downtime
VH	{8.71, 10.00, 10.00}	Cell container or battery case opens violently and major components are forcibly expelled; explosion in the test environment	Worst-case scenario: death	Purchase of new test chamber is necessary, dust accumulation, excessive service downtime

3.5. Fuzzy membership functions

The universe of discourse of all input and output variables is [1, 10], and the membership functions are triangular shaped described by the general equation (1)

$$\mu = \begin{cases} \max\left(\dfrac{x-a}{b-a}, 0\right), & x \le b \\ \max\left(\dfrac{c-x}{c-b}, 0\right), & \text{otherwise}, \end{cases} \tag{1}$$

where a, b, and c are the abscissa values of the breakpoints conform Fig. 2.

The linguistic terms and the parameters of the membership functions of the variables C, O, P, E, and S/C are presented in Tables 1, 2, and 3, respectively. The variables $Risk_{product}$, $Risk_{process}$, and $Risk_{system}$ have identical partitions with the variable C. The two types of fuzzy partitions are represented in Fig. 3.

3.6. Risk assessment matrices of fuzzy subsystems

In the HORA model, the rules were defined based on the expertise of specialists that had been working on this field for several years. All fuzzy subsystems use Mamdani type inference, and centroid type defuzzification was applied. The rules of the fuzzy subsystems are presented in Tables 4, 5, and 6, respectively.

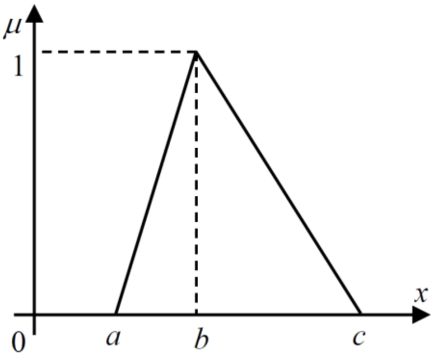


Fig. 2 – Triangle shaped membership function and its parameters.

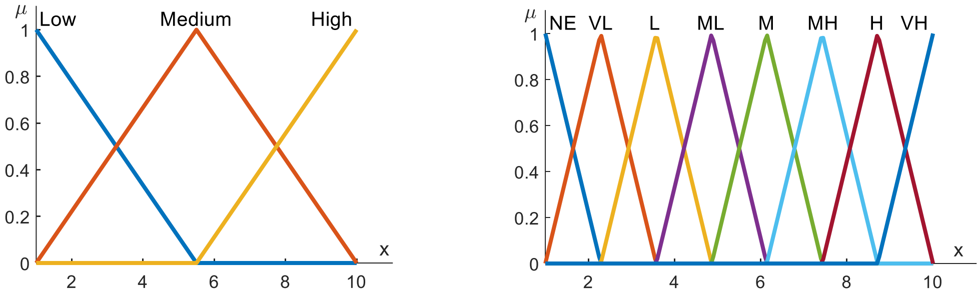


Fig. 3 – Fuzzy partitions.

Table 4

Risk Assessment Matrix of the first fuzzy subsystem

$Risk_{product}$		Occurrence		
		HIGH	MEDIUM	LOW
Controllability	HIGH	MEDIUM	MEDIUM	LOW
	MEDIUM	HIGH	MEDIUM	MEDIUM
	LOW	HIGH	HIGH	MEDIUM

Table 5

Risk Assessment Matrix of the second fuzzy subsystem

$Risk_{product}$ HIGH		Effectiveness		
		HIGH	MEDIUM	LOW
Protection	HIGH	MEDIUM	MEDIUM	HIGH
	MEDIUM	MEDIUM	HIGH	HIGH
	LOW	HIGH	HIGH	HIGH

$Risk_{product}t$ MEDIUM		Effectiveness		
		HIGH	MEDIUM	LOW
Protection	HIGH	MEDIUM	MEDIUM	MEDIUM
	MEDIUM	MEDIUM	MEDIUM	HIGH
	LOW	MEDIUM	HIGH	HIGH

$Risk_{product}$ LOW		Effectiveness		
		HIGH	MEDIUM	LOW
Protection	HIGH	LOW	LOW	MEDIUM
	MEDIUM	LOW	MEDIUM	HIGH
	LOW	MEDIUM	MEDIUM	HIGH

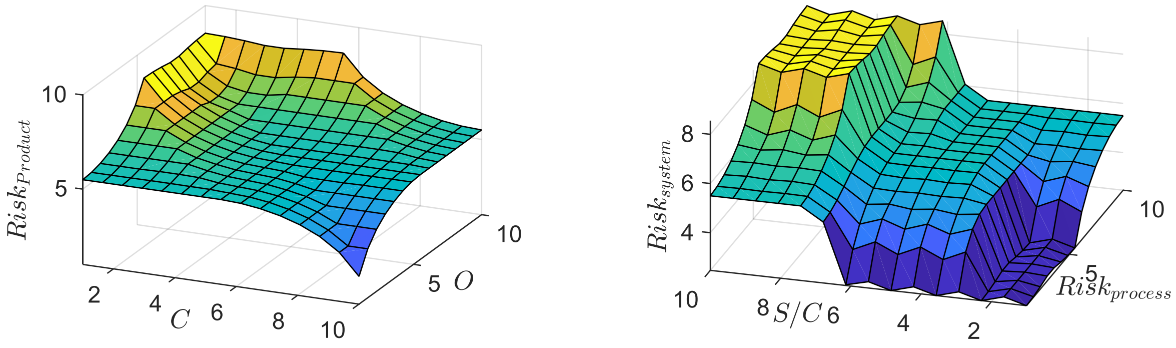
Table 6

Risk Assessment Matrix of the third fuzzy subsystem

		Severity/Cost							
		VERY HIGH	HIGH	MEDIUM-HIGH	MEDIUM	MEDIUM-LOW	LOW	VERY LOW	NO EFFECT
$Risk_{process}$	H	H	H	H	H	M	M	M	M
	M	H	H	H	M	M	M	L	L
	L	M	M	M	L	L	L	L	L

3.7. Visualisation of the output of the fuzzy logic subsystems

The hierarchical HORA model was implemented in Matlab using the Fuzzy Logic Toolbox. The output of the subsystems in function of the input values can easily visualized by a surface in case of the first and the third ($Risk_{product}$ and $Risk_{system}$) subsystems (Figs. 4a and 4b).



(a) (b)

Fig. 4 – Visualization of the output of the first and third fuzzy logic subsystems.

In case of the second subsystem ($Risk_{process}$) the results are shown on a different type of graph. As a 4D approach is not possible, the value of the output is calculated, and the colour of the dots represent the value of the output (Fig. 5).

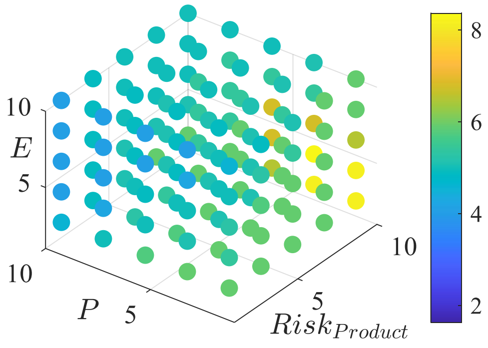


Fig. 5 – Visualization of the output of the second fuzzy logic subsystems ($Risk_{process}$).

3.8. Model validation

The validation of the HORA model was done by the help of experienced Li-ion battery test engineers. First, in case of each factor several values were selected for later trial. Five levels were determined for the factors Controllability, Occurrence, Protection, and Effectiveness as well as fifteen levels for Severity/Cost, respectively. The key idea was to include values with maximal membership value in a fuzzy set as well as values at the intersection of two neighbouring membership functions. Considering these values there are in total 9 375 possible arrangements, which would mean a too high number of evaluations for the human experts. Therefore, the design of experiments approach developed by Taguchi [10] was applied to select the lowest possible number of arrangements for actual evaluations. The design $L_{75}\ 5^8\ 15^1$ [11] fitted best the current task. It contains 75 experiments and allows the investigation of at most eight factors with five levels and one factor with fifteen levels. In course of the validation process for each of the 75 value tuples the involved test engineers compared their own $Risk_{system}$ evaluation with output of the system and gave improvement suggestions in questionable cases. Four typical examples are presented in Table

Table 7

Risk evaluation examples

	Controllability	Occurrence	Protection	Effectiveness	Severity/Cost	$Risk_{system}$
Example 1	1	1	1	1	1	7
Example 2	3	3	10	8	2	3
Example 3	6	3	8	6	9	8
Example 4	8	6	3	10	10	10

Example 1 takes the following case into consideration. The Controllability is characterized by low product level control, the Occurrence is low, the Protection is low, the Effectiveness is low, and the Severity/Cost can be evaluated as no effect and no costs. In this case $Risk_{system}$ is considered to be 7, as Controllability, Protection and Effectiveness have the lowest value, although Occurrence and Severity/Risk level is low.

Example 2 examines the following case. The Controllability is low, the Occurrence is low, the Protection level is good as several prevention actions exist, the Effectiveness is characterized by risks are clear and understood, proven effective protection devices are available, and Severity/Cost is evaluated as deformation or cleaning costs occur. In this case $Risk_{system}$ is considered to be 3 as Occurrence level is 3, and the technological events have only Severity/Cost 2 value.

Example 3 takes the following case into consideration. The Controllability level is medium, the Occurrence is low, the Protection is characterized by the existence of several prevention actions, the Effectiveness is evaluated as 6 because unknown phenomenon can occur, the Severity/Cost level is increased owing the explosion possibility and in worst case scenario death can also occur. In this case $Risk_{system}$ is considered to be 8, because although the Occurrence level is 3, the Severity/Cost value is considered to be 9.

Example 4 examines the following case. The Controllability is high, the Occurrence is medium, the Protection level is low with no/few prevention actions, the Effectiveness is high as risks are clear and understood and proven effective protection devices are available, and finally the Severity/Cost is also high owing to possible explosion in the test environment and in worst case scenario death can also occur. Purchase of new test chamber is necessary, dust accumulation, excessive service downtime is probable. In this case $Risk_{system}$ is considered to be 10, due to medium level of Occurrence and high level of Severity/Cost.

4. CONCLUSION

During battery abuse testing, hazardous battery behaviour is created by purpose. This reveals the necessity of a carefully selected risk analysis method. The usage of an analysis method that is only process related would have shortages, because it would not consider product and system level approaches at all. This suggests the implementation of a hierarchical solution, which considers the whole laboratory as a system including the testing process, and product types as well.

FMEA, which is the most traditional risk analysis method, is only partially applicable for this purpose. In manufacturing, the direct linkage of Product-, and Process FMEAs can be a useful approach but during the everyday operation of a laboratory, not all batteries are provided with FMEAs, and even if they are, the FMEAs cannot be standardized as each manufacturer handles FMEAs in different ways.

In this paper, a new method for preliminary Li-ion battery test laboratory risk analysis is presented. HORA analyses test consequences based on available information in a test environment, which deals with product-related uncertainties as well. The fuzzification of the hierarchical approach eases usage, as engineers do not have to statistically analyse each case to decide about test feasibility based on pre-evaluated risk levels. One more advantage of the recommended method is that factor thresholds (parameters of the fuzzy sets) can be flexibly adjusted for individual laboratories, with differing test and safety setups. Occurrence catalogues can be modified based on the experience of test engineers, process related (Protection, Effectiveness) catalogues can be described based on the existing safety solutions. During the validation phase of HORA, the feedbacks came from experienced battery test engineers.

Further research will consider the applicability of fuzzy signatures [12], solutions inspired by fuzzy control theory [13], cognitive maps [14], and rule base simplification techniques [15]. One possible future step is to create a decision-making (DM) application [16] in which the HORA model is expanded on. This future approach aims to provide a highly efficient DM application with flexible thresholds. With the usage of a customized DM approach the preliminary analysis can be combined with a system-built decision-making tool, which decreases time spent on project preparation tasks.

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