Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio

Published by Research Publishing, Singapore.
doi: 10.3850/978-981-18-8071-1_P478-cd

A brief review of systematic risk analysis techniques of lithium-ion batteries

Qiaoqiao Yang, Mengyao Geng, Huixing Meng*

State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing, 100081, China. E-mail: huixing.meng@bit.edu.cn

As the increasing demand and widening range of application, lithium-ion battery (LIB) is becoming indispensable equipment in daily life. However, accidents related to LIB-powered facilities have been reported continually. In this paper, we studied the LIB risk analysis techniques and battery-related emergency response. Fault tree (FT), failure mode and effects analysis (FMEA), Bayesian network (BN) and systems-theoretic process analysis (STPA) are introduced. And the applications of abovementioned techniques are reviewed. Advantages and disadvantages of these techniques are discussed, with suggestions for the method selection. Further, the discussion of battery fire-extinguishing procedure emphasizes standardization of emergency response and battery manufacturing. This work aims to inspect LIB risk in a systematic perspective, which can be instructive to battery system safety from design stage to emergency disposal.

Keywords: Lithium-ion battery, Risk analysis, Fault tree, Failure mode and effects analysis, Bayesian network, Systems-theoretic process analysis.

1. Introduction

Lithium-ion batteries (LIBs) are ubiquitous in modern society. In household and industry, LIBs have been popularly applied due to the long service life and high energy density (Liu et al., 2018, Meng and Li, 2019). In recent years, the world is witnessing the booming of electric vehicles (EVs) for carbon emission reduction (Meng et al., 2022). Moreover, LIBs are the dominant candidate for energy storage systems (ESSs) to achieve distributed energy storage (Zubi et al., 2018, Qiu and Jiang, 2022).

However, battery-induced accidents are often reported. For example, the explosion events of Samsung Galaxy Note 7, the smartphone, brought the manufacturer enormous reputational and financial losses (Yun et al., 2018). The fire and explosion events of EV and ESS frequently occurred, raising public concern.

The failure of LIBs results from thermal abuse, mechanical abuse and electrical abuse (Wen, Yu, and Chen, 2012). Thermal abuse denotes the external heating that would cause damage of inner materials. Mechanical abuse involves collision, puncture, or falling that deform the LIBs. And electrical abuse is generally from over-charging or over-discharging.

Based on the knowledge of LIB failure mechanisms, systematic analysis towards battery accidents is expected. Figuring out the evolution of failure paths and assessing the corresponding risks benefit the battery design and risk reduction. There are many analytical techniques used for battery systems such as fault tree (FT) (Qi et al., 2017), failure mode and effects analysis (FMEA) (Bubbico, Greco, and Menale, 2018), Bayesian network (BN) (Wu et al., 2021) and systems-theoretic process analysis (STPA) (Rosewater and Williams, 2015). But more academic interests are focusing on optimizing component and chemical composition involved in the batteries.

In contrast to general fire events, battery fires often associate with reignition and toxic gas releasing, resulting in higher risk. However, a research in the United States showed that first responders are not adequately prepared for EV fires (Liu et al., 2023). That over 40% surveyed first responders have never received safety training on EV accidents alerts corresponding departments to enhance emergency training (Liu et al., 2023).

This work aims to review LIB risk assessment methods and emergency response. Four systematic analysis techniques are introduced. The applications of these techniques in the field of battery safety are then summarized. Moreover, we discuss the fire-extinguishing procedure corresponding to battery failure.

The remainder of this paper is structured as follows. Section 2 presents the application status of FT, FMEA, BN and STPA in LIB systems. Section 3 shows the response to battery fire emergency. Section 4 concludes this work.

2. Applications of systematic risk analysis techniques

Systematic risk analysis techniques thoroughly examine battery safety issues. Rather than address a functional difficulty, researchers and engineers prefer to apply these techniques to find strategies to improve the reliability of a system at a macroscopic level.

2.1.*Fault tree*

FT is a commonly-used method which is suitable for both qualitative and quantitative analysis towards accidents in most industries. Owing to its capability to demonstrate interrelationships between hazardous events, FT is adopted in LIB fires and explosions analysis.

For LIB fire accidents, an FT was developed by Huang et al., (2018) based on the fire triangle. By calculating structural importance, battery shell rupture showed the biggest influence among the 15 basic events. Similarly, battery shell rupture and the production of combustion gas inside the battery simultaneously caused LIB explosion accident in FT proposed by Qi et al., (2017). In particular, combustion gas comes from the occurrence of internal short circuit or external short circuit or high temperature. Internal short circuit, one of the middle events, is caused directly by over-charge/ manufacturing defects/ over-discharge/ degradation/ penetration, as shown in Fig. 1. Their model specified the root causes to the damage of battery itself, battery management system (BMS) failure and human error.

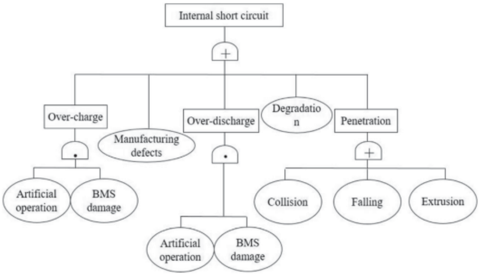

Fig. 1 Partial FT of LIB explosion (Hu et al., 2021).

Usually, battery tests are grounded on the knowledge of basic events. Hu et al., (2021) introduced 29 battery tests according to the proposed FT on EV fire. These extended tests were compared by analytic hierarchy process (AHP), which is an adaptive method to rank importance (Wang et al., 2022). It is suggested that enhancing BMS-related tests would significantly improve the safety level of the battery system.

Considering safety barriers, that is, the functional components of BMS in the battery field, Wen, Zhang, and Lu, (2015) used both event tree (ET) and FT to study battery accidents. A safety indicator set consisting of 14 basic events was proposed to represent the safety status of EVs. The probability importance, structure importance and critical importance are calculated. Yet, their analysis relied on limited experience of an engineer, consequently being relatively subjective.

To solve the subjective problem on human judgement, fuzzy logic methods are often employed for quantifying expert knowledge (Purba et al., 2015, Li et al., 2021). Firstly, the fuzzy set replaces expert's linguistic judgement with fuzzy numbers. Then, the obtained fuzzy numbers can be transformed into numerical values by defuzzification method. In this way, the uncertain variables, such as occurrence probability (Hu et al., 2021) and severity (Huang et al., 2022) of basic events can be calculated to some extent.

FT deduces the accident evolution from the very beginning but the definition of basic events is often vague. Because FT only supports binary states of an event (Occurring or Not occurring), how severe the event is occurring cannot be determined. If quantitative analysis is needed, collecting reliable probabilistic data for each basic event is also a common issue. Then the application of FT on LIB that involves not only mechanical component but also electrochemical substances is relatively less.

2.2.*Failure mode and effect analysis* FMEA is formally a well-organized chart that enables people to quickly capture the required information. The bottom-up FMEA allows engineers to analyze the system from basic components, investigate the possible failure mode, and assess the effects that each failure mode may have on the entire system.

Bubbico, Greco, and Menale, (2018) used FMEA to assess the battery system from cell, module and pack level, while the discussed basic elements are battery component (cathode, anode, separator, electrolyte, etc.), cell and module, respectively. Their results provided a comprehensive list for LIB users and operators.

While the FMEA chart is flexible to add needed contents, for instance, mechanism of failure (Imen et al., 2020), likelihood, severity and detectability of occurrence (Hendricks et al., 2015), as the example shown in Table 1.

Soares et al., (2015) expanded the FMEA analysis by taking risk mitigation measures (RMMs). The stationary LIBs for power system applications are investigated in order of operation process: production, transportation/ removal, installation/ decommissioning, storage, operation, maintenance/ periodic inspection. And for those intolerable risks, counterpart safety measures would be taken until that risk was re-evaluated as acceptable.

Table 1 An example of FMEA on LIB anode .

Process step/Input	Potential failure mode	Potential failure effects	Severity	Potential causes	Likelihood	Detectability
Anode	Particle fracture	Reduction of capacity, reduction of power	Low	Intercalation stress	Moderate	Low

Although systematic and comprehensive, FMEA cannot deal with the risk caused by multi-failure. Likewise, the quantification in FMEA highly relies on expert judgment so that subjectivity is inevitable.

2.3.*Bayesian network*

BN is a probabilistic reasoning method to treat uncertain knowledge. A BN can be mapped from FT structure (Yazdi and Kabir 2017). Given multiple states, variables in a BN model are more flexible and functional than FT. Adding dynamic nodes introduces time sequence in to BN, which forms the dynamic Bayesian network (DBN). The value of dynamic node changes with time, characterizing the enhancement or degradation of the variable.

BN is a newly emerging systematic analysis technique for LIB safety. Wu et al., (2021) used a data-driven BN model to conduct risk management strategy for EV transportation in RoPax ships. It was concluded that charging the cars increases explosion risk in the journey. Integrated DBN with machine learning (ML) algorithms, Meng et al., (2023) predicted the trend of LIB thermal runaway. The DBN structure is shown as Fig. 2. State of health (SOH) is the dynamic node, which indicates the capacity degradation of the battery. The CPT fuses statistics data, expert knowledge and information from data sets (Jung et al., 2022, Zhao, Sun, and Wang, 2020).

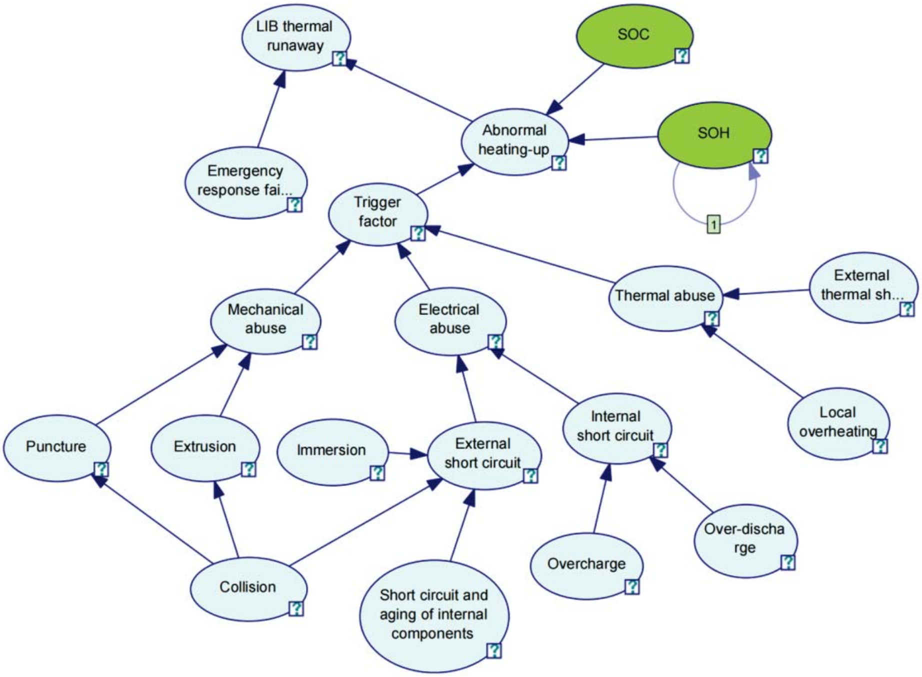

Fig. 2 The DBN of LIB thermal runaway (Meng et al., 2023).

Although BN is considered as a promising method, establishing the probability relationship between variables is still a challenge at this stage. If shortage of reliability data is solved, BN can be utilized from component optimization in cell level to emergency response in ESS level.

2.4. *Systems-theoretic process analysis*

STPA is a top-down analysis tool developed from systems theoretic accident modelling and process (STAMP) (Sulaman et al., 2019). The unsafe interaction between system components is emphasized by structuring the control loop (Madala, Do, and Tenbergen, 2022, Rausand and Haugen, 2020).

STAMP shifts the purpose from avoiding failures to enforcing safety control action (Rosewater and Williams, 2015), providing a new perspective to think about battery safety. Rosewater and Williams, (2015) investigated the way to guarantee grid-scale safety of LIB into an STPA framework as shown in Fig. 3. A controller issued a safety control order to its actuator. This actuator then implemented a controlled process. While a sensor detected if the controlled process is completed or not, taking that as feedback to the controller for updating its process mode.

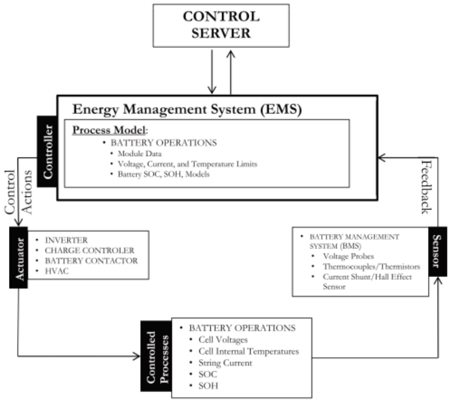

Fig. 3 A STPA control loop in battery risk assessment (Rosewater and Williams, 2015).

STPA is more capable to identify the critical failure path and feedback the failure to its controller than FT, optimizing the system operation. Thereby, STPA applies to analyze complicated systems with software (Rausand and Haugen, 2020). In the field of battery, it is especially adaptive to ESS (Choo and Go, 2022). But only qualitative results can be attained in STPA analysis.

3. Emergency response

Effective extinguishing strategies not only protects the battery pack and emergency responders, but also saves time and cost. Taking fire suppression of crashed EVs as an example, National Transportation Safety Board (NTSB) released guidance to warn the risk to responders from LIB fires in EVs (NTSB, 2020). Generally, the first response after the rescuers arriving at the site is to identify the vehicle type. Secondly, the car is immobilized to keep it away from people. Responders would then extricate occupants inside the vehicle and extinguish the fire, with the protection of personal protective equipment (PPE) and self-contained breathing apparatus (SCBA). The EV may reignite although the fire is extinguished several days ago. Therefore, monitoring the damaged vehicle is indispensible (NTSB, 2020).

According to ISO 17840 (ISO17840, 2019), EV manufacturers should provide emergency response guides for consumers and responders. The guides list common accident scenarios and corresponding actions, containing detailed parts distribution related to lessen risk when emergency occurs.

In case of fire, the manufacturers give suggestions for responders, including using copious water or ABC powder extinguisher, using infrared thermometer to monitor battery temperatures during the cooling process, disposing high voltage risk, warning reignition (NFPA, 2022).

4. Conclusion

In this paper, the applications of systematic risk analysis techniques on LIBs safety are discussed. FT uses schematic diagrams to describe the evolution of battery accidents. FMEA is used to intuitively find weak points of battery systems. BN shows the correlation of variables leading to battery failures and supports risk evolution analysis through dynamic nodes. And STPA can systematically detect the social-technical faults based on control theory and sytems theory. Then, emergency response techniques to LIB fire are reviewed. Systematic emergency management is yet to be perfect on whether before or after the hazardous events occur.

In the future works, data-driven risk analysis methodology is expected to promote the level of battery risk control. Furthermore, standardization of emergency response and battery manufacturing are significant for safer LIB systems.

Acknowledgement

This work is supported by the Beijing Institute of Technology Research Fund Program for Young Scholars (Grant No. XSQD-202002007), and the Exchange Program of High-end Foreign Experts of Ministry of Science and Technology, China (Grant No. G2022178013L).

References

Bubbico, Roberto, Viviana Greco, and Carla Menale. 2018. "Hazardous scenarios identification for Li-ion secondary batteries." *Safety Science* 108:72-88.

Choo, Boon Leong, and Yun Ii Go. 2022. "Energy storage for large scale/utility renewable energy system - An enhanced safety model and risk assessment." *Renewable Energy Focus* 42:79-96.

Hendricks, Christopher, Nick Williard, Sony Mathew, and Michael Pecht. 2015. "A failure modes, mechanisms, and effects analysis (FMMEA) of lithium-ion batteries." *Journal of Power Sources* 297:113-120.

Hu, Guangfang, Peifeng Huang, Zhonghao Bai, Qingsong Wang, and Kaixuan Qi. 2021. "Comprehensively analysis the failure evolution and safety evaluation of automotive lithium ion battery." *eTransportation* 10:100140.

Huang, Peifeng, Guangfang Hu, Zhong Yong, Binbin Mao, and Zhonghao Bai. 2022. "Fire risk assessment of battery transportation and storage by combining fault tree analysis and fuzzy logic." *Journal of Loss Prevention in the Process Industries* 77:104774.

Huang, Peifeng, Jialiang Liu, Yi Jin, Yuanliang Fan, Ke Li, and Qingsong Wang. 2018. "Fault tree analysis method for lithium ion battery failure mode based on the fire triangle model." *Journal of Safety and Environment* 18 (1):66-69.

Imen, A., H. Inès, B. Kais, and B. A. Faouzi. 2020. "Criticality assessment with Pareto diagram of the different solar batteries technologies." 2020 17th International Multi-Conference on

Systems, Signals & Devices (SSD), 20-23 July 2020.

ISO17840. 2019. Road vehicles — Information for first and second responders — Part 3: Emergency response guide template.

Jung, TaiJong, Hyobin Lee, SunHo Park, Jihun Song, Joonam Park, ChilHoon Doh, SeongWook Eom, JiHyun Yu, YongMin Lee, and YoonCheol Ha. 2022. "Statistical and computational analysis for state-of-health and heat generation behavior of long-term cycled LiNi0.8Co0.15Al0.05O2/Graphite cylindrical lithium-ion cells for energy storage applications." *Journal of Power Sources* 529:231240.

Li, Xinhong, Yi Zhang, Rouzbeh Abbassi, Ming Yang, Renren Zhang, and Guoming Chen. 2021. "Dynamic probability assessment of urban natural gas pipeline accidents considering integrated external activities." *Journal of Loss Prevention in the Process Industries* 69:104388.

Liu, Datong, Yuchen Song, Lyu Li, Haitao Liao, and Yu Peng. 2018. "On-line life cycle health assessment for lithium-ion battery in electric vehicles." *Journal of Cleaner Production* 199:1050-1065.

Liu, Jun, Ningzhe Xu, Yangming Shi, Timothy Barnett, and Steven Jones. 2023. "Are first responders prepared for electric vehicle fires? A national survey." *Accident Analysis & Prevention* 179:106903.

Madala, Kaushik, Hyunsook Do, and Bastian Tenbergen. 2022. "Identifying safety issues from energy conservation requirements." *Journal of Software: Evolution and Process* n/a (n/a):e2515.

Meng, Huixing, Mengyao Geng, Jinduo Xing, and Enrico Zio. 2022. "A hybrid method for prognostics of lithium-ion batteries capacity considering regeneration phenomena." *Energy* 261:125278.

Meng, Huixing, and Yan-Fu Li. 2019. "A review on prognostics and health management (PHM) methods of lithium-ion batteries." *Renewable and Sustainable Energy Reviews* 116:109405.

Meng, Huixing, Qiaoqiao Yang, Enrico Zio, and Jinduo Xing. 2023. "An integrated methodology for dynamic risk prediction of thermal runaway in lithium-ion batteries." *Process Safety and Environmental Protection* 171:385-395.

NFPA. 2022. "Emergency response guides." accessed 12-02. https://www.nfpa.org/Training-and-Events/By-topic/Alternative-Fuel-Vehicle-Safety-Training/Emergency-Response-Guides.

NTSB. 2020. "Safety Risks to Emergency Responders from Lithium-Ion Battery Fires in Electric Vehicles." Last Modified 11/13/2020, accessed 12-02. https://www.ntsb.gov/safety/safety-studies/Documents/SR2001.pdf.

Purba, Julwan Hendry, D. T. Sony Tjahyani, Andi Sofrany Ekariansyah, and Hendro Tjahjono. 2015. "Fuzzy probability based fault tree analysis to propagate and quantify epistemic uncertainty." *Annals of Nuclear Energy* 85:1189-1199.

Qi, Chuang, Yan-Li Zhu, Fei Gao, Song-Cen Wang, Kai Yang, and Qing-Jie Jiao. 2017. "Safety analysis of lithium-ion battery by rheology-mutation theory coupling with fault tree method." *Journal of Loss Prevention in the Process Industries* 49:603-611.

Qiu, Yishu, and Fangming Jiang. 2022. "A review on passive and active strategies of enhancing the safety of lithium-ion batteries." *International Journal of Heat and Mass Transfer* 184:122288.

Rausand , Marvin, and Stein Haugen. 2020. "Hazard Identification." In *Risk Assessment*, 259-337.

Rosewater, David, and Adam Williams. 2015. "Analyzing system safety in lithium-ion grid energy storage." *Journal of Power Sources* 300:460-471.

Soares, F. J., L. Carvalho, I. C. Costa, J. P. Iria, J. M. Bodet, G. Jacinto, A. Lecocq, J. Roessner, B. Caillard, and O. Salvi. 2015. "The STABALID project: Risk analysis of stationary Li-ion batteries for power system applications." *Reliability Engineering & System Safety* 140:142-175.

Sulaman, Sardar Muhammad, Armin Beer, Michael Felderer, and Martin Höst. 2019. "Comparison of the FMEA and STPA safety analysis methods–a case study." *Software Quality Journal* 27 (1):349-387.

Wang, Zhirong, Shichen Chen, Xinrui He, Chao Wang, and Dan Zhao. 2022. "A multi-factor evaluation method for the thermal runaway risk of lithium-ion batteries." *Journal of Energy Storage* 45:103767.

Wen, Jianwu, Yan Yu, and Chunhua Chen. 2012. "A Review on Lithium-Ion Batteries Safety Issues: Existing Problems and Possible Solutions." *Materials Express* 2 (3):197-212.

Wen, Yu, Wenjin Zhang, and Jiale Lu. 2015. "The establishment of safety indicator set of lithium-ion battery and its management system." 2015 Prognostics and System Health Management Conference (PHM), 21-23 Oct. 2015.

Wu, Bing, Yuheng Tang, Xinping Yan, and Carlos Guedes Soares. 2021. "Bayesian Network modelling for safety management of electric vehicles transported in RoPax ships." *Reliability Engineering & System Safety* 209:107466.

Yun, Jinhyo Joseph, JeongHwan Jeon, KyungBae Park, and Xiaofei Zhao. 2018. "Benefits and Costs of Closed Innovation Strategy: Analysis of Samsung's Galaxy Note 7 Explosion and Withdrawal Scandal." *Journal of Open Innovation: Technology, Market, and Complexity* 4 (3):20.

Zhao, Chunpeng, Jinhua Sun, and Qingsong Wang. 2020. "Thermal runaway hazards investigation on 18650 lithium-ion battery using extended volume accelerating rate calorimeter." *Journal of Energy Storage* 28:101232.

Zubi, Ghassan, Rodolfo Dufo-López, Monica Carvalho, and Guzay Pasaoglu. 2018. "The lithium-ion battery: State of the art and future perspectives." *Renewable and Sustainable Energy Reviews* 89:292-308.