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Solving Cell Voltage Unbalance

Strategies for Quality Improvement in Lithium-Ion Battery Production at FPT Industrial

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List of Abbreviations

5W+1H Who, What, Where, When, Why + How

8D Eight Disciplines Problem Solving Method

ACE Assistant Chief Engineer

APQP Advance Product Quality Planning

BDU Battery Disconnection Unit

BMS Battery Management System

BMU Battery Management Unit

BoL Beginning of Line

BoM Bill of Materials

CAR Capital Appropriation Request

CNG Compressed Natural Gas

CSI Customer Satisfaction Index

CSR Customer Specific Requirements

DCIR Direct Current Internal Resistance

DFMEA Design Failure Mode and Effects Analysis

DoD Depth of Discharge

DOT Driving Operation Together

EVs Electric Vehicles

FPT Fiat Powertrain Technologies

G/Y/R Green/Yellow/Red assessment codes

GPD Global Process Development for CNH Industrial

HV High Voltage

HW Hardware

IATF International Automotive Task Force

ICA Interim Corrective Action

IPR Index Priority Risk

IRW Interim Recovery Worksheet

ISO International Organization for Standardization

KAM Key Account Manager

LCVs Light Commercial Vehicles

LECU Local Electric Control Unit

LoI Letter of Intent

LSL Lower Specification Limit

LV Low Voltage

MN Management Review

NMC Lithium Nickel Manganese Cobalt Oxide

NPQ New Product Quality Manager

NPV Net Present Value

NT Natural Tolerance

OKTO OK To Order

OKTS OK To Ship

OP Operation

PA Program Approval

PAP Product Application Planning

PBoM Process Bill of Materials

PCA Permanent Corrective Action

PDCA Plan-Do-Check-Act

PFMEA Process Failure Mode and Effects Analysis

PI Program Initiation

PPAP Product Parts Approval Process

PPm Parts per Million

PR Product Request

PSW Parts Submission Warranty

QMS Quality Management System

RG Reliability Growth

SOC State of Charge

SoH State of Health

SW Software

ULR Unique List of Risks

USL Upper Specification Limit

VGT Variable Geometry Turbocharger

WBS Work Breakdown Structure

Abstract

This thesis explores quality management in e-powertrain development process at FPT Industrial, focusing on the eBS 69 battery for electric buses. It examines the integration of quality internal standards, throughout the product lifecycle. This work deals with a cell voltage disparity issue in the eBS 69 battery, detailing the problem-solving process including; root cause analysis, and corrective actions taken. This study underscores the importance of New Product Quality Support in achieving high-performance specifications and Customer satisfaction, emphasizing the role of internal standards and cross-functional team collaboration.

1 Introduction

1.1 Company Background

FPT Industrial, a leader in the automotive and industrial powertrain sectors, is renowned for its innovative approach to e-powertrain and battery technology. As a key player within the Iveco Group, FPT Industrial has a rich history of over 150 years, marked by a commitment to sustainability, efficiency, and cutting-edge technological advancements. The company's global presence is supported by numerous manufacturing plants and R&D centers worldwide, focusing on developing propulsion systems that meet the evolving needs of on-road, off-road, marine, and power generation applications. This background sets the stage for exploring the integration of quality management in the development of e-powertrain systems and batteries, reflecting on the significant strides FPT Industrial makes towards electrification in transportation.

In the last two years FPT Industrial developed its series of product with the inauguration of the new ePowertrain in Turin plant in which are manufactured electric axles, electric transmission boxes, and battery packs for light commercial vehiclesand buse application. These products empower the mobility of the future, for this reason, FPT Industrial dedicated an area of 16,600 sqm to the ePowertrain plant that can contribute with a total production capacity of 63,000 units annually.

1.2 Quality Standards

The automotive industry's commitment to quality is critical not only for meeting Customer demands but also for ensuring safety, particularly in the realm of Lithium-Ion battery production where chemical risks are present. FPT Industrial places a high emphasis on quality, integrating it as a key component of its manufacturing ethos. The adoption of ISO 9001 and IATF 16949 standards underscores the industry's dedication to quality governance, with ISO 9000:2015 and ISO 9001:2015 [1] [2] framing the core quality management principles as set by the International Organization for Standardization (ISO). Specifically, IATF 16949 introduces rigorous requirements for maintaining quality in all facets of operations, highlighting the importance of a structured approach to address potential issues proactively. This adherence to both ISO and IATF standards reflects FPT Industrial's commitment to excellence in the automotive sector. By aligning with these standards, FPT Industrial not only addresses quality challenges effectively but also promotes Customer-centricity and continuous improvement. This is further enhanced by the implementation of the DOT methodology (Driving Operation Together), leveraging Deming's Cycle (Act-Plan-Do-Check), to foster an environment of ongoing enhancement and Customer satisfaction.

1.3 Quality Management System

In the rapidly evolving automotive sector, especially with electric vehicles (EVs), adhering to quality standards throughout the product development lifecycle, from design through to launch, is crucial. FPT Industrial employs several internal standards to uphold quality, with FPI.PLI002 and FPI.IFP100 being paramount for the Quality Management System. FPI.PLI002 guides the management of product development across all stages, ensuring the development, production, and sale of quality-compliant products. Conversely, FPI.IFP100 governs issue resolution during production, detailing steps for the permanent resolution of product or process issues through optimal criteria and problem-solving tools.

1.4 Case Study

This project of thesis, centered around a case study of the eBS 69 battery used in CityBus and Crossway vehicles, highlights the critical role of quality assurance in product development. The eBS 69, vital for daily long-route operations with single recharge cycles, encountered a significant issue with cell voltage disparities impacting performance. This Customer-reported problem underscores the need for a comprehensive exploration of potential causes and solutions, emphasizing the importance of key parameters in product and process analysis.

As the New Product Quality Support, this role is crucial in resolving problems throughout the product lifecycle, adhering to internal standards, and collaborating across platform teams. The problem-solving process, involving close cooperation with the engineering team, utilized tools like the 5 Whys and Ishikawa diagram for root cause analysis. This was complemented by a Capability study to ensure process adherence to specifications. This work culminates in identifying and implementing Corrective Actions, aligning the process with stringent product specifications, and enhancing overall product quality.

2 FPT Industrial

2.1 Overview

FPT Industrial S.p.A., part of the Iveco Group (IVG: MI), specializes in designing, manufacturing, and selling propulsion systems and solutions for on-road and off-road, marine, and powertrain fields. With over 8,000 employees across 10 plants and 11 research and development centers globally, FPT Industrial has a widespread sales network and Customer service operating in approximately 100 countries. Their production encompasses six engine families ranging from 42 to over 1,000 horsepower, transmissions with torque capabilities up to 500 Nm, front and rear axles spanning from 2.45 to 32 tons, alongside natural gas engines for industrial use, offering power outputs ranging from 50 to 520 horsepower. Through its e-Powertrain division focused on electric propulsion systems, the company is swiftly moving towards carbon-neutral mobility, offering electric transmissions, battery packs, and battery management systems [3] [4].

Figure 1: FPT Global Presence with Customer proximity [6]

2.2 History

The present-day brand FPT Industrial was established on January 1, 2005, yet it inherits a legacy spanning over 150 years, stemming from the collective expertise and manufacturing activities of IVECO, Case IH, Steyr, and New Holland in the realm of engines, transmissions, and axles.

This extensive heritage, with over 100 years of know-how, traces back to 1842 with the founding of the Case Corporation in the United States, marking the world's first production of a steam tractor in 1869 and a gasoline tractor in 1892. The company has been a forerunner in technological advancements, including the adoption of the first Common Rail engine on light commercial vehicles in 1938, the development of hybrid technology for urban distribution in 2011, and the initiation of high-voltage batteries and eDriveline production in 2020 [4] [5].

In 1895, New Holland Agriculture was founded in Pennsylvania, USA.

On July 11, 1899, Fiat (Fabbrica Italiana Automobili Torino) was born in Turin. While widely recognized as an automobile manufacturer, the Fiat Group also produces tractors, trucks, buses, and specialized vehicles. Throughout Fiat's history, mergers and spin-offs occurred, leading to the formation of FPT Industrial as we know it today. In 1999, Fiat established CNH Global, resulting from the merger of New Holland and Case Corporation, specializing in agricultural and construction machinery, respectively.

In 2011, Fiat separated its automotive division from other activities. This separation led to the formation of the new group Fiat Industrial S.p.A., incorporating the non-automotive businesses of CNH Global, IVECO, and Fiat Powertrain Technologies' marine and industrial engine division (now FPT Industrial).

Subsequently, in 2013, the merger between Fiat Industrial and CNH Global gave rise to CNH Industrial. This created a global leader in the Capital Goods sector, operating through 8 different brands, including FPT Industrial, engaged in the design, manufacturing, distribution, marketing, and provision of financial services.

Figure 2: Iveco Group key figures [6]

On January 1, 2022, the spin-off of CNH Industrial and Iveco Group occurred. The newly listed group on the Stock Exchange (Euronext market in Milan) resulted from separating the commercial and specialized vehicle activities, propulsion systems, and related financial services from CNH Industrial N.V.'s business (NYSE: CNHI / MI: CNHI). From trucks, buses, firefighting vehicles, and civil protection vehicles to propulsion solutions for on-road, off-road, marine, and power generation applications, Iveco Group designs, manufactures, and sells commercial and specialized vehicles and propulsion systems.

In October 2022, FPT Industrial inaugurated the new e-Powertrain plant entirely dedicated to electric production, manufacturing electric axles, electric transmission boxes, and battery packs for light commercial vehicles, minibuses, and buses. This inauguration marks another significant step in its decarbonization journey and its strategy aimed at achieving net-zero CO_2 emissions for its products and all industrial activities. The new production site is Iveco Group's first entirely "carbon-neutral" facility, capable of achieving this goal by offsetting CO_2 emissions through the purchase of energy from renewable sources and carbon credits. Additionally, the facility generates power through solar panels installed on the facade and innovative technologies like the 'mini Wind Tower' and 'Smartflower' [4].

2.2.1 Milestones in FPT Industrial's history

- 1975: Establishment of IVECO
- 1990s: Development and patenting of Common Rail technology.
- 1998: Introduction of the first Variable Geometry Turbocharger (VGT) on heavy-duty engines.

- 2002: Launch of natural gas engines, alternative-fuel CNG engines on LCVs.
- 2005: FIAT Powertrain Technologies established.
- 2006: Establishment of the Chinese joint-venture SFH.
- 2012: Development and patenting of the exclusive HI-eSCR emission control technology.
- 2015: Development of second-generation HI-eSCR2.
- 2016: Presentation of Cursor 9 CNG, most powerful alternative-fuel truck engine ever.
- 2018: Unveiling the hydrogen cell propulsion system concept at the IAA Show in Hannover, Germany. Introduction of Cursor X, a multi-power, modular, multi-application, mindful engine concept.
- 2019: Memorandum of Understanding with Microvast (MV) to internally design and assemble high-voltage battery packs.
- 2019: Joint venture with IVECO and Nikola Motor Company to develop battery-electric and hydrogen fuel cell trucks. Acquisition of startup Dolphin N2.
- 2020: Acquisition of Potenza Technology.
- 2022: Debut of Iveco Group on the Milan Stock Exchange. The newly listed group resulted from separating commercial and specialized vehicle activities, propulsion systems, and related financial services from CNH Industrial N.V.'s business (NYSE: CNHI / MI: CNHI).
- 2022: Inauguration of the e-Powertrain plant in Turin, dedicated to producing electric axles, electric transmission boxes, and battery packs for light commercial vehicles, minibuses, and buses [5].

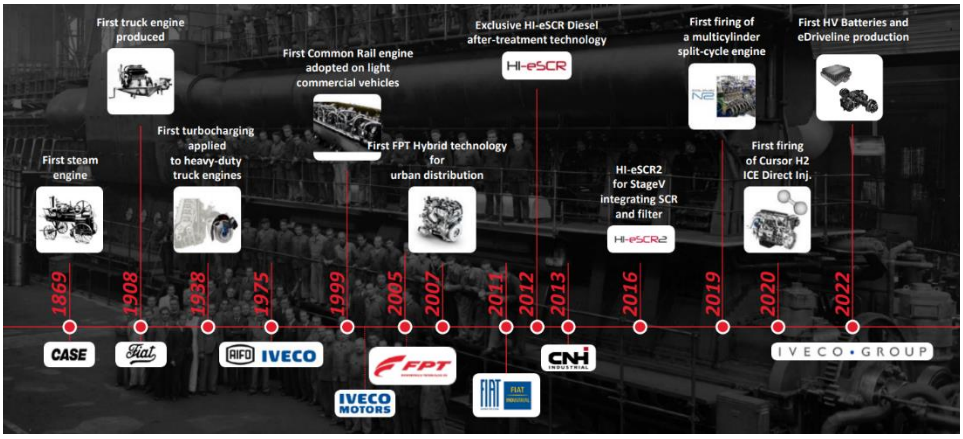


Figure 3: FPT Industrial's history [6]

2.3 FPT's Turin Site – A Hub of Innovation

The Turin facility of FPT Industrial is not just a production site; it is a testament to the company's commitment to innovation and technological advancement, it plays a pivotal role in the company's operations. Spread over 507,600 square meters, this site is a multifaceted hub, embodying the essence of FPT Industrial's diverse capabilities [4].

The Turin site is a vast complex, encompassing various production areas and functionalities. This includes areas dedicated to Customer service, a spare parts center, a technical hub, and sections for transmissions, axles, and engines. The site also serves as the headquarters for FPT Industrial.

At this facility, FPT Industrial demonstrates its manufacturing prowess. With a total area of 1,827,000 sqm and a dedicated FPT area of 507,600 sqm, the site hosts significant production capacities across various segments. The Turin Engine section alone has a capacity of producing 177,850 units per year, while the Driveline segment can produce up to 285,000 units annually. The Industrial & Marine segment contributes with 45,000 units per year, and the ePowertrain segment has a production capacity of 63,000 units annually [4].

Dedicated to the future of mobility, the Turin site is beacon of innovation, in fact, has allocated 16,600 sqm specifically for electrification, with approximately 200 employees focusing on this crucial area. This includes the development and production of front and rear eAxles for high-performance cars and HCVs, central drives for LCVs and minibuses, and various battery packs [4] [6].

Aligning with global sustainability goals, the Turin facility has made significant strides in energy efficiency and CO2 emissions reduction. In 2022, the site

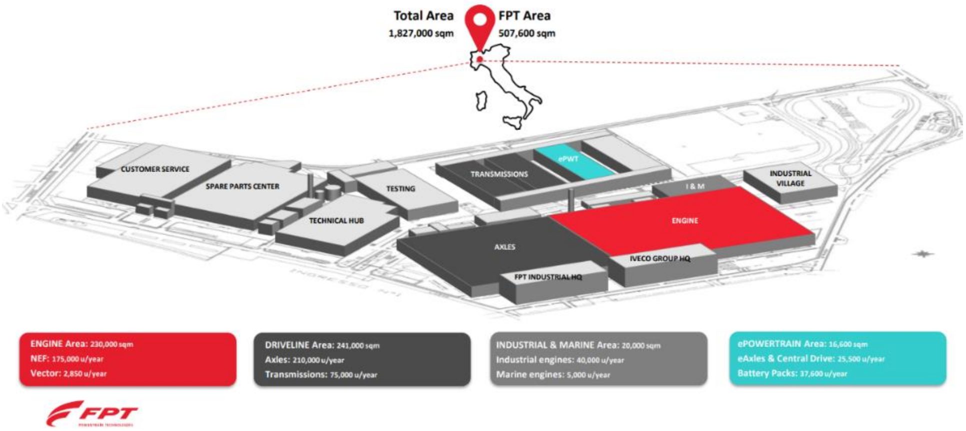


Figure 4: Turin plants overview [6]

achieved a remarkable 25% increase in energy self-production compared to the previous year, along with a substantial reduction in CO2 emissions, amounting to 9600 tons per year [6].

2.4 ePowertrain products

The battery packs produced at FPT Industrial are not just components; they are the heart of the electrification movement. The Turin site produces 37kWh and 69kWh battery packs, essential for powering LCVs and minibuses. This production is a critical part of FPT Industrial's strategy to offer a diverse range of energy solutions [4].

The Turin site is not only about production; it is also a center for technological development and testing. With state-of-the-art testing facilities, FPT Industrial ensures that its ePowertrain components are not only innovative but also reliable and efficient. The site includes eMotor test benches, battery labs, and fuel cell labs, emphasizing FPT's commitment to comprehensive development and validation of its products [4].

2.4.1 eBS 37 Description

The eBS 37 is a key component in FPT Industrial's ePowertrain range, which stands out for its performance, reliability, and top-tier quality. This range is rounded off with cutting-edge battery packs and management systems. FPT Industrial has created a partnership with Microvast, a Texas-based market leader in long-lasting, ultra-fast charging battery systems, to develop and produce battery packs catering to a wide array of application needs. These products are designed to meet various usage profiles and diverse Customer requirements.

FPT's 37 kWh battery pack for light commercial vehicles and minibuses is a modular solution integrating Microvast's exclusive lithium-ion cell technology. This technology ensures extraordinary energy density and depth of discharge (95%), bringing significant advantages in terms of battery weight reduction. Employing NMC (lithium nickel-manganese-cobalt oxide) technology, which is currently the most versatile and high-performing solution for commercial vehicles, the eBS 37 enables rapid charging. This advanced and well-designed system also boasts high energy density and stability [7].

Specifications:

Figure 5: Picture of battery eBS 37 [7]

- Cell Technology: Lithium-ion
- Cathode Technology: NMC 811
- Cooling System: Water-Glycol
- Nominal Energy (kWh): 37
- Nominal Voltage (V): 355
- Energy Density [Wh/kg]: >140
- C-rate (continuous): 1C (charging) / 2C (discharging)
- Protection: IP6K9K / IP67
- Dimensions [L x W x H, mm]: 925 x 854 x 310
- Weight [kg]: 260
- Life Cycles: > 2,500
- BMS: Microvast
- Regulatory Compliance: ECE R100.2 / ECE R10.5
- Multipack Support: Up to 3 packs in parallel | Up to 2 packs in series

2.4.2 eBS 69 Description

The eBS 69 is a prominent part of FPT Industrial's ePowertrain line, known for its exceptional performance, reliability, and quality. This line is enhanced with state-of-the-art battery packs and management systems. Developed in partnership with Microvast, a Texas-based leader in long-lasting, ultra-fast charging battery systems, FPT Industrial has crafted battery packs to meet diverse application needs, designed to address various Customer requirements and usage profiles.

The 69 kWh battery pack from FPT, intended for buses, is a modular solution incorporating Microvast's exclusive lithium-ion cell technology. This technology delivers extraordinary energy density, ensuring top-tier performance for urban buses. The eBS69, utilizing NMC (lithium nickel-manganese-cobalt oxide) technology, the most versatile and high-performing currently available, facilitates rapid charging. This advanced, meticulously engineered system also boasts high energy density and stability [8].

Specifications:

Figure 6: Picture of battery eBS 69 [8]

- Cell Technology: Lithium-ion
- Cooling System: Water-Glycol
- Multipack Support: Up to 8 packs in parallel
- Nominal Energy (kWh): 69.3
- Nominal Voltage (V): 647.5
- Energy Density [Wh/kg]: > 178
- C-rate (continuous): 1C (charging) / 1C (discharging)
- Cathode Technology: NMC 532
- Protection: IP6K9K / IP67
- Dimensions [L x W x H, mm]: 1,785 x 700 x 250
- Weight [kg]: 389
- Life Cycles: > 6,000 @ 80% DoD

2.4.3 eAX 300-F Description

FPT Industrial has joined forces with the legendary Trident House, Maserati, to craft the new high-performance electric axles. This collaboration has resulted in a single-motor solution for front installations and a dual-motor configuration for the rear.

Both the front and rear electric axles deliver a comprehensive solution in an incredibly compact design. Every component, including inverters, is seamlessly integrated into the axles, eliminating the need for placement elsewhere within the vehicle's framework. This integration offers significant benefits in terms of space utilization and weight distribution, which are particularly crucial for a high-performance automobile like the Maserati Gran Turismo Folgore [9].

Jointly developed by FPT Industrial and Maserati, the front electric axle boasts an exceptionally high power density (up to 3.86 kW/kg) and features an integrated “parking lock” system for enhanced safety, preventing any movement of the vehicle when parked. Aligning with FPT Industrial's sustainability ethos, these electric axles are manufactured at the Torino ePowertrain plant, Iveco Group's first “carbon neutral” production facility [9].

Specifications:

- Electric Motors: 1
- Layout: Compact, integrated, and complete design
- System Efficiency: > 85%
- Gears - Speeds:1
- Power Density (kW/kg): 3.86
- Maximum Power [kW]: > 300 @ 800V
- Maximum Torque at Wheels [Nm]: 3,100
- Weight [kg]: 100

Figure 7: Picture of battery eAX 300-F [9]

2.4.4 eAX 600-R Description

In a collaborative effort, FPT Industrial and the iconic Trident House, Maserati, have successfully developed new high-performance electric axles. This includes a single-motor solution for the front and a dual-motor setup for the rear.

The design of both front and rear electric axles is a hallmark of completeness and compactness. With all components, inverter included, neatly incorporated within the axle assembly, there is no need for external placement, optimizing both spatial efficiency and weight distribution. This design aspect is particularly beneficial for high-performance vehicles like the new Maserati Gran Turismo Folgore.

The rear electric axle, a joint creation of FPT Industrial and Maserati, stands out with its high power density, reaching up to 4.83 kW/kg. Additionally, its 'torque vectoring' feature allows instantaneous torque redistribution between the two wheels, significantly enhancing the vehicle's safety, stability, and control under various conditions.

In line with FPT Industrial's commitment to sustainability, these electric axles are produced at the Torino ePowertrain facility [10].

Specifications:

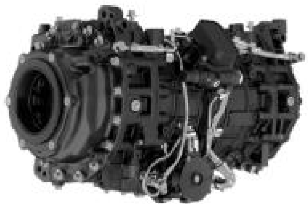


Figure 8: Picture of battery eAX 600-R [10]

- Electric Motors: 2
- Layout: Compact, integrated, and complete design
- System Efficiency: > 85%
- Gears - Speeds: 1
- Power Density (kW/kg): 4.83
- Maximum Power [kW]: > 600 @ 800V
- Maximum Torque at Wheels [Nm]: 6,500
- Weight [kg]: 160

2.4.5 eAX 840-R Description

The eAX 840-R stands as a prime example of FPT Industrial's tangible commitment to an innovative zero-emission strategy, highlighted by the joint venture between IVECO, NIKOLA, and FPT Industrial. In a remarkably short span of just two years, this collaboration has designed, engineered, and launched a product poised to lead the global market of heavy electric commercial vehicles in the near future.

The eAX 840-R is a dual-motor electrified axle designed for heavy commercial vehicles (supporting a total ground mass of up to 44 tonnes). It ensures high performance, efficiency, and reliability. The eAX 840-R also offers a low total cost of ownership, extended oil replacement intervals, and a declared lifespan of up to 1,200,000 km / 745,650 miles. It has been the first eAxle in US market in this range of tons and the first eAxle mounted on on FCEV [11].

Specifications:

- Electric Motors: 2
- Layout: Compact and integrated design
- System Efficiency: > 92%
- Gears – Speeds: 1
- Total Combined Mass [kg]: Up to 44,000
- Maximum Power [kW]: 840
- Maximum Torque at Wheels [Nm]: 45,000
- Weight [kg]: 1,390

Figure 9: Picture of battery eAX 840-R [11]

2.4.6 eCD 140 Description

The eCD 140, a Central Drive unit by FPT Industrial, is a compact and complete solution specifically engineered for light commercial vehicles. It is designed to seamlessly integrate electric propulsion systems into current conventional vehicle platforms. FPT's team of engineers has crafted an integrated and compact electric propulsion system, tailored to fit smoothly into existing platforms while maximizing the available space for battery pack installation.

Aimed at rear-wheel-drive vehicles, the eCD 140, like all FPT Industrial products, is built to be robust, efficient, and reliable, boasting a lifespan of up to 350,000 km / 217,500 miles, with lifelong oil replenishment [12].

Specifications:

- Electric Motors: 1
- Layout: Comprehensive solution
- System Efficiency: > 93%
- Gears – Speeds: 1
- Total Ground Mass [kg]: Up to 7,200

Figure 10: Picture of battery eCD 140 [12]

- Maximum Power [kW]: 140
- Maximum Torque at Axle [Nm]: 1,600
- Weight [kg]: 117
- Parking Lock: Yes – Maximum gradient 30%

3 The importance of the role of New Product Quality

3.1 Importance of Product Quality in Automotive Battery Production: Upholding Safety Standards Amid Delicate Chemical Processes

The automotive sector's transition towards electrification has accentuated the pivotal role of battery production in enabling sustainable transportation solutions. Within this domain, the significance of product quality has great importance, especially when dealing with the intricate processes and delicate chemical compositions inherent to battery manufacturing. As the automotive industry increasingly relies on electrified powertrains, the assurance of high-quality battery systems not only dictates operational efficiency but also safeguards against potential safety hazards intrinsic to these sophisticated technologies.

At the core of battery production lies a nuanced amalgamation of chemical processes aimed at harnessing the potential of energy storage. However, the use of delicate chemical components necessitates commitment to stringent safety standards throughout the production line. Ensuring the quality of batteries extends far beyond mere performance metrics; it encapsulates a comprehensive approach to mitigating risks associated with these highly reactive materials. Adherence to meticulous safety protocols not only safeguards the production processes but also underpins the end-user's confidence in the reliability and safety of the final automotive battery product.

The delicate nature of the chemical compositions Inherent to batteries necessitates a rigorous quality control framework at every stage of production. From the procurement of raw materials to the synthesis, assembly, and testing phases, meticulous attention to detail is imperative. Any deviation from specified quality parameters or oversight in handling these chemicals can have far-reaching consequences, compromising the integrity of the battery system. Striking the delicate balance between optimizing performance and upholding safety standards becomes trivial in the quest for superior product quality within automotive battery production.

The interplay between risk mitigation strategies and quality assurance measures becomes symbiotic in the pursuit of producing reliable automotive batteries. Mitigating risks associated with chemical processes involves a multifaceted approach encompassing thorough process monitoring, adherence to standardized operating procedures, continuous employee training on safety protocols, and robust quality control checks. These efforts synergistically converge to uphold the highest standards of product quality, ensuring that each battery unit rolling off the production line adheres to stringent safety benchmarks without compromising on performance or reliability.

3.2 Quality Management and Failure Resolution at FPT Industrial

The Quality Management System at FPT Industrial is defined in its Quality Manual [13], which aligns with the international standards *ISO 9001* [1] [14] and *IATF 16949* [2]. This system includes a comprehensive mapping of processes impacting product quality and Customer satisfaction. It also integrates Customer Specific Requirements (CSR) [15] into the quality system, ensuring that all internal processes meet these specified standards.

3.2.1 Scope, Application and main Actors of the QMS

FPT Industrial's QMS (Quality Management System) [13] applies to corporate processes that directly or indirectly affect the quality of products and services. It covers areas such as engine design and manufacture, and the production of transfer-gearboxes, e-axles and batteries. The system extends across various FPT Industrial sites in Europe, ensuring a uniform standard of quality across all operations.

Key roles in the company's quality management include Organizational Hierarchy, Process Owners, and Specific Work Teams. These roles are responsible for the design, development, and production of products, as well as managing the Quality Management System. This hierarchical structure ensures that quality management activities are clearly defined and effectively executed.

FPT Industrial's Quality Policy articulates its mission and strategy regarding quality. The policy is periodically updated to reflect organizational changes by IT support. Those are the objective evidence of the execution of established activities, results obtained, decisions taken and of the conformity to Customer's needs and effective functioning of SGQ. All those records are recorded in a Repository that satisfies all the requirements of standards ISO 9001 [14] and IATF 16949 [2].

Core values such as passion, quality, innovation, sustainability, and credibility underpin the company's approach to quality. The mission emphasizes technological leadership in propulsion systems, continuous product improvement, and Customer satisfaction. A sustainable growth process is foundational, focusing on environmental respect and social well-being. [13]

3.2.2 Tools and Methods for Quality Assurance and Failure Management

FPT Industrial employs various tools and methods for quality assurance and failure management, including documented procedures, process maps, and CSR interaction matrices, the flow of document management activities for the Quality System and/or originating externally and their related functional responsibilities are outlined in procedure *FPI.IFP100* [16]. These tools help identify, analyze, and resolve quality issues, ensuring continuous improvement in product performance and process efficiency.

FPT Industrial also has defined methods to detect and analyze information related to both external and internal Customers' perception regarding how well the organization has met Customer's requirements. The activities enabling the monitoring and the measurement of Customer satisfaction include:

- Measuring the performance of realization processes through product development control by the Platform and production process control via periodic audits.
- Managing and analyzing quality data and indicators, such as MERF, PPm, Warranty Costs, etc.

- Managing and analyzing Customer Complaints, both through direct access to the Customer's Quality Management Systems and specific reports from the Customer.
- Measuring delivery program performance (early deliveries/delays).
- Conducting surveys and interviews with Customers (CSI or Customer Satisfaction Index).

The indicators used to measure Customer satisfaction regarding the provided service are periodically reviewed by the Quality function in the Quality Overviews to ensure their adequacy. They are modified based on company developments and achieved results.

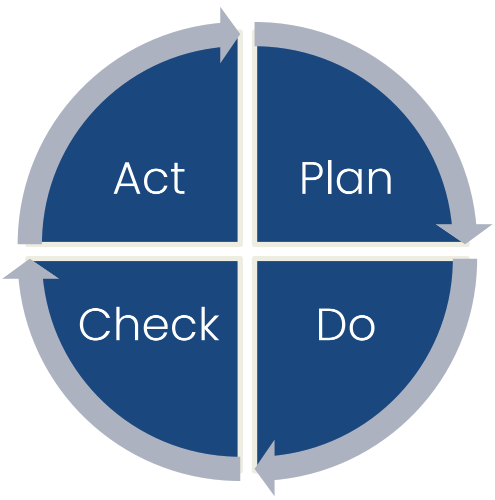
3.2.3 Context of Operation and Continuous Improvement

ACT

Take action to standardize or improve the process

CHECK

Study the results



PLAN

Plan ahead for change. Analyze and predict the results

DO

Execute the plan, taking small steps in controlled circumstances

Figure 11: : The Deming cycle

Operating in a dynamic industrial context, FPT Industrial focuses on continuously adapting and improving its Quality Management System. The methodologies for the management of continuous improvement are guided by a tool called DOT (Droving Operations Together). These actions start by *cycle of Deming* and by the four phase Plan. The company actively responds to evolving market needs, regulatory requirements, and technological advancements, ensuring that its products and services meet the highest standards of quality and Customer satisfaction.

3.3 Standards

ISO 9000:2015 and ISO 9001:2015 [1] are part of the ISO 9000 family of quality management systems standards established by the International Organization for Standardization (ISO). These standards provide guidance and tools for companies and organizations that want to ensure their products and services consistently meet Customer requirements and that quality is consistently improved [17] [18].

3.3.1 ISO 9000:2015 – Quality Management Systems – Fundamentals and Vocabulary

ISO 9000:2015 provides the fundamental concepts, principles, and vocabulary used in the entire ISO 9000 series [1]. It is designed to help organizations understand and consistently apply the terms used in other standards in the series. It serves as an essential starting point for understanding the ISO 9000 family and is often used as a reference for understanding the basic concepts and principles of quality management.

Key Components:

- Quality Management Principles: It outlines the core principles of quality management, such as Customer focus, leadership, engagement of people, process approach, improvement, evidence-based decision-making, and relationship management.
- Vocabulary: It defines key terms used in ISO 9001 and other quality management standards, ensuring a common understanding across different organizations and industries.

3.3.2 ISO 9001:2015 – Quality Management Systems – Requirements

ISO 9001:2015 sets out the criteria for a quality management system. It is the only standard in the ISO 9000 [1] family that organizations can be certified to, although certification is not a mandatory requirement. It is based on the quality management principles described in ISO 9000 and is designed to be used by organizations of any size or industry sector.

Key Components:

- Customer Focus: Ensuring that Customer requirements are identified and met, leading to increased Customer satisfaction.
- Leadership: Establishing unity of purpose and direction and creating conditions in which people are engaged in achieving the organization's quality objectives.
- Engagement of People: Recognizing that people at all levels are the essence of an organization and their full involvement enables their abilities to be used for the organization's benefit.
- Process Approach: Achieving consistent and predictable results more efficiently when activities are understood and managed as interrelated processes that function as a coherent system.
- Improvement: Successful organizations have an ongoing focus on improvement.
- Evidence-based Decision Making: Decisions based on the analysis and evaluation of data and information are more likely to produce desired results.
- Relationship Management: An organization and its external providers (suppliers, contractors, service providers) are interdependent, and a mutually beneficial relationship enhances the ability of both to create value.

Certification and Implementation:

- Organizations that wish to be certified against ISO 9001:2015 must undergo a rigorous audit process by an accredited certification body.
- The implementation of ISO 9001:2015 helps ensure Customers get consistent, good-quality products and services, which in turn brings many business benefits.

ISO 9000:2015 and ISO 9001:2015 together form a robust framework for establishing, maintaining, and improving quality management systems, enabling organizations to provide products and services that meet Customer and regulatory requirements and enhance Customer satisfaction [1] [14].

3.4 Management Review in Product Development at FPT Industrial

FPT Industrial's Management Review process, as defined in the "FPI.PLI002_Management_Review_ED3_EN" [19] standard, is designed to systematically assess the progress and status of product development projects from design through to launch and production.

3.4.1 Purpose and Scope of MR

The MR process aims to monitor and review product development programs, ensuring alignment with the FPT Development Process, in order to achieve a high level of quality and to match with market requirements and launch the product on schedule. It applies to a range of scenarios including new products, derived versions, products manufactured in new sites, and products entering new markets and, in general, every Customer Request (Captive & No Captive) leading to an upgrade of the FPT Product Portfolio and/or Plant capacity. The output is a detailed review and assessment (G/Y/R) of the status of specific measurable items or deliverables provided by Functions (Platform included) with respect to some criteria like time, costs, performance, quality, and compliance. After the approval of the Platform Leadership of the Global status of the program taking into consideration risks mitigation and problems resolution activities the Company Management decides to proceed or not to further development phases or to Launch for regular production.

The MR process Is structured into six stages, each scheduled by the Program Team according to the product development phase following program Scaling and Sizing from Functional Classification. This scheduling is vital for ensuring timely reviews and decisions throughout the product development lifecycle.

To set-up a consistent and effective scheduling for MR are required four steps:

1. FDP Full Deliverable analysis and "SCALING" if possible;
2. Program SIZING as Full/Large/Medium/Small or Extra-Small;
3. Program Macro-Timing and Lev1 initial deployment;
4. MR meeting initial scheduling.

Scaling, Program Sizing and FDP Timing are interfunctional activities to be carried out by all the involved functional representatives in the Program Team ("core" and "on call" members) under Program Manager guidance and Program Planners coordination and support [19].

3.4.2 MR Expectations and Assessment

The MR process involves detailed review and assessment of specific deliverables, considering requirements and constraints like time, price/cost, performance, quality, timing, and compliance. It also includes global status assessment of the program, considering risk mitigation and problem resolution activities. Furthermore, it has to reach the expected business profitability is in line with company targets, this is done by the usage of Key Financial Figures for profitability and the assessment of the Required Funding (R&D, Capex, NPV,...).

3.4.2.1 Global Expectations in MR Phases

Each MR phase has specific global expectations, focusing on aspects like:

- MR 0 Business Acceptance: the program plan is on time, on costs and the required resources do not exceed constrains. The profitability is in line with company targets;
- MR1 New Product Concept: it is selected and agreed by Product Platform Team.
    - This is a definition and selection of the "technical solution" that meets the Customer requirements and FPT profitability target.
    - It is done an assessment of Readiness for Beta build stage (and then it is Beta Freeze). It is necessary to go on to Preliminary Design Validation phase.
- MR 2 Verification of Approved Spending following Captive Customer and Non-Captive Customer PI/PA (GPD) or LOI/Contract preliminary confirmation from Non-Captive Customers:
    - funding availability to support the industrialization phase (CAR/WBS).
    - Testing of Beta and readiness of Gamma build stage, with following Gamma freezing with Customer.

    - OK to proceed to Final Design Validation.
- MR 3 Product Design Validation:
    - this phase gives the OK to move to Pre-Production Phases in which consist in Testing of Gamma Builds close to completion (sufficient to release a PboM).
    - Readiness for Pre-Pilot build stage.
    - OK to proceed to Process Validation Phase.
- MR 4 Completion to design validation: it assesses the Plant Readiness for Pilot Builds and so the OK to Order (OktO). This stage consists of:
    - Check of closure of possible issues on Gamma units and verification on Pre-Pilot.
    - Certification approval.
    - PCPA executed on Pre-Pilot units.
    - Process Audit @Suppliers positively executed.
    - Plant Approval and Engineering approval for Buy parts available.
    - Readiness of Internal PPAP for MR5.
    - Readiness of Operation, Service manuals for Customer OKTB and spare parts catalogue at MR5.
    - OK to build the First Pilot Unit.
- MR 5 Production Approval: it gives the OK for FPT Plants to deliver to Customer Plants production units.
    - Internal PPAP is successfully completed.
    - The Supplier PPAP is fully Approved.
    - Launch and Service Readiness for Production verified.
- MR 6 Customer Satisfaction and Lessons Learned Review: it is the formal closure of FDP Process in which are assessed the Customer Satisfaction and Lessons Learned.
    - PWT Launch performance (early indicators).

- Managerial and Functional "learning" from issued occurred in previous stages.
- Closure of still open issues from MR 5.

These expectations guide the review and decision-making process at each stage. The end of the MR6 authorizes the closure of the program ensuring that still MR5 pending items have been properly addressed and closed and Customer launch activities have been supported by FDP teams.

3.4.3 MR Assessment Rules and Global Risk Assessment

The MR includes rules for assessing individual deliverables and a global risk assessment to guide the overall program decision-making process. This involves evaluating risks and deciding on the continuation or modification of the development phases.

3.4.3.1 MR0: Always "Mandatory"

Table 1: Single Deliverables assessment

GREEN	YELLOW	RED
•Requirement evaluated	•Not fully evalueted, but preliminary rough esitmation or assumptions are available	•Not provided by Customer/FPT or not fulfilling business expectation.

Table 2: MR0 GLOBAL assessment

GREEN	YELLOW	RED
•All the Customer requirements and internal estimations are available; profitability target fulfilled and new business accepted.	•Some requirements are missing and profitability has to be confirmed: further analysis are required for final business acceptance, but it's possible to present an Offer to Customer.	•Too many requirements missing or profitability targets not fullfilled: in hte first case the MR0 has to be rescheduled; in the seond one the new business is not accepted.

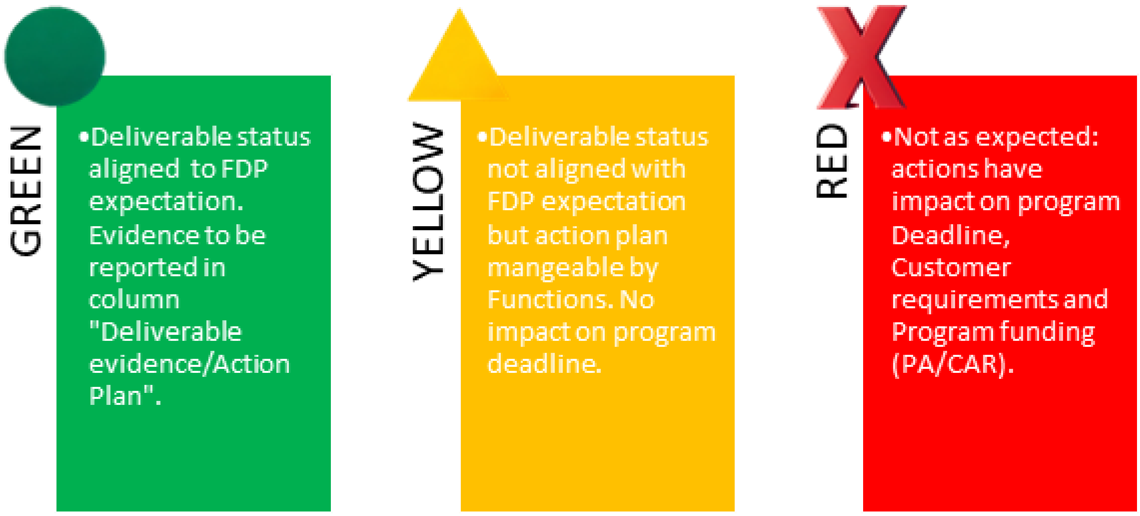
3.4.3.2 MR1-2-3-4-5

These MRs are used to assess the risk status (through the LUR tool) at the conclusion of a phase and to authorize the team to move forward to the next one or (MR5) to deliver the product as production unit (saleable). In practice, to come to the final assessment these three steps must be followed:

Step 1: Single Deliverable assessment.

Each Program Team Member downloads the deliverable check list from the web system of its specific Deliverables that must be reported at the ongoing MR and makes the assessment of their status with respect to the expectation as reported in the Deliverable sheet that is Table 9: ANNEX A – Functional Deliverables assessment (step 1) .

Table 3: Single derivable assessment



The overall risk assessment status in a Management Review is influenced by the progress of key deliverables, which are outputs from essential product development processes. These include:

- Customer Acceptance and Approval and Sign-off;
- Program Timing;
- Product Definition and Targets;
- Bench Validation;
- In-Vehicle Validation and Certification status;
- Readiness of purchased parts;

- Design and validation of Manufacturing Processes;
- Preparation of Plants for Production Approval;
- Logistics and Procurement of parts;
- Quality targets;
- Service Preparedness;
- Program funding and financial metrics.

These Key Deliverables are identified in the FDP Deliverable web System's Deliverable Cards, summarized in the MR Templates' executive summary and the Management Review Dashboard Summary, see Table 11: ANNEX C – Management review dashboard deliverable assessment list (step 3).

Step 2: Risk evaluation.

When a Y/R code is assigned to a deliverable, the New Product Quality Manager evaluates potential program risks associated with that issue. Using the LUR tool as outlined in the FPI.IFP015 procedure, risks are categorized as CRITICAL (Risk index-IPR>100) or IMPORTANT (Risk index-IPR<=100), based on severity and likelihood. The goal is to reduce high critical risks to lower Risk index-IPR values through mitigation actions. LUR management, a crucial Quality KEY Deliverable, is reviewed by the New Product Quality Manager, focusing initially on critical risks and, at their discretion, potentially extending to important risks as the program progresses, see Table 10: LUR SUMMURY CHART (FPI.IFP015 procedure) .

Step 3: Global Risk Assessment.

The results of the steps 1 and 2 are collected by the Program Manager, he/she summarizes it in a management review dashboard that is Table 11: ANNEX C – Management review dashboard deliverable assessment list (step 3) and following Management Review overall risk assessment criteria, consolidates the final output into a proposal for the assessment of the ongoing MR. At the end of the meeting, a decision is made and reported in the first page of the MR template as Global Risk assessment status:

Table 4: Criteria for the Global Risk Assessment (MR 1,2,3,4,5)

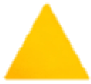
			
MR 1 MR 2 MR 3 MR 4	**No Deliverable with Red assessment in Deliverable Check List.** Follow up on closure of **Yellow** items to be managed via the Product Team meetings and reported in the Deliverable Check List assessment of next MR. LUR assessment must be Green.	**No Key Deliverables with Red assessment.** It can include Deliverables with **Red** assessment in Deliverable Check List, But the **LUR assessment** (Key Deliverable) is Green or at minimum Yellow. Follow up on closure of **Yellow** or **Red** items to be managed via Formal Program Review and reported in Check List assessment of Check List.	**It includes Key Deliverable with Red assessment and LUR assessment in Red.** **MR must be rescheduled** to verify the status of the Deliverables assessed as Yellow or Red and the mitigation of the related Risks.
MR 5	Majority of Deliverables are assessed as; **Green** it could include Deliverables with **Yellow** assessment, but the risk for **the Customer is very low.** This means that the **LUR assessment must be Green or at least Yellow** (IPR≤100; status 4). Follow up for closure of closed items must be scheduled after MR5, but before Customer OKTS.		It includes one or more **Deliverables** assessed in **Red** and considered as **High Risk for the Customer.** This means that the **LUR assessment is Red,** that is there are still some risks in status 3 or lower. **The Product cannot be sent to the Customer as saleable unit until the MR5 is repeated to verify the full risk mitigation and closure**

Table 5: From MR1 to MR4 GLOBAL assessment

Table 6: MR 5 Global Assessment

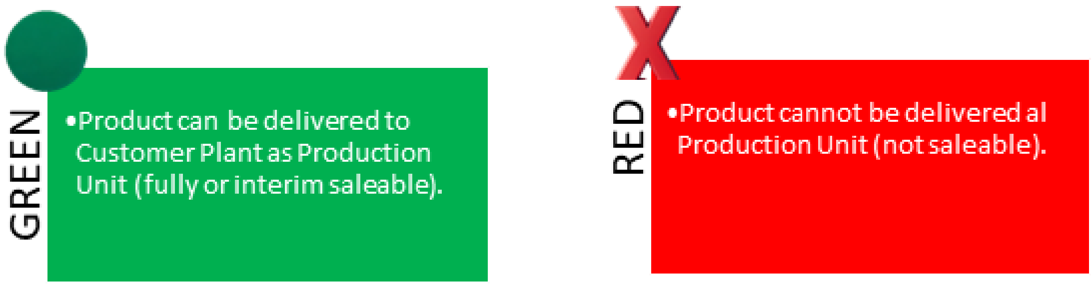


Table 7: MR 6 Single Deliverable assessment [Table 9: ANNEX A – Functional Deliverables assessment (step 1)]

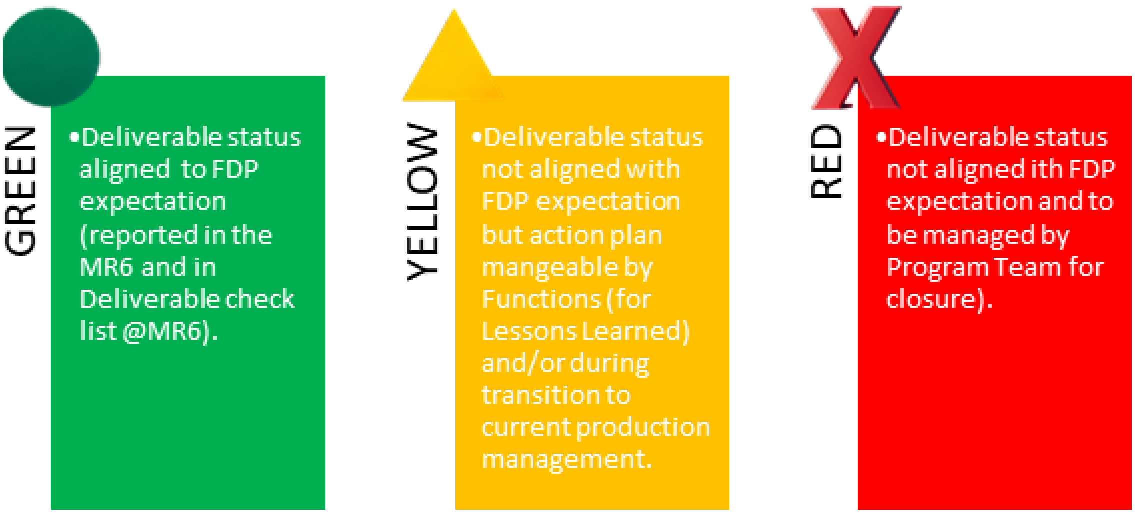


Table 8: MR6 GLOBAL assessment

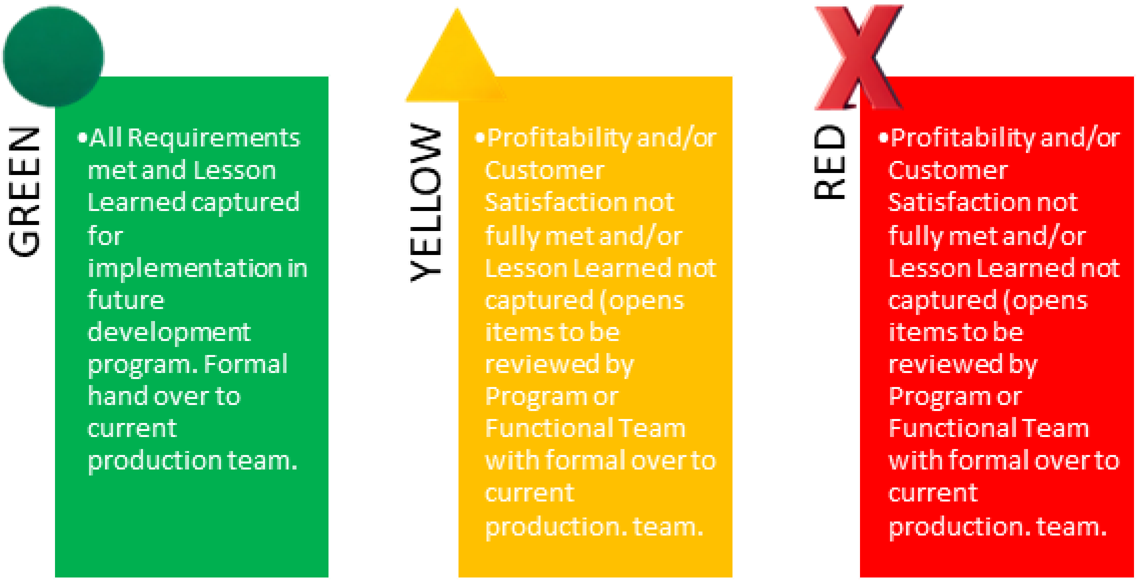
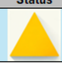
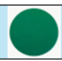


Table 9: ANNEX A – Functional Deliverables assessment (step 1) [19]

Resp. Role	Reporting in PLT	Short name	Scaling Option	Key Deliverable	MR0	MR1	MR2	MR3	MR4	MR5	MR6	Assessment Status	Note	Action Plan	LUR Code
Platform/Program Manager (NPQ Support)	Program Manager	**DIM Platform**	Must	Basic		Open Points list available	Review for closure	Review for closure	Review for closure	Review for closure	Review for LL				
PLT Planning (contributor Program Manager, Product Team)	Platform Manager	**Program Timing**	Must	Key	Macro-timing verificiation & update	Timing Review	Baseline frozen Actual vs Baseline available	Actual vs Baseline Monitoring	Actual vs Baseline Monitoring	Actual vs Baseline monitoring SoP date approval	Timing review for SoP (with LL)				
Platform/Program Manager (NPQ Support)	Program Manager	**Risk Management**	Must	Basic		Initiated	Review	Review	Review	Closure	Review for Lessons Learned				
Program manager (with functional contribution by core team)	Program Manager	**Sizing**	Must	Basic	Available	Confirmed	Confirmed and monitoring	Confirmed and Monitoring	Confirmed and Monitoring	Confirmed and Monitoring	Review for Lessons Learned				
Platoform/Program Manager	Program Manager	**Lesson Learned PL**	Must	Basic	Preliminary analysis from previous programs	Review from previous programs Lessons Learned	Review of Lesson Learned from current program	Review of Lesson Learned from current program	Review of Lesson Learned from current program	Review of Lesson Learned from current program	Review and consolidate for future launches				
Platform/Program Manager	Program Manager	**OK to sell decision**	Must	Key				Review of Pre-Pilot maturity status and possible disposure plan for PP rework	Assessment of possible Pre-Pilot saleability and OKtO to Customer preliminary OK to sell decision						
Platform/Program Manager	Program Manager	**CRF approval**	Must	Basic			CRF OKtT of Long lead Parts and Gamma BoM release approved	CRF's for PP/Pilot BOM Release approved	CRF's for PBoM release approved						
Platform/Program Manager	Program Manager	**Program Funding**	Must	Key	Product Change Request approval (PCR)	Program Initiation approval (PI)	Program Approval (PA) - Capital Appropriation Request Approved (CAR)	Monitoring	Monitoring	Monitoring	Review for LL				
Platform/Program Manager	Program Manager	**Team Stuffing**	scalable	Basic		Complete	Monitoring	Monitoring	Monitoring	Monitoring					

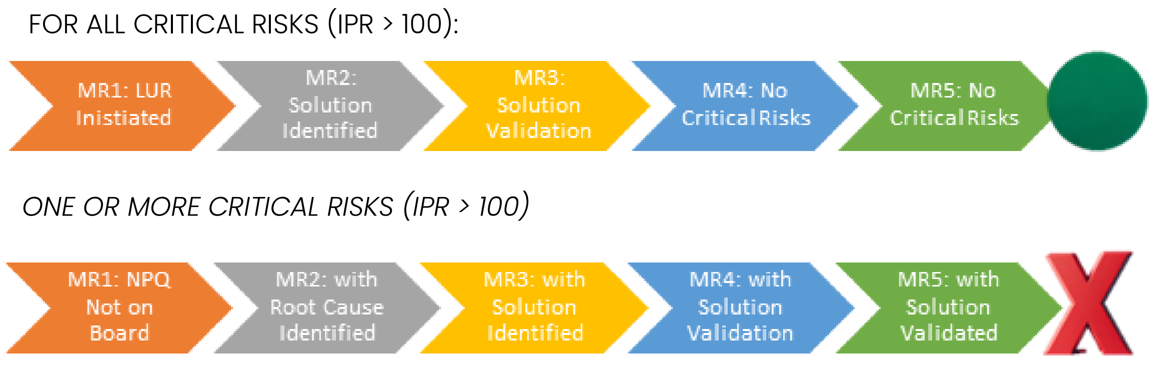


Figure 12: ANNEX B – LUR summary assessment Guideline (Program KEY deliverable) (Step 2)

Table 10: LUR SUMMURY CHART (FPI.IFP015 procedure) [19]

	STATUS						
Classi di Rischio	STATUS 0 Solution under analysis	STATUS 1 Root Cause identified	STATUS 2 Solution identified	STATUS 3 Solution under Validation	STATUS 4 Solution Validated	STATUS 5 Solution Applied	Tot for Risk level
CRITIC (IPR > 100)	1	2	1	1			5
IMPORTANT (IPR ≤ 100)	1		2	3	1	2	9
TOT FOR STATUS	2	2	3	4	1	2	14

Table 11: ANNEX C – Management review dashboard deliverable assessment list (step 3)

Owner Function	Total Deliverables	SCALED	GREEN	YELLOW	RED	FUNCTIONAL GLOBAL	NOTE
FPT Brand Market Segment	9	2				●	
Marketing	6	6				●	
Customer Management	17	6	7	2	1	▲	
Product Platform	9	1				●	
Product Engineering	49	25				●	
Manufacturing	11	4				●	
NPQ	10	2				●	
AMS	19	15				●	
Purchasing	14	10				●	
NPL Manufacturing	17	13				●	
S&OP and demand planning	3	2				●	
Finance	4	0					
TOT	168	86	7	2	1	●	

[1]

3.4.4 Build Stages

3.4.4.1 ALFA

Alfa units are intended or demonstrate or to select new concepts for product design or installation. They may be physical pieces or virtual simulation. The physical is made at Proto Facilities by making changes to a current production unit. PROTO

Engine and Calibration Maturity: full load performance at test bench. First functional assessment on alpha proto.

3.4.4.2 BETA

Beta units are intended to confirm the new concept performance and durability on proto units with finalized to Tool release. New content typically consists of prototype parts provided by Suppliers nominated for production. PROTO NOT SALEABLE

Engine and Calibration Maturity:

- Complete base calibration and beta function validation
- Base calibration (emissions, performance, fuel consumption) on beta engine

[1] Note: if a key deliverable is red, the MR overall assessment is RED.

- Preliminary application delivery at warm/cold conditions at test bench

3.4.4.3 GAMMA

Gamma units are built for production intent mainly to validate equipment and method. Consequently, the make parts could be machined and assembled at Supplier facilities (in case are new) or directly at the FPT Plant (in case of modification on existing equipment of facilities). New Buy parts should be Off-Tools. These units are used and as “pre-master” sample for assembly verification at Customer Plant. NOT SALEABLE

Engine and Calibration Maturity: refined application calibration (emissions, performance, fuel consumption) according to vehicle mission, ready to complete certification process:

Application delivery with overall performance partially validated on production intent priority.

3.4.4.4 PRE-PILOT

Pre-pilot units are used for Machinery Installation at Plant. External buy parts should be fully or interim A-B PPAP. Are not Saleable units unless “rework for selling” is agreed with Customer Plant or Facilities according to a Pre-Pilot Disposure Plan aimed to close the still open issues (External PAPP closure, calibration refining, homologation labels update, etc.)

Engine and Calibration Maturity: final application calibration and pre-pilot validation; preliminary application Sign-Off (with FPT readiness for ESOP in MR5)

Final application delivery (including fixing) based on gamma validation and production intent prototype vehicles field test (70% achieved).

Release for buy components engineering approval.

3.4.4.5 PILOT

Pilot units are made from 100% production tooling and processes; used to complete the Machinery Run-Off and as Internal PPAP samples. SALEABLE in case of positive internal PPAP outcome and Application Signed-Off with Customer

Engine and Calibration Maturity: production; application Sign-Off confirmation of Pilot vehicle for Customer OK To Ship (Customer Milestone), delivery confirmation based on pilot verification and full reliability validation for VSOP.

Table 12: ANNEX D – FDP at a Glance [19]

PROGRAM PLANNING	0	CONCEPT SELECTION	1	DESIGN VERIFICATION	2	FINAL DESIGN VALIDATION	3	PROCESS VALIDATION	4	PRODUCTION APPROVAL	5	PROGRAM CLOSURE SUPPORT TO CUSTOMER OK TO SHIP & LL	6

PHASES		
	PROGRAM PLANNING	It is the "bridge" phase between Innovation, Pre-development and Product Development for new business acquisition. Request for a new product is analyzed, in terms of Go-to-Market strategy, competitive scenario, Voice of Customers. The project targets are reviewed and estimated in terms of technical feasibility, economical effort (staffing, R&D budget, Capex and Vendor Tooling) and Timing vs Customer/market deadlines. The Program Sizing is classified according to the level of New Content (Product and Process). Following the Classification one or more of the subsequent phases can be skipped (SCALED) excepted Production Approval.
	CONCEPT SELECTION	It is the phase where the possible new "concept" required to satisfy Customer Expectations, Business Strategic Goals and Market Regulations is identified (within Advanced Engineering/Pre-Development proposed solutions), selected and confirmed on ALFA mules (either physical or virtual).
	DESIGN VERIFICATION	It is the phase where the first validation for product targets achievement is carried out to confirm functionality and durability on BETA builds with "tool release oriented" design. Suppliers for critical (long-lead) components have to be selected and nominated for production tooling.
	FINAL DESIGN VALIDATION	It is the phase where final validation is carried out to finalize product performance (functional/durability) on GAMMA builds with production design and Off Tool purchased parts. All Suppliers have to be selected and nominated.
	PROCESS VALIDATION	It is the phase where Suppliers' process qualification is completed through Process Audit@ Suppliers facilities and New Machinery Installation Run-Off @FPT Plant is conducted. Beside this, the homologation/certification process has to be completed, the regulatory requirements are reviewed for Compliance and the Service Readiness Plan is executed. Readiness to OK to Order has to be checked and communicated to Customer/market for commercial launch
	PRODUCTION APPROVAL	It is the phase where Start of Production @FPT Plant is approved, and Launch Readiness is shared and agreed w Customer (Application Sign-off, Master Sample approval, Internal PPAP, Compliance to Regulations and Service Readiness). Ok to Order confirmed and OK to Sell issued by Platforms.
	PROGRAM CLOSURE SUPPORT TO CUSTOMER OK TO SHIP & LL	It is the phase where support is provided to Customer for its launch/ramp-up phase; possible minor issues still open from previous phase are closed, Customer Service Tools and Parts are fully available and Application Final report is signed-off w Customer. Lessons learned are captured and consolidated for future programs. 0

KEY MILESTONE						
	Financial Milestones: Product Change Request pre-spending up to PI					Mng Review MANDATORY -Business Acceptance
	Program Initiate	Product Target set	G1 First Start	Beta freeze w Customer	1	New Concept selected and tested for industrialization DECISION: OK to Beta
	Program Approval 100% spending	New Suppliers nominated	OK to Tool	G2 Performance start / Gamma freeze w Customer	2	Design verified; OK to Tool for critical parts DECISION: OK to Tool
	OK to P-Pilot BoM Release	G3-4 Reliability	Run-Off @Machines Suppliers		3	Product Design fully Validated; Process set up DECISION: OK to Pre-Pilot
	Certification Approval	G5 Application Sign-off (prel)	External PPAP	OK to Order	4	Mng Review MANDATORY- PPAP readiness DECISION: OK to Order (for Customer)
	Internal PPAP	Master Sample Approval	G5 Application Sign-off	OK to Sell / SoP	5	Mng Review MANDATORY -Production approval DECISION: OK to Sell
	G6 Sign-Off confirmation	Vehicle OK to Ship			6	Product performance after Launch and LL DECISION: Program Closure

3.5 The Role of Quality and Failure Management in FPT Industrial- FPI.IFP100 Procedure

Quality at FPT Industrial is not merely a department or a function; it is an integral part of the company's ethos. With its commitment to excellence, FPT Industrial has established rigorous processes to ensure quality across all its product lines, including engines, gearboxes, axles, and batteries.

The FPI.IFP100 is an inter-functional procedure, an internal FPT Industrial protocol, epitomizes the company's systematic approach to managing failures. This process is vital during product development, serving as a foundation for both identifying and addressing potential issues for both new components and Carry Over (C.O.) components [16].

FPT Industrial's method for failure management involves several key steps: identifying, classifying, diagnosing, validation and resolving failures. This structured approach ensures that each issue is addressed comprehensively, from initial detection to final resolution.

To reproduce the *failure life cycle* workflow from the diagnosis to the closure of the failure there are many requirements to satisfy:

- Failure coding and classification (Customer, Source; Owner, etc.);
- Characterization of Product and Component;
- Data validation (from Testing);
- Problem Solving process steps:
    - Step 1: Team constitution, led by ACE (Assistant Chief Engineer) and NPQ (New Product Specialist)
    - Step 2, 3, 4: Root Cause analysis of a failure by using Problem solving tools like *5 Whys* or *Ishikawa;*
    - Step 5: Definition of Solutions;
    - Step 6: Planning of Actions for solutions validation;
    - Step 7: Closure information;
    - Step 8: Sharing acknowledgement of the results to the Team .
- Management of the annexes and report documentation

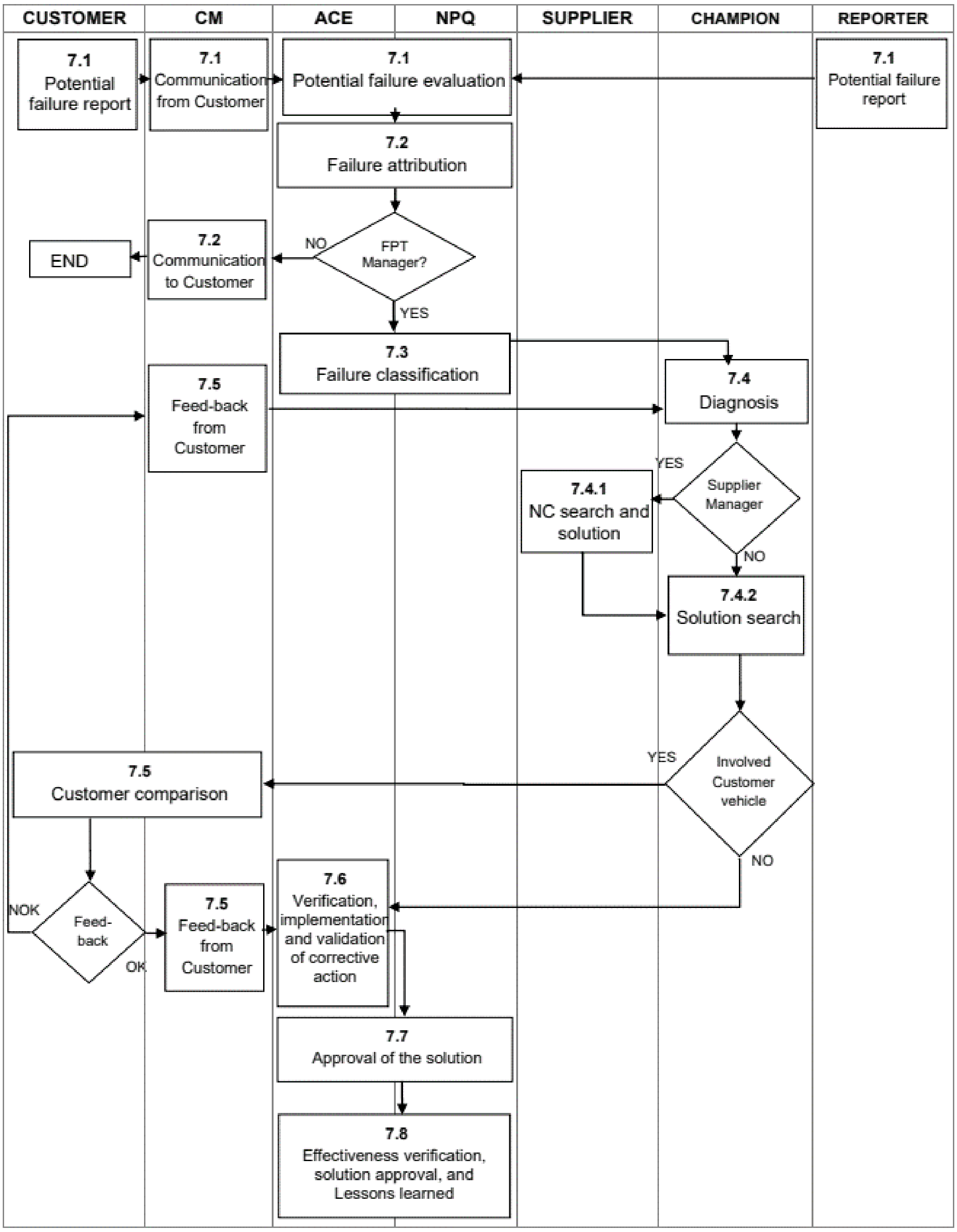


Figure 13: General flow of activities [16]

7.1 Potential failure evaluation

A potential failure can be reported by Customer through CM (Customer Manager) or directly, in case of potential failure occurred within FPT, by Testing departments, Prototypes and Plants. In both cases, ACE or NPQ shall record potential failure on FasT then submit it to preliminary assessment. After assesment, the two following is possible:

1. Potential failure does not achieve the status of failure and is solved and closed directly by reporting department; however, report record is left into FasT.
2. Potential failure reported achieves the status of failure and process is carried on as defined by activities.

7.2 Failure assessment /attribution

1. *Report from Customer*: it is assessed if failure is under FPT responsibility or not: If yes, the process is carried on FasT; if not, the Customer is informed accordingly.
2. *Internal report*: it is assessed if failure is under FPT responsibility or under Customer responsibility: if it is under Customer responsibility, ACE shall forward it to CM for sending it to Customer. ACE also evaluates if failure is occurred on a new or C.O. component: in the latter case, Problem solving responsibility is attributed to NPQ, which promote an appropriate team that by the usage of one or more problem solving tool is able to solve appropriately the problem

7.8 Failure classification

Failure shall be classified by PE-Quality-Plant team based on:

- Similarity with previous failures (father-daughter link).
- Failure severity levels:
    1. Very critical (walk home failure/production stop).
    2. Critical (strong impact for Customer or Plant).
    3. Moderately critical (moderate impact for Customer or Plant).
    4. Slightly critical (slight impact on Customer or Plant/Continuous improvement).
- Failure severity is linked to severity index used for DFMEA to assess Risk Priority Number (RPN). Specifically:
    1. Lev. A: Severity 10 to 9
    2. Lev. B: Severity 8 to 7
    3. Lev. C: Severity 6 to 5

4. Lev. D: Severity 4 to 1

- Failure risk level (to be entered to LUR, if needed, by NPQ as per procedure FPI.IFP015 and to be managed through LUR form in FAST).

If necessary, Prototype and/or Plant carry out an immediate action of containment in order to permit the activities continuation until the solution of the problem. ACE assigns the issue to a Champion, that must agree the date expected for the identification of the root cause within the inter-functional team and document the results of the corresponding analysis. The Champion is identified based on the issue nature and could not be directly involved in diagnosis of the root cause, even though he is responsible for the activity coordination

7.8 Diagnosis

Diagnosis activities shall be started by team to search for root cause/s. As specified by FasT logics, the Team PE, NPQ and ACE shall perform a first level diagnosis (failure study and first hypotheses of potential causes). If this first analysis shows clear failure causes, the validation of the root cause and the search for failure solution are carried out (point 7.4.2). When the first-level analysis shows no failure root cause, a further failure study is performed (second-level diagnosis) to identify and validate the root cause/s. This activity may involve FPT laboratories and/or suppliers for possible additional analysis. If the failure cause is under Supplier responsibility, see 7.4.1; if it is under FPT responsibility, see 7.4.2. During diagnosis, possible root cause/s (project/process) shall be validated through specific tests

1. NC search and solution by Supplier: Non-conformity analysis, definition/validation of cause and search for solution by Supplier, as per 8D methodology [20] [21].
2. Solution search by FTP: Search and identification of the solution by considering also the results of the Supplier analysis. If solution has an impact on Customer, ACE or NPQ shall ask for CM involvement for agreement (activity 7.5). If not, go to para. 7.6. In the meantime, the Product Team shall start Change Management process, i.e. engineering-cost approval of new solution submitted.

7.5 CM/Customer comparison

When the solution on vehicle, Customer involvement is required for agreement through CM. If Customer is favourable to implementation of proposed change, the verification and validation activities of the corrective action are performed (para. 7.6); if not, another diagnosis activities are carried out (back to step 7.4.1).

7.6 Verification, implementation and validation of solution

In this stage the activities required for verification and validation of identified solution are carried out. If validation tests are failed, go back to activities specified in 7.4

7.7 Approval of the solution

Engineering-cost approval of modification and updating of technical documentation for solution implementation.

7.8 Effectiveness verification, solution approval, and Lessons learned

ACE, with the inter-functional team, verifies effectiveness of solution approved and closes failure on FasT. NPQ documents and share the experience accrued during the research of solution to the occurred problem so that it becomes an instrument of Preventive Quality.

By applying methods like the FPI.IFP100, FPT Industrial incorporates solutions directly into its product development cycle. This proactive stance not only addresses existing issues but also aids in preventing potential future failures, enhancing the overall quality and reliability of FPT products.

3.6 Problem Solving Methodologies in FPT Industrial

FPT Industrial employs a structured approach to problem-solving, crucial for managing non-conformities and ensuring quality in their products. This chapter outlines the various methodologies and tools used in this process [22].

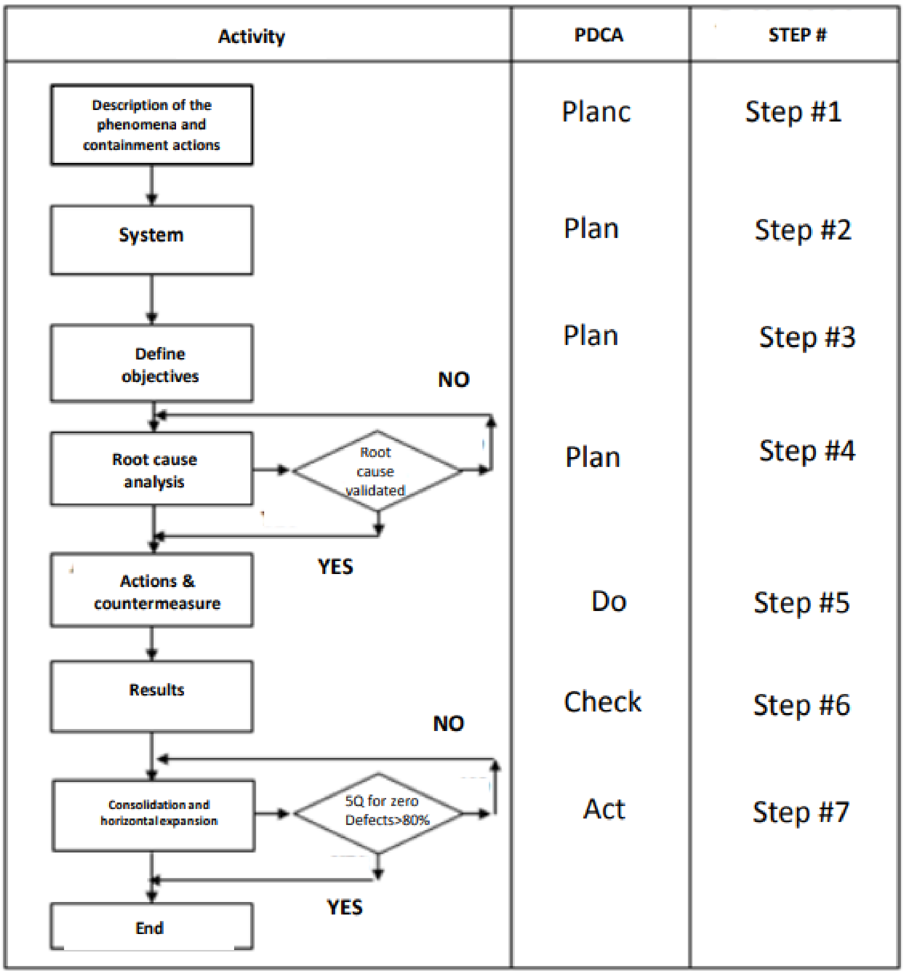


Figure 14: Problem Solving steps [22]

STEP 1: Description of Phenomena (5W+1H)

This method involves describing the problem through six dimensions:

- What object/product/flow/process etc. is the problem detected?
- When did/does the problem occur?
- Where did you see the problem?
- Who could be involved (if the issue is related to human factor/level of experience/training)?
- Which trend does the issue/problem have?
- How did the problem occur?

It is a comprehensive approach to understand the context and specifics of a problem, aiding in the identification of potential causes.

Containment Actions:

Once a problem is identified, immediate containment actions are taken to mitigate its impact. This includes steps like 100% sorting, inspections, and issuing informative service bulletins [22].

STEP 2: System Analysis

This step involves a detailed analysis of the system under normal operating conditions. It is critical for understanding how the problem deviates from the standard performance and identifying key components or phases where the issue may lie. In this context is useful at vehicle level in which are assembled more than one battery.

STEP 3: SMART Objectives

Objectives for resolving the issue are set using the SMART criteria:

- *S*: Specific
- *M*: Measurable
- *A*: Achievable
- *R*: Relevant
- *T*: Time-bound.

This ensures that the problem-solving process is focused and effective [22].

STEP 4: Root Cause Analysis and Validation

The Ishikawa Diagram, also called Fishbone Diagram, is a cause-and-effect diagram that show the potential causes of a specific event. Common uses of the Ishikawa diagram are product design and quality defect prevention to identify potential factors causing an overall effect. Each cause or reason for imperfection is a source of variation. Causes are usually grouped into major categories to identify and classify these sources of variation.

The defect, or the problem to be s"lved' Is shown as the fish's head, facing to the right, with the causes extending to the left as fishbones; the ribs branch off the backbone for major causes, with sub-branches for root-causes, to as many levels as required.

Root-cause analysis is intended to reveal key relationships among various variables, and the possible causes provide additional insight into process behavior. It shows high-level causes that lead to the problem encountered by providing a snapshot of the current situation. The Ishikawa works in four or five branches in order to fulfill all the possible causes and identify the perimeter in which the problem is limited. The groups are Method, Material, Man, Machine and Environment (4M + 1E), but they can differ by the context. The causes emerge by analysis, often through brainstorming sessions, and are grouped into categories on the main branches off the fishbone. To help structure the approach, the categories are often selected from one of the common models shown below but may emerge as something unique to the application in a specific case. Each potential cause is traced back to find the root cause, often using the 5 Whys technique.

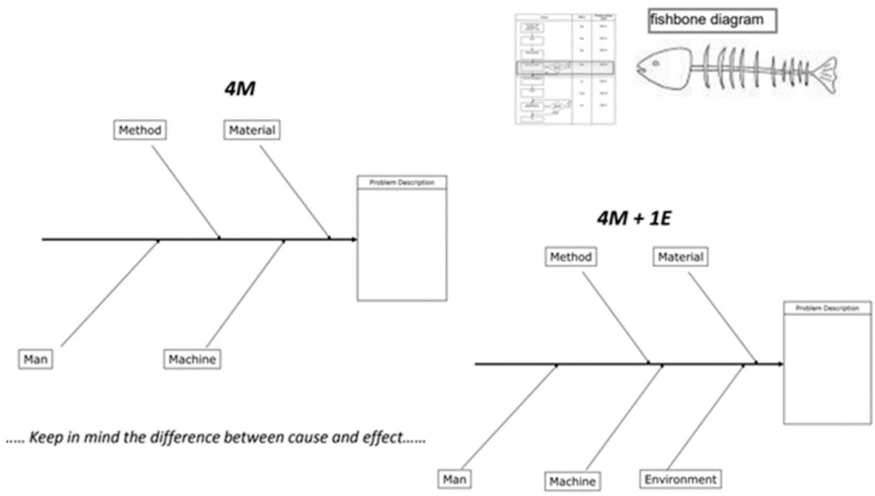


Figure 15: Ishikawa diagram [22]

Various tools like histograms, Pareto charts, scatter diagrams, cause and effect diagrams, 4M and 5 Whys are employed to analyze and identify the root cause of the problem. The validation of the root cause is crucial for ensuring that the correct issue has been addressed.

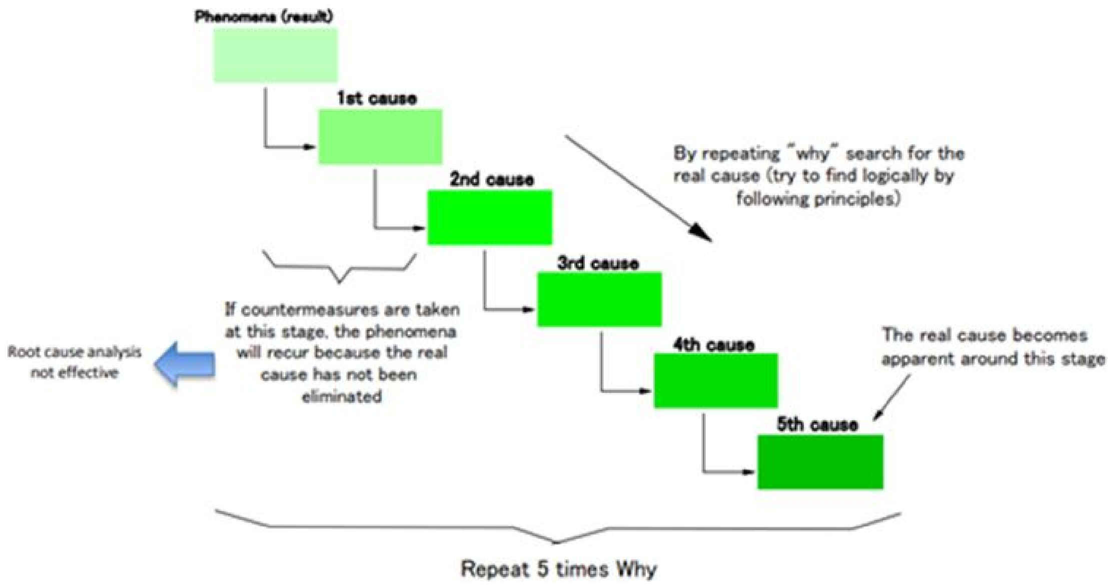


Figure 16: 5 Whys [22]

The 5 Whys technique is a problem-solving method developed by Sakichi Toyoda and widely used within the Toyota Motor Corporation during the manufacturing process. It aims to identify the root cause of a problem by asking the question "Why?" five times, or as many times as necessary, to move past symptoms and reach the underlying issue. This iterative interrogative technique is simple but effective in peeling away the layers of symptoms that can lead to the core of a problem.

The 5 Whys technique is highly effective for straightforward problems and can be adapted to more complex issues by using it as part of a broader problem-solving or quality improvement methodology. It encourages deep thinking, promotes cause-and-effect analysis, and helps teams focus on solutions rather than symptoms [22].

STEP 5: Action and Countermeasures

After identifying the root cause, appropriate actions and countermeasures are devised and implemented. This includes planning the activities and assigning responsibilities to ensure effective resolution in order to avoid the re-occurrence of the issue and/or to stop the production process phase when the issue occurs.

At this stage an ICA (Interim Corrective Action) needs to be taken. This is a temporary corrective action that helps the production to continue until a more valuable and sustainable solution will be taken, also called PCA (Permanent Corrective Action).

STEP 6: Results Evaluation

The effectiveness of the actions taken is evaluated based on criteria like Benefit/Cost calculation, warranty data, and scrap trends. To evaluate effectively the results shall pass a consistent period of time form the actions and countermeasures [22].

STEP 7: Consolidation and Horizontal Expansion

Successful strategies are consolidated and extended across similar components or parts to prevent recurrence of the issue, at this stage a PCA is consolidated. This may involve modifying documents like DFMEA, PFMEA [23], and work instructions. The evaluation of the robustness of the solution for the failure can be used the methodology *"5 questions for zero defects"* [22].

3.6.1 Questions for Zero Defects

This tool evaluates the robustness of corrective actions. It involves answering a set of five questions for each aspect of the problem, highlighted in the Ishikawa method, to ensure that conditions for zero defects are met. These five questions are useful to understand why there was a problem at that level of the process and how to get to a process with zero defects [22].

Table 13: Five questions for zero defects – man

Nr.	Question	1	3	5	POINTS
1	Are the working competences defined?	Not defined	Roughly defined	Exactly specified	
2	Is the operator skilled enough?	Low, needs supervision	Fulfills required level, works autonomy	High, can supervise others	
3	Is the operators applying working standards correctly?	Does not follow the standards	Sometimes dies exception	Follows all the standards	

4	**Does the operator do errors?**	Many errors	Only sporadic errors	Zero errors	
5	**Is the operator motivated towards improvement?**	Missing interest in proper work	Good follower, want to improve	Improves local standards, leader	
	Target tot points				>80%

Table 14: Five questions for zero defects – method

Nr.	Question	1	3	5	POINTS
1	**Is the method defined?**	Standard does not exist	Defined with sufficient details	Defined up to detail	
2	**Is the method ergonomic?**	RED evaluation	YELLOW evaluation	GREEN evaluation	
3	**The method eliminates irregularities of cycle?**	High irregularities, difficult operation	Sporadic irregularities	Easy to do and repeat	
4	**Is the method visually documented and fixed?**	Not visually documented	OPL, SOP, sketches, but not at workplace	OPL, SOP visual and disponible at workplace	
5	**Is the method robust against the errors?**	No information about result	Result of operation verified by visual aid or double check	Process Poka Yoke installed	
	Target tot points				>80%

Table 15: Five questions for zero defects – material

Nr.	Question	1	3	5	POINTS
1	**Are the material characteristics clear?**	No good definition	Each characteristic defined with measuring unit	Characteristics and tolerances defined	
2	**Are the material characteristics easy to check?**	Impossible to check during process	Check with measuring equipment	Easy to see	
3	**Are the non-conforming materials easily sorted out?**	Only by special inspection	By skilled operator	Poka Yoke to check automatically	
4	**Are the problems easy to repair?**	Difficult to repair; vehicle blocked	Repairing possible with disassembly of group	Easy to repair	
5	**Are the suppliers capable to deliver only good parts?**	100% check not applied	Check at the output of supplier process	100% control inside supplier process	
	Target tot points				>80%

Table 16: Five questions for zero defects – machine

Nr.	Question	1	3	5	POINTS
1	**Are the conditions to be set clear?**	Fixed and agreed	Exists method to check	The conditions are easy to check and see	
2	**Are the conditions easy to set?**	Difficult to set	Easy to set	Automating presetting	

3	**Does the value of condition item vary?**	During the normal production	Only at set up/start	exceptionally	
4	**Is the variation visible?**	Difficult to see or check	Standard method to check	Continuously visible	
5	**Is the variation easy to restore?**	By maintenance	By operator	Automatically	
	Target tot points				>80%

3.6.2 Kaizen and PDCA

The Kaizen approach, coupled with the PDCA (Plan-Do-Check-Act) cycle, is applied for continuous improvement. This involves planning the action, implementing it, checking the results, and acting based on the findings [22].

The Deming Cycle, also known as the PDCA (Plan-Do-Check-Act) Cycle, is a continuous improvement model that promotes a systematic approach to problem-solving and process improvement. The cycle's iterative nature helps organizations improve their products, processes, and services over time through a methodical approach. Here's a breakdown of each phase in the cycle:

1. Plan: This initial phase involves identifying a goal or a problem to solve. It requires an understanding of the current process and the formulation of a hypothesis about what changes could lead to improvement. During this stage, objectives are set, and a detailed plan to achieve these improvements is developed, including defining success metrics and the methods for data collection.
2. Do: In this phase, the plan is implemented on a small scale (if possible) to test the effects of the change. This involves executing the steps outlined in the planning phase and collecting data for analysis. It is a phase of action and experimentation, where the theoretical planning is put into practice.

3. **Check**: After the implementation, this stage is about reviewing the collected data and comparing the results against the expected outcomes defined in the Plan phase. The goal is to understand whether the changes led to improvement and to learn from the data. This phase is critical for analyzing the effectiveness of the action and identifying learning points.

4. **Act**: Based on the insights gained during the Check phase, this final phase involves acting on that knowledge. If the plan was successful, the new process is standardized and implemented on a wider scale. If the plan did not achieve the desired results, insights gained are used to inform a new PDCA cycle, beginning again with the Plan phase. This phase is about making adjustments and institutionalizing the improvements.

The Deming Cycle emphasizes a philosophy of continuous Improvement, where processes are constantly evaluated and refined in response to changes and new information. It encourages a culture of experimentation and learning, where mistakes are viewed as opportunities for growth and innovation. The cyclical nature of PDCA ensures that improvements are ongoing and that quality management is a dynamic, rather than static, process.

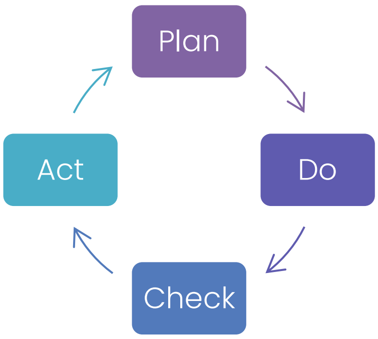


Figure 17: The Deming cycle

3.6.3 Executive Reporting

Each step of the problem-solving process is documented and reported to management, ensuring transparency and accountability. This helps in learning from each incident and improving future responses [22].

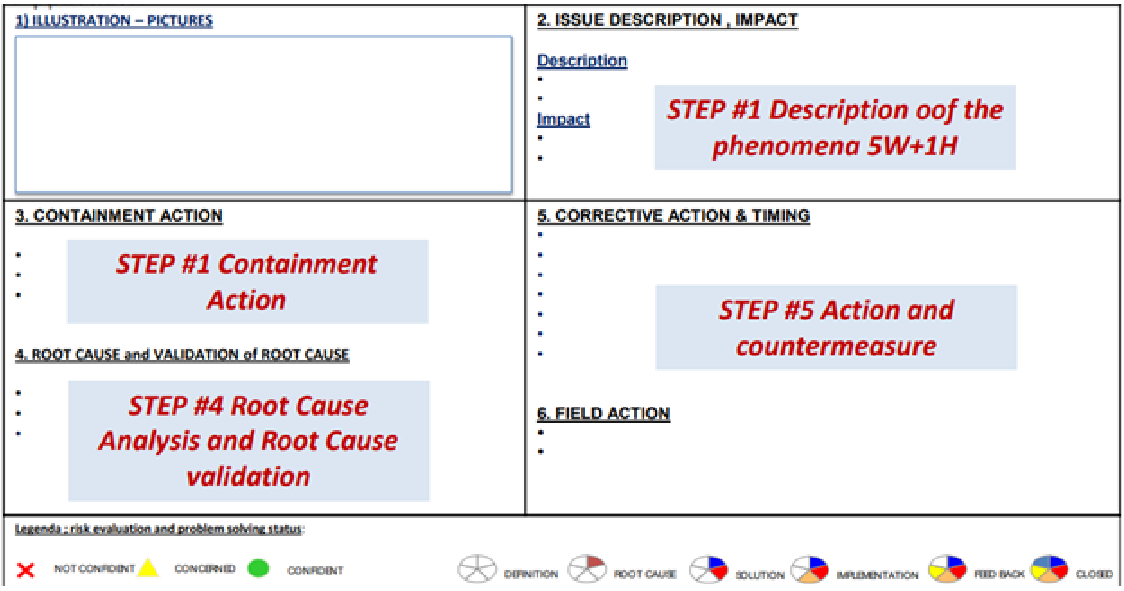


Figure 18: Problem Solving Executive Report [22]

3.6.4 Lesson Learned

The lessons learned play a pivotal role in fostering a culture of continuous improvement. They act as a bridge connecting past experiences with future actions, enabling organizations to identify and rectify shortcomings in their processes and products. By systematically analyzing and documenting what went right or wrong, teams can prevent the recurrence of issues, enhance efficiency, and drive innovation. Emphasizing the value of lessons learned reinforces the importance of proactive problem-solving and adaptability, ultimately leading to higher quality standards and greater customer satisfaction.

4 Case study

4.1 Battery Products

The Turin site is pivotal in FPT Industrial's strategy, serving as a dual hub for both the production of critical battery packs for different types of electric vehicles and as a center for technological advancement and rigorous testing of ePowertrain components.

The storage system is a fundamental component of EVs, the ePowertrain plant is involved with the production of two different models of batteries, one with Nominal Energy of 37 kWh and the other with 69 kWh. These two batteries have already been described previously in 2.4.1 2.4.2.

4.1.1 Battery structure

Both battery design use a modular structure, where the basic building block is the cell, featuring pouch technology with a configuration of 35S 2P for eBS69 and 6S 2P for eBS37. These cells are linked by welding connection point together to form a VDA module, and a collection of such modules comes together to create the entire battery pack [8] [7] [24].

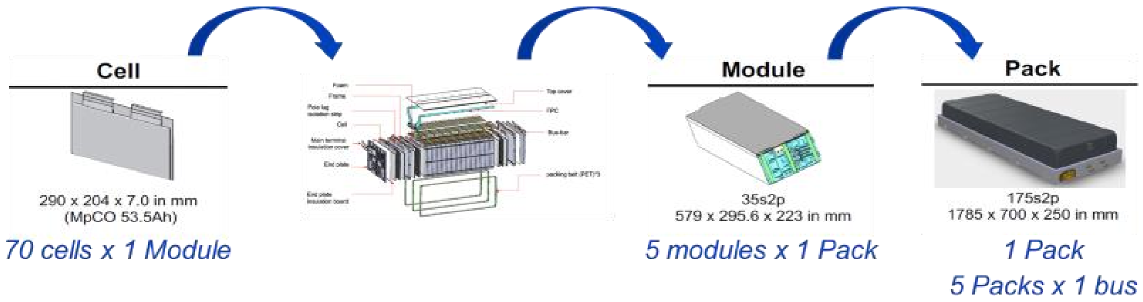


Figure 19: Battery modular structure [25]

The battery pack is intricately structured, starting with its Housing. Inside, two layers of Modules are separated by a Cooling Plate. Each module is wrapped in Insulation Tape, a crucial feature to prevent thermal runaway. The interconnectedness of these modules is achieved through a Busbar, and their performance is continuously overseen by the Battery Management System (BMS). This system comprises a Local Electric Control Unit (LECU) and a Battery Management Unit (BMU), diligently recording data regarding temperature and voltage. These modules are integrated into the system via an array of Low Voltage Internal Harnesses [24] [26] [27].

The Pack Lid sits atop the battery pack, serving a dual purpose. It not only shields the internal components from external elements but also upholds high safety standards, especially in scenarios involving thermal runaway or internal combustion. This Lid is connected to the external environment through a Pressure Equalization mechanism. At the base of the Housing, there are two critical connectors – the Low Voltage (LV) and High Voltage (HV) Connectors – flanked by a Coolant Inlet and Outlet [28].

While the configuration described pertains to the eBS 37 battery pack, it is largely similar in the eBS 69 model. The primary distinction lies in the modules used and their arrangement. In the eBS 69, the modules are positioned on a single plane, differing from the layered arrangement in the eBS 37, this implies a single cooling plate that is integrated in the housing.

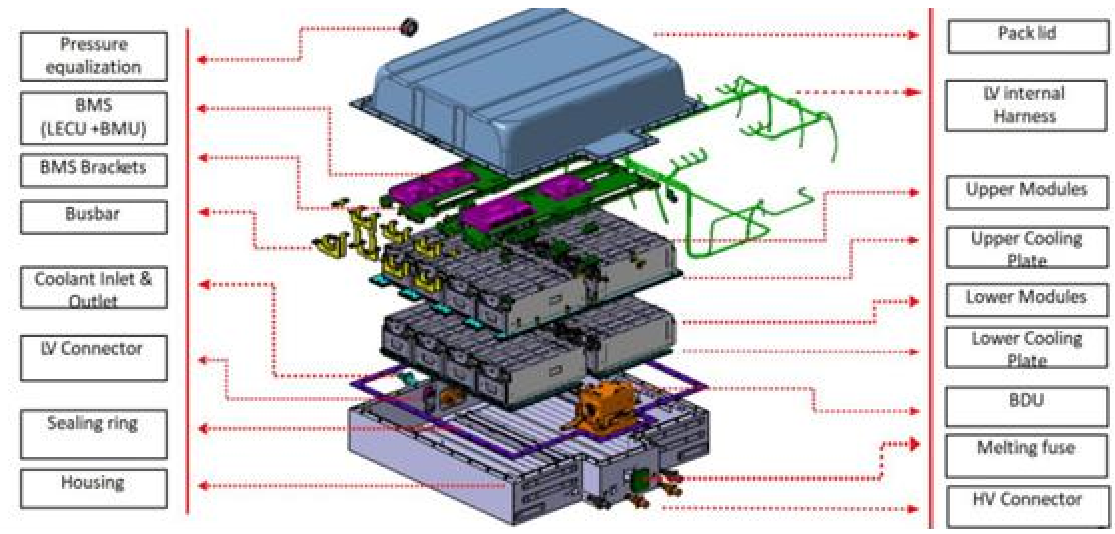


Figure 20: Battery Bill of Material [25]

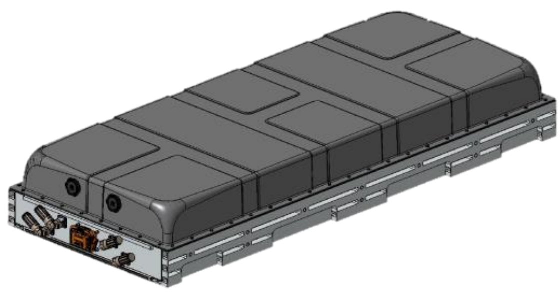


Figure 21: eBS 69 Battery Pack [25]

4.1.2 Battery Pack Assembly Line

The manufacturing process for lithium batteries, designed specifically for full electric Light Commercial Vehicles (LCVs) and Bus powertrains, is streamlined and efficient. This assembly line embraces the principles of lean manufacturing, meticulously eliminating inefficient practices and minimizing waste. Additionally, it incorporates various advanced tools of Industry 4.0, like an infotainment that guides the operator in the assembly work of the battery. This integration not only enhances safety standards but also ensures superior performance in production, aligning with the latest technological advancements in the field.

The assembly of the battery pack is carried out through a series of workstations, each designated for specific operations. Here is a simplified list of the operations at each station:

The process of constructing a battery involves a meticulously structured sequence of operations, blending manual, automatic, and semi-automatic tasks to ensure precision and functionality.

A significant portion of the process involves manual tasks.

Automatic operations play a pivotal role in the assembly process. Modules are assembled and checked with the application of fixing thermal paste in a fully automatic operation, demonstrating the integration of advanced automation technologies for enhanced precision and efficiency. Similarly, the assembly of the second layer cooling plate and modules above is automated. The last manual operation is the closing of the cover box with the tightness of the screws with the implementation of a torque-angle check as closure strategy.

Semi-automatic operations include the End-Of-Line (EOL) tests. This crucial step combines human oversight with automated testing procedures to validate the battery's functionality and safety, ensuring that each unit meets stringent quality standards before leaving the assembly line.

Throughout the assembly process, rigorous testing, including leakage tests on the cooling system in the early stages and a final leak test on the pack, is conducted to ensure the integrity of the battery's cooling system and its overall hermetic seal. These tests are vital for detecting any potential flaws and preventing future operational failures, underscoring the assembly process's emphasis on quality and reliability. Each of these operations is crucial in ensuring the quality, safety, and functionality of the battery pack. Parameters to consider during these stages include leak test results, correct assembly of electrical and mechanical components, adherence to safety standards, and successful completion of EOL tests.

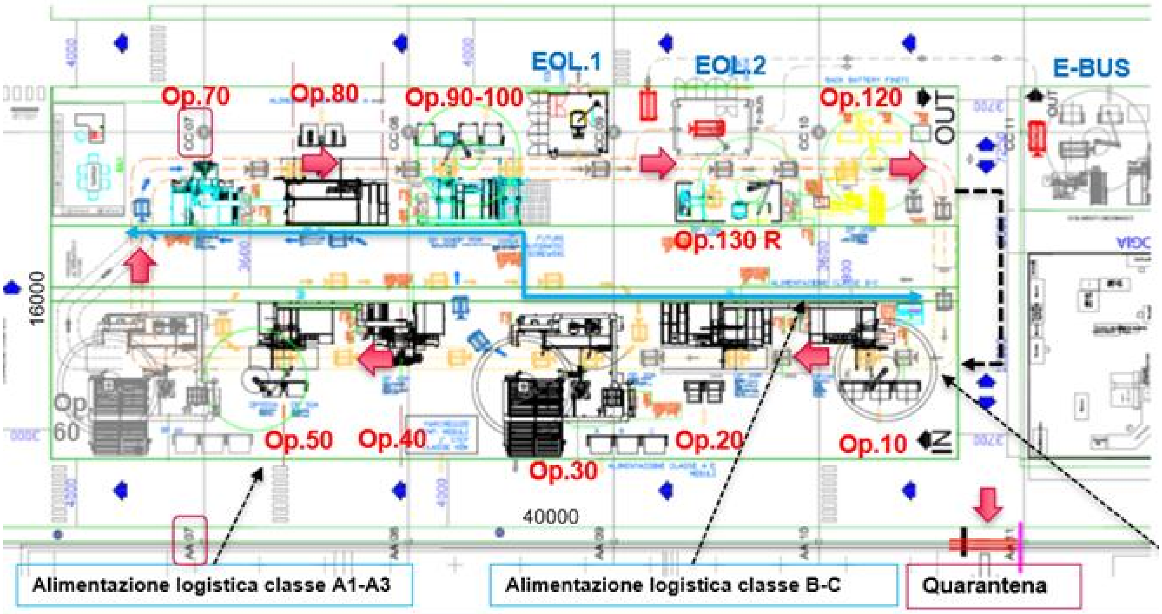


Figure 22: Battery Assembly Line [29]

4.1.2.1 EOL Test

The End-of-Line (EOL) station is a pivotal operation in the assembly line. It can assure the quality standard in terms of safety, performance, and correct assembling process during all the previous operations. The following are all the test conducted in EOL station [30] [29]:

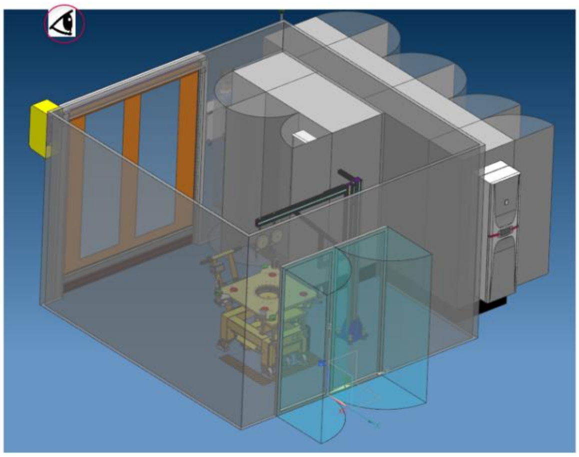


Figure 23: End of Line Station

1. **Equipotential Test**: Checks the equipotential connection of the battery housing.
2. **Electrical Test**: Validates internal CAN communication and electrical functionality.
3. **Insulation Resistance Test**: Measures insulation resistance between high voltage lines and ground.

4. **Dielectric Withstand Test**: Assesses the dielectric withstand capability between high voltage lines and ground.
5. **Insulation Monitoring System Test**: Tests the battery's internal insulation monitoring system using various resistors.
6. **Interlock Test:** Function test for the interlock system in the battery.
7. **Emergency Open Test**: Evaluates the emergency open signal response in the battery management unit.
8. **Pulse-Power Test:** Applies different current pulses to measure the battery's internal resistance and current measurement accuracy.
9. **Charging Test**: Involves charging the battery up to a target State of Charge (SOC) and monitoring cell voltage and temperature.
10. **Shutdown Test**: Concludes the test sequence with a shutdown and safety check, ensuring zero-voltage.

These tests are designed to ensure the battery's safety, functionality, and performance standards are met before deployment.

4.1.3 Parameters to monitor in Lithium-ion Battery Pack

To ensure optimal performance and adhere to safety standards in the assembly and lifecycle management of batteries, certain key parameters must be diligently monitored. These include:

1. **State of Charge** [31]**:** This parameter is critical for assessing the battery's current energy level relative to its capacity.
2. **State of Health (SOH)** [31]**:** SOH provides insights into the overall condition and efficiency of the battery over time.
3. **Delta Voltage Among Cells [mV]** [32]**:** Monitoring the voltage differences between cells is essential to maintain balance and prevent battery/vehicle performance degradation.
4. **Storage Conditions:** Keeping track of the environment where the batteries are stored, including temperature and humidity, is crucial for their longevity.

These parameters are not only critical during the manufacturing process but also throughout the entire lifecycle of the battery to maintain its quality and safety.

4.1.3.1 State Of Charge

The SOC represents the current level of charge in the battery relative to its maximum capacity. Typically expressed as a percentage, SOC indicates how much energy is remaining in the battery. Monitoring SOC is essential for managing battery usage, predicting the remaining runtime, and ensuring the battery's longevity and efficiency. This parameter is particularly important in electric vehicles, where it directly influences the driving range and overall performance of the vehicle [25] [31] [33].

SOC's Impact on Battery Performance

1. Energy Density and Efficiency: SOC directly influences the energy density of the battery. A higher SOC generally means more stored energy, which translates to a longer driving range for EVs. However, the relationship is not linear; as the battery approaches full charge, its ability to store additional energy decreases. The efficiency of a battery also varies with SOC. At different states of charge, the internal resistance of the battery changes, affecting its efficiency. Typically, batteries operate most efficiently at mid-range SOCs (around 50% of charge).

2. Charge/Discharge Rates: Batteries have optimal charge and discharge rates that depend on their SOC. Charging too quickly when the battery is near full, or discharging too rapidly when it is nearly empty, can harm the battery. Fast charging at high SOC levels can lead to issues like lithium plating, where lithium deposits form on the anode, degrading battery performance and lifespan. Most lithium-ion batteries used in EVs perform best when operated within a SOC range of approximately 20% to 80%. This range provides a good balance between delivering adequate energy for vehicle operation and minimizing stress on the battery.

3. Voltage Behaviour: The voltage of a lithium-ion battery is not constant and varies with SOC. This variance in voltage at different SOC levels impacts how much power can be delivered or absorbed by the battery. Understanding this relationship is crucial for optimizing the battery

management system in EVs to ensure maximum performance and longevity.

4. **Thermal Management**: At high SOCs, the battery can generate more heat during charging and discharging, necessitating effective thermal management systems to prevent overheating and ensure safety. Overheating can accelerate degradation processes within the battery, reducing its overall lifespan and efficiency. Most lithium-ion batteries perform best within a temperature range of about 15°C to 35°C (59°F to 95°F). This range is considered ideal for maintaining good battery efficiency and lifespan. Below 15°C the internal resistance of the battery increases, leading to reduced efficiency. Above 35°C can increase chemical activity inside the battery. While this may temporarily boost performance, it significantly accelerates battery degradation. The BMS plays a crucial role in monitoring and controlling the temperature to optimize performance and safety [33].

5. **Longevity and Degradation**: Frequent cycling of the battery (charging and discharging) at extreme SOC levels (very low or very high) can accelerate the aging process of the battery. This aging is reflected in capacity fade (loss of charge capacity over time) and power fade (reduction in the power output capability).

4.1.3.2 State Of Health

SOH refers to a measure of the overall condition of a battery and its ability to store and deliver energy compared to a new battery. It is usually expressed as a percentage of the battery's original capacity. It is critical for understanding how much life a battery has left and how its performance has degraded over time. This is important for EV owners to know how long their battery will last and when it might need replacing [34].

The SOH is of a Lithium-ion battery is affected by many external and internal factors. The SOC and SOH are strictly correlated, so they share some parameters that influence both:

1. **Cycle Life**: the number of charge-discharge cycles a battery undergoes. Frequent and deep cycling can accelerate degradation.

2. **Temperature**: Exposure to high or low temperature can hasten chemical degradation. The Batteries preserve their functionalities in time when work in a certain range of temperature, usually between 15ºC and 35ºC.
3. **Charging Practice**: Fast charging or charging to full capacity can stress the battery, while maintaining a moderate charge level (e.g., 20-80%) can prolong battery life.
4. **Age**: Over time, batteries naturally degrade due to chemical and physical changes.

As SOH decreases, the battery's ability to hold charge diminishes, known as Capacity Fade. This directly reduces the driving range of the EV. Along with Capacity Fade, there is often a reduction in the power the battery can deliver, called Power Fade, affecting the acceleration and overall performance of the vehicle.

The SOH is related to the safety too. Batteries with low SOH are more prone to failures, which can range from reduced performance to, in extreme cases, safety hazards like overheating or thermal runaway. Furthermore, degraded batteries can be more susceptible to thermal runaway, a condition where the battery generates excessive heat, leading to a risk of fire or explosion. To overcome to all these problems intervenes the BMS, that constantly monitors the battery [35].

4.1.3.3 Delta Voltage Among Cells

In the context of lithium-ion batteries, delta tension refers to the variations in voltage or state of charge across different cells within a battery pack. Consistency in cell voltages is crucial for battery efficiency and longevity. Variations can lead to uneven charging and discharging, affecting overall battery performance [32].

Cells with lower voltage or SOC are 'weaker' and can limit the performance of the entire battery pack. Uneven cell voltages can lead to reduced total capacity and efficiency, and so the overall battery pack performance degradation. Discrepancies in cell voltages lead to an inefficient use of the total capacity of the battery. Some cells will be overused while others underused, reducing the overall efficiency. Cells operating at consistently higher or lower voltages than their counterparts degrade faster. This uneven wear can shorten the battery's lifespan.

Significant delta tension can cause stress on weaker cells, potentially leading to overheating or, in extreme cases, thermal runaway. Ensuring uniform voltage across cells is key to maintaining battery safety.

Cell balancing is a key strategy used to equalize the charge across all cells, either by redistributing charge or by selectively discharging higher-charged cells. Active and passive balancing methods are employed, depending on the application and cost considerations. Modern BMS are equipped to continuously monitor cell voltages and perform balancing as needed. They play a crucial role in maintaining delta tension within safe and efficient limits.

- Active Balancing: Transfers energy from higher charged cells to lower ones, ensuring all cells maintain similar charge levels. It is more efficient but costlier. [36]
- Passive Balancing: Dissipates excess energy from higher charged cells as heat. It is simpler, cheaper, and safer for battery's SOH but less efficient. [36]

4.1.3.4 Storage Conditions

Lithium batteries contain active chemical components that are susceptible to degradation if stored for extended periods without electrical connection, or if kept in environments with temperature and humidity levels beyond their specified limits or if left in direct contact with atmospheric conditions.

The optimal SOC for Storage falls in a range between 40% and 60%. This range is crucial for maintaining battery health during storage. Moreover, is important to maintain certain environmental conditions, for instance, Storage should be in a clean, dry, and well-ventilated area, with temperatures between 10°C and 30°C, and relative humidity not exceeding 65%. Avoiding corrosive gases and keeping the batteries away from fire and heat sources is essential [33].

Another factor to take into consideration is to perform a Regular Cycling, the passage of current allows to keep a certain level of SOH and SOC during the time. If storage exceeds three months, batteries should undergo charge-discharge cycles every three months to preserve their health. The first cycle should start three months from the production date. The Cycling Procedure should be executed in a certain level of temperature, charge/discharge rate and to certain SOC levels [33].

In the suggested range of temperature, the acceptance criteria of cell voltage difference within a module should be less than 30 mV, and the internal resistance range should be maintained as specified for optimal performance.

The handling phase of the battery pack shall meet the global and local regulations for dangerous goods (class 9, UN3840). Address the requirements for moisture and vibration-proof packaging, compliance with transport regulations, and protective measures during transportation [33].

4.1.4 Application of Ohm's Law in Lithium-Ion Battery

Whenever there is a current in a conductive material the Ohm’s Laws can help to measure one of the three physic metrics knowing the other two. Exists a class of conductors whose characteristic curve is a straight line passing through the origin. These conductors are referred to as ohmic [37].

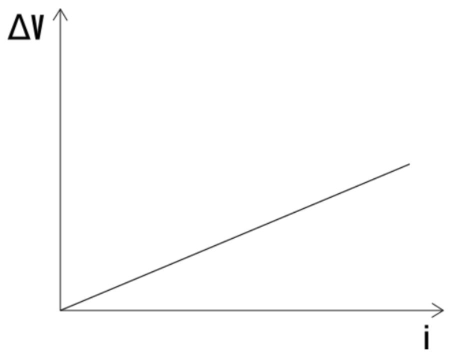


Figure 24: relation between current intensity and voltage difference

The first Ohm’s law describes that the current flowing through the battery I (measured in Ampere) [A] is directly proportional to the difference in voltage across the battery terminals V (measured in volt) [V] by a factor of internal resistance of the battery R (measured in Ohm) [Ω].

$$First\ Ohm's\ Law: V = R * I$$

In other words, the electric current depends on the ration between Voltage and Resistance, the lower the Resistance, the higher the Current.

From the first Ohm’s law derives the Second Ohm’s law that establishes the resistance of a conductor is directly proportional to its length (l) and inversely proportional to its cross section (S) and by factor ρ (resistivity) that depends by the material of the conductor [38].

$$Second\ Ohm's\ Law: R = \rho * \frac{l}{S}$$

The first and second Ohm's Law highlight the Resistance is influenced by many factors as:

- Kind of material
- The length of the conductor
- The surface of the cross section
- The temperature

Table 17: Resistivity Values for different Materials [37]

Type	Material	ρ [Ω * m]	α [°C⁻¹]
Conductor	NiCr	$1 * 10^{-6}$	0.0004
Conductor	Fe	$1 * 10^{-7}$	0.005
Conductor	Cu	$1.7 * 10^{-8}$	0.0039
Conductor	Al	$2.8 * 10^{-8}$	0.0039
Conductor	Ag	$1.6 * 10^{-8}$	0.0038
Insulating	Glass	$\approx\approx 10^{12}$	
Insulating	Teflon	$10^{22} - 10^{24}$	
Insulating	Quartz	$7.5 * 10^{-17}$	
Insulating	Wood	$\approx\approx 10^{8}$	
Semiconductor	Si	0.001 - 640	-0.075

4.2 Fault on Product

The latest phase in EV production process is the check of the assembling of all components, assure that communicate each other and test the vehicle on road to see if its performance matches with the designed one.

For this specific case study, the EV is an eBus (CityBus) with modular configuration, it can be equipped with up to five batteries connected in parallel. In this configuration the current capacity of the cells add-up, offering a higher total capacity (Ah), so it extends the driving range and allow for sustained power delivery over longer periods, essential for vehicles like buses with fixed routes. Furthermore, if one cell fails, others can compensate, maintaining system integrity. In terms of safety and reliability. The parallel configuration is easier to manage thermally and electrically, reducing the likelihood of the overheating and imbalance. It operates at lower voltages, which can be safer and less taxing on electrical insulation and components.

In the current production phase, eBS69 battery models are classified as Gamma version. Despite being in these preliminary stages, the use of the Interim Review Worksheet (IRW) allows us to assure quality and performance benchmarks are met. Consequently, this documentation enables the sale of these batteries, providing early adopters with access to our latest technology, while also allowing us to refine and enhance our products based on real-world usage and feedback. The IRW serves not only as a quality assurance measure but also as a bridge that connects the developmental phase of our batteries with the commercial market, ensuring that even at the Gamma stage, battery products are viable for sale and capable of meeting Customer expectations.

4.2.1.1 Issue Description

On a batch of 37 CityBus in OKTS phase has been assessed a specific engineering check for Bus commissioning. These tests aim to verify the behaviour of the EV on road and to check the interaction among vehicle and battery system. During this assessment, a notable deviation in voltage was observed within a single battery pack, exceeding the specified limit of Δ60 mV.

The design specification mandates a maximum voltage difference of 30 mV between the highest and lowest cells' voltage within a module, and a 60 mV delta voltage limit across the entire battery. This specification limit guarantees the optimal battery functionality, ensuring the designed power output and range are met. In the best-case scenario, all the cells have the same value of voltage and hit the target value designed by engineers, this translates in more longevity for the battery life and higher performances in terms of energy deliverable. A huge difference of these value can lead to many problems on the performance and safety of vehicle, so it is something that must be avoided.

4.3 Containment Action

In the first place is found a temporary solution by the engineers that works on vehicle, which if the unbalancing is not caused by Hardware issue inside the cells, it can be recovered with a balancing procedure (planned by product specificity).

Balancing a lithium-ion battery involves equalizing the charge levels of all the cells in the battery pack. This process ensures each cell has the same voltage level, enhancing battery performance and lifespan. There are two main types of balancing:

1. **Passive Balancing**: Energy from higher-charged cells is dissipated as heat to bring them down to the level of the lower-charged cells. It is simpler and cost-effective but less efficient in energy use [36] [36].
2. **Active Balancing:** Energy is transferred from higher-charged cells to lower-charged ones. This method is more complex and expensive but maximizes energy use and achieves faster balance [36] [36].

The choice of balancing method depends on factors like the battery's application, cost considerations, and desired efficiency. Balancing is a crucial aspect of battery management systems in maintaining the health and safety of lithium-ion batteries. In this specific case has been used a Passive Balancing strategy because it is suitable for lower power applications such as EVs [36] [36].

By the balancing procedure has been noticed that exists two different outputs as result of the balancing on vehicle. The first one is an *Irreversible Voltage Unbalance on Vehicle*, which the battery pack in unable to reach a balanced voltage status, so the cells inside the battery will have different levels of SOC. The second output is a *Reversible Voltage Unbalance on Vehicle*, which the battery pack, at the end of the balancing procedure can reach a balancing voltage status, but the balancing procedure is too slow (1 mV/h) and requires around 48h to do a complete cycle of balancing. This amount of time is a relevant issue for a CityBus which must complete the same route more times each day with a single charging in the night.

4.4 Root Cause Analysis

On a first sight analysis there is not a clear pattern between unbalancing voltage in the battery pack, once on vehicle, and a wrong procedure in assembly line. So, the first phase of Problem solving is to understand the Fault and to allocate it in order to find a good solution. In this procedure there are many tools of problem solving that help in designing the right solution, the most efficient and suited for this specific problem are the Ishikawa Diagram, which shows all the possible causes of the issue in five different dimensions (Machine, Method, Man, Material, Product Design), and the 5 WHYs, which explores the cause-effects relationship asking more time the question "Why?". Since there are two different issues has been applied two different problem-solving processes.

4.4.1 Ishikawa Diagram – Irreversible Voltage Unbalance Issue on Vehicle

The Ishikawa Diagram is the starting point of the analysis to understand, and then solve, the issue. This tool highlights all the possible cause of the problem, which each of them is well analysed to solve the issue on the product. There are 5 different categories that may be responsible for the fault and inside each of them many possible causes exist.

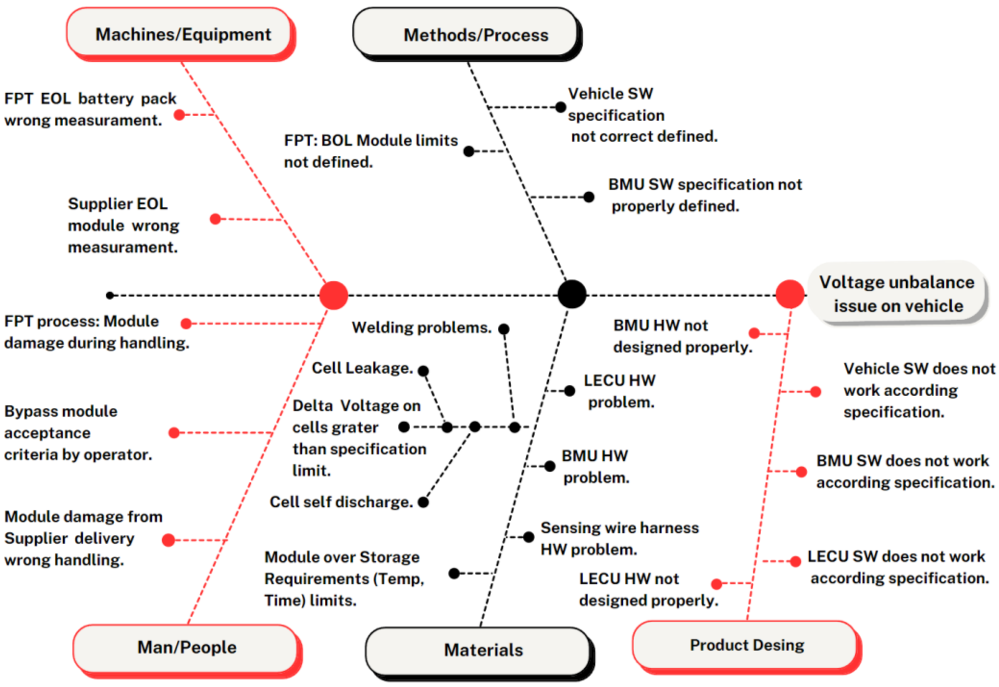


Figure 25: Voltage Unbalance Issue on Vehicle

Machine/Equipment

- **FPT EOL battery pack wrong measurement:** in FPT assembly line there are two different machines that measure the voltage value. The first one (OP 31) measures the voltage on the module before to assemble it on the battery to guarantee that is does not exceeds the limit by design. The second one is the EOL. It measures the voltage on the whole battery pack. By data it is evident that among the measurements of the two machines there is a consistency of the values. Moreover, the capacity to measure of the OP 31 has been assessed manually by a specialized operator and the two values match perfectly.
- **Supplier EOL module wrong measurement**: The supplier has shared the data approval of the module produced to assure the correct functioning of its EOL. By a simple comparison with FPT's measurement the supplier's machine is conform.

Method/Process

- **FPT - BOL module limits not defined:**
- **Vehicle SW specification is not correctly defined:** SW specification have been revised with the engineering team and with the supplier.
- **BMU SW specification not properly defined:** SW specification have been revised with the engineering team and with the supplier.

Man/People

- **FPT process – Module damage during handling:** the operators have been well trained to handle the modules and assisted during the assembly phase.
- **Bypass module acceptance criteria by operator:** the operators have been instructed not to bypass the acceptance criteria given by machine.
- **Module damage from supplier delivery wrong handling:** the supplier has shared its handling process, and an internal engineer assessed the correct module handling operation.

Materials

- **LECU HW problems:** teardown activity has been performed.

- **BMU HW problems** teardown activity has been performed.
- **Sensing wire harness HW problem**
- **Module over Storage requirements (Temperature, Time) limits:** all the Storage parameters have been respected and did not lead to any material damage.
- **Delta voltage on cells greater than specification limits:**
    - **Cell Leakage:** teardown activity has been performed.
    - **Welding Problem:** teardown activity has been performed.
    - **Cell self-discharge:** teardown activity has been performed.

Teardown Activity

To avoid the worst-case scenario, that is a Hardware issue as a result of the irreversible unbalancing issue, an external and internal teardown have been performed.

The Teardown Activity allows to understand if the issue simply comes from a self-discharge given by the chemistry of the cells, from the presence of electrolyte micro-leakage, or else from a welding issue.

All the three kinds of problems lead to a failure, but each of these issues impacts battery performance and longevity differently and requires specific strategies for identification and resolution. Among them can be highlighted some differences:

- **Self-Discharge**: This refers to the natural loss of charge by a battery, even when it is not connected to a load or circuit. All batteries exhibit some level of self-discharge, but it is typically very low in lithium-ion batteries. As written above, factors like temperature and age can affect the rate of self-discharge.
- **Cell Leakage**: This term generally refers to the physical leakage of electrolyte from the battery cell. It can occur due to damage or defects in the cell casing. Leakage is dangerous as it can lead to short circuits, reduced battery performance, and in severe cases, safety hazards. This type of fault leads to very different problems of voltage, usually the nearby cells are respectively the highest and the lowest in terms of voltage value.

Moreover, it is impossible to recover the module with the issue, the whole module will be discarded.

- **Welding Problems**: In lithium-ion batteries, cells are often connected by welding. Poor welding can lead to increased resistance at the joints, inefficient current flow, and potential points of failure. Over time, bad welds can degrade, leading to cell disconnection and battery malfunction.

Any Hardware problem, linked to a leakage of electrolyte or to poor welding, have been rejected by both Customer and supplier. The result of the teardown suggests that further investigation can be made about the self-discharge as possible cause of the issue.

Product Design

- **BMU HW not designed properly:** the entire HW design has been revised by FPT's engineering team.
- **LECO HW not designed properly engineering:** the entire HW design has been revised by FPT's engineering team.
- **Vehicle SW does not work according to specification:** the vehicle SW has been revised and updated to a newer version.
- **BMU SW does not work according to specification:** the BMU SW has been revised and updated to a newer version.
- **LECU SW does not work according to specification:** the vehicle SW has been revised and updated to a newer version.

4.4.2 Ishikawa Diagram – Reversible Voltage Unbalance Issue on Vehicle

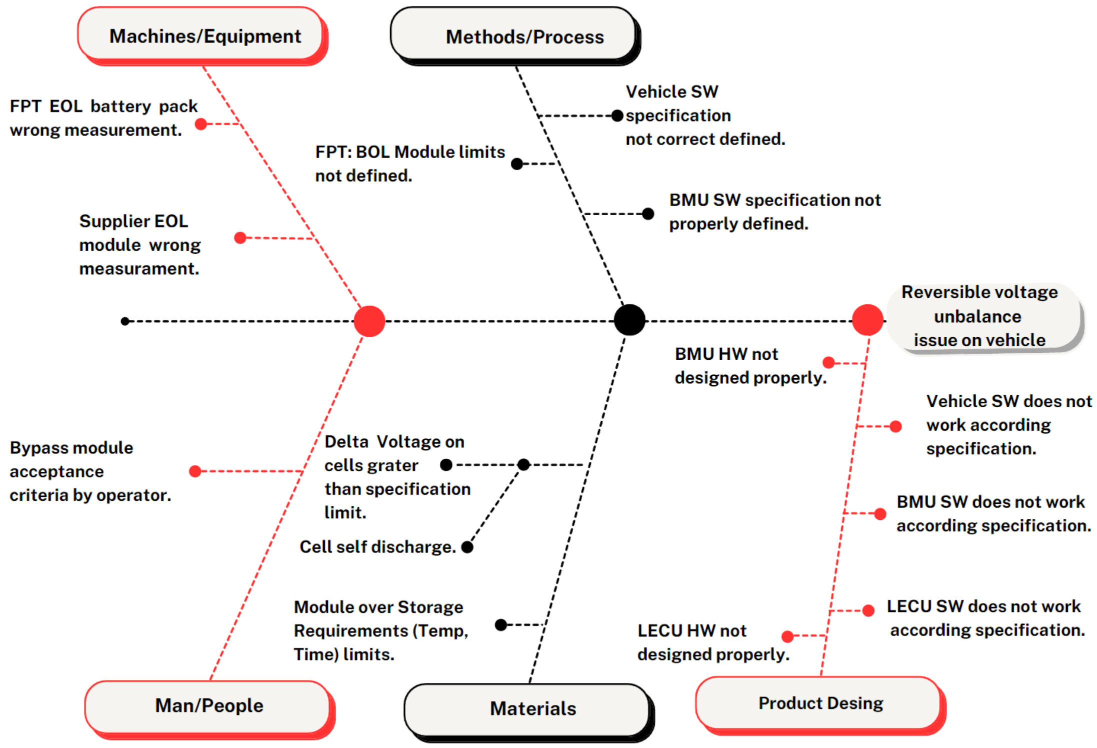


Figure 26: REVERSIBLE VOLTAGE UNBALANCE ISSUE ON VEHICLE

Machine/Equipment

- FPT EOL battery pack wrong measurement: in FPT assembly line there are two different machines that measure the voltage value. The first one (OP 31) measures the voltage on the module before its assembly on the battery to guarantee that it does not exceed the limit by design. The second one is the EOL which measures the voltage of the whole battery pack. By data it is evident that among the measurement of the two machines there is a consistency of the values. Moreover, the capacity to measure of the OP 31 has been tested manually by a specialized operator and the two values match perfectly.
- Supplier EOL module wrong measurement: to assure a right functioning of supplier's EOL, it gives the data approval of the module produced. By a simple comparison with FPT's measurement the supplier's machine is conform.

Methods/Process

- FPT - BOL module limits not defined:
- Vehicle SW specification does not correct defined: SW specification have been revised with the engineering team and with the supplier.
- BMU SW specification not properly defined: SW specification have been revised with the engineering team and with the supplier.

Man/People

- Bypass module acceptance criteria by operator: the operators have clear instructions to do not bypass the acceptance criteria given by machine.

Materials

- Module over Storage requirements (Temperature, Time) limits: all the Storage parameters have been respected and did not lead any material damage.
- Delta voltage on cells greater than specification limit
  - Cell self-discharge: teardown activity has been performed.

Product Design

- BMU HW not designed properly: the entire HW design has been revised by FPT's engineering team.
- LECU HW not designed properly engineering: the entire HW design has been revised by FPT's engineering team.
- Vehicle SW does not work according to specification: the vehicle SW has been revised and updated to a newer version.
- BMU SW does not work according to specification: the BMU SW has been revised and updated to a newer version.
- LECU SW does not work according to specification: the vehicle SW has been revised and updated to a newer version.

4.4.3 5 WHYs - Irreversible Voltage Unbalance Issue on Vehicle

This tool is an iterative method that enables to explore the relationship among cause-effect patterns for a problem asking five time the question "WHY?". The goal is to go deeper in the problem and to determine the root cause of a specific issue.

Issue description: Loss of vehicle performance on Road test

1. WHY? One battery out of five has opened the main contactor.
2. WHY? Voltage unbalancing status inside the battery.
3. WHY? Delta cells voltage inside battery and modules out of limits.
4. WHY? Huge deviation standard within cells voltage inside a battery pack.
5. WHY? Cell self – discharge.

4.4.4 5 WHYs - Reversible Voltage Unbalance Issue on Vehicle

Issue description: Increase of time for vehicle balancing operation up to 48h

1. WHY? SW balancing operation equalizes all the voltage inside the battery pack (1 mV/h).
2. WHY? High delta voltage module inside the battery pack.
3. WHY? Modules assembled with different voltage levels.
4. WHY? Cells voltage with different voltage levels.
5. WHY? Supplier does not make voltage cell sorting / capacity test.

4.5 Capability Analysis

To support the problem-solving process a capability analysis has been performed to see if the process is in statistical control and within the specification limits.

Process Capability Analysis evaluates the inherent variability of a process relative to product specifications. It determines the capability of a process to produce items that meet these specifications [39].

4.5.1 Process Capability Ratios

Process Capability Ratios (PCRs) quantitatively represent the capability of a process to produce products within specifications.

There are two main types of PCRs:

- The "first generation" PCR (for two-sided specification) is:

$$C_p = \frac{USL - LSL}{6 \cdot \sigma} \in \mathbb{R}^+$$

This metric is determined under the strict presumption that the quality attribute adheres to a normal distribution, denoted as $x \sim N(\mu,\ \sigma^2)$, leading to $NT\ =\ 6 \cdot \sigma$. In real-world scenarios, the process's standard deviation (σ) is typically unknown and is substituted with an estimated value (σ), derived from data gathered while the process operates within controlled parameters. Ideally, a C_p value greater than 1 is preferred. However, an excessively high $C_p$indicates that the NT is too narrow, potentially making the process unduly costly due to the high expense associated with minimizing variability. A commonly accepted benchmark for $C_p$is $\frac{4}{3}$, approximately equal to 1.33. The process capability ratio C_p, however, does not account for the positioning of the process mean relative to the specifications. It solely assesses the specification width in comparison to the process's NT range and thus does not consider the alignment of the process [40].

- This second metric focuses on the centering of the process, in contrast to C_p, which relates to the variability of the process. Depending on the values of C_p and C_{pk}, several outcomes can be discerned:
    - When C_{pl} (lower capability) equals C_{pu} (upper capability), it indicates that the process is perfectly centered within the specification range. In this particular scenario, C_{pk}, C_{pl}, and C_{pu} all equal C_p, signifying optimal alignment with the midpoint of the specification range [40].
    - If the Natural Tolerance limits are situated within the Specification (S) limits, then C_{pk} is equal to or greater than 1. This implies that the process's output consistently meets or exceeds the specified requirements [40].
    - Should the process average (μ) fall outside the Specification limits, C_{pk} will be less than 0, indicating a significant misalignment with specified parameters and a potential for unacceptable output [40].

- The ideal value for C_{pk} mirrors C_p, as this represents the most desirable condition where the process is not only within variability limits but is also precisely centered [40].

In summary, while C_p evaluates how well a process's variability fits within the specified limits, C_{pk} provides additional insight by assessing how well the process is centered within those limits, offering a more comprehensive view of process capability [40] [41].

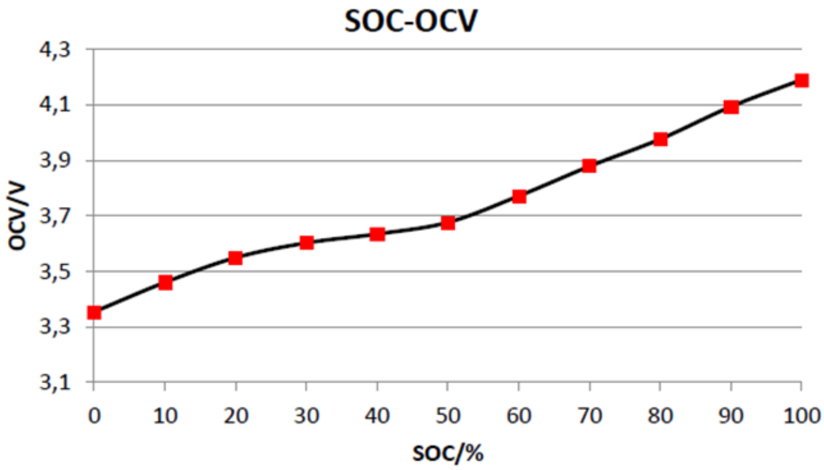
4.5.2 Measurement of Cell Voltage Condition

In the production assembling before mounting the five modules on the housing, each module is subjected to a measurement of the tension for each cell. All the values of cell voltage are registered in a local computer and can be downloaded to perform any sort of analysis on them. This is a fundamental automatic step that helps the capability analysis to be more precise, because it has been performed on the whole population and not just on a limited batch.

The cells' voltage measurement must be performed in certain conditions to have a consistency in the results.

Conditions:

- **Current:** 200 A
- **Time**: 18 s in discharge conditions
- **DCIR:** ≤ 30 mV
- **SOC (State Of Charge):** 50%
- **Temperature:** 25° C [33]



	SOC(%)										
OCV (V)	0	10	20	30	40	50	60	70	80	90	100
	3.354	3.46	3.549	3.602	3.634	3.676	3.771	3.878	3.976	4.093	4.19

Figure 27: Cell SOC-OCV, SOC-DCIR [33]

There are three kinds of batteries produced, Beta Battery (only for testing purposes, not saleable), Gamma Battery (saleable), Gamma Battery after corrective action (saleable). To have solid results has been performed a capability test for each of these batteries group.

4.5.3 Capability of Production Gamma Batteries

To verify if the process can produce the same component with the same nominal value each time with a certain tolerance, a capability test has been performed of the values of the single cell voltage level.

For this first kind of battery, given the production data, 1926 values of cell voltage have been recorded, all in the same condition.

From the data emerges as:

$$x \sim N\,(\mu = 3684\,;\,\sigma = 9{,}46)$$

Where x is the variable Cell Voltage.

From drawing the nominal value of Cell Voltage value is 3676 mV and the Upper and Lower specification limits are respectively $\boldsymbol{USL} = 3691$ and $\boldsymbol{LSL} = 3661$.

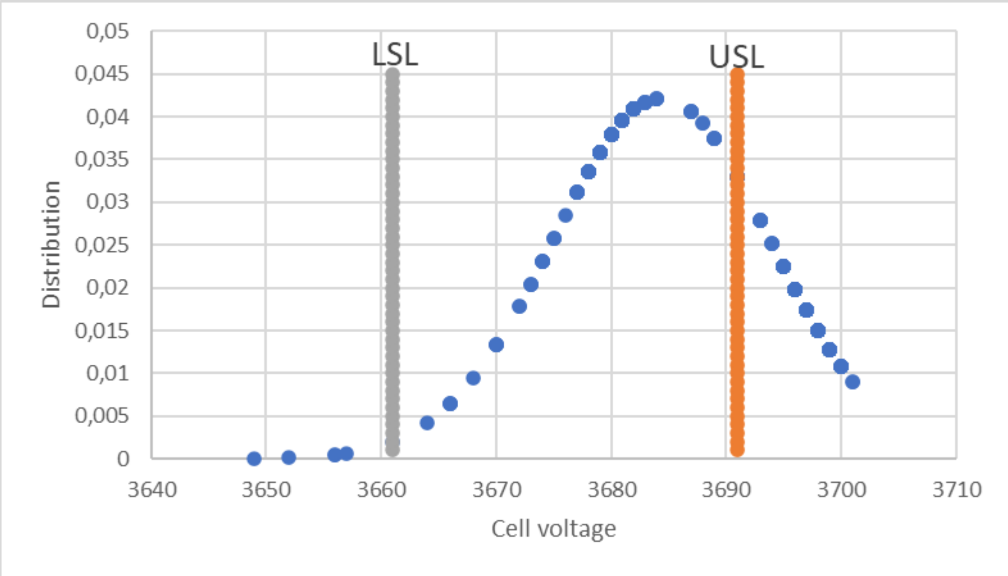


Figure 28: Capability Analysis Gamma Batteries

By plotting the values, it is clear that the Cell Voltage follows a normal distribution. Moreover, there is an evident problem in the process, because there is a considerable number of cells with voltage value plotted outside the specification interval limits. The average value is close to the Upper Specification Limit (USL), and the variance is quite large. To evaluate the capability of the process the values of C_p and C_{pk} have been calculated as described above, with the following results:

$$C_p \ = \ 0{,}530$$
$$C_{pk} = \ 0{,}233.$$

Since the target value of both indexes is 1,33, the process is clearly not within specification limits. It is shifted and with too wide variability.

Another tool that helps to assess the process quality is the Control Chart. In presence of natural variability, the process needs to be in statistical control. The control chart can highlight a process out of control and helps to investigate on the variability of the process. To build the control chart on the entire population of Gamma Battery, all the cell voltage values are plotted, and they should be within the Upper Control Limit (UCL) and Lower Control Limit (LCL) [40].

These two limits are defined as: $UCL = \mu + 3 * \sigma$ and $LCL = \mu - 3 * \sigma$ as we are plotting the entire population and not only limited sample.

The result of the control chart is the following:

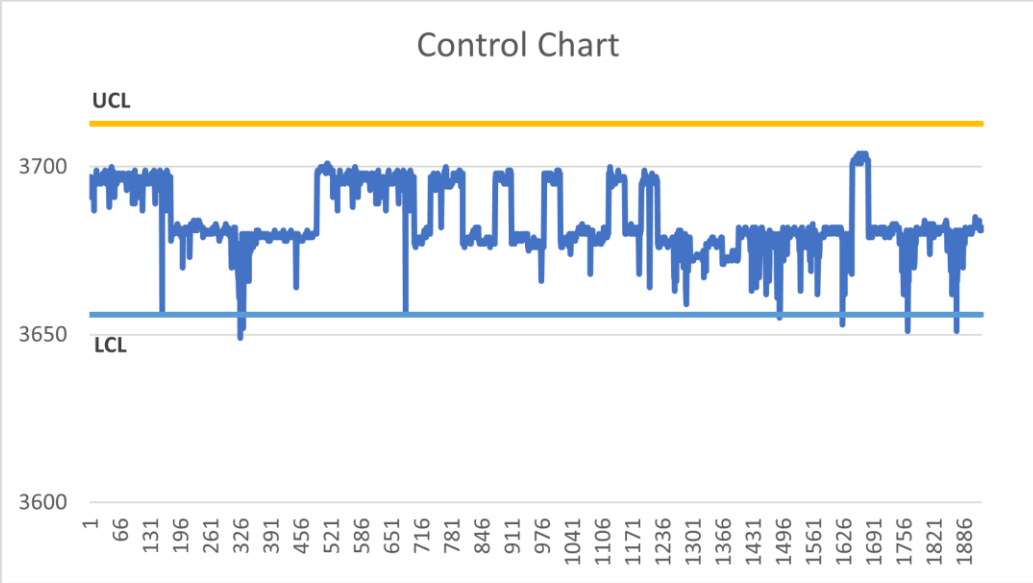


Figure 29: Control Chart Gamma Battery

The chart shows that the process is in statistical control as almost all the cell voltage values are plotted inside the control limits. Despite a process quite in control there are some information that can help to improve the process, 5 out of 1926 values plot outside the control limits. Furthermore, the whole population is not well centered between the control limits.

The Capability Analysis and the Control Chart are useful to support the root cause Analysis, and it is evident as, by the data recorded in the FPT's plant, the supplier process of modules production has large room of improvement.

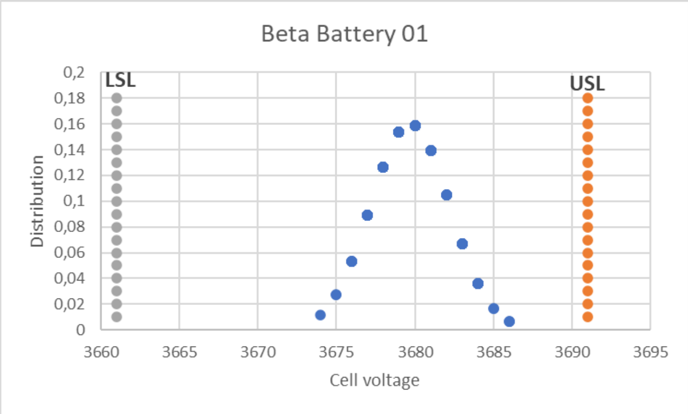
4.5.4 Capability of Production Beta Batteries

Before the production of Gamma Batteries started, there was a period of production of Beta Batteries (not saleable product).

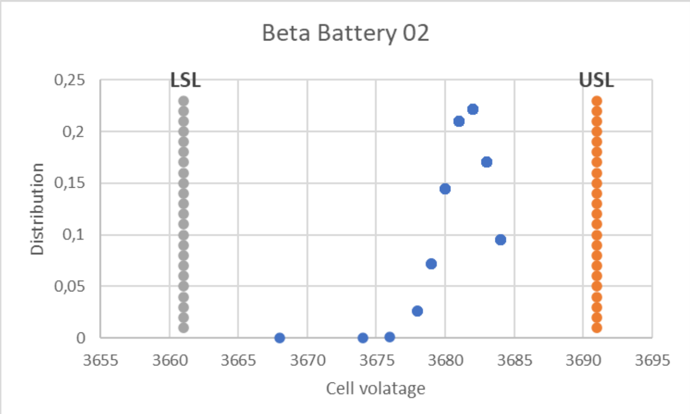
The Beta production phase is useful to highlight all the possible issues of the product, to solve them and to test the product itself on the vehicle. In this phase the modules were sent by the supplier within a group of five modules, called "*kit*", all five of them will be mounted on the same battery. Each kit is produced to be on the same level of voltage, in this way there is a huge reduction in the difference of voltage between the cells inside a module, and so, in the battery.

For the analysis of this group of production a capability analysis for each battery has been performed for which the population is composed by 175 values' cell voltage (35 cells for module times 5 modules). This is due to the assembly kitting

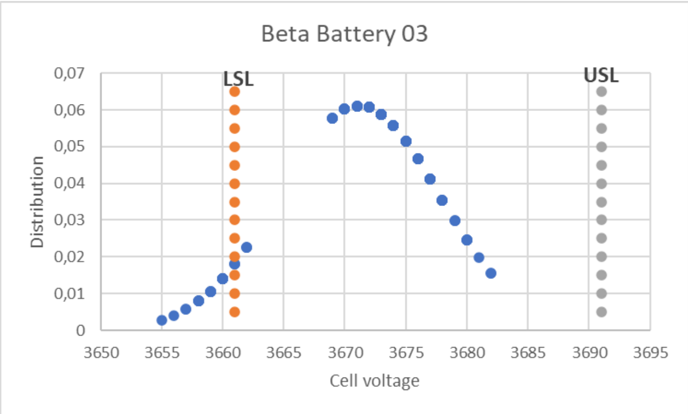
strategy, which only the cells inside the same battery, so the same *kit*, can interact to create the capability analysis.
By the analysis of four different battery packs, the followings are the results in terms of distribution and capability ratios:



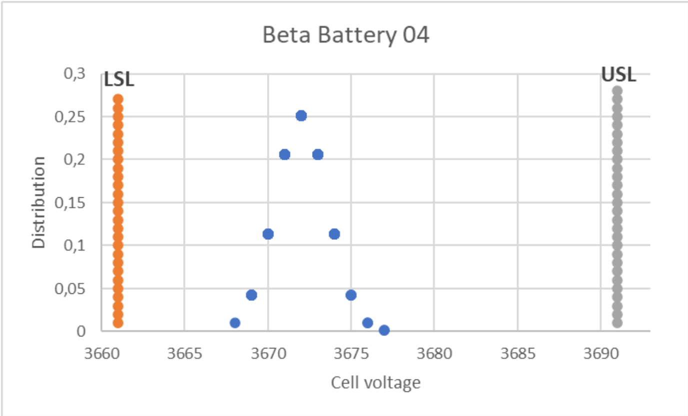
$$x \sim N\,(\mu \;=\; 3679.70\;;\;\sigma \;=\; 2.50)$$
$$C_p \;=\; 2$$
$$C_{pk} = \; 1.51$$



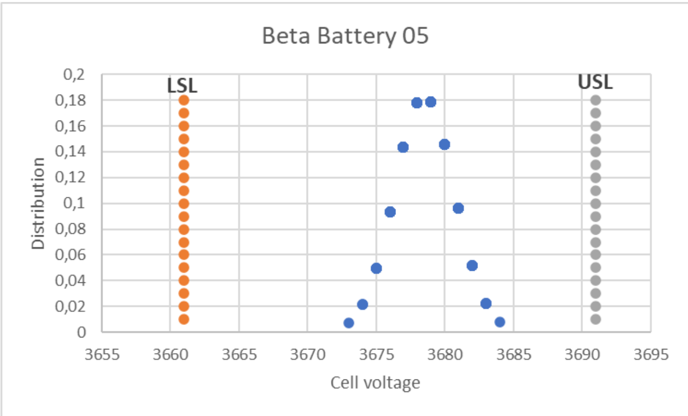
$$x \sim N\,(\mu \;=\; 3681.67\;;\;\sigma \;=\; 1.77)$$
$$C_p \;=\; 2.82$$
$$C_{pk} = \; 1.76$$



$$x \sim N\,(\mu \;=\; 3671.19\;;\;\sigma \;=\; 6.53)$$
$$C_p \;=\; 0.77$$
$$C_{pk} = \; 0.52$$



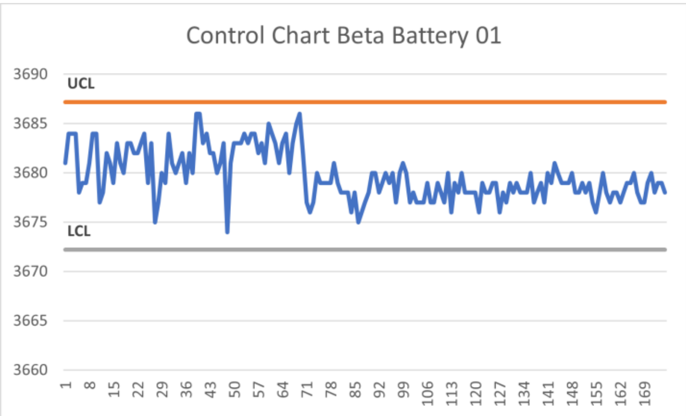
$$x \sim N\,(\mu \;=\; 3672\,;\, \sigma \;=\; 1.59)$$
$$C_p \;=\; 3.15$$
$$C_{pk} = \; 2.31$$



$$x \sim N\,(\mu \;=\; 3678.53\,;\, \sigma \;=\; 2.18)$$
$$C_p \;=\; 2.29$$
$$C_{pk} = \; 1.91$$

Figure 30: Capability Analysis for Beta Battery 1, 2, 3, 4, 5

With the following control charts:



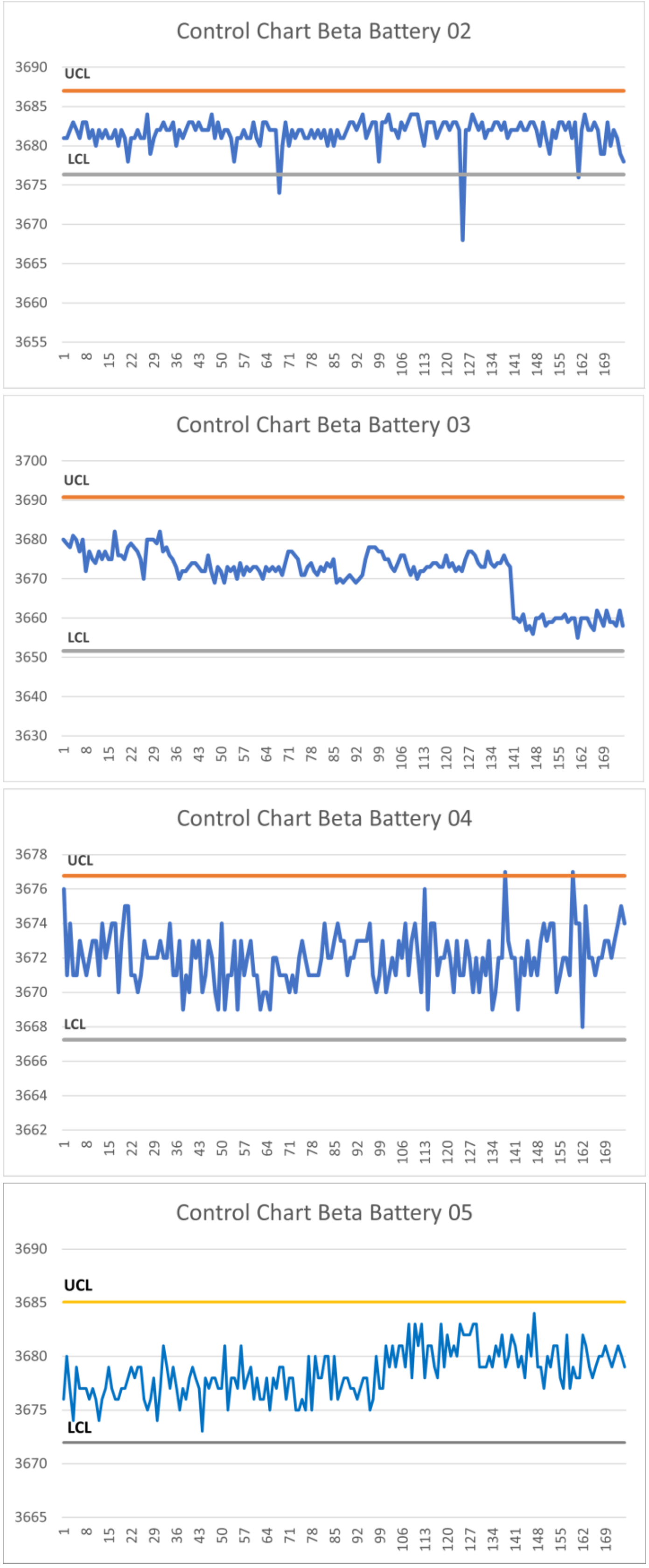
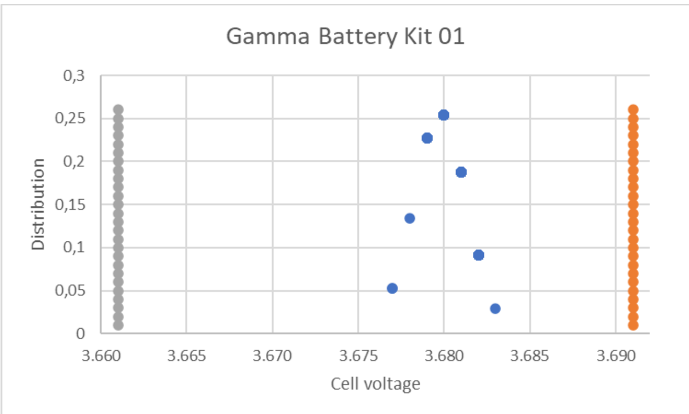


Figure 31: Control Charts Beta Battery 1, 2, 3, 4, 5

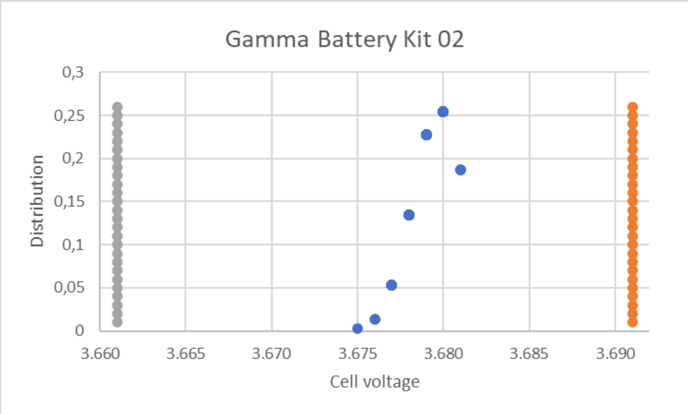
By the analysis of these batteries Beta version, it is evident that the strategy to assembly the modules with similar level of tension, pre-measured by the supplier, is a strategic choice that helps to decrease the level of output to reject and so to increase the production performance of the plant.
Although, the control charts show some problems in the process of these modules. In fact, the values distribution of the process is not fully random and some patterns of cell behaviour inside the module are evident as showed in Beta Battery 03. Moreover, in Beta Battery 02 the module has two spikes that plot the cell values outside the control limits. At this stage of product development (Beta stage) a process not in control yet is admissible with the goal to improve it in the following product development stages.
Given the success of the kitting assembly strategy to keep the process inside specification limits, in accordance with the supplier the quality team decided to use the kitting strategy on Gamma batteries too, until a better solution is found.

4.5.5 Capability of Production Gamma Batteries – Kit Assembly Strategy

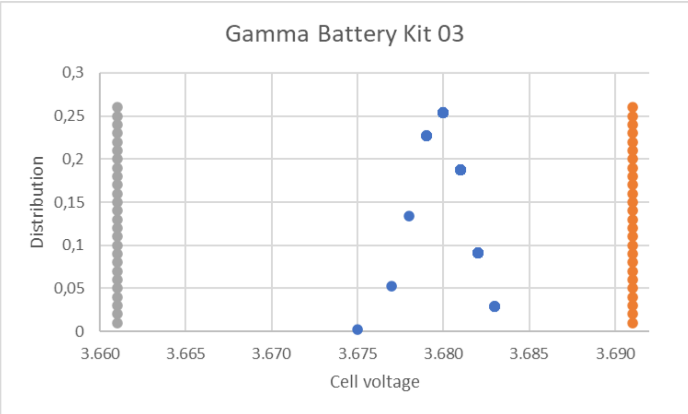
As showed by the results above it is more efficient to assemble five modules, grouped by supplier for their cell voltage level, in order to reduce the delta voltage inside the battery pack.
This decision is supported by the following results of the capability analysis with Kit Assembly Strategy on taking for example four batteries packs:



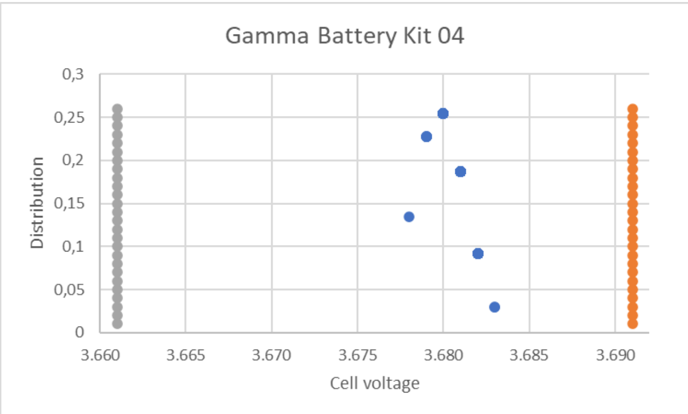
$$x \sim N\,(\mu = 3680\,;\,\sigma = 1.02)$$
$$C_p = 4.88$$
$$C_{pk} = 3.41$$



$$x \sim N\,(\mu = 3679\,;\,\sigma = 0.99)$$
$$C_p = 5.02$$
$$C_{pk} = 3.99$$



$$x \sim N\,(\mu = 3681\,;\,\sigma = 1.1)$$
$$C_p = 4.55$$
$$C_{pk} = 3.14$$



$$x \sim N\,(\mu = 3681\,;\,\sigma = 0.91)$$
$$C_p = 5.51$$
$$C_{pk} = 3.75$$

Figure 32: Capabilty Analysis Gamma Batteries Kit 1, 2, 3, 4

This analysis shows a process within the specification limits and a huge increase in the values of capability ratios. Moreover, the means of cell voltage on different batteries are very similar with a small variability.

With the following control charts:

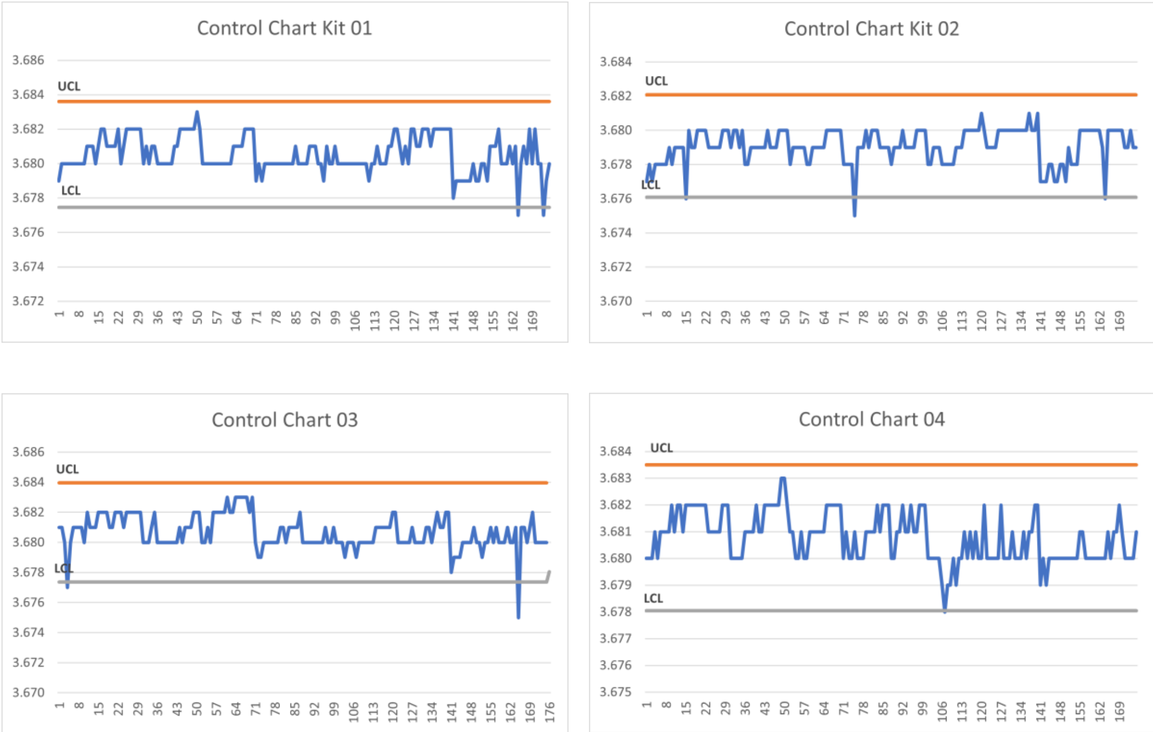


Figure 33: Control Charts Kits Gamma Battery

These control charts show a better distribution of cell values and the processes of each module are more randomly distributed even if there is still the presence of some spikes that fall outside the control limits.

it is reasonable to try to perform a capability analysis on the whole population of Gamma Batteries and study the possibility to came back to a random assembly production given all the logistic challenges to coordinate the warehouse stocks and lead in assembly line with a FIFO logic the modules of the same *kit*.

The whole Gamma Battery population, until now, counts 5075 modules assembled with the kitting strategy. Looking for the capability analysis of the entire population, these are the results:

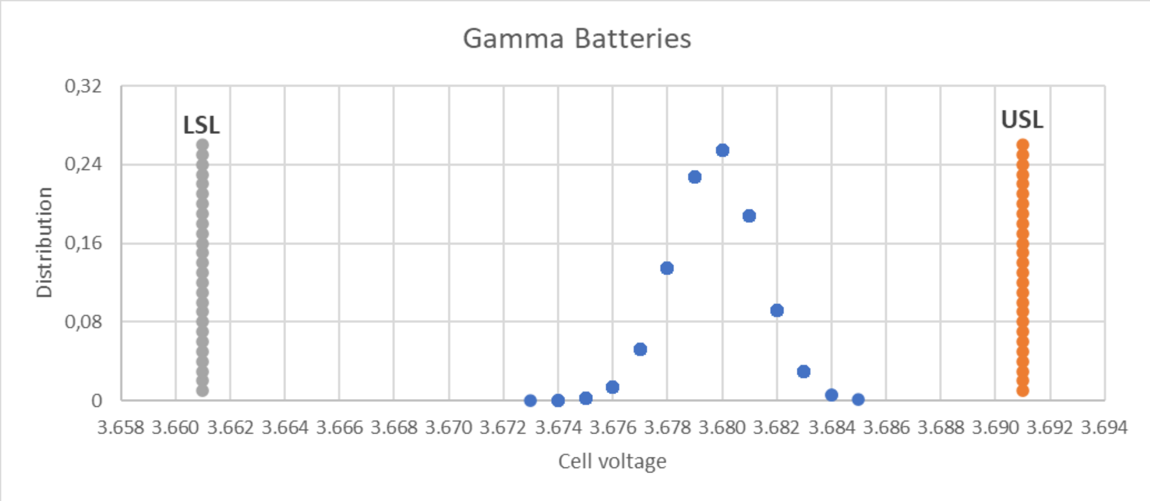


Figure 34: Capability Analysis on whole Population Gamma Batteries after Kitting

$$x \sim N\,(\mu = 3680\,;\,\sigma = 1.55)$$
$$C_p = 3.22$$
$$C_{pk} = 2.41$$

This analysis on Gamma Batteries' population shows that the production is centered and with a low variability. This implies that there has been an improvement of the cells' production by the supplier.

This improvement is showed also by the control chart:

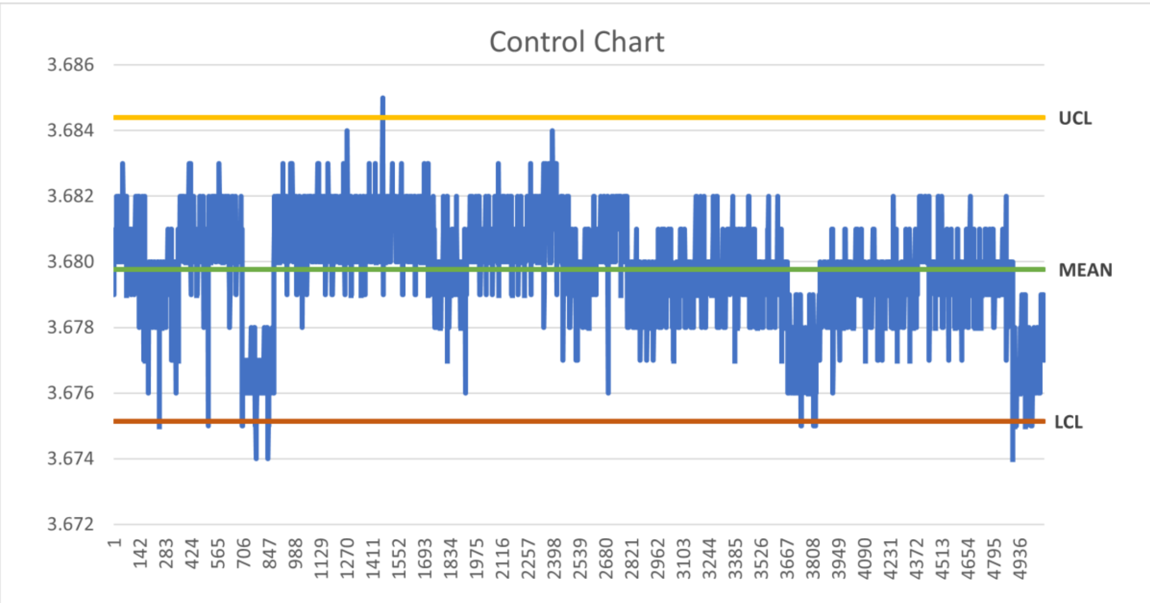


Figure 35: Control Chart entire population Gamma Battery

This capability analyses performed on different production stages and different assembly strategy show as, at this stage, the Gamma Battery production can sustain a random production without the use of any specific assembly strategy. By the study emerges a process in control and inside the specification limits.

4.6 Solution

Whenever there is a major issue that requires a lot of effort from both sides of the production and supply chain, there is a unique and definitive solution, but the problem solving process requires many actors involved and many valuable solutions identified. For each of these solutions a study has been performed to sustain the best option in terms of cost and efficiency.

For this specific case of problem solving, about the poor performances of batteries and therefore vehicles, the 5 WHYs and the ISHIKAWA have been used. These tools help to explore all the possible causes of the issue and to find the root cause of the fault.

To assure that the production keeps going avoiding this specific fault on vehicle an ICA (*Interim Corrective Action)* has been applied in the first place. After many analyses with the collaboration of both quality team and supplier's quality team, a PCA (*Permanent Corrective Action)* has been found too.

4.6.1 Interim Corrective Action

As shown above in the Capability Analysis of the Beta Battery production, to overcome the problem of the unbalancing issue, the assembly *kit strategy* has been implemented also to Gamma Battery production. In this way all the batteries produced are very centered on the mean value of the cells' voltage inside that battery with a low variability.

Nevertheless, applying ICA implies throwbacks in terms of cost and time efficiency:

1. The logistic organization is not easy, given that the modules of the same kit are not delivered in a unique box, but in two different boxes, with three and two modules inside respectively. This can lead to an overcost of the logistic to allocate more resources to manage this additional task, or worse, the out of stocks in the buffer area in assembly line.
2. A higher rate of modules discarded, because whenever a module is outside the specified limit of delta voltage there are other four modules

that comply to these limits, but they are an incomplete kit, so they will be rejected too for one missing module for the kit.

These two major problems that come from the ICA are not sustainable on the long term, so it is necessary to find a more valuable solution that does not include any collateral effects for the production and for the plant. This long-term solution is called PCA.

4.6.2 Permanent Corrective Action

According to the battery production data a more valuable solution has been found working in synergy with the supplier's quality team to evaluate the best option to optimize the product quality and to reduce the most as possible the discarded modules.

This solution is to improve the supplier modules production, in particular the *Capacity Test.*

The capacity test in the production of lithium-ion batteries is a crucial quality control step that measures the battery's ability to store and deliver power. It involves fully charging the battery, then discharging it to its lower voltage limit while monitoring the total energy output. This process ensures that each battery meets or exceeds the manufacturer's specified capacity. The test helps in identifying any cells with poor performance or defects, ensuring that only batteries with optimal capacity reach the market. This is vital for maintaining the reliability and performance of lithium-ion batteries in various applications [42].

Moving the *Capacity Test* from module level to cell level makes the process more reactive to detect the cells that do not comply with specified capacity by drawings. Keeping this test at module level helps to reject the modules with poor capacity performance, but it is not able to detect the cells in self-discharge, that with the pass of time will lead the module to a higher delta voltage level.

This change in capacity test started together with the kitting assembly strategy for Gamma Batteries. From the *Capability Analysis* of the entire population of Gamma Batteries, it is evident that the all the cells are quite similar with a centered and low variable dispersion. The reasons for which the ICA and the PCA have started simultaneously are different. In the first place the ICA assures to satisfy the battery demand, then, with the ICA the quality team collects enough data to support the root cause analysis and the permanent solution.

5 Conclusion

This thesis ends after a long journey highlighting the importance of the Quality in a production system, in a delicate context such as automotive sector for Electric Vehicles that needs to deal with delicate chemicals that might lead to insulation fault or to a thermal runaway. Given this context and consideration is very important to manage the quality along the whole production process, from supplier to Customer.

The first part of the thesis focuses on the presence of FPT Industrial in the world, how it is structured and its gamma of products. The host company has a rich history of 150 years being one of the top players in the market of automotive making the know-how one of its points of strength. The historical plant of Turin is also one of the most innovative which is located the ePowertrain plant where are produced front and rear eAxles, eTransferboxes, and different types of battery packs. In this way the company can reach the Customer needs towards a market that goes in a neutral carbonization context with a development of EVs.

Among the portfolio of products, the one of which this thesis operates is the battery pack eBS 69. It is a lithium NMC technology battery with nominal energy of 69.3 kWh and nominal voltage 647,5 V.

A deep dive is made in how FPT manages the quality and deals with failure resolution and the quality is a stringent parameter in the production process. Most of the internal standards rely on the of two main groups of standards, the ISO 9001 and the IATF 16949. By these intentional documents, that operate in the context of quality and automotive, the company has written the procedure that regulates how to manage a high quality standard. In the context of tools and method for quality assurance and failure management there is the FPI.IFP001 procedure, one of the most important procedures to implement a problem solving analysis and implement a continuous operation improvement by applying the Deming Cycle that is an iterative methodology divided in four stages (Plan, Do, Check, Act).

All the quality standards need to be satisfied in the whole production process alongside all the stages of the development of the product and for this activity the main procedure is the FPI.PLI002. To reach Customer requirements a new product needs to go through six different stages of approval, called

Management Review (MR), and in each of them a certain risk evaluation to pass at the next stages needs to be declared. To achieve the last step of the Management Review all the deliverables' statuses should be aligned with FDP's expectations, all the requirements met, and lessons learned applied for implementation in future development program. The MRs are useful to manage all the different kinds of issue that might happen during the development of a new product and allow to build the product prototype in its Alfa stage to the Pilot stage in which the product can be sold.

Not all the problem-solving techniques are the same and not all the faults have the same impact on the product, but the FPI.IFP100, an inter-functional procedure, is an internal protocol that describes a systematic approach to manage the failures and solve them, in order to fulfill successfully fulfill the Deming Cycle and sustain a Kaizen approach. This procedure emphasizes the main steps to analyze a fault, study a root cause and define a solution to implement as a corrective action, not only for that specific fault, but also for future production and product development. These steps involve the creation of inter-functional teams with many actors for the resolution. To effectively find the resolution. The main activities start with the identification of the Non Conformity (NC) and the implementation of a containment action not to expand the fault on the other products; then an important study of root cause is implemented with the cross-functional team and the failure is classified based on its severity impact on the vehicle. After many evaluations with both Customer and supplier an effective solution is implemented. In many cases, if the issue has a huge impact on the product or the process, the solution needs to be monitored and some analyses must be performed to support the decision taken. The overall problem solving activity is well described in seven steps that start with the description of the phenomena and with the implementation of the new strategy that prevents recurrence of the issue with a PCA, also by modifying source documentation such as DFMEA and PFMEA. The core of this analysis relies on exploring the root cause of the problem and understanding the real origin of the fault. Many tools that help to elaborate the root cause exist, the most useful are the Ishikawa diagram and 5 WHYs technique. Both are cause-effect tools which help to understand the cause of the issue starting from the fault itself.

For the specific fault elaborated in this thesis project all the discussed procedures and tools have been used to solve the issue claimed by Customer.

In particular, a fault of unbalanced cells inside the same battery over the specification limits by design has been observed. The only type of battery affected by this NC was the eBS69 battery pack, the one that will be mounted on buses, so there is a main focus on this specific product. To perform the study with all the information needed it is important to make an overview on how the product is composed, which are the production process, phases and all the parameters to take in account for the correct functioning of the product. The main concepts to keep in mind, in order to explore the possible root cause are the State Of Charge (SOC), the State Of Health, charge/discharge rates and the voltage behavior, and the storage conditions.

This case study shows how to manage an important failure on battery. The first step, as described by the procedure, is to understand the issue and how it affects the performance on vehicle. Then it is also important to apply a containment action to assure that the production keeps going. In the case of unbalancing cell voltage inside the battery pack, the best option to delivery all the batteries is to apply the right balancing strategy on vehicle (Passive balancing) that will not deteriorate the battery life. Unfortunately, not all the batteries could be balanced, after further investigation two different kind of unbalancing have been distinguished: one reversible that can be recovered, and the other one irreversible due to a self-discharge of the cell itself. The main tools used to perform the analysis and to reach the root cause of the problem are the Ishikawa and the 5 WHYs techniques for both Reversible and Irreversible issues, these tools are useful to fully understand the problem and to explore all the possible causes.

A work of Capability Analysis has been performed to support the root cause exploration and to evaluate which could be the optimal corrective action. This analysis evaluates the capability of the process to produce the same battery on big volumes inside the specification cell voltage level. As shown the main issue relies in the production of the cells, that are the fundamental units of the battery, because the complex chemistry makes it difficult to keep the process in control. For this reason, the Beta battery production seems to be more stable than the Gamma battery production, even if it is a more advanced stage of product development. The reason behind this unintuitive discovery is that the supplier applies more stringent controls on the cells production of Beta batteries have. Although, the control charts show a cell process with some trends or with spike out of control limits. In particular, some cell levels are below the lower control limit.

After many evaluations by the cross-functional team with the supplier the solution to improve the supplier's cells production process has been found by simply moving the Capacity test from the module level to the cell level, in this way, even in case of cell in self-discharge, all the cells will reach the same level of voltage.

The achievement of the PCA is supported by the capability analyses and by the control charts, especially in gamma battery stage. By the capability analyses we can see if the process is inside specification limits evaluating the position of the mean values compared to the target value and the variability of the processes using the two indices C_P and C_{pk}. By the control charts, instead, we can see if the process is in statistical control. The results of these analyses describes that now the process on gamma batteries has been improved by the supplier. The optimal solution, to implement as PCA, has been identified in order to solve the fault of the unbalancing cell voltage issue.

In conclusion this thesis is a comprehensive work in the Quality field, which describes how to deal with fault on product and more specifically how FPT sustains a high-quality standard in the automotive industry. The Quality world is still an open problem which has to deal always with new issues, for this reason a fundamental structure to develop an adequate Problem solving is necessary to find the right solution specially in dynamic sectors such as the automotive field, and this work gives an example on how to manage failures in an environment with a large room of improvement as the EVs.

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