Acta Nat. Sci. (2026) 7(1): 1-17
DOI: 10.61326/actanatsci.v7i1.370
e-ISSN: 2718-0638

Review Article
info@actanatsci.com
www.actanatsci.com

ACTA NATURA ET SCIENTIA PRENSIP

The Origin and Development of FMEAs in the North American Automotive Industry: A History Review

Matthew Barsalou[1]✉

[1] QPLUS, Bahrain Financial Harbour, Level 22, West Tower, P.O. Box 20705, Manama, Bahrain; matthew.a.barsalou@gmail.com

✉ Corresponding Author: matthew.a.barsalou@gmail.com

Please cite this paper as follows:
Barsalou, M. (2026). The Origin and Development of FMEAs in the North American Automotive Industry: A History Review. *Acta Natura et Scientia*, *7*(1), 1-17. https://doi.org/10.61326/actanatsci.v7i1.370

ARTICLE INFO

Article History
Received: 29.05.2025
Revised: 04.10.2025
Accepted: 25.10.2025
Available online: 25.02.2026

Keywords:
Failure Modes and Effects Analysis
FMEA
Automotive industry
Risk analysis
Standards

ABSTRACT

The concept of Failure Modes and Effects Analysis has been around for almost three-quarters of a century, yet many authors give contradictory dates for the origin of the Failure Modes and Effects Analysis and different dates for the spread of Failure Modes and Effects Analysis in the automotive industry. This paper seeks to establish a timeline for the development of Failure Modes and Effects Analysis and Failure Modes and Effects Analysis usage in the North American automotive industry. This paper uses a historical review. Literature was identified and reviewed to document the development of the Failure Modes and Effects Analysis in the North American automotive industry using primary sources. The first standard for the Failure Modes and Effects Analysis was MIL-P-1629 in 1949. Failure Modes and Effects Analysis were used in the aerospace industry in the 1950s and the usage of Failure Modes and Effects Analysis at Ford Motor Company in 1972 and Toyota in 1975 has been confirmed. Automotive companies mandated use of the Failure Modes and Effects Analysis in the 1980s and automotive industry-specific standards were released in the 1990s and revised over the years. This paper contributes a timeline of key Failure Modes and Effects Analysis related events that is supported by documented evidence.

INTRODUCTION

An FMEA (Failure Modes and Effects Analysis) is widely used in industry (Xiao, 2011) and may be a PFMEA (Process Failure Modes and Effects Analysis) for a process or a DFMEA (Design Failure Modes and Effects Analysis) for a design (Anleitner, 2011). The FMEA is "a step-by-step approach for identifying all possible failures in a design, a manufacturing or assembly process, or a product or service" (Fonseca et al., 2015). The use of an FMEA is helpful for improving both the quality of products and delivery performance by preventing problems in both design and manufacturing (Ghadge et al., 2017).

The topic of FMEAs is well researched. For example, Zulfiqar et al. (2025) investigated the use of FMEAs in institutions of higher learning and Ali et al.

(2025) explored the use of FMEAs for the management of risks in cross-country pipelines when using Geographic Information Systems (GIS). Darmawan (2025) explains the use of FMEAs for Islamic banking product marketing Tangestani et al. (2025) describe the use of FMEAs as part of an indoor air pollutant risk assessment model for healthcare. Singh (2025) describes the application of FMEAs for improving work-life balance (WLB) in the healthcare sector in India and Kar & Rai (2025) describe the application of a fuzzy FMEA for a Six Sigma risk assessment in Quality 4.0. Risk prioritization in sustainable shipbuilding was described by Yılmaz & Köse (2025) using the integration of FMEAs and machine learning and Gandhare et al. (2025) describe the use of FMEAs for the development and validation of a medical equipment framework in Industry 4.0.

The origin of FMEAs is well-documented in the literature; however, much of the literature is contradictory. The first use of FMEAs has been attributed to the U. S. military in the 1940s (Manos & Vincent, 2012). Korenko et al. (2012) state that FMEAs started in 1949 with MIL-P-1629 and were then used in 1963 for NASA’s Apollo program before entering the automotive industry through Ford in 1973.

According to Hatty & Owens (1994), the “FMEA was developed during the early 1960s in the U.S. aerospace industry” and the U.S. Department of the Army also credits NASA with developing the concept of FMEAs (2006). Sharma et al. (2007) attribute the origin of FMEAs to NASA in 1963. The development of FMEAs has also been attributed to the U.S. Navy’s Bureau of Aeronautics in the early 1950s (Dhillon, 2003).

Ginn et al. (1998) attribute the origin of FMEAs to the aerospace industry in the mid-1960s and Plinta et al. (2021) state FMEAs were “born in the 1950s for the needs of the arms industry”. The origin of FMEAs has also been attributed to the Grumman Aircraft Corporation in the 1950s (Bowles, 2002; Sharma & Sharma, 2010).

According to SAE (2009), FMEAs have been in use in the automotive industry since the 1960s, but the use of standard criteria for ranking and standard forms did not arrive till the 1990s. Carlson (2015) explains that Ford introduced the world to the automotive industry in the late 1970s due to the Ford Pinto situation and Anleitner (2011) states that the use of FMEAs became widespread at Ford in the mid-1970s due to the Pinto situation.

This paper seeks to establish a definitive timeline for the origin and development of FMEAs in the North American automotive industry.

An FMEA may be for a complete system, the design of a product, a manufacturing or assembly process (Carlson, 2015), or a service (Doshi & Desai, 2016). An FMEA uses multi-functional teams with members from various departments, such as quality, reliability, design, and manufacturing to identify and prevent failures before they occur (Maisano et al., 2020).

Failure modes, failure causes, and failure effects are identified in an FMEA. The failure mode is the way in which a process or product fails to fulfill the intended function of the product or process. Failure causes are what lead to the failure mode and failure effects are the consequence of the failure mode (Pillay & Wang, 2003). The failure effects may be identified for a component, subassembly, or complete system. Prevention actions are identified to prevent the failure cause and detection actions are identified to detect the failure mode or failure cause (Correia dos Santos et al., 2012).

The severity is rated with a value from one to ten based on how bad the consequences of the failure are. The occurrence of the failure cause is rated on a scale of one to ten based on how well the failure cause can be prevented. Detection is also rated on a scale of one to ten based on how well the failure cause or failure mode can be detected. The severity, occurrence, and detection ratings are determined using tables (Maisano et al., 2020). Table 1 depicts a severity table, Table 2 depicts an occurrence table, and Table 3 depicts a detection table. Different standards and different organizations may use different tables.

Table 1. Severity table reproduced from Department of the Army (2006). *TM 5-698-4, Failure Modes, Effects and Criticality Analyses (FMECA) for Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance (C4ISR) Facilities*.

Ranking	Effect	Comment
1	None	No reason to expect failure to have any effect on Safety, Health, Environment or Mission.
2	Very Low	Minor disruption to facility function. Repair to failure can be accomplished during trouble call.
3	Low	Minor disruption to facility function. Repair to failure may be longer than trouble call but does not delay Mission.
4	Low to Moderate	Moderate disruption to facility function. Some portion of Mission may need to be reworked or process delayed.
5	Moderate	Moderate disruption to facility function. 100% of Mission may need to be reworked or process delayed.
6	Moderate to High	Moderate disruption to facility function. Some portion of Mission is lost. Moderate delay in restoring function.
7	High	High disruption to facility function. Some portion of Mission is lost. Significant delay in restoring function.
8	Very High	High disruption to facility function. All of Mission is lost. Significant delay in restoring function.
9	Hazzard	Potential Safety, Health or Environmental issue. Failure will occur with warning.
10	Hazzard	Potential Safety, Health or Environmental issue. Failure will occur without warning.

Table 2. Occurrence table reproduced from Department of the Army. (2006). *TM 5-698-4, Failure Modes, Effects and Criticality Analyses (FMECA) for Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance (C4ISR) Facilities*.

Ranking	Failure Rate	Comment
1	1/10,000	Remote probability of occurrence; unreasonable to expect failure to occur.
2	1/5,000	Very low failure rate. Similar to past design that has, had low failure rates for given volume/loads.
3	1/2,000	Low failure rate based on similar design for given volume/loads.
4	1/1,000	Occasional failure rate. Similar to past design that has had similar failure rates for given volume/loads.
5	1/500	Moderate failure rate. Similar to past design having moderate failure rates for given volume/loads.
6	1/200	Moderate to high failure rate. Similar to past design having moderate failure rates for given volume/loads.
7	1/100	High failure rate. Similar to past design having frequent failures that caused problems.
8	1/50	High failure rate. Similar to past design having frequent failures that caused problems.
9	1/20	Very high failure rate. Almost certain to cause problems.
10	1/10+	Very high failure rate. Almost certain to cause problems.

Table 3. Detection table reproduced from Department of the Army. (2006). *TM 5-698-4, Failure Modes, Effects and Criticality Analyses (FMECA) for Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance (C4ISR) Facilities*.

Ranking	Detection	Comment
1	Almost Certain	Current control(s) almost certain to detect failure mode. Reliable controls are known with similar processes.
2	Very High	Very high likelihood current control(s) will detect failure mode.
3	High	High likelihood current control(s) will detect failure mode.
4	Moderately High	High Moderately high likelihood current control(s) will detect failure mode.
5	Moderately High	Moderate likelihood current control(s) will detect failure mode.
6	Low	Low likelihood current control(s) will detect failure mode.
7	Very Low	Very low likelihood current control(s) will detect failure mode.
8	Remote	Remote likelihood current control(s) will detect failure mode.
9	Very Remote	Very remote likelihood current control(s) will detect failure mode.
10	Almost Impossible	No known control(s) available to detect failure mode.

The severity, occurrence, and detection values are multiplied to derive an RPN (Risk Priority Number) that is used for prioritizing improvements (Doshi & Desai, 2016). A known weakness of FMEAs prioritized using RPN is that severity, occurrence, and detection all have equal weight (Pillay & Wang, 2003; Sharma et al., 2007; Maisano et al., 2020). A solution to this was introduced by AIAG/VDA (2019) with the use of Action Priority (AP) in place of RPN. In place of multiplying severity times occurrence times detection to calculate an RPN for prioritization, AP is derived using tables for severity, occurrence, and detection, with the greatest emphasis on severity, followed by occurrences and then detection with the least emphasis (AIAG/VDA, 2019).

MATERIAL AND METHODS

This paper is a historical review, which is used to follow the history of a topic (Collins & Fauser, 2005). The objective was not to perform a systematic review that seeks to capture all available research. The approach used is a semi-systematic review, which is a method used for gaining an overview or historical events and establishing a timeline (Snyder, 2019). Databases used to identify papers were from Blackwell, Routledge, Elsevier, Taylor and Francis, and Science Direct, as well as American Society for Quality (ASQ's) database of ASQ journals. The search terms included "Failure Modes and Effects Analysis," "Failure Modes Effects and Criticality Analysis," "FMEA," and "FMECA." An internet search was also performed to locate copies of original documents that were identified in the papers that were reviewed. Target documents included copies of original guides and standards, contemporaneous accounts, and firsthand accounts that were published after the event in question. The search objective was to identify the dates of key developments in the history of FMEAs to establish a timeline of developments in FMEAs in the North American automotive industry.

The Emerald Insight database was also used to identify changes over time in the number of publications related to both FMEAs and FMECAs (Failure Mode Effects and Criticality Analysis). The search terms "Failure Modes and Effects Analysis" and "Failure Modes Effects and Criticality Analysis" were both used to identify the number of publications in five-year intervals, starting with 1949, which was the year in which FMECAs were introduced. Using five-year intervals starting in 1949 and ending in the year before the study was performed ensured all possible full years were covered.

The concept of an FMEA was introduced in 1949 by *Procedures for Performing a Failure Mode, Effects and Criticality Analysis Mil-P-1629* (Department of Defense, 1949). An FMECA is much like an FMEA, but uses a criticality calculation (Carlson, 2015). The standard was later canceled in 1963 (Department of Defense, 1963).

An FMEA standard was published in 1966 for the Apollo program and the standard described an FMEA together with a criticality analysis, as well as use of a block diagram. The criticality shown in Eq. 1 was calculated as:

$$C_r = \sum_{n=1}^{j} (\beta \alpha K_E K_A \lambda_G \; t \; \times 10^6)_n \,, \mathrm{n} = 1, 2, 3, \ldots, \mathrm{j} \qquad (1)$$

where C_r is criticality, j is the number of critical failure modes, β is the conditional probability that the failure effects occur if a failure mode has occurred, α is the fraction of failures due to the failure mode, K_E is an environmental factor that adjusts λ_G for the difference between environmental stresses where λ_G was measured and λ_G will be used, K_A is an operational factor that adjusts λ_G for the difference between operational stresses where λ_G was measured and λ_G will be used, λ_G is a failure rate in hours or cycles, t is operating time in hours or cycles, and n is an index summation of critical failure modes of a component (NASA, 1966).

An FMEA standard, *ARP926 Fault/Failure Analysis Procedure*, was published by SAE in 1967 and this was followed by *MIL-STD-1629 (ships) Procedures for Performing a Failure Mode, Effects and Criticality Analysis*, in 1974 (Department of Defense, 1974), which was superseded by MIL-STD-1629a in 1980. MIL-STD-1629A used two approaches for determining criticality. One was a qualitative approach with five levels for when data was unavailable. The levels were:

- Level A - Frequent: Failure probability > 0.20
- Level B – Reasonably probable: Failure probability 0.10 - 0.20
- Level C - Occasional: Failure probability > 0.01 to < 0.10
- Level D - Remote: Failure probability > 0.001 to < 0.01
- Level E - Extremely unlikely – Failure probability < 0.001 (Department of Defense, 1980)

The quantitative approach shown in Eq. 2 used calculated criticality as:

$$C_m = \beta \alpha \lambda_p \; t, \qquad (2)$$

where C_m is the criticality for the failure mode, β is the conditional probability of mission loss, α is the failure mode ratio, λ_p is the part failure rate, and t is operating duration in hours or cycles (Department of Defense, 1980).

Ford Motor Company has been credited with bringing FMEAs into the automotive industry in 1977 (VDA, 2012). However, Termaat & Freeman (1972) mention the use of an FMEA for the development of a crash sensor at Ford Motor Company in 1972 and Durstine (1973) reported on the use of an FMEA for the development of a truck steering system at Ford Motor Company in 1973. The use of a scale of one to ten for rating severity, occurrence, and detection to derive an RPN at Ford Motor Company was described in 1975 for the third generation of the Econoline van by Walsh (1975), who called FMEAs a "key reliability tool" used for design, processes, and services.

The use of FMEAs for the development of catalectic converters at Toyota Motor Company was documented in 1975. The form sheet included function and failure mode as well as columns for the failure effect at the subsystem and at the engine. In place of an RPN, the FMEA used criticality, which was derived by multiplying the intensity of damage with a correction factor for how quickly a repair is expected (Matsumoto et al., 1975)

According to Smith (2005), who retired from Ford Motor Company after 27 years in quality, there was a "Major push on failure modes and effects analysis (FMEA)" at Ford Motor Company between 1977 and 1980. Ford Motor Company released an FMEA training video in 1986 and Jaguar Cars Limited released an instruction guide for FMEAs in 1988 (Aldridge et al., 1991). Ford Motor Company then released *Potential Failure Mode and Effects Analysis in Design (Design FMEA) and for Manufacturing and Assembly Processes (Process FMEA) Instruction Manual* in 1988 (SAE, 2001).

Automotive companies had their own standards for suppliers to fulfill in the early 1990s, which resulted in suppliers needing to conform to multiple standards when delivering to different customers. As a result, QS-9000 was developed for the automotive industry (Fong & Antony, 2001) based on collaboration between Chrysler Corporation, Ford Motor Company, and General Motors Corporation with technical experts (Manos & Vincent, 2012).

The standard *QS-9000* contained automotive industry-specific additions to ISO 9000 and included a requirement for FMEAs (Stamatis, 1996). The standard was introduced in 1994 and mandated use of DFMEAs and PFMEAs and referred readers to *Potential Failure Mode and Effects Analysis Reference Manual* for guidance (Chrysler Corporation et al., 1998).

In addition to *QS-9000*, there were additional automotive industry quality standards worldwide, from organizations such as VDA, EAQF, and AVSQ; therefore, these were harmonized with ISO/TS 16949 (Fong & Antony, 2001). The current version is *IATF 16949:2016* and the use of FMEAs is still mandated (IATF, 2016).

The *Potential Failure Mode and Effects Analysis Reference Manual* was initially released in 1993 and revised multiple times with a fourth and last edition released in 2008 (Chrysler LLC et al., 2008) and then superseded by *AIAG/VDA FMEA Handbook* in 2019 (AIAG/VDA, 2019). A VDA standard for FMEAs in the German automotive industry was released in 1996 and the approach was different than the approach used in the North American automotive industry (Fritzsche, 2011). The release of *AIAG/VDA FMEA Handbook* resulted in a harmonization of VDA and AIAG approaches to FMEAs (Plinta et al., 2021).

A 1988 fact-finding mission to Japan found a widespread use of FMEAs (Atkinson, 1989) and according to Henshall (1989), Ford Motor Company in Europe was using FMEAs to identify special characteristics that would be controlled through Statistical Process Control (SPC) in 1989. The use of FMEAs with RPNs at Garrett Automotive Group in 1991 was described by Aldridge et al. (1991), who reported FMEAs were used due to Original Equipment Manufacturers (OEMs) requiring FMEAs.

Swift & Flynn (1989) recommend the use of a PFMEA with a standardized form sheet. The authors presented an example for a form sheet, which included columns for function, failure mode, mechanism and cause of failure, effect of failure, and one column for current controls, as well as columns for recommend and taken actions and a re-evaluation. However, in place of RPN, the authors used risk priority measure, which was derived by multiplying S for seriousness, D for likelihood of a customer receiving a defect, and P for the probability of an occurrence. The authors also provided an evaluation table with scores ranging from one to five for S, D, and P.

A study by Dale & Shaw (1990) on 78 automotive industry organizations in the United Kingdom found that most organizations only implemented the use of FMEAs due to customer requirements; however, some organizations were seeking to apply FMEAs for continuous improvement. The study also found the need for software for FMEAs. The use of software for FMEAs was also described in 1991 (Webber, 1990).

By 1992, there was also an FMEA guide for the semiconductor industry with RPN, severity, occurrence, and detection evaluation tables and a form sheet comparable (Villacourt, 1992) to later form sheets (Chrysler LLC et al., 2008; SAE, 2009). A 1994 FMEA example displays a form sheet (Hatty & Owens, 1994) that aligns with the later versions of the form sheet (Chrysler LLC et al., 2008; SAE, 2009).

In 1998 MIL-STD-1629A was canceled with a recommendation to refer to national and international documents for FMECA guidance (Department of Defense, 1998) due to a memorandum from the Secretary of Defense instructing the Department of Defense to increase the use of commercial products and commercial practices (SAE, 2001).

The use of a boundary diagram for DFMEAs and process flow chart for PFMEAs was added to the *SAE J1739* in the 2009 version due to increased use of those tools for FMEAs in industry (SAE, 2009). The boundary diagram for DFMEAs and flow chart were both recommended in the 2001 third edition of *Potential Failure Modes and Effects Analysis (FMEA): Reference Manual* (DaimlerChrysler Corporation et al., 2001). The use of a boundary diagram was described as far back as 1992 in a semiconductor industry standard (Villacourt, 1992). The p-diagram (parameter diagram) was included in the fourth edition of *Potential Failure Modes and Effects Analysis (FMEA): Reference Manual (*Chrysler LLC et al., 2008), but was not mentioned in 2002 edition of *SAE J 1739* (SAE, 2002).

The approach to FMEAs used in *Potential Failure Modes and Effects Analysis (FMEA): Reference Manual* and the German *VDA Volume 4* differed significantly, resulting in two sets of FMEA standards. This was remedied with a harmonized approach in *AIAG/VDA FMEA Handbook* released in 2019 (Plinta et al., 2021). The *Potential Failure Modes and Effects Analysis (FMEA): Reference Manual* used flow charts for PFMEAs and boundary diagrams and p-diagrams for DFMEAs with a simple form sheet (Chrysler LLC et al., 2008). The VDA approach did not use boundary diagrams and p-diagrams for DFMEAs and flow charts for PFMEAs. Instead, a structure analysis was performed to break products and processes down from the complete system to the individual elements. A function analysis was then performed to assign functions to every level of the product or process. A failure analysis was then performed to assign failures to functions (VDA, 2012). The VDA approach was more complicated and required the use of software.

AIAG/VDA Failure Modes and Effects Handbook harmonized AIAG and VDA approaches with a new approach that could be done either using a spreadsheet, or in FMEA software. The VDA structure, function, and failure analysis are required; however, they can either be performed in FMEA software or completed in the form sheet. The use of a boundary diagram and p-diagram for DFMEAs is only needed if a structure tree and function tree created in FMEA software is not used. For PFMEAs, a structure tree in software can be used, or a flow chart for PFMEAs that are not created in FMEA software. In place of an RPN, an AP is used for prioritization (AIAG/VDA, 2019).

The standard SAE J1739 was updated in 2021 with the release of *Surface Vehicle Standard J1739: (R) Potential Failure Mode and Effects Analysis (FMEA) Including Design FMEA, Supplemental FMEA-MSR, and Process FMEA*. The update included boundary diagrams, p-diagrams, and flow charts. The update also included *AIAG/VDA FMEA Handbook* severity, occurrence, and detection tables as well as AP tables for determining AP, but with the option to choose between use of AP or RPN (SAE, 2021).

RESULTS

The first FMEA standard was *MIL-P-1629* released by the U.S. Department of Defense in 1949. A standard was released by NASA in 1966, which was followed by an SAE standard for aerospace, *SAE ARP 926* in 1967. The U. S. Department of Defense *released MIL-STD-1629 (ships)* in 1974, which was canceled and later replaced by *MIL-STD-1629A*.

The use of FMEAs in the automotive industry in the early 1970s was confirmed with a publication describing the use of FMEAs at Ford Motor Company in 1972 (Termaat & Freeman, 1972) and Toyota Motor Company in 1975 (Matsumoto et al., 1975). FMEAs were used in the automotive industry in the 1980s (Aldridge et al., 1991) and Fong & Antony (2001) explain that suppliers were confronted with multiple standards, resulting in QS-9000 in 1994. The *QS-9000* standard transitioned into *ISO/TS 16949* and then *IATF 16949*. The standards required FMEAs, but did not specify how to do an FMEA. Guidance was provided in *FMEA Manual* and then *SAE J1739*. Both standards underwent revisions, with the AIAG's fourth edition being replaced by *AIAG/VDA FMEA Handbook*, which harmonized AIAG and VDA approaches to FMEAs. *SAE J1739* was also updated in 2021. A timeline of major FMEA events and standards is shown in Figure 1.

DISCUSSION

The 1966 standard used by NASA has some overlap with a modern FMEA, but also significantly differs, with NASA using the criticality approach. The columns in the NASA standard (NASA, 1966) bear resemblance to the columns in the 1980 *MIL-STD-1629*, which also used criticality (Department of Defense, 1980). The FMEA described at Ford in 1973 bore a strong resemblance to modern FMEAs, but with separate columns for the effect of failure on a part and system and failure effect on the vehicle as well as only one column for fixes, if available, but no prevention or detection action control column

(Durstine, 1973). The columns in FMEAs used by NASA in 1966, Ford in 1973, and *MIL-STD-1629A* are shown in Table 4.

The *Potential Failure Modes and Effects Analysis (FMEA): Reference Manual* (Third Edition) provided one form sheet for DFMEAs and one form sheet for PFMEA and suggested use of a block diagram for DFMEs and a process flow chart for PFMEAs (Chrysler Corporation et al., 1998). The *Potential Failure Modes and Effects Analysis (FMEA): Reference Manual* (Fourth Edition) offered six possible DFMEA forms labeled A through E and eight different PFMEA forms labeled A through H. For DFMEAs, the main differences are in how item, function, and requirements are listed, with one version listing all three in one column and other versions listing different combinations of two out of the three in one column and the third in a different column. All but one version has current design controls for prevention and detection in separate columns; however, there is also a version that lists current design controls above a column for cause and a column for failure mode. The PFMEA form sheets have various combinations of process step, function, and requirements. There are also two form sheets with ID, product, and process listed in columns underneath process. Comparable to the DFMEA form sheet, there is also a column for cause and a column for failure mode listed underneath current detection process controls. The use of either a block diagram or a p-diagram was suggested for DFMEAs and PFMEAs were recommended to use a process flow diagram. The DFMEA failure effects were required to be described from the view of the end user and PFMEA failure effects were to consider customers, including internal and external customers (Chrysler LLC et al., 2008).

Table 4. Content of form sheets in early FMEAs

***Procedure for Failure Mode. Effects, and Criticality Analysis (FMECA)* (NASA, 1966)**	**FMEA at Ford (Durstine, 1973)**	***Military Standard: Procedures for Performing a Failure Mode, Effects and Criticality Analysis MIL-STD-1629A* (Department of Defense, 1980)**
Name	Failure Mode	Identification Number
Ident. Number	Failure Cause(s)	Item/ Functional Identification (Nomenclature)
Reliability Logic Diagram Number	Failure Effect on Part / System	Function
Function	Failure Effect on Vehicle	Failure Modes and Causes
Failure Mode and Cause	Probability of Failure Mode Occurrence	Mission Phase/ Operational Mode
Mission Phase	Probability of Severe Consequences	Failure Effects Local Effects
Failure Effect on Component / Functional Assembly	Probability of Failure Detection	Failure Effects Next Higher level
Failure Effect on Subsystem	Risk Priority Number	Failure Effects End User
Failure Effect on System	Present Fixes, if Any	Failure Detection method
Failure Detection Method	Recommended Corrective Action and Remarks	Compensating Provisions
Corrective Action Time Available/ Time required		Severity Class
Useful Life		Remarks

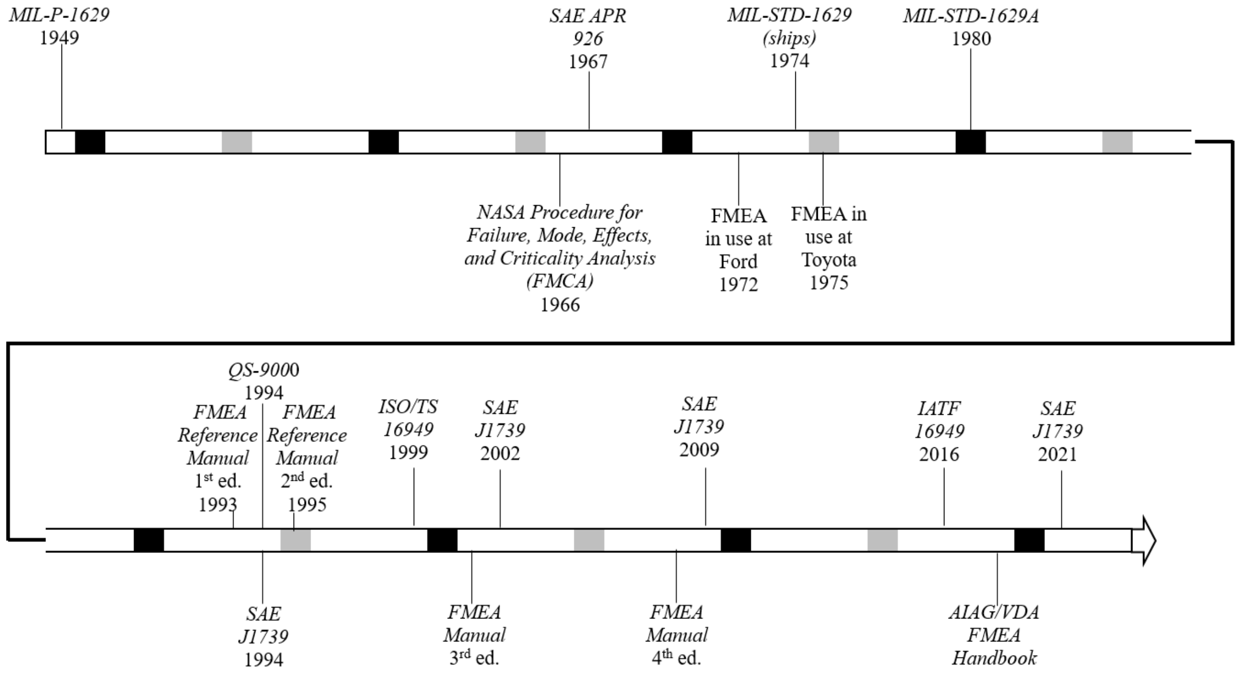

Figure 1. Timeline of major FMEA events and standards (by author)

The 2002 version of *SAE J1739* stated that a PFMEA should start with a flow chart and a DFMEA should begin with a block diagram, but no mention is made of a p-diagram. There were two possible form sheets for both DFMEAs and PFMEAs; one had current controls for prevention and detection combined in one column, and the other had current controls for prevention and detection in two separate columns (SAE, 2002). The 2009 revision of *SAE J1739* suggests a block diagram or boundary diagram for DFMEAs and a process flow diagram for PFMEAs. There was only one form sheet for DFMEAs and one form sheet for PFMEAs and both had separate columns for prevention and detection controls. The failure effects for the DFMEA considered the next assembly, the finished product, and the customer and the PFMEA failure effects pertain to the next operation, customer operations, and the end user (SAE, 2009).

The form sheets for DFMEAs and PFMEAs used in the 2008 edition of *Potential Failure Modes and Effects Analysis (FMEA): Reference Manual* and the 2009 edition of *SAE J1739* are shown in Table 5. The two standards were aligned (Chrysler LLC et al., 2008) and the main difference is in terminology with SAE J1739 including the term requirement together with item and function for DFMEAs and using abbreviations for severity, occurrence, and detection.

The *AIAG/VDA FMEA Handbook* offers a standard DFMEA form sheet, an alternative DFMEA form sheet, and a software view DFMEA form sheet, as well as a standard DFMEA MSR (Monitoring and System Response) form sheet and a software view DFMEA MSR form sheet. There is a standard PFMEA form sheet as well as four alternate form sheets and a PFMEA software view form sheet. The *AIAG/VDA FMEA Handbook* requires either a structure tree in software or a boundary diagram and the structure listed in the form sheet, as well as either a function tree in software, or a p-diagram with functions listed in the form sheet. The failure effects for the DFMEA can be for either the next higher level in the system, the end user, or both the next level in the system and the end user. The failure effects for a PFMEA are for the plant, the plant the part is shipped to, and the end user. The RPN was replaced with AP for prioritization (AIAG/VDA, 2019). The latest version of *SAE J1739* only has one DFMEA and PFMEA form sheet as well as a DFMEA MSR. Block diagrams and p-diagrams are recommended for DFMEAs and process flow diagrams for PFMEAs. The failure effects are the same as in the previous edition. Either RPN or AP can be used for prioritization. (SAE, 2021).

Table 5. Content of later FMEA form sheets

DFMEA Form A - Potential Failure Modes and Effects Analysis (FMEA): Reference Manual Fourth Edition (Chrysler LLC et al., 2008)	**PFMEA Form A - Potential Failure Modes and Effects Analysis (FMEA): Reference Manual Fourth Edition (Chrysler LLC et al., 2008)**	**DFMEA- SAE J1739 (SAE, 2009)**	**PFMEA- SAE J1739 (SAE, 2009)**
Function / Item	Process Step / Function / Requirements	Item / Function / Requirement	Process Step / Function / Requirement
Potential Failure Mode	Potential Failure Mode	Potential Failure Mode	Potential Failure Mode
Potential effect(s) of Failure	Potential effect(s) of Failure	Potential Effects(s) of Failure	Potential Effects(s) of Failure
Severity	Severity	SEV	SEV
Classification	Classification	Classification	Classification
Potential Cause(s) of Failures	Potential Cause(s) of Failures	Potential Cause(s) of Failure	Potential Cause(s) of Failure
Occurrence	Occurrence	OCC	OCC
Current Design Controls Prevention	Current Process Controls Prevention	Current Design Controls Prevention	Current Process Controls Prevention
Current Design Controls Detection	Current Process Controls Detection	Current Design Controls Prevention	Current Process Controls Prevention
Detection	Detection	DET	DET
RPN	RPN	RPN	RPN
Recommended Action	Recommended Action	Recommended Action	Recommended Action
Responsibility Target and Completion Date	Responsibility Target and Completion Date	Responsibility & Target Completion Date	Responsibility & Target Completion Date
Action Results Action Taken and Effective date	Action Results Action Taken and Effective date	Action Results Actions Taken & Effective Date	Action Results Actions Taken & Effective Date
Action results Severity	Action Results Severity	Action Results SEV	Action Results SEV
Action Results Occurrence	Action Results Occurrence	Action Results OCC	Action Results OCC
Action Results Detection	Action Results Detection	Action Results DET	Action Results DET
Action Results RPN	Action Results RPN	Action Results RPN	Action Results RPN

Table 6 depicts the form sheets for *AIAG/VDA FMEA Handbook* and SAE J1739. The latest editions of the two standards have diverged significantly in the form sheet with *AIAG/VDA FMEA Handbook* having many more columns to accommodate changes required to harmonize with the VDA approach.

Table 6. Content of the latest FMEA form sheets

Standard DFMEA - *AIAG/VDA FMEA Handbook* (AIAG/VDA, 2019)	**Standard PFMEA - *AIAG/VDA FMEA Handbook* (AIAG/VDA, 2019)**	**DFMEA - *SAE J1739* (SAE, 2021)**	**PFMEA- *SAE J1739* (SAE, 2021)**
Issue #	Issue #	DFMEA Technical Risk Analysis Item	Technical Risk Analysis Item (Op-Seq)
Continuous Improvement History / Change Authorization (As Appropriate)	Continuous Improvement History / Change Authorization (As Appropriate)	DFMEA Technical Risk Analysis Function(s)	Technical Risk Analysis Process Function
Structure Analysis (Step 2) 1. Next Higher Level	Structure Analysis (Step 2) 1. Process Item System, Subsystem, Part Element or Name of Process	DFMEA Technical Risk Analysis Potential Failure Mode(s)	Technical Risk Analysis Requirements
Structure Analysis (Step 2) 2. Focus Element	Structure Analysis (Step 2) 2. Process Step Station No. and Name of Focus Element	DFMEA Technical Risk Analysis Potential Effect(s) of Failure	Technical Risk Analysis Potential Failure Mode
Structure Analysis (Step 2) 3. Next Lower level or Characteristic Type	Structure Analysis (Step 2) 3. Process Work Element 4M Type	DFMEA Technical Risk Analysis Potential Cause(s) of Failure	Technical Risk Analysis Potential Effects of Failure
Function Analysis (Step 3) 1. Next Higher Level Function and Requirement	Function Analysis (Step 3) 1. Function of the Process Item Function of System, Subsystem, Part Element or Process	DFMEA Technical Risk Analysis Current Design Controls- Prevention (P)	Technical Risk Analysis Potential Cause(s) of Failure
Function Analysis (Step 3) 2. Focus Element Function and Requirement	Function Analysis (Step 3) 2. Function of the Process Step and Product Characteristic (Quantitative value is optional)	DFMEA Technical Risk Analysis Current Design Controls- Detection (D)	Technical Risk Analysis Current Process Controls- Prevention (P)
Function Analysis (Step 3) 3. Next Lower Level Function and Requirement or Characteristic	Function Analysis (Step 3) 3. Function of the Process Work Element and Process Characteristic	Risk Assessment SEV (S)	Technical Risk Analysis Current Process Controls- Detection (D)
Failure Analysis (Step 4) 1. Failure Effects (FE) to the Next Higher Level Element and/or Vehicle End User	Failure Analysis (Step 4) 1. Failure Effects (FE)	Risk Assessment OCC (O)	Risk Assessment SEV (S)
Failure Analysis (Step 4) Severity (S) of FE	Failure Analysis (Step 4) Severity (S) of FE	Risk Assessment DET (D)	Risk Assessment OCC (O)
Failure Analysis (Step 4) 2. Failure Mode (FM) of the Focus Element	Failure Analysis (Step 4) 2. Failure Mode (FM) of the Process Element	Risk Assessment Risk Prioritization	Risk Assessment DET (D)

Table 6 (continued)

Standard DFMEA - ***AIAG/VDA FMEA Handbook*** **(AIAG/VDA, 2019)**	**Standard PFMEA -** ***AIAG/VDA FMEA Handbook*** **(AIAG/VDA, 2019)**	**DFMEA -** ***SAE J1739*** **(SAE, 2021)**	**PFMEA-** ***SAE J1739*** **(SAE, 2021)**
Failure Analysis (Step 4) 3. Failure Cause (FC) of the Next Lower Element or Characteristic	Failure Analysis (Step 4) 3. Failure Cause (FC) of the Work Element	Risk Assessment Potential Special Characteristics(s)	Risk Assessment Risk Prioritization
Risk Analysis (5) Current Prevention Control (PC) of FC	Risk Analysis (5) Current Prevention Control (PC) of FC	Action Plan Recommended Action(s)	Risk Assessment Potential Special Characteristics(s)
Risk Analysis (5) Occurrence (O) of FC	Risk Analysis (5) Occurrence (O) of FC	Action Plan Responsibility & Target Completion Date	Action Plan Responsibility & Target Completion Date
Risk Analysis (5) Current Detection Controls (DC) of FC or FM	Risk Analysis (5) Current Detection Controls (DC) of FC or FM	Action Results Action(s) Taken & Effective Date	Action Results Action(s) Taken & Effective Date
Risk Analysis (5) Detection (D) of FC/FM	Risk Analysis (5) Detection (D) of FC/FM	Action Results New (s)	Action Results New (s)
Risk Analysis (5) DFMEA AP	Risk Analysis (5) PFMEA AP	Action Results New (o)	Action Results New (o)
Risk Analysis (5) Filter Code (Optional)	Risk Analysis (5) Special Characteristics	Action Results New (D)	Action Results New (D)
Optimization (Step 6) DFME Prevention Action	Risk Analysis (5) Filter Code (Optional)	Action Results New Risk Prioritization	Action Results New Risk Prioritization
Optimization (Step 6) DFMEA Detection Action	Optimization (Step 6) Prevention Action		
Optimization (Step 6) Responsible Person's Name	Optimization (Step 6) Detection Action		
Optimization (Step 6) Target Completion Date	Optimization (Step 6) Responsible Person's Name		
Optimization (Step 6) Status	Optimization (Step 6) Target Completion Date		
Optimization (Step 6) Action Taken with Pointer to Evidence	Optimization (Step 6) Status		
Optimization (Step 6) Completion Date	Optimization (Step 6) Action Taken with Pointer to Evidence		
Optimization (Step 6) Severity (S)	Optimization (Step 6) Completion Date		
Optimization (Step 6) Occurrence (O)	Optimization (Step 6) Severity (S)		
Optimization (Step 6) Detection (D)	Optimization (Step 6) Occurrence (O)		
Optimization (Step 6) DFMEA AP	Optimization (Step 6) Detection (D)		
Optimization (Step 6) Filter Code (Optional)	Optimization (Step 6) SpPrpd Char		
Remarks	Optimization (Step 6) PFMEA AP		
	Remarks		

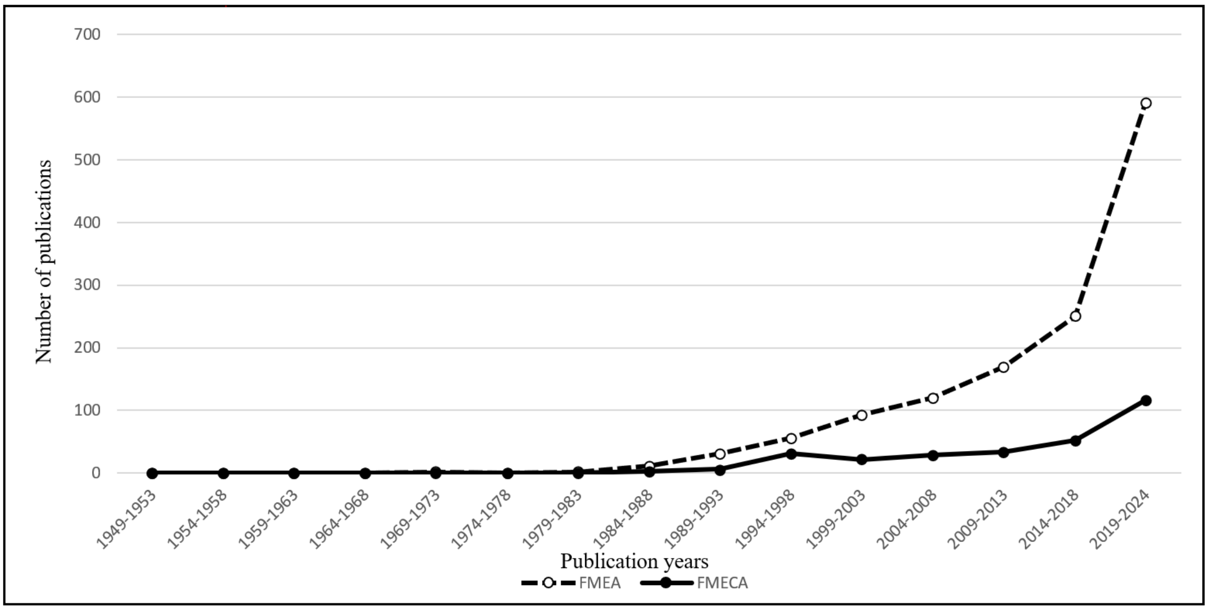

Figure 2. FMEA and FMECA paper publications by year (by author)

The number of publications related to FMEAs greatly increased over time. There were only 5 papers related to FMEAs between 1969 and 1984. The number of FMEA-related publications started to increase around 1984 and more than doubled between the time period 2014 to 2018 and the time period 2019 to 2024. The first papers on FMECAs appeared in the 1984 to 1988 time period and increased slowly until the number of publications more than doubled between the time period 2014 to 2018 and the time period 2019 to 2024. Figure 2 depicts the number of FMEA and FMECA-related publications over time.

A potential direction for future research would be a systematic literature review to identify and assess all literature on the topic of FMEAs. Such a study could increase the resolution of the timeline of FMEA development. Another avenue for future research would be investigating the possibility of returning to criticality calculations when big data is available. Another future research direction could be to investigate the reason interest in FMEAs and FMECAs doubled around 2018 and 2019.

Although the first FMEA standard was issued by the U.S. Department of Defense in 1949 (Korenko et al., 2012), even the Department of Defense has misattributed the origin of FMEAs to NASA (Reliability Analysis Center, 1993). The history of FMEAs was traced back to *MIL-P-1629* in 1949 and FMEAs have been confirmed as in used in the automotive industry sooner than has been reported.

CONCLUSION

The use of criticality was replaced by RPN in the automotive industry and the form sheet used in 1973 was different than the form used by the latest revision of *SAE J1739* in 2021; however, the 1973 form sheet was not too different than the 2021 form sheet. Although changes have happened to the FMEA form sheet in the automotive industry over the years, the greatest change was with the AIAG and VDA harmonization in 2019, as well as the introduction of AP.

Half a century ago, FMEA form sheets had separate columns for failure effects at the part, the complete system, and the vehicle level. A future consideration for managers would be to add back the additional columns to make clear where the effects of failure are happening.

Compliance with Ethical Standards

Conflict of Interest

The author declares that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

Funding

No funding was provided for this paper.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI Disclosure

The author confirms that no generative AI was used in writing this manuscript or creating images, tables, or graphic.

REFERENCES

AIAG/VDA. (2019). *AIAG/VDA failure modes and effects handbook*. (1st ed.). USA: AIAG.

Aldridge, J.R., Taylor, J., & Dale, B. G. (1991). The application of failure mode and effects analysis at an automotive components manufacturer. *International Journal of Quality and Reliability Management*, *8*(3), 44-56. https://doi.org/10.1108/02656719110142780

Ali, J. A., Khodakarami, L., Abdulqadir, S., Abdulrahman, H., & Mazar, G. (2025). Modified FMEA quality risk management technique for cross-country petroleum pipeline using GIS. International *Journal of Quality & Reliability Management*, *42*(6), 1672-1705. https://doi.org/10.1108/IJQRM-08-2023-0271

Anleitner, M. A. (2011). *The power of deduction: Failure modes and effects analysis for design*. Milwaukee, WI Quality Press.

Atkinson, P. (1989). TQM fact finding mission to Japan. *The TQM Magazine*, *1*(2), 120-124. https://doi.org/10.1108/EUM0000000003001

Bowles, J. B. (2002). Failure modes and effects analysis. In W. T. Becker & R. J. Shipley (Eds.), *ASM handbook: Volume II failure prevention and analysis* (pp. 50-59). Materials Park, OH, ASM International.

Carlson, C. S. (2015). *Understanding and applying the fundamentals of FMEAs. Reliability and maintainability symposium, January, 2015.*

Chrysler Corporation, Ford Motor Company, General Motors Corporation. (1998). *Quality system requirements QS-9000*, (3rd ed.). International Organization for Standardization.

Chrysler LLC, Ford Motor Company, General Motors Corporation. (2008*). Potential failure modes and effects analysis (FMEA): Reference manual*. (4th ed.). Automotive Industry Action Group.

Collins, J. A., & Fauser, B. C. J. M. (2005). Balancing the strengths of systematic and narrative reviews. *Human Reproduction Update*, *11*(2), 103-104. https://doi.org/10.1093/humupd/dmh058

Correia dos Santos, R. N., Saraiva Caldeira, L. M. M., & Serra, J. P. B. (2012). FMEA of a tailings dam. *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, *6*(2), 89-104. https://doi.org/10.1080/17499518.2011.615751

DaimlerChrysler Corporation, Ford Motor Company, General Motors Corporation. (2001). *Potential failure mode and effects analysis (FMEA): Reference manual*. (3rd ed.). Automotive Industry Action Group.

Dale, B. G., & Shaw, P. (1990). Failure mode and effects analysis in the U. K. motor industry: A state-of-the-art study. *Quality and Reliability Engineering International*, *6*(3), 179-188. https://doi.org/10.1002/qre.4680060304

Darmawan, D. (2025). The failure mode and effect analysis of Islamic banking product marketing in Indonesia. *Journal of Islamic Marketing*, *16*(1), 290-305. https://doi.org/10.1108/JIMA-08-2023-0268

Department of Defense. (1949). *Military standard: Procedures for performing a failure mode, effects and criticality analysis MIL-P-1629*. Washington, D.C.: Department of Defense.

Department of Defense. (1963). *Military standard: Procedures for performing a failure mode, effects and criticality analysis MIL-P-1629 – cancelation notice*. Washington, D.C.: Department of Defense.

Department of Defense. (1974). *MIL-STD-1629 (ships) procedures for performing a failure mode, effects and criticality analysis*. Washington, D.C.: Department of Defense.

Department of Defense. (1980). *Military standard: Procedures for performing a failure mode, effects and criticality analysis MIL-STD-1629 A*. Washington, D.C.: Department of Defense.

Department of Defense. (1998). *MIL-1629A: Procedures for perfuming a failure Mmde and effects and criticality analysis*. Washington, D.C.: Department of Defense.

Department of the Army. (2006). *TM 5-698-4, failure modes, effects and criticality analyses (FMECA) for command, control, communications, computer, intelligence, surveillance, and reconnaissance (C4ISR) facilities*. Washington, D.C.: Department of Defense.

Dhillon, B. S. (2003). Methods for performing human reliability and error analysis in health care. *International Journal of Health Care Quality Assurance*, *16*(6), 306–317. https://doi.org/10.1108/09526860310495697

Doshi, J., & Desai, D. (2016). Application of failure mode and effect analysis (FMEA) for continuous improvement – Multiple case studies in automobile SMEs. *International Journal for Quality Research*, *11*(2), 345-360. https://doi.org/10.18421/IJQR11.02-07

Durstine, J. W. (1973). The truck steering system from hand wheel to road wheel. *SAE Transactions*, *82*, 93-150.

Fong, J. L. F., & Antony, J. (2001). QS 9000: An overview and comparison with ISO 9000. *The TQM Magazine*, *13*(5), 315-318. https://doi.org/10.1108/09544780110401871

Fonseca, L., Lima, V., & Silva, M. (2015). Utilization of quality tools: Does sector and size matter?" *International Journal for Quality Research*, *9*(4), 605–620.

Fritzsche, R. (2011). *Failure mode and effects analysis (FMEA): A comparison between VDA-Approach versus QS-9000*. SAE Technical Paper 2011-01-2280. https://doi.org/10.4271/2011-01-2280

Gandhare, S., Kumar, P., Madankar, T., Singh, D., & Bhamu, J. (2025). Development and validation of a FMEA-based medical equipment maintenance framework using Industry 4.0. *International Journal of Quality & Reliability Management*, *42*(8), 2250-2290. https://doi.org/10.1108/IJQRM-07-2024-0246

Ghadge, A., Fang, X., Dani, S., & Antony, J. (2017). Supply chain risk assessment approach for process quality risks. *International Journal of Quality & Reliability Management*, *34*(7), 940-954. https://doi.org/10.1108/IJQRM-01-2015-0010

Ginn, D., Jones, D., Rahnejat, H., & Zairi, M. (1998). The "QFD/FMEA interface. *European Journal of Innovation Management*, *1*(1), 7-20. https://doi.org/10.1108/14601069810198448

Hatty, M., & Owens, N. (1994). Potential failure modes and effects analysis: A business perspective. *Quality Engineering*, *7*(1), 169-186. https://doi.org/10.1080/08982119408918774

Henshall, E. J. (1989). Quality engineering. *The TQM Magazine*, *1*(5), 293-298. https://doi.org/10.1108/eb059486

IATF. (2016). *IATF 16949 automotive quality management standard*. (1st ed.). International Automotive Task Force (IATF).

Kar, A., & Rai, R. N. (2025). A modified fuzzy PFMEA model for risk-centric Six sigma assessment under the paradigm of Quality 4.0. *International Journal of Lean Six Sigma*, *16*(1), 197-230. https://doi.org/10.1108/IJLSS-08-2023-0131

Korenko, M., Krocko, V., & Kaplík, P. (2012). Use of FMEA method in manufacturing organization. *Manufacturing and Industrial Engineering*, *11*(2), 48-50.

Maisano, D. A., Franceschini, F., & Antonelli, D. (2020). dP-FMEA: An innovative *Failure Mode and Effects Analysis* for distributed manufacturing processes. *Quality Engineering*, *32*(3), 267–285. https://doi.org/10.1080/08982112.2020.1729991

Manos, A., & Vincent, C. (Eds.). (2012). *The lean handbook: A guide to the bronze certification body of knowledge*. ASQ Quality Press.

Matsumoto, K., Matsumoto, T., & Goto, Y. (1975). Reliability analysis of catalytic converter as an automotive emission control system. *SAE Transactions*, *84*, 728–738.

NASA. (1966). *Procedure for failure, mode, effects, and criticality Analysis (FMCA)*, U.S. Department of Commerce.

Pillay, A., & Wang, J. (2003). Modified failure mode and effects analysis using approximate reasoning. *Reliability Engineering and System Safety*, *79*(1), 69-85. https://doi.org/10.1016/S0951-8320(02)00179-5

Plinta, D., Golinska, E., & Dulina, Ľ. (2021). Practical application of the new approach too FMEA method according to AIAG and VDA reference manual. *Communications - Scientific Letters of the University of Zilina*, *23*(4), 325-335. http://www.10.26552/com.C.2021.4.B325-B335

Reliability Analysis Center. (1993). *Failure mode, effects and criticality analysis (FMECA).* Reliability Analysis Center.

SAE. (2001). *ARP5580 recommended failure modes and effects (FMEA) practices for non-automotive applications*. SAE International.

SAE. (2002). Surface vehicle standard J1739: (R) Potential failure mode and effects analysis in design (Design FMEA), potential failure mode and effects analysis in manufacturing and assembly processes (process FMEA), and potential failure mode and effects analysis for machinery (machinery FMEA). SAE International.

SAE. (2009). *Surface vehicle standard J1739: (R) Potential failure mode and effects analysis in design (design FMEA), potential failure mode and effects analysis in manufacturing and assembly processes (process FMEA)*. SAE International.

SAE. (2021). *Surface vehicle standard J1739: (R) Potential failure mode and effects analysis (FMEA) including Design FMEA, supplemental FMEA-MSR, and process FMEA*. SAE International.

Sharma, R. K., & Sharma, P. (2010). System failure behavior and maintenance decision making using, RCA, FMEA and FM. *Journal of Quality in Maintenance Engineering*, *16*(1), 64-88. https://doi.org/10.1108/13552511011030336

Sharma, R. K., Kumar, D., & Kumar, P. (2007). Modeling and analysing system failure behaviour using RCA, FMEA and NHPPP models. *International Journal of Quality and Reliability Management*, *24*(5), 525-546. https://doi.org/10.1108/02656710710748385

Singh, R., Sharma, M., Nadeem, R., Patidar, A., & Anchliya, N. (2026). Enhancing work–life balance in the Indian health-care sector: prioritizing failures and implementing corrective interventions through failure mode effects analysis (FMEA). *International Journal of Organizational Analysis*, *34*(2), 612–631, https://doi.org/10.1108/IJOA-08-2024-4702

Smith, L. R. (2005). Back to the future at Ford. *Quality Progress*, *38*(3), 50-56.

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333-339. https://doi.org/10.1016/j.jbusres.2019.07.039

Stamatis, D. H. (1996). FMEA and the QS-9000 requirement. *SAE Transactions*, *105*, 61-73.

Swift, J. A., & Flynn, T. J. (1989). Methodology for developing a quality plan within a manufacturing company. *Quality Engineering*, *1*(4), 467-486. https://doi.org/10.1080/08982118908962681

Tangestani, M., Jafari, A. J., Kermani, M., & Kalantary, R. R. (2025). Development application of FMEA risk assessment model for indoor air pollutants in healthcare organizations: Focus on suspended particles and bioaerosols in hospitals. *MethodsX*, *14*, 103342. https://doi.org/10.1016/j.mex.2025.103342

Termaat, K. B., & Freeman, K. A. (1972). Development of the crash sensor/vehicle interface. *SAE Transactions*, *81*, 1412–1432.

VDA. (2012). *Quality management in the automotive industry volume 4: Quality assurance in the process landscape – General, risk analyses, methods, procedure models, product-and process FMEA*. (2nd ed.). Verband der Automobilindustrie (VDA).

Villacourt, M. (1992). *Failure mode and effects analysis (FMEA): A guide for continuous improvement for the semiconductor equipment industry*. International SEMATECH Technology.

Walsh, T. J. (1975). Engineering the third generation Econoline. *SAE Transactions*, *84*, 1192-1233.

Webber, J. (1990). FMEA: Quality assurance methodology. *Industrial Management & Data Systems*, *90*(7), 21-23. https://doi.org/10.1108/02635579010002046

Xiao, N., Huang, H. -Z., Li, Y., He, L., & Jin, T. (2011). Multiple failure modes analysis and weighted risk priority number evaluation in FMEA. *Engineering Failure Analysis*, *18*(4), 1162-1170. https://doi.org/10.1016/j.engfailanal.2011.02.004

Yılmaz, A. F., & Köse, O. (2025). Advancing sustainable shipbuilding through a hybrid risk prioritization model: integrating FMEA and machine learning. *Engineering Science and Technology, an International Journal*, *70*, 102158. https://doi.org/10.1016/j.jestch.2025.102158

Zulfiqar, M., Bhat, S., Sony, M., Salentijn, W., Swarnakar, V., Antony, J., Cudney, E. A., Furterer, S., McDermott, O., Jayaraman, R., & Foster, M. (2025). Unveiling the potential of FMEA in higher education: pathway to improved risk management and quality. *The TQM Journal*, *37*(6), 1666–1686. https://doi.org/10.1108/TQM-01-2024-0017