MINISTRY OF EDUCATION
University POLITEHNICA of Bucharest
Doctoral School of
Industrial Engineering and Robotics

Dina E. DIGA (BANTEA)

DOCTORAL THESIS

Contributions on Problem Solving Process Optimization in the Automotive Industry applied on Door Panels subjected to Accelerated Life Tests using Six Sigma and 8D Approach

SUMMARY

PhD supervisor,
Prof.dr.eng. Irina SEVERIN (UPB)

- 2022 -

Content

List of abbreviations

N°.	Abbrev.	Significance
01	AET	Accelerated Environmental Testing
02	AHAT	Accelerated Heat Aging Testing
03	ALT	Accelerated Life Testing
04	CAD	Computer-aided Design
05	CDF	Cumulative Distribution Function
06	DMAIC	Define, Measure, Analyse, Improve, Control
07	FMEA	Failure Modes and Effects Analysis
08	ICA	Interim Containment Action
09	KLT	Key Life Test
10	KPI	Key Performance Indicators
11	LH	Left Hand
12	LSL	Lower Specification Limit
13	MIS	Mileage in Service
14	PCA	Permanent Corrective Action
15	PLC	Programme Logic Controller
16	PPS	Practical Problem Solving
17	RH	Right Hand
18	SIPOC	Suppliers, Inputs, Process, Outputs, Customers
19	SPD	Standard Problem Definition
20	TIS	Time in Service
21	TQM	Total Quality Management
22	USL	Upper Specification Limit
23	8D	8 Disciplines of problem solving

Preface

The doctoral thesis was written during my experience as a Lead Test Engineer in a testing laboratory of mechanical components and subsystems, within a company in the automotive field, having the responsibility of managing project development activities and physical testing of components on the vehicle body. I gained valuable experience working with the physical testing of various components and subsystems and strengthened my project management skills and deepened my knowledge of quality processes. The doctoral agenda contains the preparation, presentation and support of scientific examinations and reports, further study, proposal and optimization of the development of the automatic problem-solving process in the application of door panels subjected to accelerated life tests using the Six Sigma and 8D approaches.

The research and development of this thesis aims to address the issues of Six Sigma and 8D literature in identifying and analysing problems in the automotive field, optimizing the problem-solving process by developing flow charts; aiming to develop a new concept for accelerated testing of life and durability with application to vehicle door panels. This research paper presents results from two aspects taken into account. A first concern of the paper is related to the need for Six Sigma in organizations and the estimation of the success and progress of automotive companies due to the implementation of Six Sigma. This is achieved by conducting a detailed analysis of the applicability of Six Sigma in industrial engineering over time and the different chairman's view on the benefits and criticism of its implementation. The results obtained by analysing specialized books, scientific papers and published articles, indicate that the approach has been implemented largely in industrial fields and is among the most successful and progressive. The second aspect presented in the paper is related to the development of a new vision in detecting, analysing, and solving problems that arise during the process of development and industrialization in the automotive field using the methodology of the theory based on Six Sigma and 8D. The results of my Quality studies, were published in UPB Scientific Bulletin, AHFE Conference 2021 and MDPI Sustainability 2021.

The paper focuses on the success factors that contribute to the problem-solving process and follows 8D steps in developing a robust assessment of the identified problem of door handles malfunction at low temperature and evaluating the side door system by performing three life acceleration tests. The entire testing process and related methodology is presented in the paper in the form of a case study, there are 8 case studies for this study. The analysis of the data obtained following the tests of ALT - KLT, AET and AHAT have the role to investigate the root cause of the problems appeared, the door components being subjected to extreme high and low temperatures. The data are presented in tabular form and valuable information in graphical form using the Minitab Statistical software and Six Sigma tools. All process flows and mapping default behaviours are being developed by Axure RP 10. The results of my Testing studies, were published in 36th IBIMA Conference and IBIMA JIBBP 2021.

I would like to express my sincere thanks to the PhD supervisor, Prof. PhD. Eng. Irina Severin who offered me all the necessary support with kindness and understanding and made a valuable contribution to my professional development.
The conclusions of my research on metrology were disseminated within the project BeAntreprenor! I would like to thanks Prof. Mihaela Ulmeanu for the support provided during the project.
Thank you to everyone in the family for being so supportive during my doctoral studies, as well to my friends who supported me during this period.

Chapter I. The research background of the Doctoral Thesis

1.1. Research Background

The need for technology and quality at the highest level has become indispensable. We are in a continuous movement in terms of evolution and each movement requires a well-thought-out analysis and statistics. The engineering and automotive industries have become one of the most highly valued industries in the world, the requirements being so diverse and wide. Customers have very high expectations, starting from technology, aesthetics, digitization and of course quality at the best price. In order to satisfy the clients' needs, the engineering ensures at each stage of the project the transparency and trust of the well-done work throughout it. The paper aims to show a clear and transparent Six Sigma approach and its usefulness in detesting and solving engineering problems. Operational management and process optimization aim to streamline working and quality methods, improve industrial processes and components, operational and productive safety, satisfaction of employees and customers of the company. The purpose of the research is to survey the concepts and techniques of using knowledge in the Six Sigma implementation process, as well as how knowledge management concepts could be integrated into a Six Sigma structure for the implementation of a forecast in the development process and industrialization of products in the automotive industry.

1.2. Research Objective

The general objective of the thesis is to present a new approach regarding the use of Six Sigma and 8D in solving the problems that appear during the process, in the automotive field. The thesis proposes to address the following aspects: literature review and synthesis of the current study of research on Six Sigma in the automotive field; six Sigma and 8D approach and the process of solving the problems approached in engineering; following the 8D approach for evaluating the problems appeared on the side doors systems; presentation of door testing methods and analysis of results; validation of results and proposals for process improvement and optimization.

1.3. Purpose of this Thesis

The doctoral thesis aims to develop an original study, with potential in studies and research on defect detection following accelerated life testing of components on door systems. The research study follows the methodology of the eight stages in solving the issues, starting by identifying the issue: "Driver door malfunctions in low or freezing temperature conditions - door lock not working at low temperatures" and following the entire process of definition, analysis and validation. The study is based on a number of tools such as the Deming cycle, the Pareto chart, the Ishikawa Diagram and Failure mode and effects analysis. It also uses a series of flow charts to define processes and test methodologies to identify root causes.

1.4. Thesis structure

The thesis is divided into nine chapters, which include an introduction to the thesis, a review of the Six Sigma literature and its implementation in the automotive field, current presentation of Six Sigma status, research literature, reviews of accelerated life test results and case studies, interpretation of results and validation and, in conclusion are discussed, the implications, limitations and future research steps.

Conclusions of the PhD Thesis

Chapter I of the thesis begins with the introduction of this research paper and the presentation of the problem in the study, the purpose of the research, the theoretical bases, the importance of the study, the research methodology and hypotheses regarding the present research, research conclusions and limitations.

Chapter II includes an examination of the Six Sigma literature backgrounds and an evaluation by academics and practitioners. The vision that literature has about Six Sigma and its impact on new challenges. A number of criticisms and benefits are listed, along with publications that justify the need for revision.

Chapter III is assigned the methodology for presenting Six Sigma, the roles, processes and levels that certify the performance in use. The customer voice has an essential role, together with the tools used to achieve his level of satisfaction. The chapter presents the System Requirements methodology focused on engineering practices, which has the role of staging the process.

Chapter IV shows the problem-solving process and the research involved in providing possible solutions. Research methodology and analysis of failure mode, Tool framework, Suppliers, Inputs, Process, Outputs, Customers (SIPOC) process with process inputs and outputs, Define, Measure, Analyse, Improve, Control (DMAIC) framework and process flow chart on problem solving. At the same time, similarities are presented between the essential tools for managing and tracking the problem.

Chapter V presents the methodology for developing and researching accelerated life tests such as Durability Key Life Test (KLT), Accelerated Environmental Testing (AET), Accelerated Heat Aging Testing (AHAT). The test methodology presents the Accelerated Life Testing (ALT) test conditions, Environmental effects and reliability, the ALT objectives regarding the door systems, the experimental procedure and the working procedure according to the standards, the equipment and facilities allocated for testing and measurement and the types of measurements related to the tests.

Chapter VI addresses the 8 Disciplines of problem solving (8D) approach in validating the study on "Driver door malfunctions in low or freezing temperature conditions - door lock not working at low temperatures". The case study follows the 8D steps in defining the problem, analysing the root cause and validating the possible solution. The actions undertaken in this chapter have the role of presenting essential data that have led to the degradation of the vehicle door functionality. The study includes practices in analysis and quality tools such as Plan-Do-Check-Act (PDCA), Standard Problem Definition (SPD), Ishikawa, Pareto and graphical representation of results.

Chapter VII validates the test results stated in the previous chapters. The test methodology presents the test method of each test according to the working procedure. Following each test, a series of measurements and their interpretation are presented. The KLT presents experimental setup and measurements of: Hinge and Check arm, Latch and Striker Torque, Door gaps and Flushness, Door drop, Latch and Striker - Engagement and release load. The AET shows the experimental setup and measurements of the interior door panel gaps. The AHAT shows experimental setup, Arrhenius and Weibull Distribution. Module plate gap measurements can be found in the analysis part.

Chapter VIII presents the results obtained and represented by performance indicators, validation of qualitative and quantitative results in a product quality plan, prevention and analysis of defects using FMEA. Team recognition based on results and productivity level.

Chapter IX concludes the contributions and final conclusions regarding the case study and research of the paper. The contributions of the paper are: presentation of Six Sigma background through a study of identifying and finding events, chairman's and benefits that have participated over the years through continuous development and improvement; the new approach of presenting the 8D analysis method in solving problems by developing flow charts and optimizing the process; a new overview of development and research of the Accelerated Life Test Door panels methods; interpretation of results by using the Minitab graphic representation software.

Chapter II. Research Literature review of Six Sigma Background

In this section, an assessment of the literature covering a period of thirty years (1991-2021) describing visions, sources and discoveries. It aims to summarize the essential literature with an emphasis on rooting Six Sigma in automotive corporations. The subject of Six Sigma is notorious and not many critics, over time have had only good words. However, the very large number of articles published on this subject and its reinterpretation, once again certifies its academic veracity.

2.1. Six Sigma literature review

The application of six-sigma is a technique of approaching statistics, based on the objective of specialized institutions to prevent misuse and to participate in improving performance by using techniques promoted by academics and analysts. From the literary databases, literary contributions were extracted, most of them being documented from specialized articles [M01] and from the considerable attention received in the public press in time. The authors of the Six Sigma literature strongly believe that critiques will help academics and practitioners to understand some essential margins in the implementation of Six Sigma as a business improvement strategy [M19]. It was reported in 2010 in the Wall Street Journal that 60% of Six Sigma projects failed [S07]. Much higher education institutions have not adopted Six Sigma due to unavailability of information and data management, unavailability of knowledge about the contribution and benefits of the institution's methodology and lack of cultural adherence to novelty and innovation [J02].

2.1.1. Key criticisms of Six Sigma

Academics and practitioners, in their articles, PhD theses and books have criticized the Six Sigma approach**,** in various industries. There is lesser-known information that Six Sigma can be used as an approach to strategic change and it can be applied in other industrial fields [R08]. A review of the state of the art in the six-sigma literature associated with the paper presents a number of ten critiques identified in the scientific papers of twelve academics and literary critics. Any criticism brought to the present subject, makes a notification of the need for improvement and optimization in the six-sigma approach.

2.1.2. Benefits of Six Sigma

By implementing the concept of quality, many companies have managed to obtain positive financial results and it is desired to focus on how to streamline the company's strategy [C03]. Cultural changes need time and commitment before they can be firmly established in the organization [Y01].
Six Sigma programs are expanding into corporations around the world, with substantial results and massive savings in billions. Six Sigma has supporters as well as critics; some claim that it is nothing innovative, and others conclude that it is revolutionary [A03]. The organizational point of view is to support Six Sigma as a methodology in Total Quality Management (TQM), representing a mixture of previous and current tools, referring to that Six Sigma tools are similar and related more strategically than is usually indicated by the historical use of these tools [A06].

Six Sigma Background

The Engineering team-oriented approach to Six Sigma techniques has proven to maximize efficiency and dramatically improve profitability for automotive companies around the world. The information obtained through the intensive review of the literature is used as a basis by which essential features of the research are stated. As long as the six-sigma background will be known and its principle, the Six Sigma level of performance will be understood in the industrial field over time. Six Sigma Background are briefly presented from 1911s, during the industrial, technological, socio-economic and cultural revolution - to the present day, when in 1995 J. Welsh, applied the Six Sigma methods.

Conclusions and contributions

The following key points can be concluded from the literature review:

- The literature cites Six Sigma as a systematic improvement of organizational processes;
- For Six Sigma to be successful, the selection of techniques and tools is very important at every stage of the project;
- The most important factors in organizing the automotive process are management's commitment to managing deliverables and performance indicators, focusing on customer satisfaction, selecting and prioritizing activities according to customer expectations and requirements, changing organizational culture and institutional policies;
- Criticisms of Six Sigma techniques have had a beneficial impact on continuous improvement and have raised awareness of some points that need to be reviewed;
- The Six Sigma key performance indicators in organizations are financial benefit, reduction of variation, time to delivery, quality of production and customer satisfaction;
- Six Sigma techniques during implementation, by collecting data on the industries concerned, the accuracy and integrated nature of the data can prevent considerable problems that occur during this cycle.

The original contributions of this chapter can be listed in the following types:

a) **Theoretical Contribution**: The findings of the literature review offer an overview of Six Sigma techniques in Industrial Engineering, criticisms, benefits, and limitations.
b) **Methodological Contribution**: The findings can provide guidelines to other future research on the methodology of Six Sigma background. Studies, scientific papers, articles and books provide invaluable information that will be helpful for the future studies.
c) **Empirical Contribution**: Offers a historical analysis based on evidence and good practices in the industrial and educational field.
d) **Data Collection Contribution**: Critical evaluation of data sources: researcher works and case studies.

Chapter III. Six Sigma Research Methodology in the Automotive field

The research study supplies an elaborate presentation of practices and processes for solving problems in the automotive field, the company produces plastic components for subassemblies and assemblies on vehicle doors. These techniques are implemented as basic of a robust program in door systems engineering analysis and failure mode avoidance. The work presents the principle of two major theoretical perspectives of problems and solving them, namely the methodological technique focused on process excellence in engineering and the robust approach in systemic analysis engineering.

System Engineering Methodology

The destination of engineering systems is to combine the interactional elements to achieve the objectives proposed within the team, respectively in the company. Products and processes are declared systems that provide results according to standardized provisions (ISO 15288:2015) [***09]. System Engineering is a multidisciplinary manner of business and technical aspects to designing and building successful complex products [D03]. The system defines the needs of customers and the functionality required at the beginning of the development cycle. Creates a structured methodology that goes from concept to manufacturing and maintenance underpinned by fully traceable documentation. Functional requirements are function of the system, which define what to do, not how it is done or how well it is done. This typically include internal function and Input / Output requirements with the system interface.

Six Sigma Methodologies

The idea of innovation is approached by a large number of companies that concentrate on improving their internal processes taking into account the background of the past ones, on increasing the value of the business, plus the benefit of seeing their customers extremely satisfied with the products they offer. Six Sigma, a relatively well-known approach to achieving excellent, high-performance results can help multinational executives discover new opportunities for innovation beyond simple operations, achieve high productivity, sound financial performance and an inherent in innovation [A07, R09].

3.1. Six Sigma Roles

Six Sigma has an established and well proven track record during the time. Since it was first introduced, the Yellow Belt, Green Belt and Black Belt practitioners have been applying statistical tools and techniques to drive sustainable improvements into company products and business processes. Enabling and sustaining Six Sigma deployment requires this population of dedicated 'Belts' who are tasked with facilitation problem solving activities.

3.2. Voice of the Customer

The customer's voice requires special attention, in terms of the process and response to its requirements. In response to its needs, Six Sigma helps engineering go through the entire process to recognize and resolve problems that arise throughout the life of the product and provide a guarantee of the best quality product. The customer's voice is the limits of the customer's specifications. The limits of the specifications are different from the control limits, which are calculated according to the control diagram [A01].

3.3. Process Roadmap

Project toolbox includes a series of design tools, statistics, Lean approach, customer requirements tools, quality control and management tools. All these tools have the role of supporting the project at every stage in development [F02]. The project process includes steps and activities that are followed within the company or at external suppliers, both must go in sequential to have results.

3.4. Optimize Quality to Gain Customer Loyalty

Ways to increase customer loyalty are based on the fact that customer service is a priority, in this way the company shows how much it appreciates customers. The best way to get customers to come back is to reward them for their loyalty by giving them all the support and answers to their needs. Focusing on customer feedback on product use can make the process easier to understand. Considering the efficiency of the process, so that customers can respond in turn to the company's needs. Customer loyalty is essential for a stable business.

3.5. Six Sigma process mean

The characteristics of projects and processes can be analysed, measured, optimized and managed. The entire organization must be involved in optimizing and improving quality, especially the managerial part - leadership [J12]. The Six Sigma is a continuous improvement for engineering techniques. The approach is to simplify the organisations processes. Predictable performance control and manage the simple processes than complex processes using standard methods. Six Sigma optimal improvement and gradual improvement have a very close connection, the difference being in the times allocated to the process which is reflected in years and improvement quota.

3.6. Levels of Six Sigma

Six Sigma aims to streamline the effort to improve and be effective at the same time at all levels. For the Six Sigma satisfaction level to be reached, the process must not exceed the index of 3.4 defects per million opportunities [T02]. The limits of the specifications must accurately present the true requirement of the customer [A01, B05]. The level of performance recorded in companies is two or three on the scale levels, which means between 308,538 and 66,807 customer grievances or complains per million customer connections [T02, A03].

3.7. Case study

Process or product Six Sigma level can be calculated using the equation below:

$$\left(\frac{\#\,of\ opportunities - \#\,of\ defects}{\#of\ opportunities}\right) \times 100 = Accuracy \quad (1)$$

The quality department receives monthly complaints from customers. Consider that 150 complaints were received in one month on door side systems. One of the topics is that they have a problem with the door lock not working at low temperature. The problem was reported by 5 customers.

The quality team estimate that 100 vehicles could have issues. The door lock process has 150 opportunities for an issue each month and an estimated 200 defects.

$$\left(\frac{150-100}{150}\right) \times 100 = Accuracy\ of\ \ 33.3\% \qquad (2)$$

DPMO can be calculated using the equation below:

$$DPMO = \frac{D}{N \times O} \times 10^6 \qquad (3)$$

$$DPMO = \frac{150}{100 \times 5} \times 10^6 = 300\,000\ DPMO \qquad (4)$$

Conclusions and contributions

The following key points can be concluded from the research methodology:

- The research methodology presented in this chapter aims to highlight the need for a well-documented and combined engineering system through the interaction of processes within the team and at the same time adapting six sigma to the company's need to meet its customers' expectations;

- The Six Sigma methodology recalls the roles, levels and processes that have contributed and continue to supply to the continuous advancement of products and processes in the automotive industry;
- The information obtained through intensive reading of the literature is used as a basis for stating the essential features of the research, in terms of Yellow Belt, Green Belt and Black Belt techniques; the trials documented by Juran, Taguchi, Deming and Shewhart.

The original contributions of this chapter can be listed in the following types:

a) **Theoretical Contribution**: the findings of the System Engineering and Six Sigma methodology based on the experience gained in the automotive industry, in companies in the country and abroad.
b) **Methodological Contribution**: the findings may contribute to future research on the methodology of Six Sigma. Studies, scientific papers, articles and books provide invaluable information that will be helpful for future studies.
c) **Empirical Contribution**: Defects Per Million Opportunities (DPMO) calculation and representation through Six Sigma capability report.
d) **Data Collection Contribution**: Critical evaluation of data sources: researcher works and case studies.

Similar topics can be found in the published article:

- Dina Diga and Irina Severin., " Bonnet cable defect analysis using Six Sigma DMAIC techniques", UPB Scientific Bulletin, Series D: Mechanical Engineering 43(2):203-214, ISSN 1454-2358, 2021.

Chapter IV. Problem Solving Research based on the Six sigma - 8D - DMAIC methodology

In this paper were analysed only the most relevant tools that ensure effective operations and performance management and help the company to keep control of processes and improve them continuously. The evaluation and control tools that are applied throughout are Six Sigma DMAIC and 8D approach, Root Cause effects, 5 whys, Problem-Solving analysis, Measurement Systems [L01, M16], etc. Improvement tools used: Total Quality Management, Lean Manufacturing, Six Sigma, Excellence models and testing methods, ISO Standards and work procedures [***08], etc. In planning, the most common tools and techniques encountered are Quality Function Deployment, Stakeholder matrix, Affinity diagram, Brainstorming, Benchmarking, Decision tree, etc. The implemented solutions must be evaluated to reveal if it has led to the improvement of the process.

Problem-Solving Methodologies

Studies validate these statements by locating Six Sigma in the literature due to models and competitive strategy. The main importance of the projects is validated by the operational results and the efficiency of the teams. Skills in problem solving organized and efficient decision-making and practices - have the competitive advantage of participating in the company's strategy and its integration as a potential source in optimization [J06]. Methodologies represent the highest levels in terms of thinking and designing problem-solving methods. In this research study, the methodologies have approached a set of techniques and principles in solving existing problems based on a methodological philosophy that focuses on results and achieving the proposed targets.

4.1. Framework

Problem-solving techniques are the most important process approaches in the automotive industry, both in design and in production and sales markets. The management of the problems that appeared during the entire implementation cycle, ensures the simplification and identification of the main causes and the provision of constant and interim results to recurrent non-conformities, by minimizing the non-functional time of the process and the loss of productivity. Problem-solving management can eliminate the reduction of nonconformities. The research paper explains how Six Sigma and DMAIC tools and techniques can be used effectively to make active problem-solving management, with major benefits, efficiency, continuously improved, in all areas of business.

4.2. Problem solving process

The problem-solving focused on the design using an analogy between the 8D approach and the Six Sigma technique, in conjunction with the key methodical tests of the working procedure. A detailed approach to the Six Sigma and 8D problem solving stages, the deliverables for each stage will be known and presented, the process requirement by defining the problems, understanding the current situation, detecting the root cause, implementing the improvement and preventing future recurrence for the problems and the toolkit that provides guidance in the use of tools related to each stage of problem solving.

4.3. The DMAIC Framework

Research in the Six Sigma DMAIC approach (Definition, Measurement, Analysis, Improvement and Control) uses principles of quality management and optimization where each stage of the problem is optimized efficiently, as the process as an entire will work efficiently [A05]. Projects for process improvement - Y=f(x) Cascade: Six-Sigma DMAIC projects are often scoped to deliver process improvement, rather than response to specific reported issues or 'error states'; where project identification for process improvement is undertaken, the Y=f(x) cascade is an important tool for project scoping; a fundamental concept of Six-Sigma methodology:

- "Y" is a function of "X"
- i.e., Output is a function of input…. A transfer functions.

  $Y = f\,(X1, X2, X3...Xn)$

The Y=f(x) cascade approach helps to scope projects to be valuable for the business, aligned to objectives, and deliverable for the project team [***07].

4.4. Six Sigma DMAIC - 8D - PDCA similarities

An analogy of the established results-based methodology is presented by the relationship and traceability of PDCA - Deming, Six Sigma DMAIC, PPS / RCCM and the 8D approach. The DMAIC strategy is to provide the necessary framework to improve the process [B05]. 8D is presented as a standard in the automotive industry, necessary in a structured problem-solving process, used in identifying, correcting and eliminating problems.

Problem-solving Process flow

The process flow outcomes are: Critical consideration of assigning a process designed to solve engineering problems (DMAIC and 8D); appropriate use of quality tools in implementing the processes of improvement and solving engineering problems; selection of projects to be improved and use a well-organized and well-structured problem-solving process; the capacity of the process to reinvent itself following the decisions taken in optimization and the innovative quality tools; process analysis and evaluation are related to the process of solving problems, team efficiency, and results related to the work process [J07]; the success of each project is supported by the involvement of management, organization, resources and monthly or half-yearly reviews [R02].

SIPOC process

The SIPOC outcomes are: Establish the right team and gather the team with daily escalation meeting; Use a robust problem-solving methodology and data evidence; Drive timing safely within the <95-day target that comply with 8D approach; Communicate effectively actions; Determine the Root Cause using the SPD or 8D approach and communicate the results across the business stakeholders.

Conclusions and contributions

The following key points can be concluded from the problem-solving research:

- Six-sigma engineering projects are based on a continuous approach and, in order to be successful, the management of the organization should be convinced that the results will be worth the effort. Without the highest level of support, project leaders will be overwhelmed and give up pressures within the organization. This unpleasant situation can only be prevented if the leadership at the highest level of the organization will lead the process of defining the processes and will monitor the project at regular intervals;
- The paper presents problem-solving process tools, such as Six Sigma DMAIC and 8D Team Oriented Problem Solving, which aim at the detailed analysis of the existing problem, following a series of logical steps to define, analyse, measure and solve them by implementing an efficient framework to prevent recurrence and eliminate nonconformities;
- The process flow aims to be successful in solving problems using the Six Sigma DMAIC approach in tracking the problem, allocating standardized times for each stage and team responsibilities at each stage of the process evolution, at the same time using quality tools and graphically delimiting the flow of assigned activities;
- A SIPOC analysis was used to identify relevant factors in carrying out a project and in improving and optimizing the process.

The original contributions of this chapter can be listed in the following types:

a) **Theoretical Contribution**: The use of quality techniques and tools in research to solve problems in the automotive field.
b) **Methodological Contribution**: The development of a process flow using Six Sigma-DMAIC - 8D methodologies. Studies, scientific papers, articles and books provide invaluable information that will be helpful for the future studies.
c) **Empirical Contribution**: The implementation of the SIPOC process based on the practical experience gained from the position of Quality Leader in the Vehicle department.

d) **Data Collection Contribution**: Quality evaluation of data sources and recommendations for process improvement. To learn using Axure RP 10 software has been necessary and it has allowed the development of all the flow processes in the thesis.

Similar topics can be found in published article:

- Dina Diga and Irina Severin., "Key Life Test Process Optimization Using Six-Sigma Approach", Journal of Innovation & Business Best Practice, Vol. 2021, Article ID 536861, DOI: 10.5171/2021.536861

Chapter V. Accelerated life tests - Research and development methodology applicable to the Door panel

The methodology presents the testing principles and the visions of analysts and practitioners regarding the performance of life tests and their results. Important features in carrying out metrology, testing and optimization activities. By establishing regulations between separate tests and the testing time of the critical components, the project can be maintained in the trajectory. The investigations were carried out following 33 articles of the specialized literature regarding the testing of the life of different products within several industrial branches. The study aims to analyse the results of accelerated life testing methods, in order to continuously and sustainably improve customer satisfaction.

Research testing methodology

The technology is in a continuous development and the optimization of the processes ongoing, the need of consumers remains the same, to have extremely reliable and quality products, so the competitive markets put constrains on automotive makers to deliver better quality and reliable vehicles according in accordance with Accelerated life test standards and procedures. This paper examines the techniques for testing the life durability of physical components and the current simulation model of techniques for validating the performance of materials subjected to climatic conditions and presents the method of applicability over the entire life cycle in the testing process [H01]. The test methodology specifies the performance requirements and test methods for vehicle door system components and door locks. The specified conditions apply to all parties and rear doors and door components falling within the scope.

ALT Benefits:

- By revealing failure modes, you increase the reliability of products and processes.
- Feedback provided on time is very valuable in the design of quantitative tests and is a precursor to a quantitative test [***01].

ALT Disadvantages:

- The reliability of the product under normal conditions of use should not be quantified.
- Reliable products cannot fail within a reasonable time [D01].

The components are subjected to several stress environments, which may include heat shock, electric stress, vibration, thermal cycling, humidity. Each of the actual profiles depending on the type of stress, change rates or exposure to extreme stress must be adapted according to the component that needs to be tested.

The objectives of Accelerated Life Test on Door panel

The Accelerated Life Testing is used to detect durability defects that would occur during normal operating environmental condition, customer usage conditions, for locking door systems controlled by vehicles. The test buck or vehicle must represent a fully built production intent rear end closure system, and comprise of all the following rear end closure components as a minimum but not exclusive to which could be affected by the cycling. The test shall be carried out using the necessary side door system, verified by the test engineer, together with the painted or buck representative vehicle, to assess the durability, fit and operation of the systems. Latch operation check and harnesses must be provided. At the sign off event we need to see full latch operation. The Fig. 5.1. shows the performance of acceleration tests, as listed: Key Life Test, Environmental Test, Heat Ageing Test.

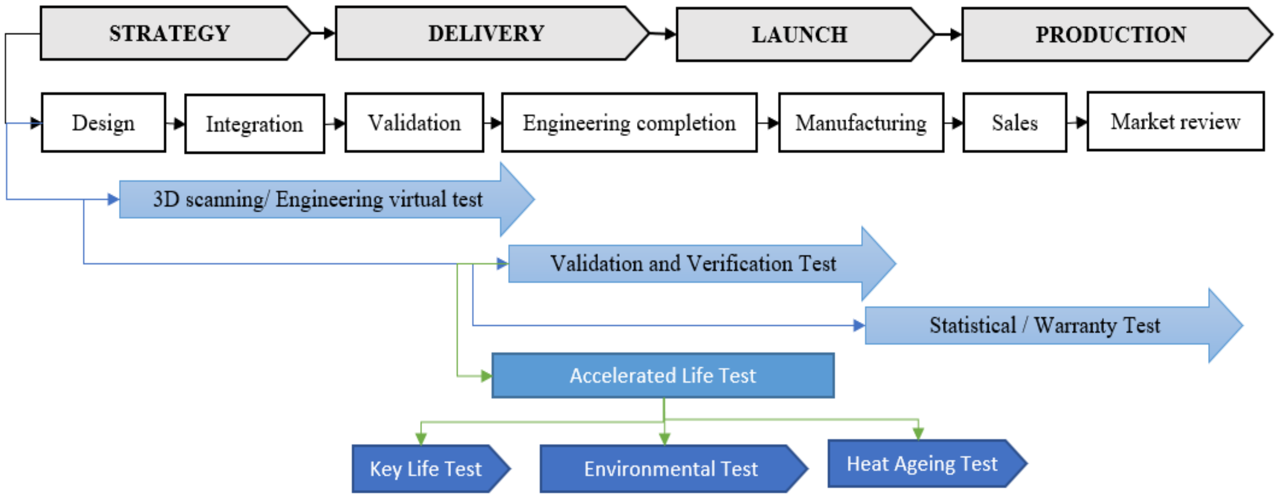


Fig. 5.1 ALT Gateways

Experimental procedure

The experimental testing procedure has four very well detailed phases such as the planning phase, preparation, actual testing and analysis. All phases include everything you need to carry out accelerated life testing and at the same time customize every need in response.

The Acceleration of life test procedures presented in this study include the results gained from the Key Life Test, Environmental Test and Heat Aging Test. Each of these tests follows a series of criteria and properties to generate the best results, as presented:

- **Durability Key Life Test** - the test procedure used to test the durability and functionality of components, under normal environmental conditions or exposed to extreme conditions of temperature and humidity during complete cycles of simulating the life of the vehicle or door components.
- **Environmental Test** - the test process for assessing the performance of materials and components subjected to extreme environmental cycling. The purpose of such a test is to

identify any fit, finish, or functionality issues with the trim as a direct result of exposure to environmental cycling.

- **Heat Aging Test** - this test method is used to validate the performance of the material and components after their long-term exposure to heat in order to assess both the long-term effect on the surface and the structural properties of the door materials and components under the test.

5.1. Related testing standards

The quality characteristic of accuracy is assessed following verification, validation and testing performed in the testing laboratory, according to environmental standards, climate test chambers, applicability of measurements and validated product. Testing standards related to ALT are:

- ISO / IEC 17025:2017 Testing and calibration laboratories
- BS EN 60068-2-6:2008 Environmental testing
- IEC 62506: 2013 Methods for product accelerated testing
- ISO 75-1:2020(en) Plastics - Determination of temperature of deflection under load
- EN ISO 6789-2003 Assembly tools for screws and nuts - Hand torque tools.
- GMW15094:2016 Door System - Slam Durability Test etc.

5.2. Equipment and Facilities

The paper presents a complete range of equipment and tools, the ability to reproduce real-world climatic and environmental conditions for the analysis of vehicle performance and components. The measuring instruments and testing equipment used to perform the tests and measurements are: Force Gauge for measuring engagement and release load, Torque Wrench for measuring hinge and bolts torque, Vernier for measuring distances, Feeler gauge and Gap and step gauge for measuring gap and flushness, PLC used to simulate the door slam.

<u>Test Rig set-up</u>

The test pneumatic rig is designed for durability testing and simulation of the complete performance and strength life of side doors, door handles, door locks, door seals and other assemblies for side doors and side sliding doors of commercial vehicles, according to IEC 62506: 2013. The role of the rig assembly is to perform and measure in real time the door unlocking force, confirming the position signal received from a micro-switch and opening the door. Side door opening force and closing force, closing force and rotation angle of the door, performance curve opening force, unlocking force and electric glass lift during measurement test, rear-view mirror and operating current Door locks are measured with Programme Logic Controller (PLC) Alpha controller. A nominal speed meter was used to identify the minimum shut speed defined by test procedure.

<u>Environmental Chamber</u>

Testing the cyclic temperature of early production vehicles allows customers to determine their performance across the range of markets in which the vehicles will operate. The vehicle's environmental test chambers record various data, such as the temperature of the test components, the panel gaps and the operating efforts of the subsystem.

5.3. Testing approach

The following test measurements were performed:

- **Torque measurements** - the object of the Torque measurements is to ensure that bolted joints under test are assembled, tightened, marked, monitored, checked, and the results recorded and interpreted in accordance with a consistent process and EN ISO 6789:2003 requirements. The objective is to simulate, as far as practicable using a manual assembly method, the actual or proposed production assembly process.
- **Gap and Flushness measurements** - the gap and flush measurements were performed at the beginning of the test and after each temperature cycle. Measurements were performed 5 times and then an average was calculated.
- **Engagement and release load** - load and release measurement represents the testing of the performance of a component or software when used under an expected load.

Conclusions and contributions

The following key points can be concluded from the Accelerated life test methodology:

- The research of the paper presents the gateways and the experimental procedure, together with the related testing standards that meet the requirements of accelerated testing.
- Climate and environmental conditions show in the Equipment and facilities section a complete range of equipment and tools and test facilities used to perform the lifetime test.
- Test measurements approach door panels subject to torque measurements, gap and flushness measurements, operating and coupling efforts and release the load.
- Each of the process steps complies with the door system testing procedure and customer requirements presented in this paper.

The original contributions of this chapter can be listed in the following types:

a) **Theoretical Contribution**: The findings of the literature and processing information based on the experience gained in the accelerated testing laboratory and durability, in the position of Lead Test Engineer.

b) **Methodological Contribution**: The conceptual approach to the testing methodology by standardized follow-up of working procedures and instructions.

c) **Empirical Contribution**: The development of the process flow of the torque measurement method of screws, bolts, fixings etc.

d) **Data Collection Contribution**: Understanding of testing conditions and limitations in line to standards requirements, design of testing procedures for KLT, AET, AHAT; Implementation of testing procedure and proceeding the testing for Door system Durability Key Life Test. Validation of testing results for Door panel components.

Chapter VI. Problem-solving process evaluation on the door panel failures using 8D approach

This chapter presents 8D applicability in the automotive field and the delimitation of the stages to make the process more efficient. Identifies the best variables in the process of managing and collecting data and complaints from the customers. In the first phase, it responds urgently to the customer's request, through an ERA analysis. Using SPD to identify and define the symptom. Once the problem is identified, was used units to measure the degree of failure. Identify and verify the root cause by using Ishikawa, Pareto analysis and graphical evidence based on data collected from customers and dealers. An immediate response was presented from the first phase of the methodology presentation.

8D Case Study

The current study aims to investigate the problem on door panel components and to use a series of quality tools and techniques to determine the main cause of failure. The problem is part of a six-sigma study, conducted in a company in the automotive industry, the company develops and manufactures various components and subsystems for car side doors used for assembling the door system. The customer's requirement for the identified problem is to conduct a detailed study, to analyse and evaluate the problem of the "Driver door malfunctions in low or freezing temperature conditions - door lock not working at low temperatures" using the Six Sigma and 8D approach.

6.1. D0: Emergency response Action

The symptom generates and experiences in terms of an undesirable effect and can be related using the information to specify the gap between the expanded and existential effect. An urgent response action will be developed to protect the customer and run the 8D initiation process. An Internal Audit was performed and the assembly line was stopped for inspection, as shown in Table 6.1.

Table 6.1 Corrective action plan

Immediate action	Root cause corrective action	Preventive (Systemic) root cause corrective action
Batch of components are inspected for the problem but by another worker	Design changed to mandate completion of certain fields	Verification before implementation whenever possible
Defective component replaced with another and retested	Redesign of the component for the variability in production	Design change on the process to test the variations recorded on the supplier's components
100% sorting of components Multiple check for shipment Rework Recalling components in the factory	Pareto analysis - most common causes that occur Organise causes with Cause-and-Effect Diagram Use 5 Why – define the root cause of symptoms	Make sure that the process is followed and does not cause defects
See if the immediate action was successful. Prevent the appearance of a new defect generated by the temporary solution	Eliminate the error and document the effected process or product	Process development to identify the risk. Check the BOM prior to release.
Ensure effective actions are compliant and prevent unwanted effects on the customer until the implementation of permanent actions	Provide viable evidence to solve the problem and prevent it from recurring in the future	Measure the effectiveness of corrective actions

Customer satisfaction	Identify the process that caused the issue – management to address.	Store all documents in system of records, obtain customer feedback and management recognition.

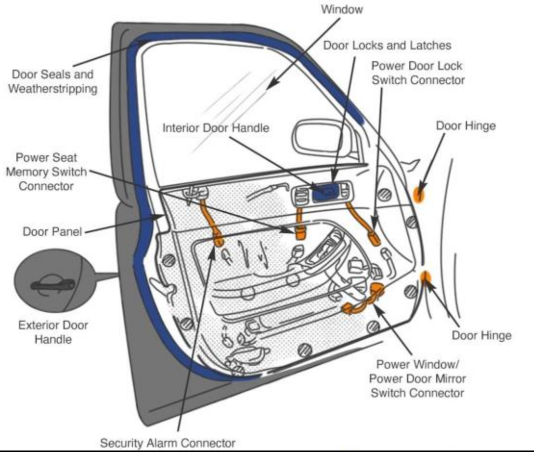
6.2. D1: Use a team approach

The 8D approach needs a disciplined and professionally skilled team to put in the effort and essential knowledge to detect the root cause of the problem. Team members must have extensive knowledge of the development process and tools and techniques needed to solve this problem.

6.3. D2: Describe the Problem

The problem of the door failure was noticed by the customer when he could not open or close the driver's door at low or freezing temperatures of the vehicle (- 4 ^{o}C and below). After unlocking the vehicle, the driver’s door remained locked and it was not possible to open the door neither from outside nor from inside the vehicle, and external door did handle have no tension at all, while it was pulled. The vehicle was driven inside the warm garage. After approximatively 20 minutes front left hand door locking mechanism started working normally.
The issue will be escalated across the 8D approach, with 95 days to identify the main cause and feasible result. The study was assisted by: the Door quality team, Exterior door trim engineers and the Service team in charge of the problems communicated on international markets, as shown in SPD and 5W's method analysis, in Table 6.2.

Table 6.2 Standardised Problem Definition [H03]

<table>
<tr><td rowspan="3">2A</td><td>Problem Definition: Driver door malfunctions in low or freezing temperature conditions.</td><td>Sketch / Photo of Door panel</td></tr>
<tr><td>Symptom:
Customers are unable to open or close the driver’s door when the vehicle low or freezing temperatures (circa -4 ^{o}C and below).</td><td rowspan="2">
</td></tr>
<tr><td>VOC: Door cannot be closed, opened, door handles jammed when it is cold and freezing.

Customer(s): Customer expects to open and close every time with no extra effort (defrosting of door).</td></tr>
<tr><td>2B</td><td>IS</td><td>IS NOT</td></tr>
<tr><td>Who</td><td>Who is affected by the problem?
• LH Drive
• Drivers’ door
• Exterior & interior door handles
• Door handle module
• Latch cable
Who first observed the problem?
• Nurenberg, South East Germany
• Vehicle was parked outside overnight

To whom was the problem reported?
To markets and dealers</td><td>Who is not affected by the problem?
• RHD

Who did not find the problem?
• Other winter climate environments</td></tr>
</table>

What	What type of problem is it? • Door unable to open from inside & door unable to close (not latch) • Water on door module & latch cables What has the problem (part id, lot #s, etc.)? • Yes, All vehicle Do we have physical evidence of the problem? Yes, in all vehicles	What does not have the problem? • Latch position incorrect What could be happening but is not? • The defect occurs in all doors What could be the problem but is not? • Striker position
Why	Why this is a problem (degraded performance)? • This is a problem because the door handles are no longer functional. Is the process stable? • The process is stable but the root cause must be identified	Why is it not a problem? • It can't be a problem for other types of vehicles
Where	Where was the problem observed? • Both interior and exterior door handles • Driver's Door • Water found on latch cables and door handle module Where does the problem occur? • Russia • Winter conditions (circa -4 ^{o}C and below) Customer driving in cold conditions for 4 hours.	Where could the problem be located but is not? • Passenger doors Where else could the problem be located but is not? • Countries reaching temperatures of -4 ^{o}C and below
When	When the problem was first noticed? • Dec 2020 • Winter conditions (Snow & frost) • Temperatures circa -4 ^{o}C and below • 3 – 6 MIS When has it been noticed since? • Vehicles are outside for 4< hours • Winter conditions (circa -4 ^{o}C and below)	When the problem could have been noticed but was not? • Any MIS • Autumn / Spring • Circa -4 ^{o}C and below temperatures
How Many	Quantity of problem (ppm)? • 2 Germany • 1 Russia • 3 vehicles in winter climates (circa -4 ^{o}C and below) • Drivers' door only How much is the problem costing in money, people, & time?	How many could have the problem but don't? • All vehicles • All 4 doors (passenger) How big could the problem be but is not? • All in countries that reach circa -4 ^{o}C and below temperatures
How Often	What is the trend (continuous, random and cyclical)? • Only seen in winter Has the problem occurred previously? • Yes. Exterior door handle not retracting in winter climate environment.	What could the trend be but is not? • Other door usage increase • Colder winter periods

2C	**Problem Description** Drivers' door unable to open with interior or exterior handles. When door opened customer unable to close door (does not latch). **Incident Description:** The vehicle was washed by jet wash without drying on January 3rd and was parked outside since that time. Ambient temperature, when this issue happened, was -3 °C. Most likely, this abnormal driver's door lock operation occurred due to frozen water inside the door locking mechanism.

6.4. D3: Developing Interim Containment Actions

Immediate actions were taken to validate the effectiveness of the steps taken during the planned activities according to the project requirement, as presented in Fig. 6.1.

DONE	ACTION	ASSIGNED TO	DATE ASSIGNED	DATE DUE	PRIORITY	STATUS	% COMPLETE	NOTES
✓	D1-D2 Define the issue - SPD	Quality Team	01/22/21	02/01/21	High	Complete	100%	SPD complete
✓	Establish Team and set dayly meeting	Product integration / Engineering	01/23/21	01/30/21	High	In Progress	90%	Action Items and Gantt planning
✓	D2-D4 Cause and effect diagram and failure mode analysis	Quality Team	02/02/21	03/17/21	High	Complete	100%	Ishikawa analysis complete
	Review altenative corrective action	Quality Team / Engineering	03/17/21	03/21/21	Low	On Hold	80%	
	Select and implement altenative corrective action	Quality Team / Engineering	03/21/21	03/24/21	Medium	Overdue	60%	
	D5 - Analize test report	Quality Team / Test team	05/22/21	05/23/21	Medium	In Progress	30%	
	D6 Raise process and management sign off event	Quality Team / Engineering	05/23/21	05/25/21	Medium	In Progress	50%	
	D7 - Prevent re-occurrence and Raise Forward model AIM	Quality Team / Engineering	05/25/21	05/30/21	Medium	In Progress	50%	
	D8 Recognise the succes and leasson learned	Quality Team / Engineering	05/30/21	06/01/21	Medium	In Progress	40%	

Fig. 6.1 Action Item

6.5. D4: Identifying & Verifying Root Cause

The Fig. 6.2 shows various influences on a process to help identify the most likely causes of problem. Asking 'Why' will identify potential causes, add these details as small branches off major bones. Asking 'Why' 5 times should get to sufficient details.

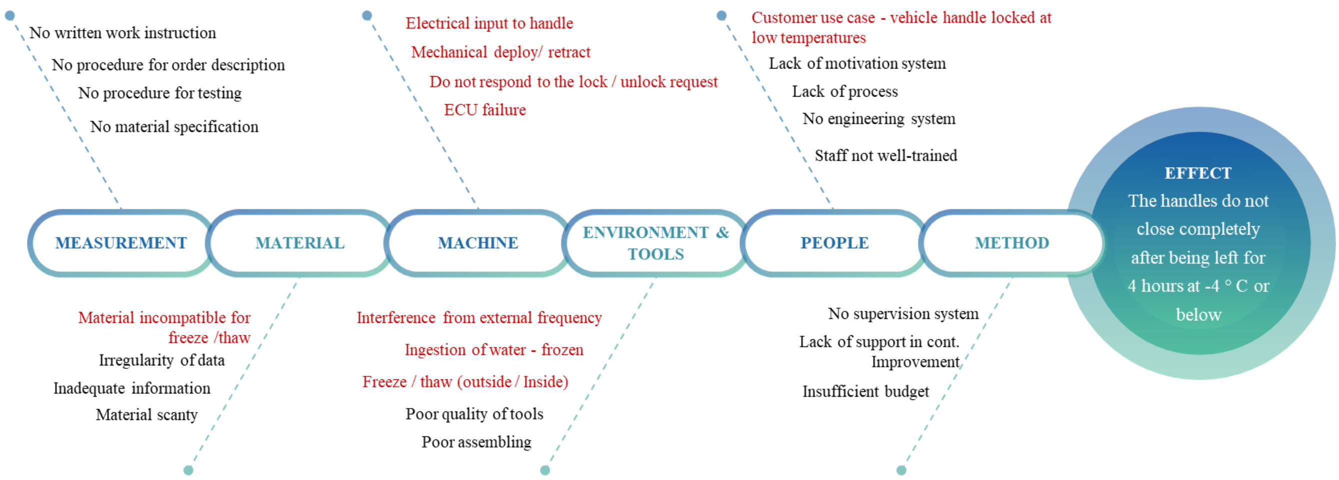


Fig. 6.2 Ishikawa analysis

As presented in the Ishikawa diagram, the biggest influence in generating the problem has the electrical signal - Can analyser and the climatic impact that the component has at cold temperatures below temperatures of -4°C. The component must be subjected to durability and environmental tests in accordance with the requirements of the working procedures for body interior and exterior trim.

Pareto analysis is applied to assess the priorities of development issues, assembly line - production, stock, defects, accidents, etc. Improvement efforts aim at the areas of greatest impact within the company.

Table 6.3 Defective Part / Area

Cause	**Effect**	**Cumulative percentage**
Category/ description	**Count**	
Door lock	58	50.4%
Handle – Door Release	17	65.2%
Drivers Door	16	79.1%
Lever – Door Pull	9	87%
Latch – Door RH	5	91.3%
Latch – Door LH	4	94.8%
Latch cables	4	98.3%
Other	2	100%

The Pareto graph highlights the main source of failure and its effect in percentages, representing the main cause of failure. In this case, the door lock has the greatest impact in the failure of the entire batch of subassemblies, having a number of 58 registered defects, having a high efficiency in causing other defects in the subassemblies and at the level of the entire vehicle.

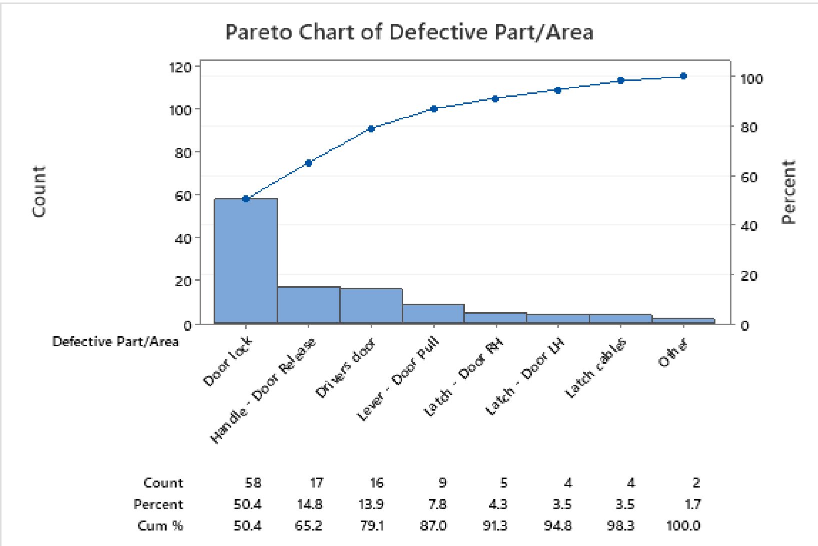


Fig. 6.3 Pareto analysis

Conclusion: the blue line of representation of the Pareto chart shows that (58 + 17) / 99 ≈ 80% of the defective components come from 2 out of 10 = 20% of the defective component types. This is how the Pareto principle is applied.
The histogram in the Fig. 6.4 and Fig. 6.5 shows a detailed record of the time and mileage allotted in service of the vehicle until the problem was detected.

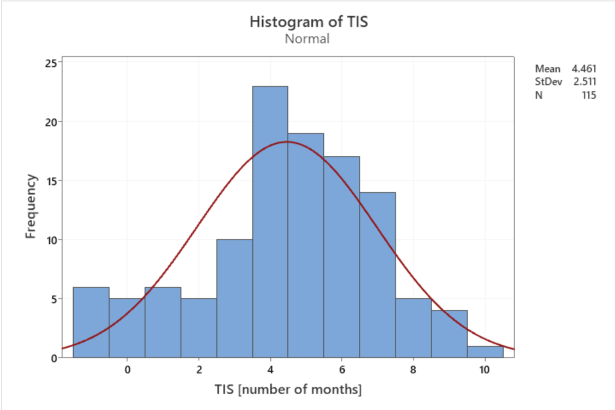


Fig. 6.4 Vehicle Time in Service

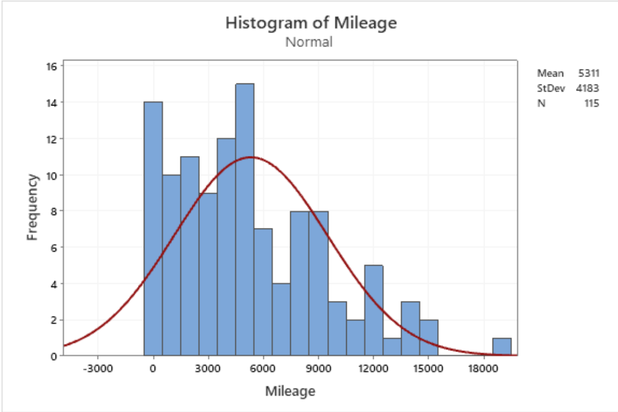


Fig. 6.5 Vehicle Mileage

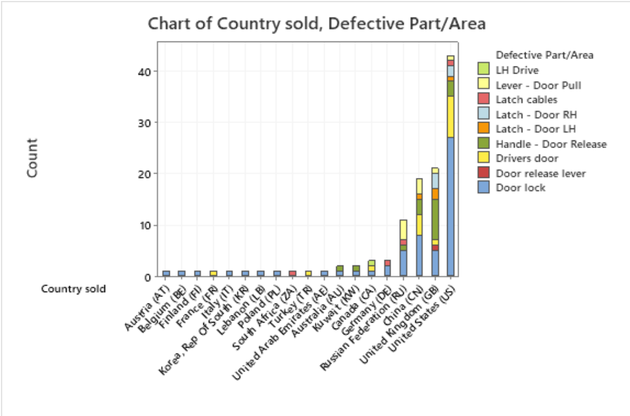


Fig. 6.6 Country sold by defective part

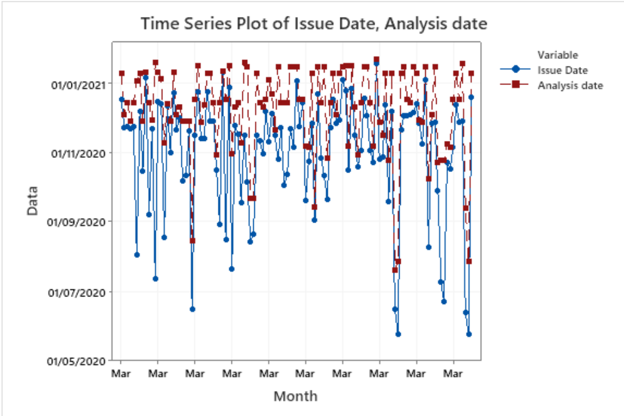


Fig. 6.7 Chart of Time Series Plot of Issues

Each of the possible root causes presented in the histograms in Fig. 6.6 and Fig. 6.7 will be represented by a practical activity in the next chapter to investigate the possible causes. This will be done in experimental terms whenever possible and will illustrate the root cause that led to the degradation and malfunction of the door handle at temperatures below -4 °C.

Conclusions and contributions

The following key points can be concluded from the 8D approach to the quality study:

- In the first phase, it was decided to apply the Emergency Response Action (ERA), where a series of actions were taken in order to protect customers. Once it was concluded, that the problem required a broader approach, the PDCA process was developed by defining the problem based on data from customer complaints, defining the Interim Containment Action (ICA) and Permanent Corrective Action (PCA) action plan.
- The problem was defined according to the customers requirement by identifying and describing in quantifiable terms what is wrong using the problem statement approach. The SDP was used to detail the problem in quantifiable terms. The assertion of the Is / Is not problem answered questions related to the 5Ws method, which aims to highlight all the key factors involved in the degeneration of non-compliance by presenting the information received from the stakeholders involved. The impact of the business was quantified in terms of quality, delivery, cost and performance.

The original contributions of this chapter can be listed in the following types:

a) **Theoretical Contribution**: The conceptual approach to the project by validating the study through a new approach to the 8D method.
b) **Methodological Contribution**: The development the process flow using the PDCA approach in staging emergency response actions, ICA and PCA.
c) **Empirical Contribution**: The use of the SPD - 5Whys, Ishikawa – cause and effect diagram, Pareto and graphical presentation of the analysed data based on complaints.
d) **Data Collection Contribution**: The defining and analysing the complaints received from customers and information related to Time in Service (TIS), Mileage in Service (MIS), Country sold and type of issue using Minitab Six Sigma software.

Similar topics can be found in published articles:

- Dina Diga and Irina Severin., "Bonnet cable defect analysis using Six Sigma DMAIC techniques", UPB Scientific Bulletin, Series D: Mechanical Engineering 43(2):203-214, ISSN 1454-2358, 2021.
- Dina Diga and Irina Severin., "Sill Panel Corrosion in Automotive Industry", Springer AHFE 2021, pp. 140–147, LNNS 274, 2021. https://doi.org/10.1007/978-3-030-80462-6_18
- Dina Diga, Irina Severin and Nicoleta Daniela Ignat., "Quality Study on Vehicle Heat Ventilation and Air Conditioning Failure" MDPI Sustainability, 13, 13441, ISSN 2071-1050, 2021. https://doi.org/10.3390/su132313441

Chapter VII. D5: Validation of research based on Accelerated life test results

The simulation study was performed in a laboratory for testing components and subassemblies within an automotive company. The objective of the research study is to analyse and inspect the results obtained from tests subjected to environmental conditions. Life cycle validation and verification are extremely important for the success of a comprehensive study to simulate the functional properties of automotive components. Based on this premise, the door components have undergone several types of accelerated life tests, the Durability KLT, AET and AHAT.

Durability Key Life Test

The side door system has been subjected to a Door slam durability test to GMW15094:2016 and GB 15086:2013, which states: The side door system shall have a useful life of 10 years (240,000 Km). This will be demonstrated by completing the Side Door Key Life Test without any functional or attribute failures, as identified in the design verification method pass or fail criteria.

7.1. Testing method

This test report shows the results obtained during the running of the first part of the KLT, where the side doors were slammed 42,000 times over a period of 480 hours, in a climate test chamber.

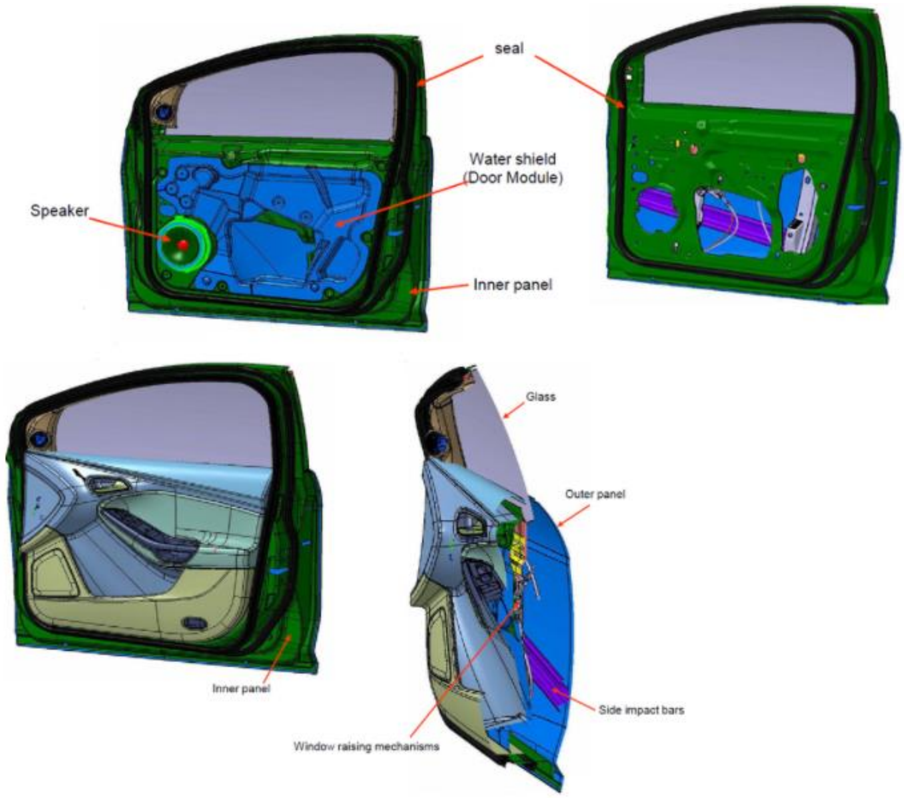


Fig.7.1 Overview of Door Trim Panel [https://skill-lync.com/student-projects/week-11-final-project-99, [H03]]

The test was performed using a pneumatic rig to simulate the opening and closing of doors set in the climate chamber, where the running temperatures were set between -40 and 80°C, with humidity conditions of up to 85% RH according to Test procedure.

7.2. Experimental set-up

Temperature differences indicate the maximum and lower temperature levels at which the components have the highest failure rate. At the ambient temperature will be performed 21,580 cycles on the door system at 12V followed by 5 cycles at 9.6V. The temperature will be increased to 45 ºC with 85 % humidity and will be performed 7,800 cycles. Next stage will be 80 ºC and to perform around 1,500 cycles, then reduce the temperature to 0 ºC. Reducing temperature to -20 ºC and perform 2050 cycles and at -40 ºC performing last 80 cycles.

7.3. Laboratory Test Report

The Test report performed presents the results obtained from the measurements of Torque according to EN ISO 6789-2003 (Hinges, Check arms, Latch and Striker), Gap and Flushness according to FGP FP 210-15-10 (Front door and Handle), Engagement and release load according to GB 15086-2013 (LH Door, Latch and Striker).

7.3.1. Torque measurements

Following test completion, where access is possible, the torque required to rotate the fixing in the loosening direction (break-loose or crack off torque), and to re-tighten it to the previous position (return to mark or re-torque) shall be recorded.

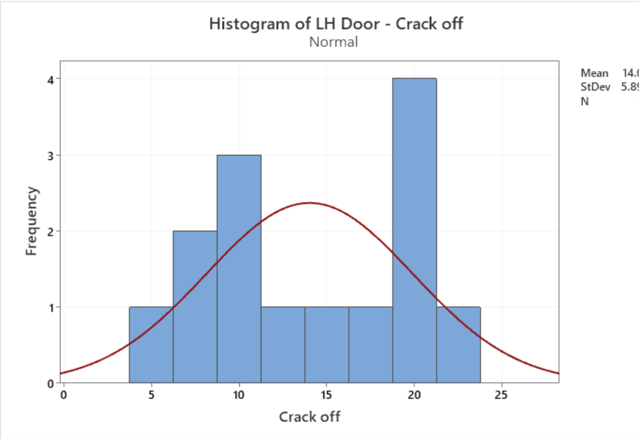
Hinges and check arms ('crack off = 'anti-clockwise)

A first step in making torque measurements is to know the process of collecting data on the bolts and hinges on the parts to be tested. On test completion, has been no joint slippage nor rotation of the fastener, and the residual torque is no lower than 70% of the initial set torque, as presented.

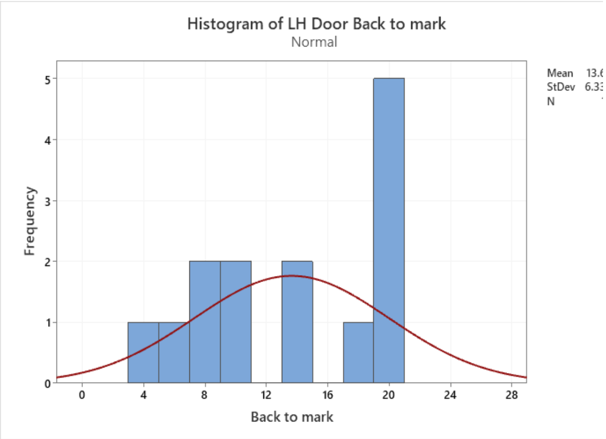
Tabel 7.1 Hinge and Check arm Torque measurements

Torque [Nm]	Spec	Left Door			Right Door		
		Set	Crack off	Back to mark	Set	Crack off	Back to mark
Upper hinge to body top	30	30	14	13	30	17	17
Upper hinge to body bottom	30	30	19	18	30	15	15
Lower hinge to body top	30	30	13	14	30	20	19
Lower hinge to body bottom	30	30	18	19	30	15	15
Upper hinge to door top	30	30.3	20	20	30.0	20	20
Upper hinge to door bottom	30	30.1	21	21	30.4	18	19
Lower hinge to door top	30	30.1	22	21	30.0	19	20
Lower hinge to door bottom	30	30.1	20	21	30.3	22	21
Upper hinge pin bolt	13.5	13.5	10	9.5	13.5	9.8	8.5
Lower hinge pin bolt	13.5	13.5	11	10	13.5	9.5	9
Check Arm to door upper	12	10.4	7	8	10.4	9	8
Check Arm to door lower	12	10.4	8.75	7	10.4	9.5	8
Check Arm to body top	12	10.2	7.5	6.5	10.2	7	6
Check Arm to body lower	12	10.2	5	3	10.3	6	3.5

The histograms in Fig. 7.2 and Fig. 7.3 have the role of highlighting the differences in the data obtained after performing Torque measurements.



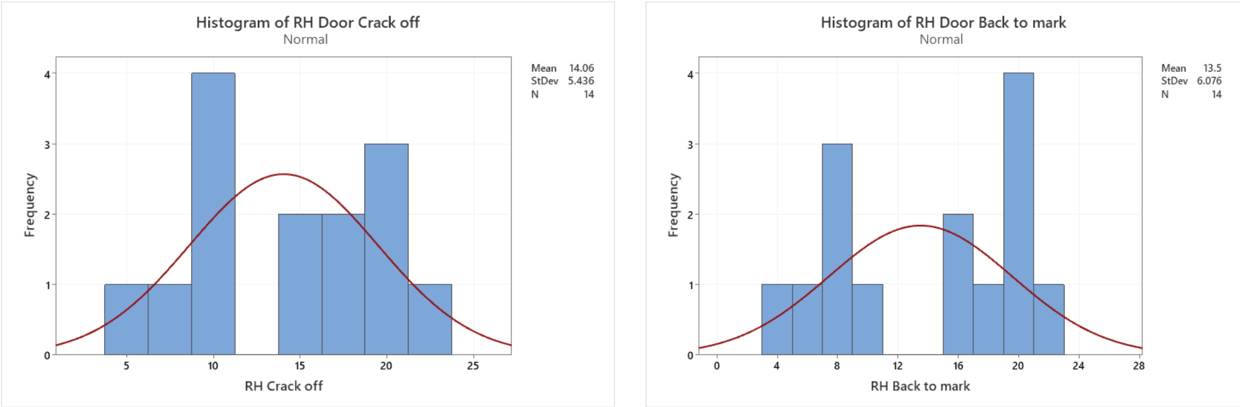
a.



b.

Fig. 7.2 Histogram of Left-hand Door -Torque Crack off (a), Torque Back to mark(b) [Nm]

The data obtained show an analogy between the nominal torque and the results obtained from the measurements that were performed after the hinges and bolts were subjected to temperatures of -40 ºC and + 80 ºC / 85% RH’. It can be concluded that during the running of the test in the climate test chamber, the fixations underwent changes.



a. b.

Fig. 7.3 Histogram of RH Door -Torque Crack off (a), Torque Back to mark (b) [Nm]

In conclusion, the fasteners lost their functionality during the acceleration life test.

Latch and Striker ('crack off = 'anti-clockwise) The data in Table 7.2 contain multiple observations, with different predictive values in the determined failure.

Tabel 7.2 Latch and Striker Torque measurements

Torque [Nm]	Spec	Left Door			Right Door		
		Set	Crack off	Back to mark	Set	Crack off	Back to mark
Latch upper 1	8.1	8.3	4.7	6.5	8.1	5	5
Latch lower outer 2	8.1	8.1	5.5	4	8.3	5	4
Latch inner 3	8.1	8.2	6	5.5	8.1	5.2	5.5
Striker upper	21.2	21.2	10	11	21.2	15	15
Striker lower	21.2	21.2	12	13	21.2	10	11

The latch upper, lower outer and inner indicate obvious variations between the essential values and those obtained along the way. These three torque bolts holding the latch in the door are loosened and the measurement results show the losses recorded.

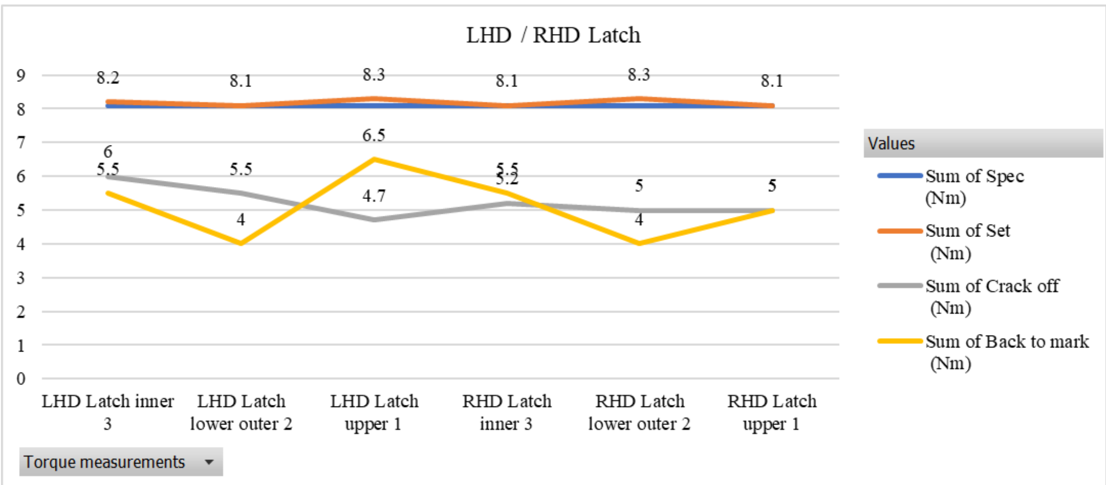


Fig. 7.4 Latch torque measurements [Nm]

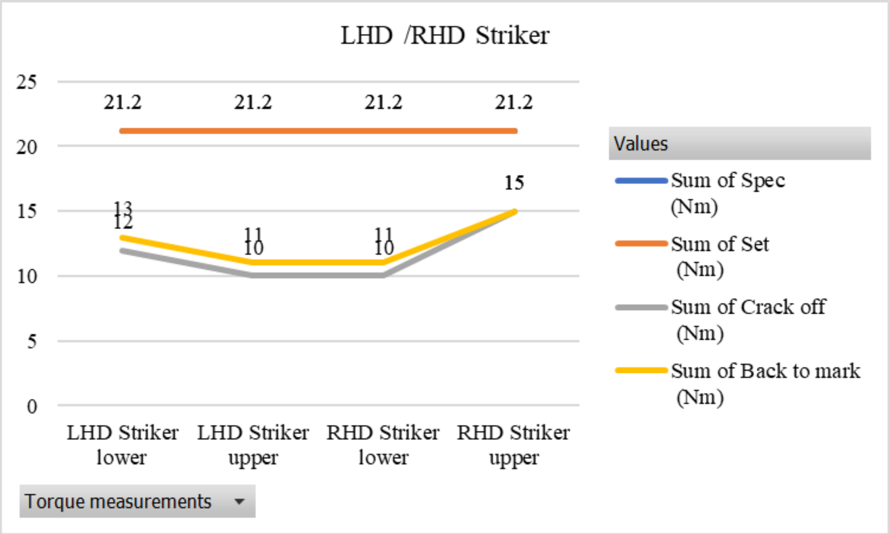


Fig. 7.5 Striker torque measurements [Nm]

The torque checks in Fig. 7.5 shows the assumed amount of torque relaxation, without the movement of the fastening device for all fastening devices on strikes, resulting in a lower torque to be loosened than was initially applied.

7.3.2. Gap and Flushness measurements

As the doors are used repeatedly by the vehicle owner, they influence the perception of the need for high quality of the vehicle and overloading the open door is an abusive charging requirement for customer use. The drawing of the door, locks and fixing components are shown in Fig. 7.8 on an appropriate scale and in detail. The requirement states that there should be no visible evidence of shrinkage, gapping, cracking or deterioration of door components.

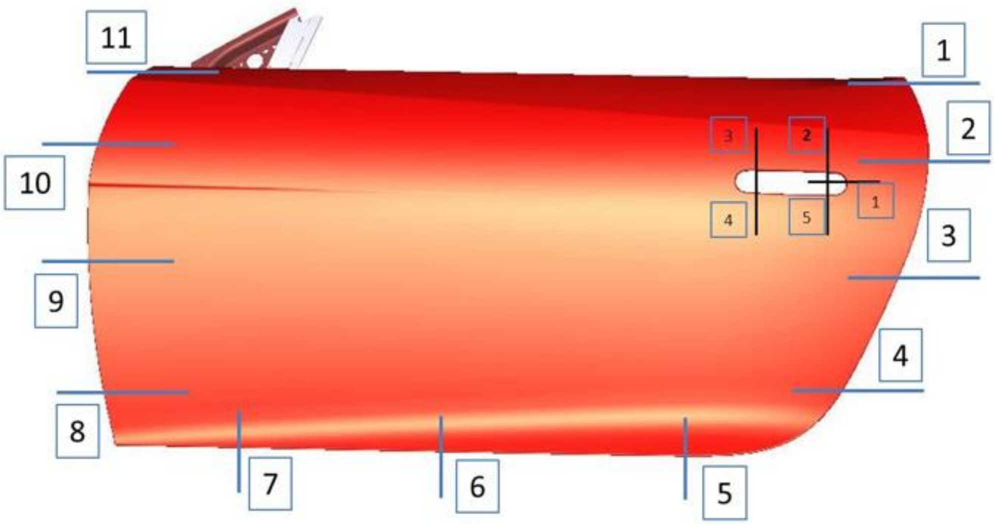


Fig. 7.6 Front Door measuring positions

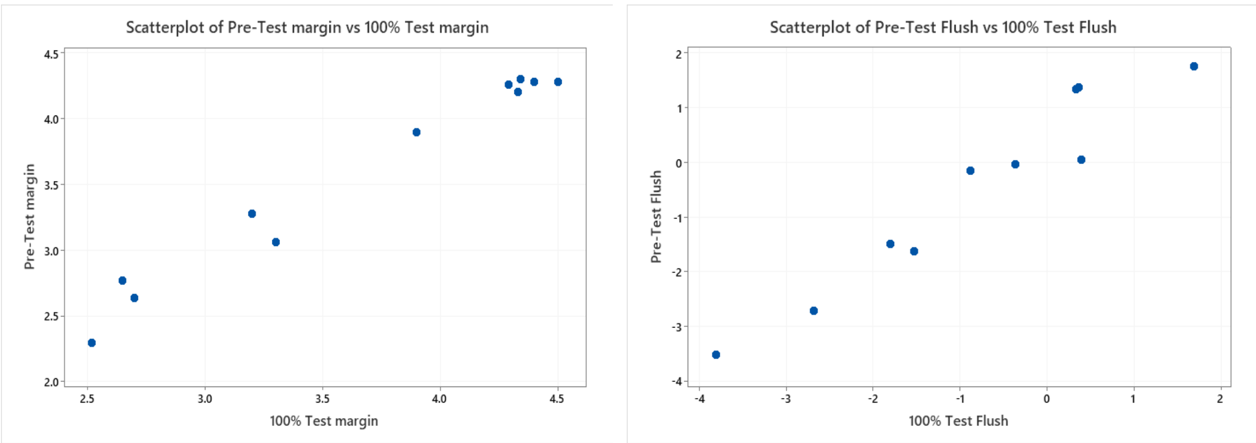
The measurement of the gap was taken between the first tangent point on the inner radii of the edge. Gap and Flushness changes after testing are presented and evaluated using Fitted Line Plot (Minitab) analyses, shown in Table 7.3.

Table 7.3 Door Gaps and Flushness measurements

Front Door Positions [mm]	Pre-Test gaps	50% Test gaps	100% Test gaps	Pre-Test gaps	50%Test gaps	100% Test gaps
1	2.64	2.71	2.70	-2.71	-1.20	-2.68
2	2.30	2.50	2.52	0.05	0.59	0.4
3	2.77	2.63	2.65	-0.15	-0.19	-0.88
4	3.06	3.30	3.30	-1.62	-2.4	-1.53
5	4.28	4.44	4.50	-3.51	-4.33	-3.8
6	4.28	4.33	4.40	-1.49	-1.74	-1.8
7	3.90	3.90	3.90	-	-	-
8	4.30	4.23	4.34	-0.04	-0.04	-0.36
9	4.26	4.27	4.29	1.33	1.31	0.34
10	3.28	3.12	3.20	1.36	1.32	0.37
11	4.20	4.26	4.33	1.75	2.35	1.69

*Flushness relative to body (+ = Door Low, - = Door High)

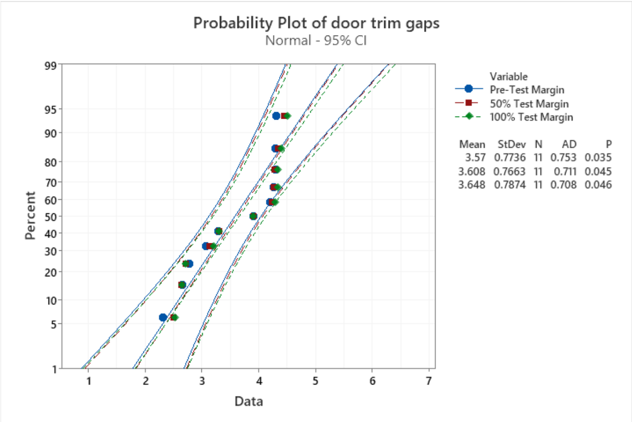
All measurements performed on the door gap and flushness are captured in the table and verified according to the minimum specifications imposed by the working procedure



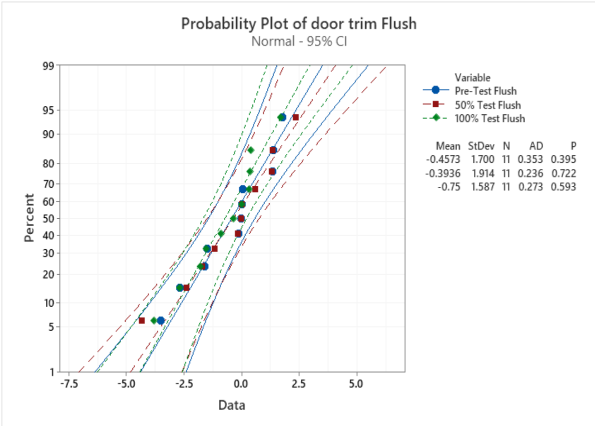
a. b.

Fig. 7.7 Pre-test margin vs 100**%** Test margin (a), Pre-test flush vs 100**%** Test flush(b) [mm]

Scatterplot diagrams show that, pre-test gap/ margin results are increased during the life test and can see an increase of almost 0.2mm in the stage of 100% test gap/ margin measurements, also increased flushness measurements, with an expansion of 0.5mm in some door areas, that can be observed throughout the measurements pre-test flushness, 50% test flushness and 100% test flushness in Fig. 7.7. Graph a) and graph b) show the 11 control points for margin and flushness. As can be seen, there are 22 control points for measuring the position of a single door only. The variables are correlated and the variation models can be extracted from the data. Consequently, all control points are measured at each measurement point listed in the table header.



a.



b.

Fig. 7.8 Probability plot of doors gaps (a), doors flush variable (b) [mm]

Handle Gap and Flushness measurements presented in the Table 7.4 were partially performed because the door handle latch encountered difficulties in operation during the test, at minimum temperatures of -4 C° or lower. Which confirms once again that the latch is the problem identified since the previous phases of validation analyses.

Table 7.4 Handle Gap and Flushness measurements

LH Handle [mm]	Pre-Test Margin	50% Test Margin	100% Test Margin	Pre-Test Flushness	50%Test Flushness	100% Test Flushness
1	2.38	No Data available due to door latch failure and part changed from Original		-	-	-
2	3.05			-	-	-
3	1.48			-	-	-
4	2.10			-	-	-
5	0.90			-	-	-

Continuous measurement of all surfaces is not feasible, so it is necessary to define a set of control points to measure dimensional quality.

7.3.3. Engagement and release load measurements

The load measurements performed on the door were tested in accordance with the requirements of GB15086-2013, listed in Table 7.5 a series of results of the external release handle the opening load, check arm door retention loads, and door drop. All loads were normally applied to the surface component.

Table 7.5 LH Door load measurements

LH FR Door load measurements [N]	Start of Test	Above +40C	25% of Test	50% of Test	Above +40C	75%	-20°C @84000 cycles	84000 cycles
Ext. release handle opening load (1/2 way along handle opening) [N]	46			85		90	93.4	87.0
Check arm door retention loads (at mid exterior door handle) [N]:								
Open to (1st) mid check	32	26	25	27	27	27.5	42.8	31
Open from inner mid (1st) check to outer mid (2nd)	35	32	32	32	33	32	41.4	32
Open from outer mid check (2nd) to fully open	37	34	36	33	33.5	35	39.5	34
Close from fully open to outer mid check (2nd)	33	30	32	27	31	26	33.6	27
Close from outer mid check (2nd) to inner mid (1st) check	34	34	35	30	32	31	30.6	28
Close from inner mid (1st) check	36	33	34	32	33	29	33	29

The load was applied no faster than 20 N/s. All points were measured with an extension and a 10 mm flat disc, simulating thumb pressing. The force was applied with a force meter ensured that it is zero each time. Based on the results obtained in Table 7.5, the door check arm retention load was found to be a useful for non-compliance, as can be seen in graphical form, in Fig. 7.9.

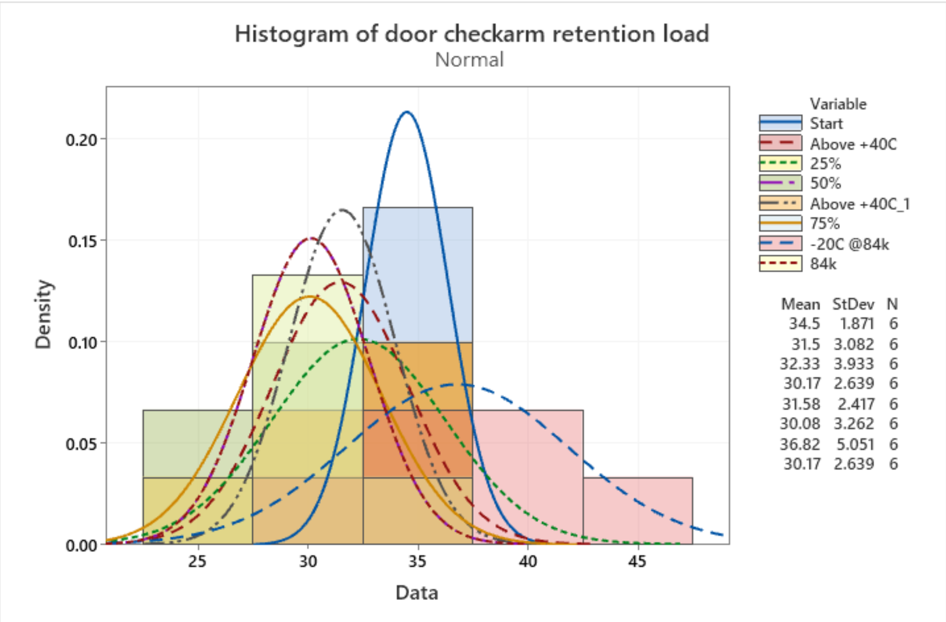


Fig. 7.9 Door check arm retention load [N]

The graph accurately illustrates the deviation from the nominal encountered in the case of the results recorded at "Above + 40°C". This proves once again that components subjected to extreme temperatures behave differently and have a higher degree of failure.

Table 7.6 Door drop measurements

Door measurements	Start of Test	Above +40°C	25% of Test	50% of Test	Above +40°C	75% of Test	-20ºC @84000 cycles	84000 cycles
Door drop closed [mm]	0	-	0	0	-	0	-1.8	-1.67
Door drop open [mm]	0.66	-	0.78	1.07	-	1.38	-1.8	-0.7
Min closing speed [m/s]	0.70	-	-	0.50	-	1.4	-	0.8

The graph shows the distribution of data values for closed and open door drop measurements.

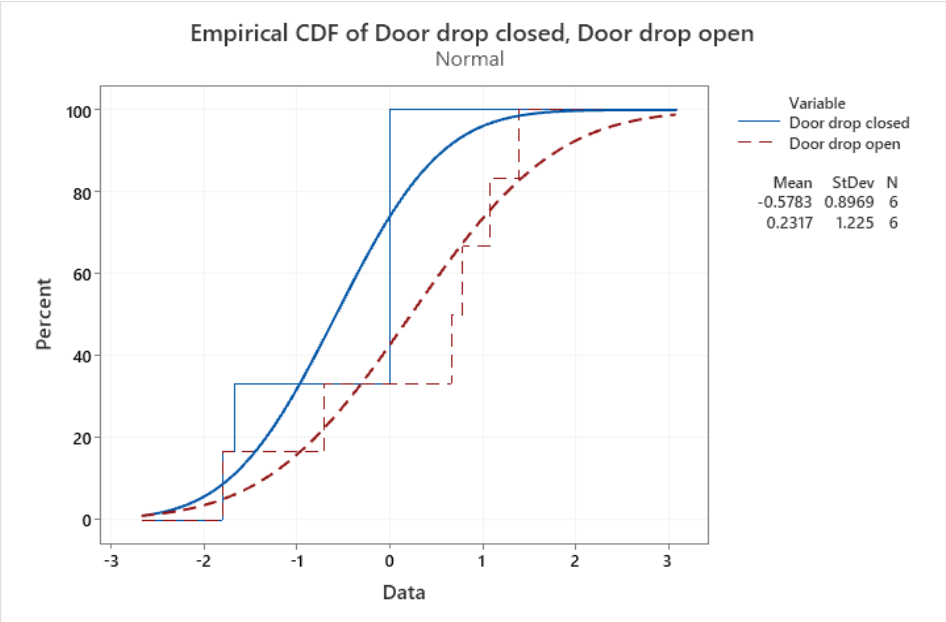


Fig. 7.10 Door drop closed/ Door drop open CDF [N]

In Fig 7.10. was used an Empirical CDF plot to evaluate the fit of distribution to Door drop closed and Door drop open data, to estimate the percentile of population and door drop values, to compare door drop distributions. The mean squared deviation, measure the average of the root mean square errors, which is -0.5783 for door drop closed and 0.2317 for door drop open.

Latch and Striker – Engagement and release load

As shown in Table 7.7, where the initial latch engagement load has indicated a different application force than the primary latch engagement load, to which a higher load is applied, around 400N due to the closing resistance of the latch in the open position.

Table 7.7 Engagement and release load results

Right Hand Front Door [N]	Start of Test	25% of Test	50% of Test	75% of Test	End of Test
Initial Latch Engagement Load (engage secondary latch) (N)	91.90	83.05	90.03	112.30	124.20
Primary latch engagement load (N)	399.80	370.80	392.70	390.00	402.00
Initial Latch Release Load (secondary latch release) (N)	49.20	52.02	49.80	52.90	52.60
Primary Latch Release Load (N)	65.80	55.20	65.20	65.00	64.10

The Fig. 7.11 provides clear references between the tabular and the graphical representation, where it can be seen in all 5 measuring positions that there are similarities between the results. At the same time, Initial Latch Engagement load loses its functional properties from the measurement point of 75% of Test.

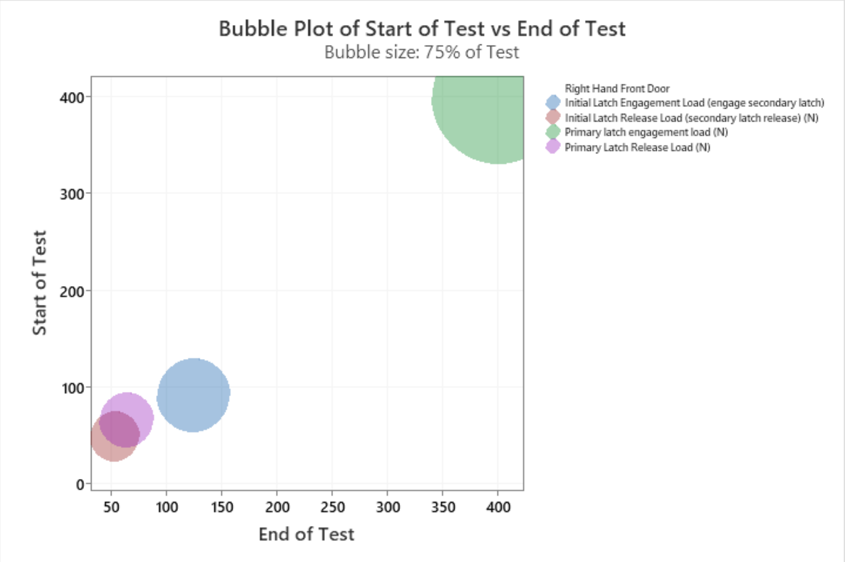


Fig. 7.11 Latch engagement 75% of Test [N]

The graph provides a means of analytical representation of the ability of the door closing system to withstand inertial loading.

7.3.4. Conclusion

The tested components did not meet the acceptance criteria when visually inspected during a post-test inspection. A total of two issues were raised as a result of the test procedure, these are outlined:

- The door fixed glass was detached from the initial position, during cycling at 80°C.
- The top roller was deformed at the end of the 45 °C/ 85 RH stage. The door completed 50K cycles.

Accelerated Environmental Test

This test documents the results of the Door trim panel Accelerated Environmental cycling conducted in the component and subsystem test laboratory, in a climatic chamber according to CETP:00.00-l467 and ISO 75-1:2020.

7.4. Testing method

This test method is used to investigate the performance of components and assemblies after 240 hours of exposure to a higher temperature range and is intended to evaluate the dimensional properties of the materials and components that comply with BS EN60068-2 and DEF STAN00-35 procedure.

7.5. Experimental set-up

The environmental cycle requires the following test procedure, presented in Table 7.8. The in-service temperature specified for this test is 85 °C.

Table 7.8 Testing temperature profile

Temperature [°C]	Hours	Humidity [%]
22	2	50%
-40	22	50%
22	2	50%
85	22	85%
22	2	50%

The working procedure has 3 cycling loops, with temperatures recorded between -40°C and + 85°C / 85%RH. The table shows a single complete test loop.

7.6. Laboratory Test Report

The Test report presents the results obtained from the Door trim gap measurements.

7.6.1. Door trim margin measurements

The gap is defined as a horizontal margin between the door trim and the door to be measured, or between the door and the body of a vehicle.

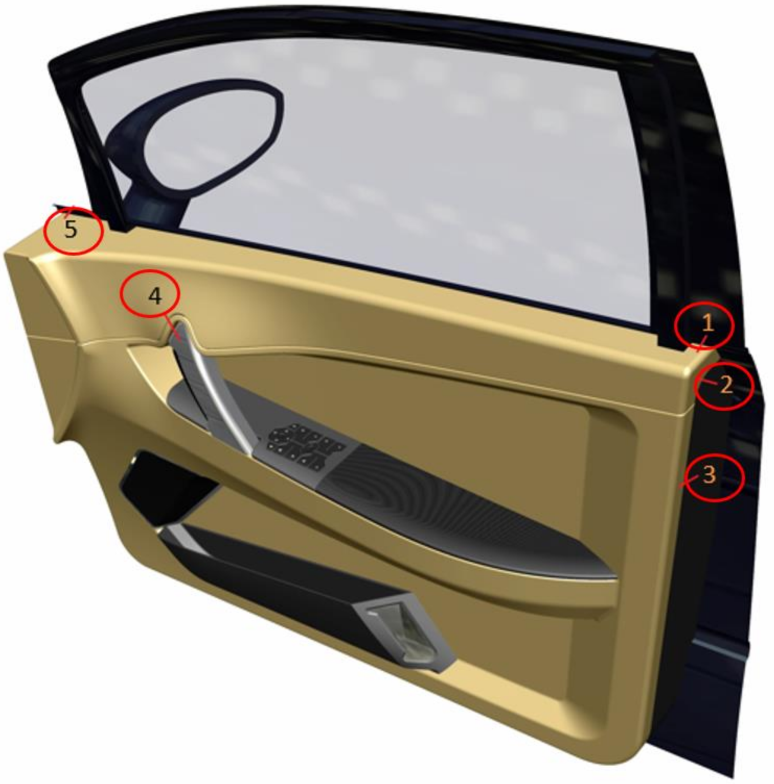


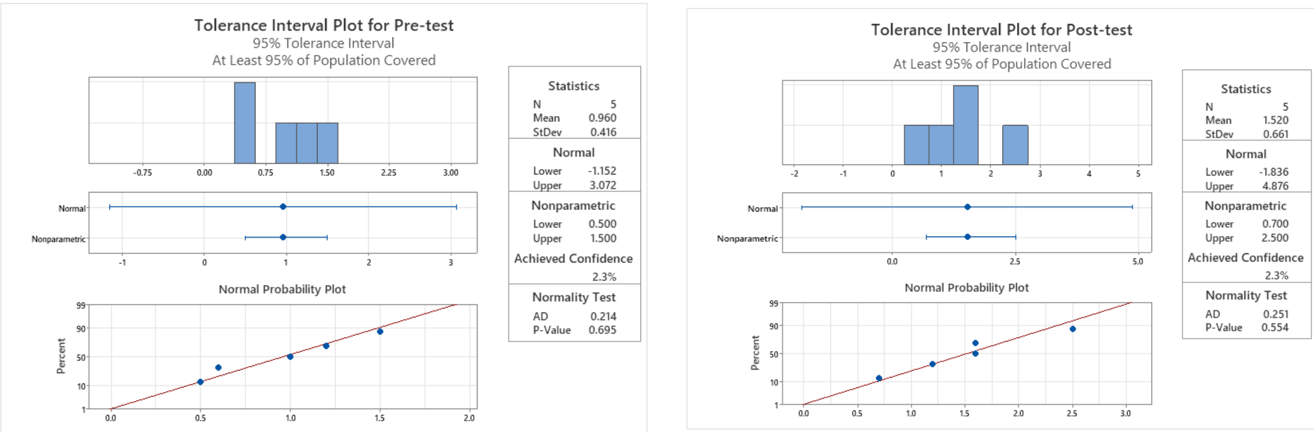
Fig. 7.12 Door trim panel gap positions [***05]

The gap of door trim in Figure 7.12 is a Computer-aided Design (CAD) representation of the location of the position to be measured.

Table 7.9 Gap Measurement stages

Measurement stages [mm]	**Position 1**	**Position 2**	**Position 3**	**Position 4**	**Position 5**
CAD Gap	1±0.7	0±0.8	1±0.7	0.7±0.6	1±0.5
Pre-test	1.2	1.5	1	0.6	0.5
Post-Test	1.6	1.6	**2.5**	1.2	0.7
Gap increase	0.4	0.1	1.5	0.6	0.2

The tabular representation of data shows the difference of gap measurements between pre-test and post-test running. The difference can be seen in the CAD Gap specification of nominal measurements according to design validation requirement and the rest of the measurement that have been performed.



a. b.

Fig. 7.13 Door trim Pre-test gaps (a), Post-test gaps (b) [mm]

In the graphical representations of the data obtained, it can be seen that the gap increases at each measured position, with a large impact on the tolerance intervals, where the differences confirmed that the test did not meet the requirements and there is a presence of malfunction.

7.6.2. Conclusions

Following the cycling of the environmental test for a period of 240 hours, without stopping, the following changes were observed on the door trim panel surface.

- The surface was deformed (wrinkling, waviness) on the door trims after performing the environmental cycles at the temperature of 85°C/85HR'.
- The fixed glass of the door was detached during the cycle at 82°C. The problem is also known, treated with the problem of testing the key life previously seen during climate cycles. The door glass was fixed with tape to continue environmental cycling.
- The deformation of the top roller was also observed. The issue known from the first part of key life test results. After completing the test, there were only signs left on the top roll, the other components recovered.

Accelerated Heat Ageing Test

The Heat Ageing test documents the results of the interior door trim samples tested for 500 hours, at 80 ºC, 90 ºC and 100 ºC Heat Age and 50% Humidity to speed up the deterioration, conducted in the Component and Subsystem Test Laboratory.

7.7. Testing method

The test method is performed to validate the performance of the material components after long-term exposure to heat in order to analyse both the long-term effect on the surfaces and the dimensional properties of the components of the tested materials. Occurrence of any of the following shall be cause for rejection of interior trim components: tackiness, spewing, grain loss, blistering, warping, distortion, delamination, cracking, crazing, fibre deterioration, wrinkling, waviness, milking, blushing, hazing.

7.8. Experimental set-up

According to ASTM D3045 and BS EN 60068-2, the door trim components were subjected to extreme exposure conditions and were tested for validation of their resistance to degradation and simulation of functional properties. Maintains compliance with ISO17025, IATF16949, ISO 45001 and all process associated activities.
The components of the door assembly subjected to the hear aging test can be seen in Fig. 7.14.

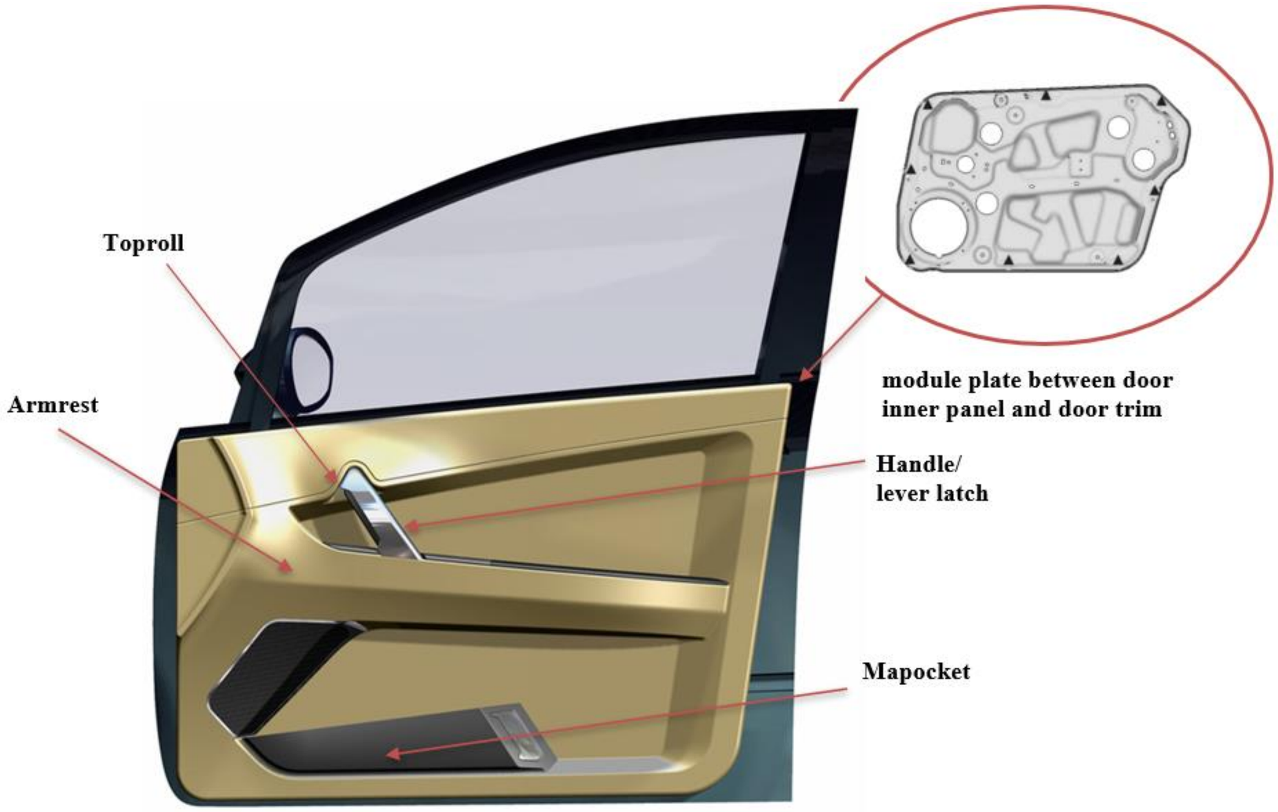


Fig. 7.14 Door trim samples [***04, ***05]

Accelerated Heat Aging Test was conducted on door trim components and results were presented as a case study in Minitab. Six samples were tested at each the temperature 80ºC, 90ºC, 100ºC.

7.8.1. Weibull Distribution (hours versus temperature)

The Weibull distribution analyzes the life data of the components and the analysis of the time to failure in the design stage and in-service time. The purpose of the test was to estimate life of design temperature of 70 ºC.

The Heat Aging test shows in the table the analogy temperature versus allocated hours per cycle. In the Censor column, 1- means that the component failed and 0 - means not failed. The failure time of some of the samples are not known or the test may be discontinued.

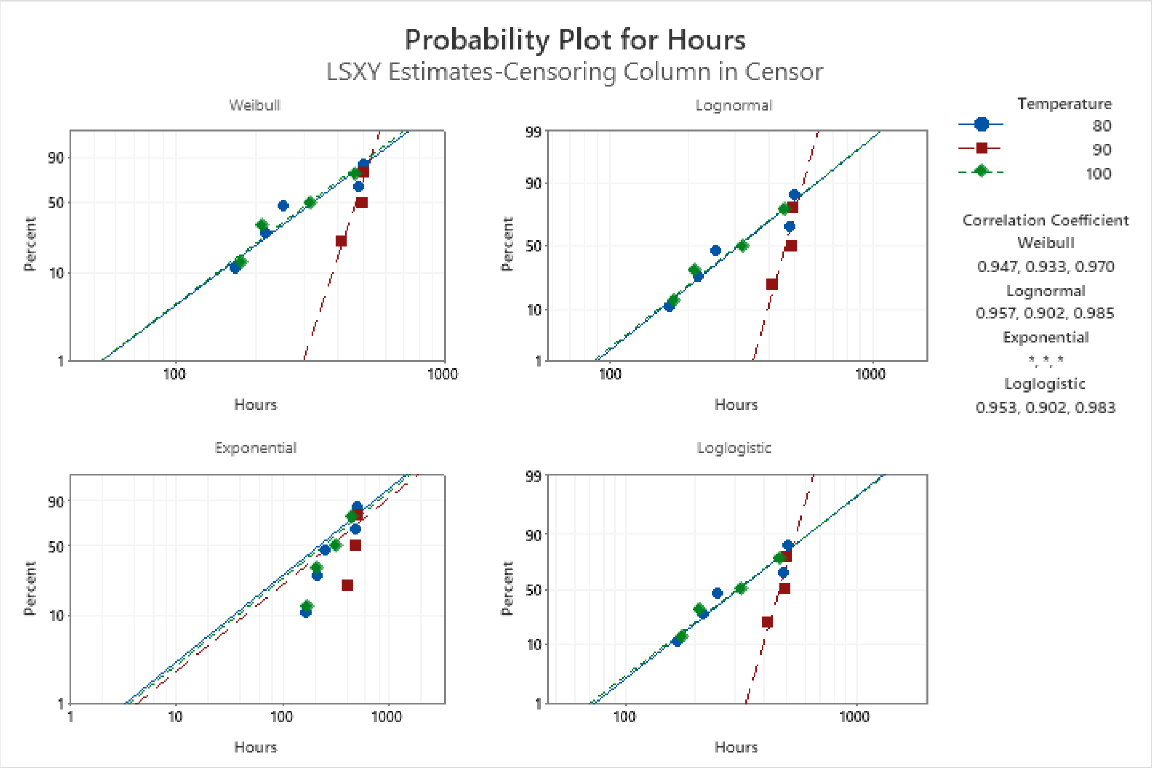


Fig. 7.15 Probability plot – Correlation with Weibull, lognormal, Exponential and Loglogistic distribution

The following distributions were generated:

- Distribution of the Weibull probability of estimating the allocated hours
- Distribution of the probability of the minimum temperatures assigned for testing on heat exposure.
- The Weibull probability distribution, lognormal, exponential and normal are represented graphically in Fig. 7.15.

The correlation coefficient indicates that the Weibull distribution is slightly better than the Lognormal distribution. The correlation coefficient of the Loglogistic distribution is higher than better for the correct distribution, while the exponential distribution is completely missing.

It can be concluded that the impact of the hours versus temperature determined at each stage the degradation of the components. There is a tendency to fail with an impact of 80% and out of 14 samples only 3 have passed.

7.8.2. Arrhenius distribution (hours versus temperature)

Arrhenius' law states that the speed of a simple chemical reaction depends on temperature. The Arrhenius relationship was used in the graph to describe elements that fail due to degradation caused during temperature exposure. The data collected from the test were used to generate a series of inverse Weibull probability censoring for hours, as shown in Fig. 7.16.

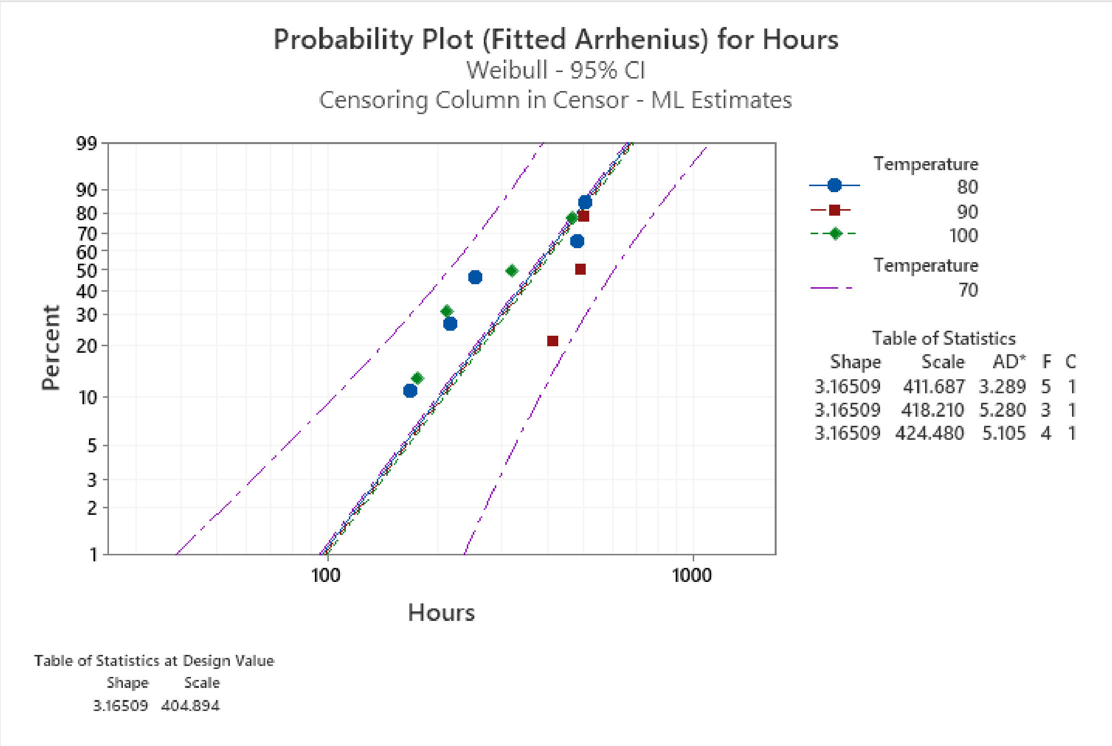


Fig. 7.16 Arrhenius - Probability plot

The fitted lines are based on, Weibull distribution, and Arrhenius Regression models are always parallel because the shape parameter is assumed to be equal. In this case, the points drawn do not closely follow each fitted line, and any of the hypotheses may be unfulfilled. The fitted line and the confidence level at 70 °C are also included in the plot.

The Arrhenius model [***08]:

$$In\ T = \beta_0 + \beta_1 \frac{11604.83}{s+273.16} + \frac{1}{2.8246} W \quad (1)$$

Were,

W= Gumbel/ Weibull

S = temperature in °C.

$$In\ T = 6.59121 + (-0.0173753) \frac{11604.83}{s+273.16} + \frac{1}{2.8246} W \quad (2)$$

The failure time is the estimated lifetime of the product described in this test study. The time to failure is related to the factors involved in the degradation process. An essential relationship was established between the degradation time and the applied load, and the acceleration was calculated using the standardized loads from the aging test and its applicability, as shown in Fig. 7.17.

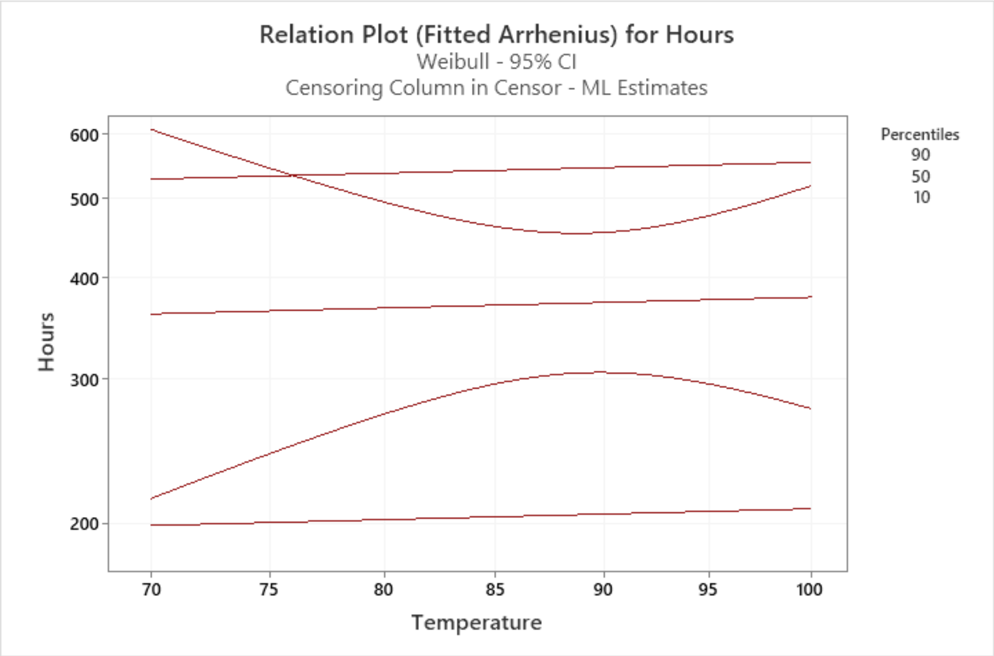


Fig. 7.17 Fitted Arrhenius – Relation Plot

7.9. Laboratory Test Report

The Test report presents the results obtained from the measurements of Torque Module plate screws.

7.9.1. Module plate torque measurements

Torque measurements performed on module plate screws recorded two measurement stages, one before the test called crack-off and the second measurement after the heat test called retorque. The data collected from the measurements show signs of failure, both stages do not fall within the specifications of the material. The measured positions are indicated in Fig. 7.18.

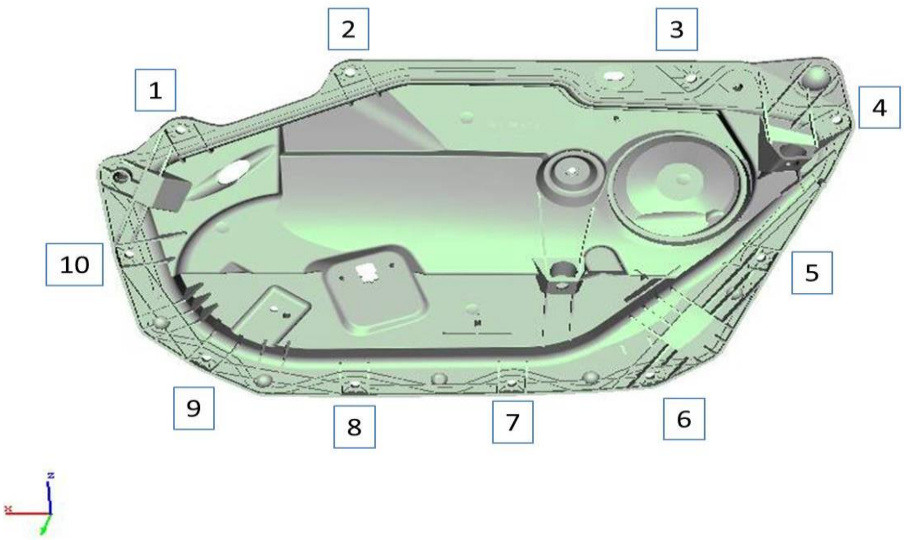


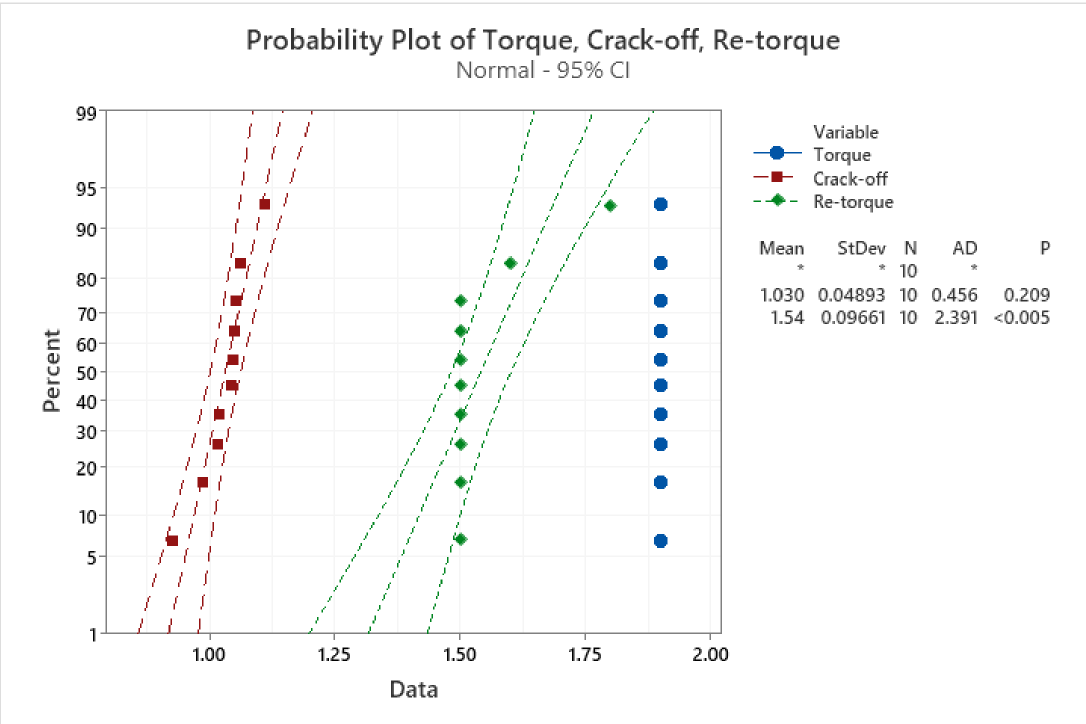
Fig. 7.18 Door Module plate positions [S09]

Table 7.10 shows all the data recorded following the torque measurements, taking into account the nominal Torque of 1.9 and tolerance of ±0.3.

Table 7.10 Crack-off and re-torque measurements

No.	Torque nominal [Nm]	Crack-off [Nm]	Re-torque [Nm]
1	1.9±0.3	0.926	1.8
2	1.9±0.3	0.986	1.5
3	1.9±0.3	1.11	1.6
4	1.9±0.3	1.06	1.5
5	1.9±0.3	1.043	1.5
6	1.9±0.3	1.045	1.5
7	1.9±0.3	1.018	1.5
8	1.9±0.3	1.051	1.5
9	1.9±0.3	1.016	1.5
10	1.9±0.3	1.1	1.9

It can be easily noticed that the reported data are in the material specifications and follow the working procedure.



*CI – Confidence Intervals

Fig. 7.19 Door Module plate screw Torque results [Nm]

Based on these data, a probability plot was developed in Fig. 7.19, to represent the registered records. Thus, the positioning of each measurement can be seen in accordance with the nominal torque data provided by the testing requestor. Values below nominal tolerance were recorded, as shown in Fig. 7.20, which concludes that test requirements did not meet test specifications.

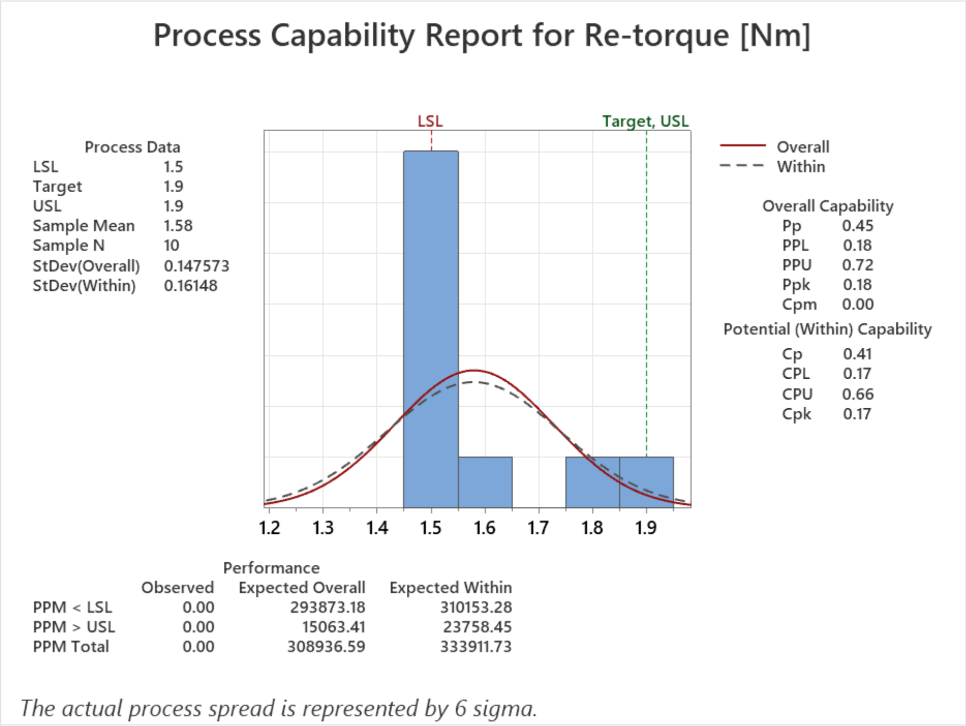


Fig. 7.20 Re-Torque capability report

7.9.2. Conclusions

The final visual state of the components was compared against the BS EN 60068-2 requirements. During the 500 hours of heat exposure, the test was observed wrinkling, distortion failure. The failure appears in the first 24 hours at 80 ºC heat exposure, and there are (door latch, top roll, glass) that not met the procedure test requirements. The exposure time was fixed in advance according to the test procedure and the temperature profile was allocated by the customer according to material specification.

Conclusion and contributions

The following key points can be concluded from the validation of test results:

- The probability graph of the correlation coefficient is presented by estimating the Weibull distribution, lognormal, exponential and normal, so that it can be plotted at each stage of the research.
- The research study validates the results collected from three accelerated life tests: the Key Life Test, the Accelerated Environmental Test and the Accelerated Heat Aging Test.
- The effect of accelerated temperature conditions on the properties of polymeric components was studied for the component tested in this study. It has been shown that as the aging temperature increases, the material retains its properties. The tested components showed a low failure rate on short exposures compared to their longer exposure.

The original contributions of this chapter can be listed in the following types:

a) **Theoretical Contribution:** The validation of the results obtained following the accelerated life tests of the door panel components.
b) **Methodological Contribution**: Design and implementation of testing procedures for durability testing, draft, and review of working procedures for testing, set-up of the methodology, and experimental documentation.
c) **Empirical Contribution**: Results analysis using Alpha PLC, HBM Catman (data Acquisition), Quantum (hardware), CANalyser and Minitab Six Sigma software.
d) **Data Collection Contribution**: Performing all testing and measurements using tools and data acquisition.

Similar topics can be found in published articles:

- Dina Diga, Elena Lascu and Georgiana Chisiu., "Key Life Tests for Automotive Design Validation" Proceedings of the 36th International Business Information Management Association (IBIMA), ISBN: 978-0-9998551-5-7, 4-5 November 2020, Granada, Spain.

Chapter VIII. Recognize team success and document problem-solving results

In this chapter are structured the final results of the thesis and its orientation towards the improvement of processes and products. The paper presents well-structured information throughout the development of the 8D and Six Sigma approach in order to present the best practices for identifying, analysing and solving problems in the automotive industry.

Key Performance Indicators

8.1. D6: Validate the Results

Laboratory test reports have shown a number of results from exposure of components to various ambient temperatures and measurements. As a result of these results, defects of the door system components were identified, defects that had a major impact in the non-validation of the final product. Table 8.1 shows the defects identified in the validation process.

Table 8.1 Defects on validation reports

No.	Defect description	Defect no.	Validation
1	Door fixed glass detached	3	Test Report
2	Top roller deformed	2	Test Report
3	Door handle latch lock and unlock issues	5	Quality Report
4	The body hinges and bolts, latch and striker screws torque fail	19	Test Report
5	Door panel gap 2.5mm out of specs	1	Test Report
6	Door trims surface deformed	3	Test Report
7	Door module plate screws torque fail	10	Test Report

The graph in Fig. 8.1 shows the average number of defects per sample is 6.14 and failed the requirements because the data are outside the control limits.

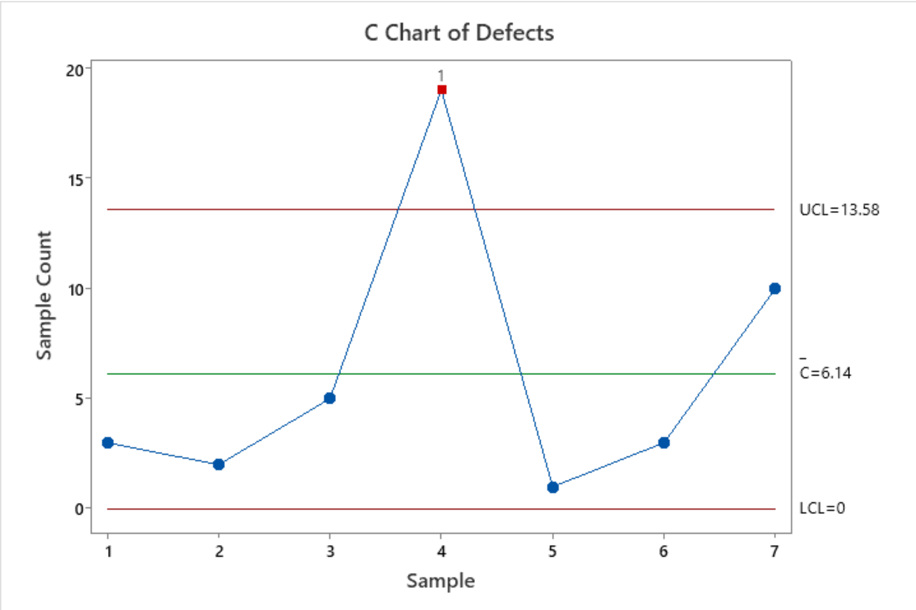


Fig. 8.1 Defective samples

Product quality plan is presented as a calculation matrix between qualitative tools and quantitative evidence. Data collection is performed in the product development process and a failure response is required. The qualitative-quantitative ratio is expected to be 3:1, as shown in Table 8.2.

Table 8.2 Product Quality plan

		Qualitative						**Quantitative**		
Door System Requirements	**Impact on Customer**	**Design specs.**	**Process review**	**Simulation**	**FMEA**	**Test**	**Audit**	**QRR**	**DVP**	**QRR/ DVP**
Door handle latch - parts rework in service	5		3		1		3	80	15	5.33
Top roller rework - adding a layer of fibre to the leather	5		3	3	1	3		45	30	1.5
Door handle latch – Design change	5	5			1			40	50	0.8
The body hinges and bolts, latch and striker screws on specs.	5	3	3	3	1	3	3	65	45	1.44
Door module plate screws on specs.	5	3	3	3	1	3	3	65	45	1.44

*DVP - Design Verification Method; QRR - Quality Requirement Review.

8.2. D7: Prevention and analysis techniques

The analysis technique used in this stage is Failure mode and effect analysis which has as main purpose the determination of the potential effects, cause of failure, the recommendations related to each action in solving the problems and the prevention of the recurrence of the future failure. Table 8.3 shows all the non-conformities identified and the steps taken for problem-solving process.

Table 8.3 Failure mode and effects analysis (FMEA)

Test	Identified Failure Mode	Potential Effects	Potential Cause of Failure	Recommended Action	Possible Prevention
KLT	Door fixed glass detached	- Damage during fitting - Rework required at subsequent operation - Escape to customer	Wrong choice of seal material	- Parts inspection - Confirm parts revision with supplier - Replace the seal - Fit the seal with glue to the door fixed glass	- Supplier parts retesting - Supplier process review
	Top roller was deformed during the end of 45 °C/ 85 %RH	- Time wasted - Damage to product	- Heat temperature impact - The poor leather quality or inadequate leather type	- Re-testing the Top roll - Adding a layer of fibre to the leather	- Supplier parts retesting - Supplier process review
	Door handle latch lock and unlock issues in low temperature	Design change on the Door handle	Failure to comply with design tolerances	- Design Review - Parts revision with supplier - Tolerances - parts in specification	- Parts assembly verification - DFMEA - Supplier process audit
	The body hinges and bolts, latch and striker screws loss of properties	Component detaches in service or after vehicle sale	- Wrong design of the part on the mounting hole - Wrong fixation	Design review of the part (DFMEA)	- Parts assembly verification - DFMEA - Supplier process audit
AET	Door panel gap 2.5mm out of specification by 0.9mm	- Product performance not optimum - Escape to customer	- Incorrect tooling used - Mounting requires proper skills	Process review of the parts (PFMEA)	- Parts assembly verification - PFMEA - Supplier process audit
	Door trims surface deformed at 85°C/85HR	- Unable to fit component - Damage to component	Heating the component to an inadequate temperature	The in-service temperature given by the requestor must be changed (see 85 °C) according to material specs.	- Parts assembly verification - Process review - Parts retesting

	The fixed glass of the door was detached during the cycle at 82°C	- Damage during fitting - Rework required at subsequent operation - Escape to customer	Wrong choice of seal material	- Parts inspection - Confirm parts revision with supplier - Replace the seal	- Supplier parts retesting - Supplier process review
AHAT	Top roller wrinkling, distortion failure at 80°C	- Time wasted - Damage to product	- Heat temperature impact - The poor leather quality or inadequate leather type	- Re-testing the Top roll - Adding a layer of fibre to the leather	- Supplier parts retesting - Supplier process review
	Door fixed glass detached at 80°C	- Damage during fitting - Rework required at subsequent operation - Escape to customer	Wrong choice of seal material	- Parts inspection - Confirm parts revision with supplier - Replace the seal - Fit the seal with glue to the door fixed glass	- Supplier parts retesting - Supplier process review
	Door module plate screws fail to meet the nominal torque requirements	Fail to torque	- Heat temperature impact - Failure to comply with design tolerances	Design review of the part (DFMEA)	- Parts assembly verification - DFMEA - Supplier process audit

Following the FMEA, it was concluded that 90% of the identification problems have sustainable solutions and only 10% of the problems require a more detailed analysis.

8.3. D8: Measure team success

The activities related to testing and the results obtained are presented in Fig. 8.2 - Fig. 8.5 through a series of Key Performance indicators.

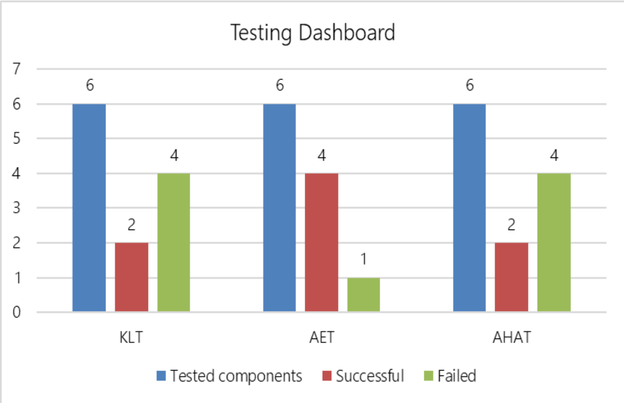


Fig. 8.2 ALT dashboard result

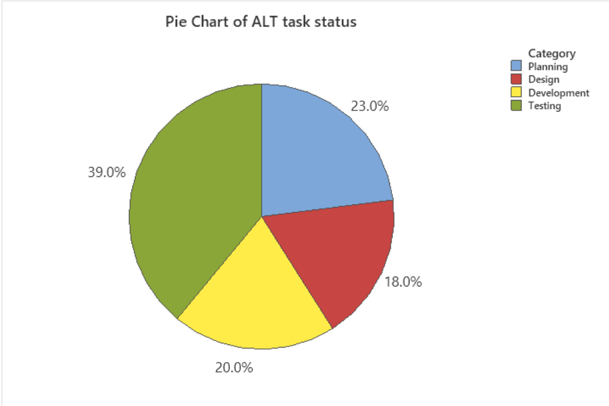


Fig. 8.3 ALT task status

Fig. 8.4 Histogram of tested components

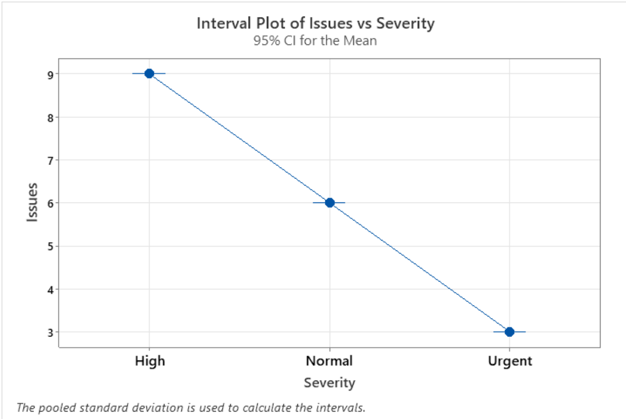


Fig. 8.5 Issue vs Severity impact

Performance indicators indicate the need for continuous improvement and the impact of defective components on the entire door system panel assembly.

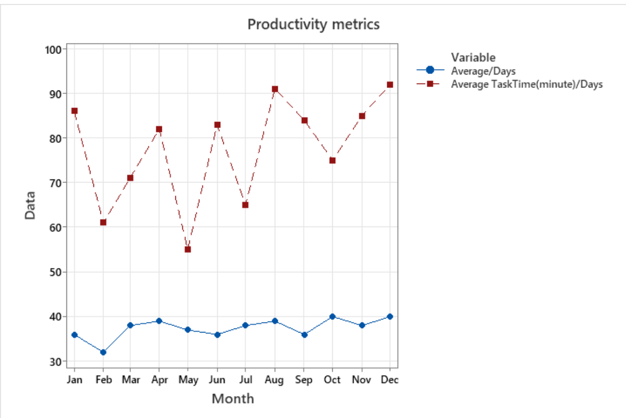


Fig. 8.6 Productivity metrics

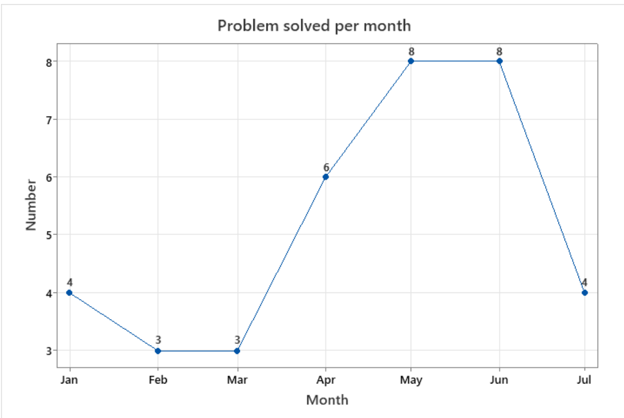


Fig. 8.7 Problems solved per month

The graphs in Figs. 8.6 and Fig. 8.7 show the team's contribution to solving problems and the corresponding level of productivity. From the presented evidence we can observe a high degree of involvement in the problem-solving process, the team validating success indicators.

Conclusions and contributions

The following key points can be concluded from the final results:

- This chapter validates the results and identifies a number of defects on the door panel following accelerated testing.
- In the Product quality plan, a series of qualitative and quantitative ratios are assigned to door system requirements.
- Failure mode and effect analysis was used to determine potential effects, important causes, prevention, and recommendations for continuous improvement.
- The team's achievements in terms of performance and productivity, following analysis and testing, were measured by the KPI.

The original contributions of this chapter can be listed in the following types:

a) **Theoretical Contribution:** The study contributes by exploring the factors that will help to optimize the process and to build a loyal customer.
b) **Methodological Contribution**: Design, adaptation and implementation of the methodology.
c) **Empirical Contribution**: Use of KPI for graphical representation of results.
d) **Data Collection Contribution**: Briefing techniques and methodology to measure team success.

Chapter IX. Final conclusions, main contributions and further research

In recent years, quality has been majorly enacted as a result of increased globalization and national and international market. Continuous progress in all areas of industry has facilitated trade and connected domestic and foreign consumers, producers and traders around the world. The performance of the organization is focused on optimizing the work process and eliminating problems by using Six Sigma. Its objective is focusing on innovation and process improvement. The complexity of the process being analysed and oriented towards transforming the business being purely functional to becoming process-oriented. The information obtained through the intensive review of the literature is used as a basis by which essential features of the research are stated. As long as the six-sigma background will be known and its principle, the Six Sigma level of performance will be understood in the industrial field over time. The work presents problem-solving process tools, such as Six Sigma DMAIC (Define, Measure, Analyse, Improve and Control) and 8D (8 disciplines of problem solving) Team Oriented Problem Solving, which aims at the detailed analysis of the existing problem, following a series of logical steps of defining, analysing, measuring and solving them by implementing an effective framework for the prevention of recurrence and elimination. A SIPOC (Suppliers, Inputs, Process, Outputs, and Customers) analysis was used to identify relevant factors in pursuing a project and in improving and optimizing the process.

The Standardised Problem Definition template was used to detail the problem in quantifiable terms. The problem statement Is / Is not, answered questions related to the 5Ws method, which seeks to highlight all key factors involved in non-compliance degeneration by presenting the information received from the stakeholders involved. The business impact was quantified in terms of quality, delivery, cost and performance. In the paperwork, the Ishikawa and Pareto methods were used to discover the root cause of the problem: Driver door malfunctions in low or freezing temperature conditions. Ishikawa analysis shows that the potential causes are generated by the electrical signal - the CANalyser program and the climatic impact that the component has at cold temperatures below temperatures of -4 °C. The Pareto analysis shows that the door lock has the biggest impact on the failure of the entire subassemblies and causes other defects in the subassemblies at the level of the entire vehicle. The Graphical Evidence presents the TIS (Time in service) and Mileage Histogram by showing the life of the vehicle aftermarket. At the same time, the countries in which the highest failure rate of left-hand drive, lever, latch and handle components have been identified are presented in Country sold by defective part chart and by issue date in Chart by Issue date plot.

The research study validates the results collected from three accelerated life tests, namely Key Life Test, Environmental Testing and Heat Aging Test. The effect of accelerated temperature conditions on the properties of polymeric components was studied for the specimen tested in this study. It has been shown that as the aging temperature increases, the material retains its properties. The polymers indicated a low failure rate on short exposures compared to their exposure to longer durations. The study validates the results and identifies a number of defects on the door panel following accelerated life testing. The study went through a series of stages of analysis and evaluation of defects. Pareto, Ishikawa, DPMO (Defects per million opportunities), FMEA (Failure mode and effects analysis) methods of analysis participated in the validation of the final results. The probability graph of the correlation coefficient is presented by estimating the Weibull distribution, lognormal, exponential and normal, so that it can be plotted at each stage of the research. This part of the analysis describes a series of Minitab macros that make versions of Sequential sum of squares and Mean Square of the regression on basic statistical techniques and suggest ways in which macros could be used in statistics. The study highlighted the need for statistical techniques in monitoring performance indicators.

The original contributions of the Doctoral Thesis can be outlined as:

a) **Theoretical Contribution:**
   - Documentation of the applicability of the six-sigma method in relation to the technological evolutions in industrial engineering.
   - Formalization of the 8D analysis method by introducing and elaborating flow charts for process optimization.
   - Design and implementation of testing procedures for durability testing, draft and review of working procedures for testing, set-up the methodology.
   - The validation of the results obtained following the Accelerated life tests of the door panel components.
   - Process optimization and Key Performance Indicators approach to problem- solving.

b) **Methodological Contribution**:
   - Design, adaptation and implementation of the methodology.
   - Guidelines to other future research on the methodology of Six Sigma.
   - Development of a problem-solving process flow.
   - Development of a new concept for Accelerated life and durability testing with application to vehicle door panels.
   - Development of the process flow using the PDCA approach in staging ICA and PCA.

- The optimization of the door panel durability testing methodology and applicability of testing techniques and methodology, tools and equipment.

c) **Empirical Contribution**:

- Based on the Six Sigma Yellow Belt and Green Belt certification courses, conducting all the processes and validation of the problem-solving process and managing complex situations in practice has been possible.
- Case study on the evolution of Six Sigma and the impact on the industrial and educational environment.
- Case study on the Six Sigma product level using DPMO and Process Capability representation with Sigma Level 2.02, which confirms the need for improvement.
- The implementation of the SIPOC process in order to establish transparent input and output data between stakeholders.
- Development of the process flow of the torque measurement method.
- The use of the SPD - 5 Whys, Ishikawa, and Pareto diagram to certify D0-D4 progress.
- The evaluation of the thermal characteristics based on Weibull distribution and Arrhenius' law. The assessment was designed to determine the level of exposure to temperature and the time of degradation.
- Development of the durability life testing pneumatic rig setting and wiring in accordance with the testing requirement and PLC Alpha program.
- Design, documentation and carrying out the accelerated life tests and all measurements presented in the thesis, in the climate test laboratory.
- Testing design, collection and analysis of testing results following the Torque, Gap and Flushness Engagement and release load measurements.
- Histogram, Time series plot, run chart, Scatter Plot, Probability plot, Bubble plot, Tolerance interval, C chart, and Pie chart representation of results using Minitab Six Sigma Software.
- The use of KPI for graphical representation of team results.
- Identification of lessons learnt, ensuring that lessons learned and points of escape are captured to prevent recurrence.

d) **Data Collection Contribution**:

- Invaluable information provided for future studies. Critical evaluation of data sources: researcher works and case studies.
- Quality evaluation of data sources. Based on learning to use Axure RP 10 software, all the flow processes in the thesis were developed.
- Data acquisition for the testing process and the presentation of the methods related to the Accelerated life tests.
- The defining and analysing the customer complaints through TIS, MIS, Country sold and type of issues.
- Documentation and organization of testing procedures, validation of procedures, interpretation of results using Alpha PLC, HBM Catman (data Acquisition), Quantum (hardware), CANalyser, Axure RP10 and Minitab Six Sigma software.
- Briefing and applicability of techniques and methodology to measure team success.

Future actions and improvements will focus on the following objectives:

Components	Improvements	Actions
Door Lock	The affected vehicles were recalled to service	The problem is in Design Verification and CAE virtual analysis
	All vehicles in the same series are analysed for the same problem - a first cause was identified being the tolerances between the fasteners.	
	Waterproof spray remover in frozen condition	
Top Roll	The identified problem was reanalysed and resolved by adding the layer of fibre to the leather surface.	Lesson Learned; A fix is available and has been demonstrated as 100% effective; A communication has been issued through Technical Service Bulletin; A prevent re-occurrence action (D7) is completed.
Door Glass	The door glass was fixed by adding glue to the door trimming.	Lesson Learned; A fix is available and has been demonstrated as 100% effective; A communication has been issued through Technical Service Bulletin; A prevent re-occurrence action (D7) is completed.

Developing a new component or system requires additional time, resources and costs. Problems identified during the process have resulted in significant results due to the fact that non-compliant components have been replaced or reworked, customer vehicle can be fixed at the retailer, thus eliminating additional costs and delays in the process. At the same time, having an important impact in identifying gaps in the process and optimizing the problem-solving process. All the steps taken in solving the problems had a significant impact on the company and, at the same time, on the engineering team's performance indicators.

Future research will focus on the followings:

- **Standardization of the problem-solving process and of the allocated times**: The flow of the problem-solving process presented in Chapter IV will be validated and approved by the management board and then transposed into other departments.
- **The development of a model for reducing the level of failure during testing when components are exposed to temperatures above 80°C**: The model that will be developed will involve the elaboration of a structural program and its assignment to the climate chamber settings, in order to reduce the level of impact during exposure to high temperatures. A thorough evaluation of the impact factors and adaptability to the new model will be elaborated.
- **Defect analysis by damage and corrosion**: Impact or tensile testing to determine the mechanical properties of materials; Non-destructive ultrasound testing or radiographic testing to locate damage; Chemical analysis (optical emission

spectroscopy); Hardness tests for materials and components (Brinell, Vickers, Rockwell) and Corrosion test.

- **Integration of all testing concepts into a common database**: Creating a common database as an interface between stakeholders to define the type of test and design, planning, organizing and managing test reports. The goal of the database will be data management and information traceability.
- **Conducting 8D and Six Sigma quality studies on other vehicle components and finishes**: Application of the quality study developed in Chapters VI and VII to the other components on the vehicle body, reported in the related development or industrialization process. Develop a strategy to minimize the repeatability of non-compliance.

Research methodology and main findings may be transferred to other components in automotive industry, but to other industries too, as follows:

- **Problem awareness**: Identifying and defining the problem has an essential role in product investigation and concern initiation as the first answer to the customer's concern. The traceability of information between stakeholders facilitates the process of solving the problem and establishing the investigation team.
- **Identifying the most suitable tests**: Potential factors involved in product degeneration can be identified by replicating the problem using validation tests. Accelerated Life tests have high applicability in various industries, especially for polymer products. ALT includes: Key Life Test, Environmental Test, Heat Aging Test, Humidity Test, Corrosion Test, Warranty test, Fatigue testing etc. The results of ALT have a 90% reliability and 80% confidence level according to Ansys - Life prediction setup.
- **Documentation and implementation of testing procedures**: Six Sigma concepts are applicable in any industrial field and create sustainable continuous improvement. Testing standards, testing procedures and work instructions have a massive contribution in different industries, with applicability in product life testing. Test documentation stands for test strategy, test data, test plans, test types, test case studies, test measurements, and test report results.
- **Instrumentation Setup**: Development and design of pneumatic test rigs can be accommodated to several different technologies, with fully integrated control and instrumentation for measuring and certifying complete systems and components, with applicability to the following industries: Automotive, Research and development of materials, Aerospace, Civil Engineering, Injection Moulding, Equipment for agriculture etc.
- **Application of test software for analysis of results**: Using software to test components and systems helps prevent errors, improve performance, and reduce development costs. The application of validation software has given excellent results in applied computing, engineering and physical sciences.
- **Team level communication of the results obtained**: Validating the results within the team is essential, having a great impact on every activity in the process. Measuring team success is beneficial for motivating the team and validating performance indicators as a quality standard.

Reference

[A01] A. Alowad, P. Samaranayake, K. Ahsan, H. Alidrisi and A. Karim (2021). Enhancing patient flow in emergency department (ED) using lean strategies–an integrated voice of customer and voice of process perspective, Business Process Management Jour, Vol. 27 No. 1, pp. 75-105.

[A02] A.B. Subramaniyan (2020). Reliability Assessment Methodologies for Photovoltaic Modules, Dissertation or Thesis.

[A03] A. Chiarini (2012). Book: From total quality control to lean six sigma: evolution of the most important management systems for the excellence, Springer.

[A04] A. Chiarini (2011). Japanese Total Quality Control, TQM, Deming's System of Profound Knowledge, BPR, Lean and Six Sigma, International Journal of Lean Six Sigma, Vol. 2, no. 4, pp. 332-355, Emerald Insight.

[A05] A. Douglas, S. Middleton, J. Antony, S. Coleman (2009). Enhancing the Six Sigma problem-solving methodology using the systems thinking methodologies, International Journal of Six Sigma and Competitive Advantage. DOI: 10.1504/IJSSCA.2009.025166

[A06] A. Pugna, R. Negrea and S. Miclea (2016). Using Six Sigma Methodology to Improve the Assembly Process in an Automotive Company, Procedia - Social and Behavioural Sciences, Vol. 221, pp. 308-316.

[A07] A. Romle, A. Salleh, M. Zakaria, S. Zakinuddin, M. Zolkepli and R. Daud (2016) The Effects of TQM Practices on Organizational Culture: A New Movement. World Applied Sciences Journal 34 (5): 553-560, ISSN 1818-4952 © IDOSI Publications.

[A08] A. S. Patel, K. M. Patel (2021). Critical review of literature on Lean Six Sigma methodology, International Journal of Lean Six Sigma.

[B01] B. A. Lameijer, J. De Mastm and R. J.M.M. Does (2017). Lean Six Sigma Deployment and Maturity Models: A Critical Review, Quality Management Journal. https://doi.org/10.1080/10686967.2017.12088376

[B02] B. Cazzell and J. M. Ulmer (2009). Measuring Excellence: A Closer Look at Malcolm Baldrige National Quality Award Winners in the Manufacturing Category", Journal of Technology Management & Innovation v.4 n.1.

[B03] B. Lindqvist (2015). Accelerated lifetime models - at NTNU.

[B04] B. Marr (2010). Book: The 10 biggest mistakes companies make with KPIs.

[B05] B. R. Krishnan and K. A. Prasath (2013). Six Sigma concept and DMAIC implementation, International Journal of Business Management & Research (IJBMR) ISSN 2249-6920, Vol. 3, Issue 2, pp. 111-114.

[C01] C. A. Riesenberger and S. D. Sousa (2010). The 8D Methodology: An Effective Way to Reduce Recurrence of Customer Complaints? Proceedings of the World Congress on Engineering, Vol III, WCE 2010.

[C02] C. Fragassa and A. Pavlocic (2014). Using a Total quality strategy in a new practical approach for improving the product reliability in automotive industry, International Journal for Quality Research, 8(3) 297-310, ISSN 1800-6450.

[C03] C. Stokes-Brown (2014). The Industrial Revolution, World History Project.

[C04] C.V. Kifor (2006). Book: Quality engineering: 6 sigma improvement (Ingineria calităţii: îmbunătăţirea 6 sigma), University Lucian Blaga, ISBN 9737390350

[C05] C.V. Kifor and N. Tudor (2013). Quality System for Production Software as tool for monitoring and improving organization KPIs, International Journal of Computers, Communications and Control, ISSN 1841-9836, E-ISSN 1841-9844, Vol. 8, No. 2, pp. 236 – 247.
[C06] C.V. Kifor, C. Oprean, C. Alexe, L. Lobont (2011) Process based architecture for organization reengineering. Proceedings of the 1st International Conference on Quality and Innovation in Engineering and Management, ISBN 978 –973 – 662 – 614 – 2.
[D01] Dr. L. Freeman (2011). Accelerated Life Testing, Tutorial with NASA and DOD Applications, Institute for Defense Analyses.
[D02] D. M. Buede (2009). Book: The Engineering Design of Systems: Models and Methods, Second Edition, Wiley Series in Systems Engineering and Management.
[D03] D. M. Buede and W.D. Miller (2016). Book: The Engineering Design of Systems, Third Edition, Wiley Series in Systems Engineering and Management.
[D04] D. Rodriguez (2020). The Evolution of Six Sigma.
[D05] D. W. Benbow and A. Zarghami (2017). Introduction To 8D Problem Solving (E-Book). ISBN: 978-0-87389-955-0
[E01] E Gijo, S. Bhat, and N.A. Jnanesh (2014). Application of Six Sigma methodology in a small-scale foundry industry, International Journal of Lean Six Sigma, Vol. 5 No. 2, pp. 193-211.
[E02] E. Lascu, F.D. Lascu, F. Stinga and I. Severin (2020). Process redesign to reduce stocks of obsolete parts in automotive industry, Quality Access to Success, vol. 21, nr. 178, pp. 43-49.
[E03] E. P. W. M. Veenendaal and G. Bath (2013). Book: Improving the Test Process: Implementing Improvement and Change - A Study Guide for the ISTQB Expert Level Module.
[E04] E. Shevtshenko (2014). Quality improvement methodologies for continuous improvement of production processes and product quality and their evolution, 9th International DAAAM Baltic Conference Industrial Engineering 24-26 April.
[E05] E. Swan and T. O'Rourke (2018). Book: The Problem-Solver's Toolkit: A Surprisingly Simple Guide to Your Lean Six Sigma Journey, Independently Published.
[E06] E. Tippmann, P. S. Scott and V. Mangematin (2012). Problem solving in MNCs: How local and global solutions are (and are not) created, Journal of International Business Studies, Vol. 43, No.8, pp. 746-771.
[F01] F. Dia, N. Mbengue, O. Sarr, M. Diagne, M. Niasse, A. Dieye, M. Niang, B. Ba and C. Sene (2016). Model Associated with the Study of the Degradation Based on the Accelerated Test: A Literature Review. Open Journal of Applied, S. 6, 49-63.
[F02] F. Franceschini, D. Maisano and L. Mastrogiacomo (2015). Customer requirement prioritization on QFD: a new proposal based on the generalized Yager's algorithm, Research in Engineering Design volume 26, pages171–187.
[F03] F. Juliani, O. J. Oliveira (2020). Lean Six Sigma principles and practices under a management perspective, Journal Production Planning and Control, Vol.3, pp.1223-1244.
[F04] F. Stinga, I. Severin, I.A. Mitrache and E. Lascu (2020). Redesign of the curing area of the tire manufacturing process. Sustainability, MDPI, Vol. 12, Issue 17, 6909.
[F05] F. W. Taylor (2013). The Principles of Scientific Management 1910, Ch. 2: The Principles of Scientific Management Excerpts, National Humanities Centre.
[G01] G. Arcidiacono and A. Pieroni (2018). The Revolution Lean Six Sigma 4.0, International Journal on Advanced Science Engineering, Vol. 81, No. 1, ISSN: 2088-5334.

[G2] G. Belforte, A. M. Bertetto and L. Mazza (2012). Test rig for friction force measurements in pneumatic components and seals, Proceeding of the Institution of Mechanical engineering. Part J, Journal of Engineering Tribology, vol. 227 n. 1, pp. 43-59. ISSN 1350-6501.

[G03] G. Yadav, T. N. Desai (2016). Lean Six Sigma: a categorized review of the literature, International Journal of Lean Six Sigma.

[H01] H. Hiraoka, T. Tanakaa, T. Sugaharaa and H. Saitoa (2021). Assembly model of mechanical products for their life cycle simulation, 28th CIRP Conference on Life Cycle Engineering, Procedia CIRP 98, 553–55.

[H02] H. Lester (2018). Systems Engineering: Enabling Operations Management, Books: Contemporary Issues and Research in Operations Management. DOI: 10.5772/intechopen.76224

[H03] H. Molker, R. Gutkin and L. E. Asp (2019). Industrial Framework for Identification and Verification of Hot Spots in Automotive Composite Structures, SAE International Journal of Materials and Manufacturing, Vol. 12, No. 22, pp. 107-120.

[I01] I.A. Mitrache, F. Stinga, and I. Severin (2020). Continuous improvement in practice within oil and gas industry, Quality Access to Success, vol. 21, nr. 175, pp. 52-58.

[I02] I. Bass, Book: Six Sigma Statistics with Excel and Minitab, McGraw-Hill Professional Pub; 2nd edition. 2015.

[I03] I. Severin, M.F. Ilinca, B. Dumitru and M. Caramihai (2018). Productivity increases through carousel posts balance for engine wiring fabrication: A Business Process Reengineering, Case Study, Proc. 32nd IBIMA, Seville, pp 1420-1431.

[J01] J. A. Garza-Reyes (2015). Green lean and the need for Six Sigma International Journal of Lean Six Sigma, Vol. 6 No. 3, pp. 226-248. https://doi.org/10.1108/IJLSS-04-2014-0010

[J02] J. Antony, "Lean Six Sigma for higher education", International Journal of Productivity and Performance Management, 2017.

[J03] J. Antony, M. Sony, M. Dempsey, A. Brennan, T. Farrington and E. A. Cudney, "An evaluation into the limitations and emerging trends of Six Sigma: an empirical study", The TQM Journal, 2019.

[J04] J. Antony, R. Snee, R. Hoerl, "Lean Six Sigma: yesterday, today and tomorrow, International Journal of Quality & Reliability Management, Vol. 34 No. 7, pp. 1073-1093, 2017.

[J05] J. A. Defeo, J.M. Juran, Juran's Quality Handbook: "The complete guide to Performance Excellence, McGraw-Hill Professional", 2010.

[J06] J. A. Defeo and W. Barnard, Book: "Juran Institute's Six Sigma Breakthrough and Beyond: Quality Performance Breakthrough Methods", 2003.

[J07] J. de Mast, J. Lokkerbol. "An analysis of the Six Sigma DMAIC method from the perspective of problem solving", International Journal of Production Economics, Vol. 139, Issue 2, pp. 604-614, 2012. https://doi.org/10.1016/j.ijpe.2012.05.035

[J08] J. Gangai and G.R. Naik (2014). Process Optimization by using Lean Manufacturing Technique (Six Sigma) – A Case Study in Manufacturing Industry, International Journal of Innovations in Engineering and Technology, ISSN: 2319 – 1058.

[J09] J. Goding and M. Hammer (2001). Putting Six Sigma in Perspective, Quality, Vol. 40, No. 10, pp. 58-62.

[J10] J. E. Ross, Book: Total Quality Management, Text, Cases, and Readings, Third Edition. 2017. https://doi.org/10.1201/9780203735466

[J11] J. Jeston and J. Nelis (2006). Business Process Management: Practical Guidelines to Successful Implementations, Butterworth-Heinemann.

[J12] J.M. Juran (2003). Book: Juran on Leadership for Quality, Simon and Schuster.
[J13] J. Potkalitsky and J. Novak (2017). Putting the RS into DMAIC, The Center for Corporate and Professional Development, Kent State Facilitators.
[J14] J. R. Vest and L. D. Gamm (2009) A critical review of the research literature on Six Sigma, Lean and Studer Group's Hardwiring Excellence in the United States: the need to demonstrate and communicate the effectiveness of transformation strategies in healthcare, Implementation Science Vol. 4, Art: 35.
[J15] J. van Iwaarden, T. van der Wiele, B. Dale, R. Williams and B. Bertsch (2008). The Six Sigma improvement approach: a transnational comparison, International Journal of Production Research. https://doi.org/10.1080/00207540802234050
[L01] L. A. P. Carmona (2019). A Graphical Approach for Interpreting Out-of-Control Signals in Multivariate Control Charts.
[L02] L. Bertolaccini, A. Viti and A. Terzi (2015). The Statistical point of view of Quality: The Lean Six Sigma methodology. Doi: 10.3978/j.issn.2072-1439.2015.04.11
[L03] L. B. Weinstein, J. A. Petrick, J. Castellano and R. Vokurka (2018). Integrating Six Sigma Concepts in an MBA Quality Management Class, The Journal of Education for Business 83(4):233-238. DOI: 10.3200/JOEB.83.4.233-238
[L04] L. Fonseca, D. Leite, V. Lima (2014). Six Sigma methodologies: Implementation and impacts on Portuguese small and medium companies (SMEs), International Journal for Quality Research.
[L05] L. M. Klyatis (2012). Book: Accelerated Reliability and Durability testing technology, Wiley series in System Engineering and Management, Published by John Wiley & Sons, Inc., Hoboken.
[L06] L. Ramanan, Dr M. Kumar and Dr K. Ramanakumar (2014). Six Sigma - DMAIC Framework for Enhancing Quality in Engineering Educational Institutions". International Journal of Business and Management Invention. ISSN (Online): 2319 – 8028, ISSN (Print): 2319 – 801X, www.ijbmi.org Vol. 3 Issue 1, pp.36-40.
[M01] M. Aboelmaged (2010). Six Sigma quality: A structured review and implications for future research, International Journal of Quality & Reliability Management 27(3):268-317.
[M02] M. Barney (2002). Motorola's Second Generation, American Society for Quality.
[M03] M. B. Santos (2019). The Integration of Six Sigma and Lean Manufacturing, Lean Manufacturing and Six Sigma.
[M04] M. Esmaily, M. Ström, J.E. Svensson, M. Halvarsson and L.G. Johansson (2015). Corrosion Behavior of Alloy AM50 in Semisolid Cast and High-Pressure Die Cast States in Cyclic Conditions, NACE International.
[M05] M. G. Aboelmaged (2010). Six Sigma quality: a structured review and implications for future research, International Journal of Quality and Reliability Management.
[M06] M. Hasan and M Chiu (2016). The History and Development of Six Sigma Quality Management, School of Mechanical and Manufacturing Engineering, Proceedings of the International Conference on Industrial Engineering and Operations Management.
[M07] M. Hekmatpanah, M. Sadroddin, S. Shahbaz, F. Mokhtari and F. Fadavinia (2008). Six Sigma Process and its Impact on the Organizational Productivity, World Academy of Science, Engineering and Technology 43.

[M08] M. Koripadu, K. V. Subbaiah (2014). Problem Solving Management Using Six Sigma Tools & Techniques". International Journal of Scientific and Technology Research, Vol. 3, Issue 2, ISSN 2277-8616.
[M09] M. L. George (2002). Book: Lean Six Sigma: Combining Six Sigma Quality with Lean Production Speed, McGraw-Hill.
[M10] M. Miletić and I. Miletić (2017). Lean Methodology and its derivates usage for production systems in modern industry, Applied Engineering Letters, Vol.2, No.4, pp.144-148.
[M11] M. M. Parast (2011). The effect of Six Sigma projects on innovation and firm performance, International Journal of Project Management, Vol. 29, Issue 1, pp. 45-55.
[M12] M. Murray (2018). Supply chain management/ operations, Lean Six Sigma.
[M13] M. P. Aristigueta (2008). The Integration of Quality and Performance, International Handbook of Practice-Based Performance Management.
[M14] M. Patel, D. A. Desai (2018). Critical review and analysis of measuring the success of Six Sigma implementation in manufacturing sector", International Journal of Quality & Reliability Management.
[M15] M. Radley (2015). A3 Practical Problem Solving-Principal Document, GENEO Consulting Limited.
[M16] M. Sharma, S. Sharma and S. Sahni (2020). Structured Problem Solving: combined approach using 8D and Six Sigma - case study, Engineering Management in Production and Services 12(1):57-69.
[M17] M. Sokovic, D. Pavletic and K. K. Pipan (2010). Quality Improvement Methodologies – PDCA Cycle, RADAR Matrix, DMAIC and DFSS. The Journal of Achievements in Materials and Manufacturing Engineering.
[M18] M. Singh and R. Rathi (2018). A structured review of Lean Six Sigma in various industrial sectors", International Journal of Lean Six Sigma.
[M19] M. Sony, J. Antony, S. Park and M. Mutingi (2020). Key Criticisms of Six Sigma: A Systematic Literature Review, IEEE Transactions on Engineering Management, Vol. 67, Issue 3
[M20] M. T. Patel (2017). Six Sigma in Service Organization – A Critical Review", International Conference on Emerging Trends in Mechanical Engineering.
[M21] M. Wojtaszak and W. Biały (2015). Problem solving techniques as a part of implementation of Six Sigma methodology in tire production. Case study, Management Systems in Production Engineering, nr 3 (19) 133—137.
[O01] O. Busche (2015). The Lazy Leader's Toolbox: Root Cause Countermeasures RCCM.
[P01] P. B Sangode and H. R. Hedaoo (2018). Six Sigma in Manufacturing Industries: Barriers to Implementation. Amity Journal of Operations Management, 3 (1), (12-25).
[P02] P. Jirasukprasert, J. A. Garza-Reyes, H. Soriano-Meier and L. Rocha-Lona (2012). A Case Study of Defects Reduction in a Rubber Gloves Manufacturing Process by Applying Six Sigma Principles and DMAIC Problem Solving Methodology, International Conference on Industrial Engineering and Operations Management.
[P03] P. Nonthaleerak and L.C. Hendry (2006). Six Sigma: literature review and key future research areas, International Journal of Six Sigma and Competitive Advantage.
[P04] P. Pusporini, K. Abhary and L. H.S. Luong (2012). Environmental Performance as Key Performance Indicators in the Lean Six-Sigma Methodology, Advanced Materials Research (Volumes 488-489).
[P05] P. S. Pande (2001). Book: What is Six Sigma, McGraw-Hill.

[Q01] Quality and Productivity Research Conference (2021). NISS, niss.org
[R01] R. Andersson, H. Eriksson and H. Torstensson (2006). Similarities and differences between TQM, Six Sigma and Lean, The TQM Magazine.
[R02] R. Basu (2011). Fit Six Sigma, A Lean Approach to Building Sustainable Quality Beyond Six Sigma, A John Wiley and Sons, Ltd., Publication.
[R03] R Bhargav (2021). History and Evolution of Six Sigma.
[R04] R. Cyert and J. March (1963). Book: Behavioral theory of the firm.
[R05] R. D. Snee and R. Hoerl (2017). Time for Lean Six Sigma 2.0? Quality Progress 50-53.
[R06] R. L. Vitalo (2016). Deming Revisited: The Real Quality Model for Commerce.
[R07] R. Mann (2008). Revisiting a TQM research project: The quality improvement activities of TQM, In Honor of Professor Kanji's 70th Birthday. Total Quality Management & Business Excellence, Vol. 19, Issue 7-8.
[R08] R. McAdam, S.A. Hazlett and J. Henderson (2005). A critical review of Six Sigma: exploring the dichotomies, International Journal of Organizational Analysis.
[R09] R. Rohan (2014). Efficient management methods specific to production systems. Six Sigma Methodology - Quality Management Course (Metode eficiente de management specifice sistemelor de producţie. Metodologia Six Sigma - Curs Managementul Calităţii).
[R10] R. Sorensen (2010). Accelerated Life Testing - presentation, Sandia National Labs.
[S01] S. Albliwi, J. Antony, S. A. H. Lim and T. van der Wiele (2014). Critical failure factors of Lean Six Sigma: a systematic literature review", International Journal of Quality & Reliability Management.
[S02] S. Barone, E. Lo Franco (2012). Book: Statistical and Managerial Techniques for Six Sigma Methodology: Theory and Application, John Wiley & Sons.
[S03] S. Bisgaard and J. D. Mast (2006). After Six Sigma -What's Next? Quality Progress.
[S04] S. Furterer (2009). Book: Lean Six Sigma in Service, Applications and Case Studies.
[S05] S. M. Sapuan (2005). A Conceptual Design of the Concurrent Engineering Design System for Polymeric-Based Composite Automotive Pedals, American Journal of Applied Sciences.
[S06] S. N. Selvaraj (2013). Applying Six Sigma for Quality Management in Educational Institutions, Global Business and Management Research: An International Journal 2(1):70-74.
[S7] S. S. Chakravorty (2010). Where Process-Improvement Projects Go Wrong", Wall Street J.
[S08] S. Kadry (2013). Six Sigma Methodology for the Environment Sustainable Development, Mechanism Design for Sustainability pp 61-76.
[S09] S. Vinay Seeba, S. Srikari and V. K. Banthia (2010). Design and analysis of a plastic door module for car body application, Microsoft Word - sasTech V9I1. Volume 9, Issue 1.
[T01] T. M. Fehlmann (2016). Book: Managing Complexity: Uncover the Mysteries with Six Sigma Transfer Functions.
[T02] T.M. Kubiak and D. W. Benbow (2016). The Certified Six Sigma Black Belt Handbook, Third Edition. Hardcover, 946 pages. ISBN: 978-0-87389-941-3
[T03] T. Pyzdek and Paul Keller (2014). Six Sigma Handbook, Fourth Edition, McGraw-Hill Education. ISBN: 9780071840538
[T04] T.T. Allen (2019). Book: Introduction to Engineering Statistics and Lean Six Sigma, Statistical Quality Control and Design of Experiments and Systems.
[V01] V. Majstorovic and N. Stefanovic (2005). Six Sigma — the Methodology for Achieving Total Business Excellence, Published in: E. Kuljanic (Ed.) Advanced Manufacturing Systems and Technology, CISM Courses and Lectures No. 486, Springer Wien New York.

[W01] W.H. Chen, L. Gao, J. Pan, P. Qian and Q.C. He (2018). Design of Accelerated Life Test Plans - Overview and Prospect, Chinese Journal of Mechanical Engineering vol. 31, Art. 13.
[W02] W. Nelson (2004). Book: Accelerated Testing: Statistical Models, Test Plans, and Data Analysis, Volume 550 of Wiley Series in Probability and Statistics.
[W03] W. Shewhart and W. E. Deming. The journal Quality Technology and Quantitative Management" published a special issue in on Advances in the Theory and Application of Statistical Process Control. ISSN 1684-3703.
[X01] X. Zu, L. D. Fredendall and T. J. Douglas (2008). The evolving theory of quality management: The role of Six Sigma, Journal of Operations Management, Vol. 26, Issue 5, pp. 630-650.
[Y01] Y. H. Kwak and F. T. Anbari (2006). Benefits, obstacles, and future of Six Sigma approach, Tec novation Vol. 26, Issues 5–6, pp. 708-71.
[Y02] Y. Wooluru, S. D.R and P. Nagesh (2014). The process capability analysis – a tool for process performance measures and metrics – a case study, International Journal for Quality Research 8(3) 399-416, ISSN 1800-6450.
[Z01] Z. Zhuo (2019). Research on using Six Sigma management to improve bank customer satisfaction, Zhuo International Journal of Quality Innovation.
[***01] Accelerated Life Testing Reference (2015). ReliaSoft Corporation.
[***02] ASTM D3045 https://www.micomlab.com/micom-testing/astm-d3045/
[***03] Basic Force Gauge https://www.dmv-uk.com/specsheets/373.pdf
[***04] Feeler Gauge https://www.gerotools.ro
[***05] Cad door trim [https://grabcad.com/library/car-door—1]
[***06] Gap and Step https://www.stepgauge.com/
[***07] Green Belt training module (2018). Product Engineering Six Sigma Team.
[***08] IATF 16949:2016 Quality management system for organizations in the automotive industry.
[***09] ISO/IEC/IEEE 15288:2015(en) Systems and software engineering — System life cycle processes.
[***10] ISO/IEC 17025:2017 General requirements for the competence of testing and calibration Laboratories.
[***11] Millbrook - Vehicle Environmental Testing Services | Millbrook | Specification Sheet.
[***12] PLC https://www.unitronicsplc.com
[***13] Programming and Problem Solving through C Language O Level / A Level, Chapter -2: Flowcharts for Problem Solving.
[***14] Project: Lean Six Sigma (2010). Lean Six Sigma – getting better all the time, International Journal of Lean Six Sigma 1(1):9-29 Follow journal.
[***15] Renewing door hinge pins and hinges https://www.howacarworks.com
[***16] Six Sigma Yellow Belt certification course.
[***17] The Council for Six Sigma Certification (2018). www.sixsigmacouncil.org
[***18] Torque Wrench https://www.machinemart.co.uk
[***19] Vernier Calliper https://www.dm-tools.co.uk