CONGRESSO NACIONAL DE EXCELÊNCIA EM GESTÃO & INOVARSE
ISSN 1984-9354
Rio de Janeiro, Brasil, 26 e 27 de setembro 2024

AUTOMOTIVE SUPPLY CHAIN INDUSTRIAL PROCESS ANALYSIS BASED ON THE FMEA HARMONIZATION PROPOSED BY AIAG AND VDA

Márcio Pedroso Bastos
Universidade Federal Fluminense; marcio_bastos@id.uff.br

Henrique Martins Rocha
Universidade Federal Fluminense; prof.henrique_rocha@yahoo.com.br

Nilson Brandalise
Universidade Federal Fluminense; nilson_01@yahoo.com.br

ABSTRACT: *Failure management and the minimization of process variability have gained prominence in the 21st century to ensure the performance of enterprises. To guarantee the quality of their products, the automotive sector, in particular, requires its suppliers to use Failure Mode and Effects Analysis (FMEA) for risk control of their processes. The standard accepted in the North American market is the 4th Edition FMEA manual by the Automotive International Action Group (AIAG), published in 2008, while German companies adopt the Product and Process FMEA standard by the Verband der Automobilindustrie (VDA), published in 2012. In a globalized world, to facilitate requirements in their supply chains, the AIAG and VDA published a new version of FMEA in 2019, harmonizing its concepts and introducing the Action Priority (AP) criterion to replace the Risk Priority Number (RPN), referred to as the AIAG & VDA FMEA Manual 1st Edition. Although this solution provides more accurate and robust analyses, its development is complex and generally relies on commercial software. A methodological procedure has been developed to enable the application of the steps proposed in the manual, using Excel® and its Power Query® module. This methodological procedure was applied to a flat steel laser welding process in the automotive supply chain, revealing 327 distinct Failure Modes with their respective causes, among which 19 Failure Modes were considered higher priority.*

Keywords*: Action Priority, AIAG, FMEA, Power Query, VDA*

1. Introduction

The primary purpose of a quality control system is to ensure that products achieve the appropriate characteristics and specifications with minimal variation, through methods that measure their quality, customer satisfaction, and production performance (Grigg, 2021). Numerous failures occur during production that can cause financial losses. Therefore, companies must recognize and mitigate risks in a production system (Ozkok, 2014). Risk management has gained prominence in the 21st century (Grigg, 2021), with risks being defined as uncertainties with positive or negative consequences arising from different events (Islam; Tedford; Haemmerle, 2008). Organizations should understand their context and map risks as a basis for planning, developing a preventive quality management system with a risk mindset (Associação Brasileira de Normas Técnicas, 2015).

Various quality techniques and tools have been developed to control risk based on practical needs (Leopoulos; Kirytopoulos; Voulgaridou, 2006; Leopoulos; Kirytopoulos; Malandrakis, 2006), and they can be used for failure control (Oliveira; Brandalise, 2020). Among the techniques developed, Failure Mode and Effects Analysis (FMEA) is one of the most widely used due to its visibility and simplicity (Huang *et al.*, 2020). FMEA can be applied in the phases of design, processes, or systems, and its objective is to eliminate or reduce the associated risks before they materialize, through the anticipation of their occurrence (Monforte; Oliveira; Rocha, 2015).

Since its development, several guides for FMEA implementation have been proposed, and in 2019 the Automotive Industry Action Group (AIAG) and the *Verband der Automobilindustrie* (VDA) proposed a new manual aimed at harmonizing their criteria (Kluse, 2020). In addition to the benefits of applying preventive techniques to processes, it is mandatory for companies doing business with the automotive sector to obtain certification under the IATF 16949:2016 standard, meeting its requirements, including the implementation of FMEA (Plinta; Golinska; Dulina, 2021). Additionally, few studies have addressed the use of the Action Priority criterion of AIAG & VDA and its implications (Sun; Yeh; Pai, 2022).

In the North American market, the accepted standard is the 4th Edition FMEA Manual by AIAG, published in 2008, while in Germany, the Product and Process FMEA standard by VDA, published in 2012, is adopted. This causes confusion for suppliers serving both markets (Kluse, 2020). The harmonization of their concepts replaced the respective publications of AIAG and VDA with the AIAG & VDA FMEA 1st Edition Manual, aiming to mitigate the confusion of criteria for the same supplier, and to achieve precise, robust, and effective FMEAs through the improvement of the overall development process (Kluse, 2020). However, its use is complex and dependent on specific software. Its implementation in Excel® for processes with more than one component is challenging, posing a significant obstacle since this is the most popular tool for FMEA implementation (Harpster, 2022). It is expected that companies such as Ford, General Motors, and Stellantis will demand the use of this new manual through the publication of Customer Specific Requirements for IATF-16949:2016 certification (Harpster, 2022).

Thus, this research aims to answer the following question: How can process risks be mapped using the harmonized FMEA proposed by AIAG & VDA without relying on commercial software? The general objective is to develop a methodological procedure based on the AIAG & VDA FMEA 1st Edition Manual, applicable to industrial processes without the need for proprietary software. This procedure will be detailed in the form of a guide, allowing for replication in processes that must meet the specific requirements of IATF-16949:2016 within the automotive supply chain. The developed framework is available for entrepreneurs who wish to establish businesses with companies in this sector. To achieve the general objective, the following specific objectives are established:

- Identify the steps to FMEA AIAG & VDA in the literature.
- Develop a framework for analyzing industrial processes using the recommendations of AIAG & VDA FMEA harmonization without the use of commercial software.
- Conduct a case study on an industrial process using the developed procedure, analyze the results, and propose actions that can reduce the risk level of the process.

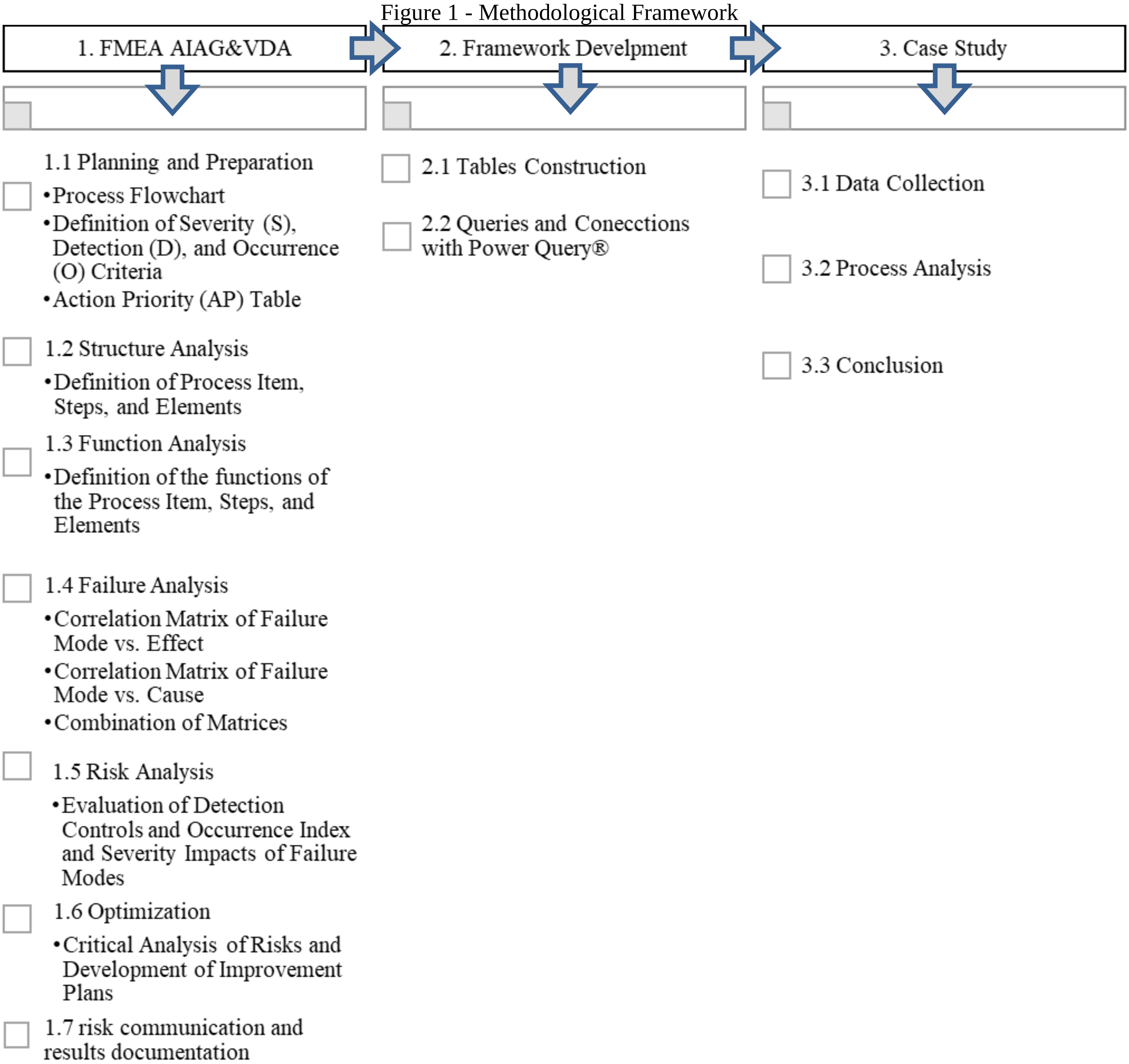
2. Materials and Methods

This section outlines the strategies for assessing process risks and their associated impacts. Subsequently, the proposed framework examines a Flat Steel Laser Welding Process. Figure 1 illustrates the proposed Methodological Procedure. Initially, a literature review on the topic was conducted. Following this, a structure for the proposed procedure was defined, developed with the support of Excel® software and its Power Query® add-in. A case study was conducted using data from a Laser Welding Process on Steel Sheets obtained between June 2021 and May 2022.

Over the years since its creation, FMEA has undergone several evolutions in its approach. Its mandatory adoption by the automotive industry began in 1994, highlighting two main approaches: the VDA and AIAG standards. These approaches were unified in 2019 (Plinta; Golinska; Dulina, 2021). The AIAG & VDA FMEA approach consists of seven steps: (1) planning and preparation; (2) structure analysis; (3) function analysis; (4) failure analysis; (5) risk analysis; (6) optimization; and (7) documentation of results (Kluse, 2020; Plinta; Golinska; Dulina, 2021). These steps are summarized in Figure 2. Step 1, Planning and Preparation, involves all actions necessary to initiate the study. The manual recommends the 5Ts method illustrated in Figure 3. In step 2, the structure of the process is defined with all steps, components, and subcomponents, referred to as elements. In step 3, the functions of each element are defined, and in step 4, the possible ways each element can fail to fulfill its function, thus generating the failure mode, are identified (Harpster, 2022). In this step, the Failure Chain is defined, with its central element being the Failure Mode, which includes the failure occurring in the analyzed element, the cause of the failure, and its effect from the perspective of internal and external customers, as well as legal requirements, schematically shown in Figure 4 (Plinta; Golinska; Dulina, 2021)

To proceed with the study next steps, the essential tools needed were the process flowchart (which maps all stages), the preliminary FMEA study, and the tables defining the scoring criteria for Severity, Occurrence, and Detection. Figure 5 illustrates the flowchart standard and symbols recommended in the AIAG and VDA Manual. Figure 6 exemplifies the scoring tables.

Figure 1 - Methodological Framework



Source: Prepared by the authors (2024)

In the structure analysis, the Process Items, Stages, and Elements are defined. For this purpose, process flowcharts and the six M's analysis (Materials, Machine, Manpower, Method, Measurement, and Environment) will be used (AIAG & VDA, 2019). A Process Item is the highest level of the process flowchart or the product to be produced. The focus element is the stages of the process described in the flowchart, and the lowest level consists of the elements that compose the stages. Six M's are applied to map the components of the stage (Kluse, 2020). This structure tree is schematically illustrated in Figure 7.

Figure 2 - FMEA AIAG & VDA Steps

Steps	Description
1. Planning and Preparation	Identification of the process to be studied. Technique of the 5 T's: ***inTent*** (Motivations for conducting the study), ***Timing*** (schedule), ***Team*** (FMEA team), ***Tasks*** (FMEA steps), ***Tools*** (additional study support elements).
2. Structure Analysis	Definition of the process structure with all steps, components, and subcomponents, referred to as elements.
3. Function Analysis	Definition of the functions of each of the elements.
4. Failure Analysis	Identification of the possible ways in which each element can fail to fulfill its function, thus generating the failure mode.
5. Risk Analysis	Evaluation of Severity, Occurrence, and Detection scores, generating the Action Priority (AP) index.
6. Optimization	Action plan to mitigate priority risks.
7. Documentation of Results	Documenting improvements on the standard form.

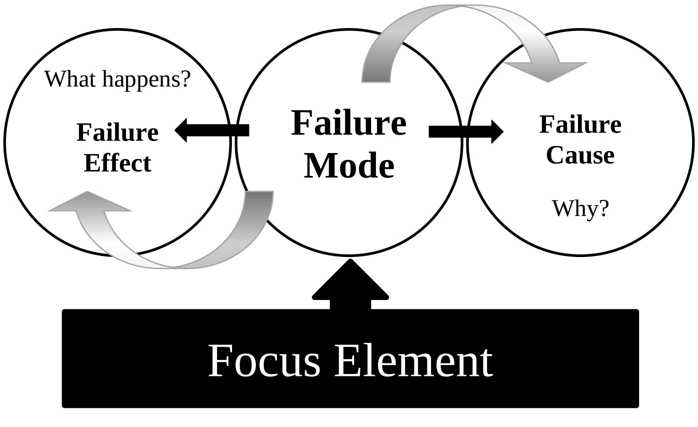
Source: Adapted from Gueorguiev; Kokalarov; Sakakushev, (2020); Harpster, (2022)

Figure 3 - Five T's

Five T's	Description
InTent	Why are we studying the FMEA?
Timing	When FMEA must be done?
Team	Who we need in the team?
Task	What work need to be done?
Tool	How is the FMEA analyzed?

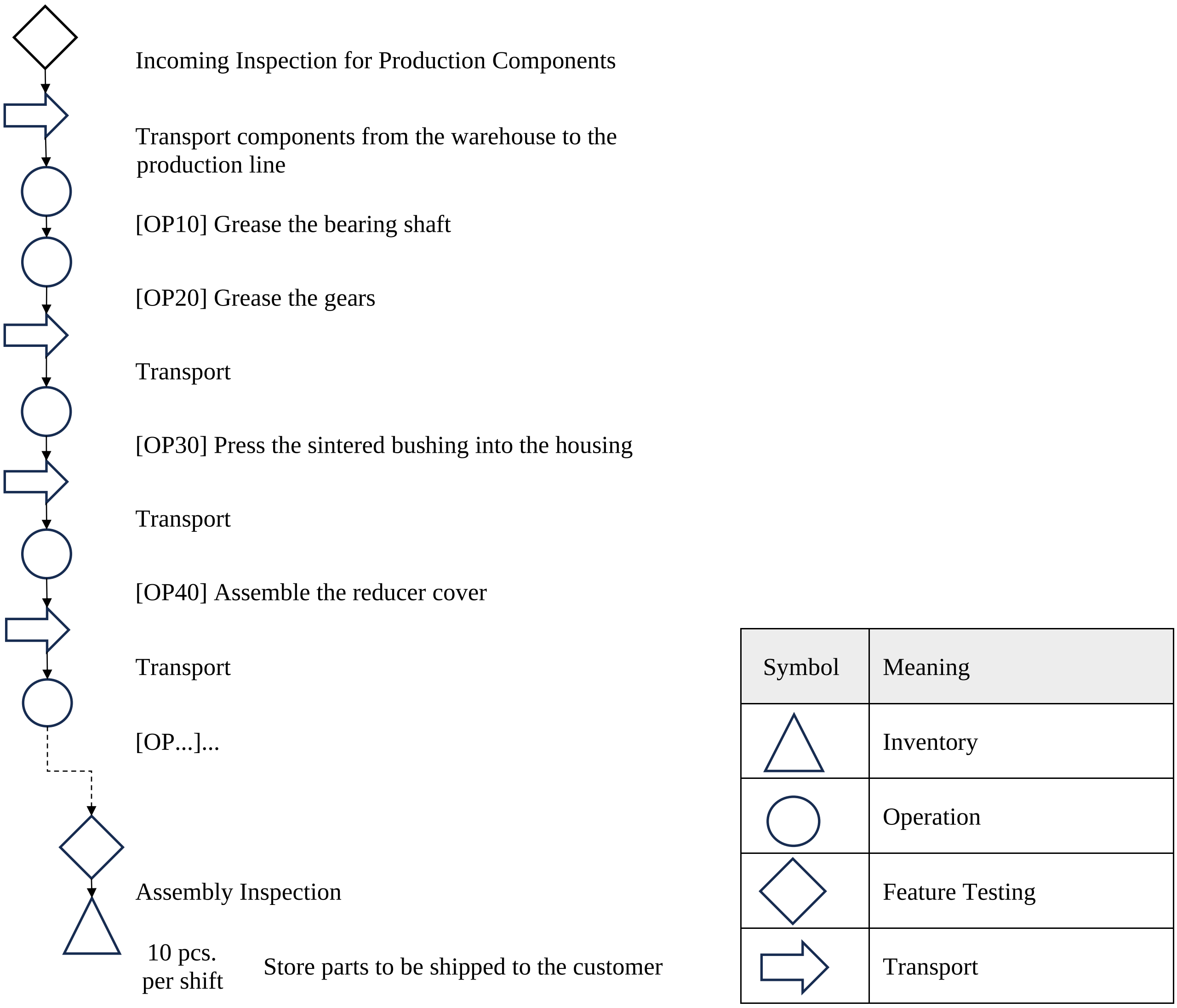
Source: Adapted from AIAG & VDA, (2019)

Figure 4 - Failure Chain



Source: Adapted from AIAG & VDA, (2019)

Figure 5 - Process Flowchart



Source: Adapted from AIAG & VDA, (2019)

In the next step, Function Analysis, the key is to connect the process requirements or characteristics with their functions (Plinta; Golinska; Dulina, 2021). There may be more than one function for each process item or stage. Information such as process and product functions, requirements, manufacturing environmental conditions, cycle times, occupational and safety requirements, environmental impacts, and others are the basis for this step (Anackovski; Kuzmanov; Pasic, 2021).

The process item will have its function defined according to the internal and external expectations of the customer or end user. Failure to meet the function of a Process Item will result in the Failure Effect (AIAG & VDA, 2019). The Function of the Process Stages describes the characteristics of the resulting product produced at the station. This is the central element of the structure, and failure to fulfill this function will define the Failure Mode (AIAG & VDA, 2019). The functions of the process Work Elements describe their contributions to the Stage in creating the process/product characteristics. Failure to meet their functions characterizes the causes of the failures (AIAG & VDA, 2019). Figure 8 illustrates the tables relationships using Excel®.

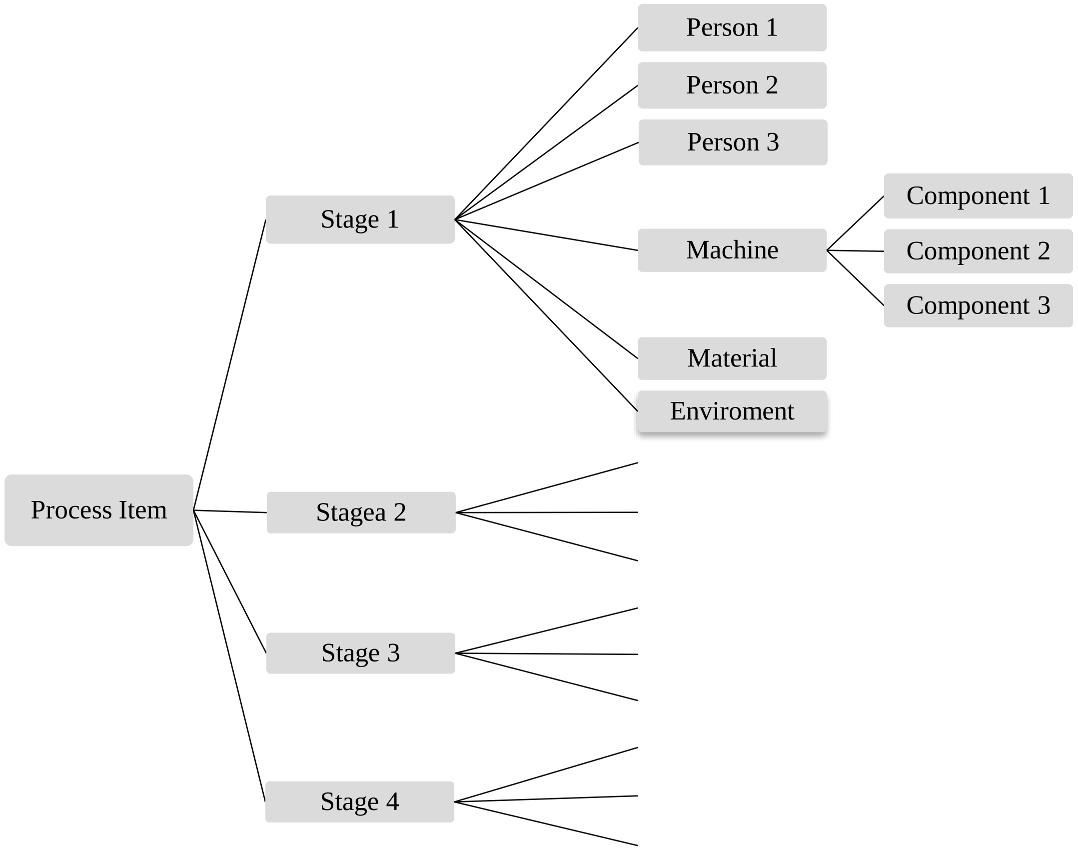
Figure 6 - Example of a Scoring Table

Score	Severity	Occurrence	Detection
10	Very High (failure affects vehicle safety and/or involves non-compliance with government regulations with or without warning)	Very High (failure is almost inevitable, ≥ 1 in 2)	None (Control design will not or cannot detect the potential cause/mechanism and subsequent failure mode; or no control design)
9	Very High (a potential failure affects the safe operation of the vehicle and/or involves non-compliance with government regulations with or without warning)	Very High (1 in 3)	Rare (rare chance that the control design will detect the potential cause/mechanism and subsequent failure mode)
8	Very High (vehicles/item inoperative, with loss of primary function)	High (repetitive failures, 1 in 8)	Rare (rare chance that the control design will detect the potential cause/mechanism and subsequent failure mode)
7	High (Vehicle/item operational but with reduced performance level. Customer dissatisfaction)	High (1 in 20)	Low (low chance that the control design will detect the potential cause/mechanism and subsequent failure mode)
6	Moderate (Vehicle/item operational but comfort/convenience items inoperative. Customers experience discomfort)	Moderate (occasional failures, 1 in 80)	Low (low chance that the control design will detect the potential cause/mechanism and subsequent failure mode)
5	Moderate (Vehicle/item operational but comfort/convenience items inoperative. Customers experience discomfort)	Moderate (1 in 400)	Reasonable (reasonable chance that the control design will detect the potential cause/mechanism and subsequent failure mode)
4	Low (Vehicle/item operational but comfort/convenience items operate at reduced level. Customers experience some discomfort)	Moderate (1 in 2000)	Moderate (moderate chance that the control design will detect the potential cause/mechanism and subsequent failure mode)
3	Very Low (finish and adjustment items with noise and non-compliance. Perceptible to most customers)	Low (few failures, 1 in 15000)	High (high chance that the control design will detect the potential cause/mechanism and subsequent failure mode)
2	Very Low (finish and adjustment items with noise and non-compliance. Perceptible to average customers)	Very Low (relatively few failures, 1 in 150000)	Very High (very high chance that the control design will detect the potential cause/mechanism and subsequent failure mode)
1	None (No Effect)	Remote (failure is unlikely ≤ 1 in 1.5×10^6)	Certain (control design will certainly detect the cause/mechanism and subsequent failure mode)

Source: Adapted from Chin; Chan; Yang, (2008)

With the functions defined, in step four, the Failure Chain is established. Experts must analyze the failure modes, as central elements, and correlate the effects perceived by the customers mapped in the function analysis of the process items. Similarly, the causes mapped in the function analysis of the elements are evaluated as potential generators of the failure mode if the element fails to fulfill its function.

Figure 7 - Structure Tree

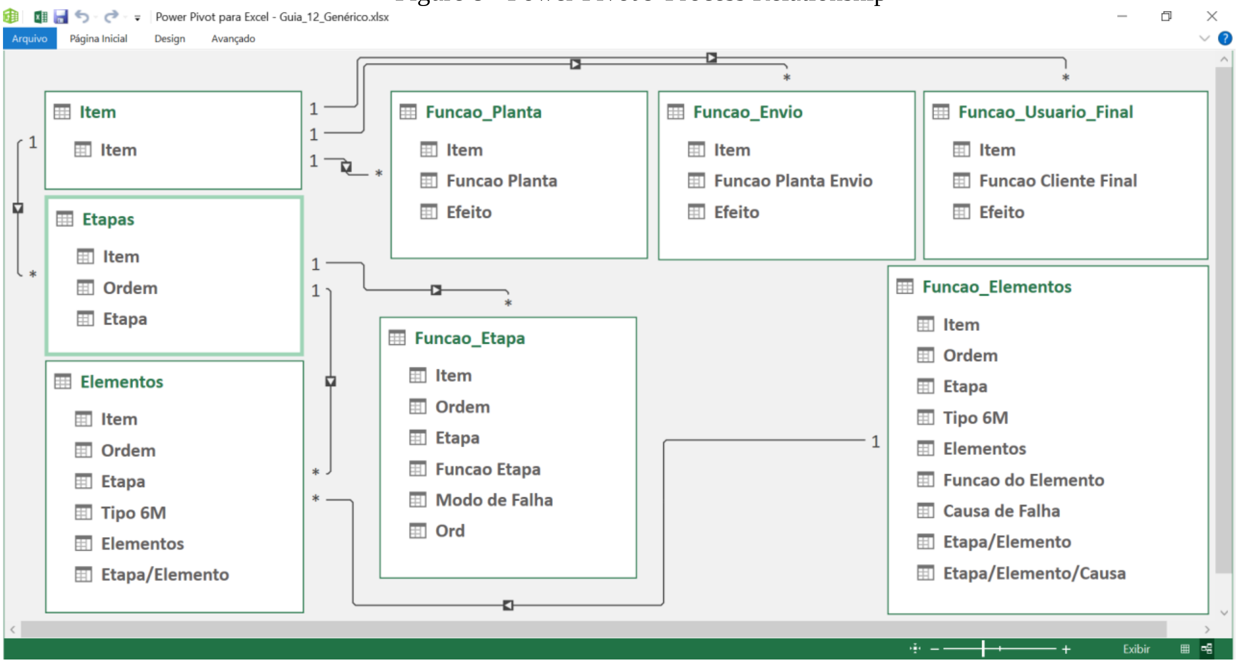


Source: Adapted from Thurnes et al., (2015)

For this evaluation, two matrices were proposed, composed of binary values defined by the experts. Equation (1) describes the matrix used for the correlation between the effects on customers and the Failure Modes. There should be one matrix for each customer. Customers can include End Users, Shipping Plants that deliver products directly to end users, Manufacturing Plants that are part of the product supply chain, governmental entities, the community, and other stakeholders, external or internal, as defined for evaluation. Although there are various effects depending on the number of customers, each customer should perceive only one effect per failure mode.

Equation (2) defines the criteria for constructing the correlation matrix between failure modes and their causes. In this case, each failure mode may have more than one cause, and the restriction stated in Equation (1) does not apply. Thus, with the combination of matrices obtained from the experts, considering the failure mode as the central element and the elements $a_{ij} = 1$, the failure chain is defined, as schematically illustrated in Figure 9.

Figure 8 - Power Pivot® Process Relationship



Source: Prepared by the authors (2024)

Failure Effect
Manufacturing, Assembly and
Final Customer

Failure Modes

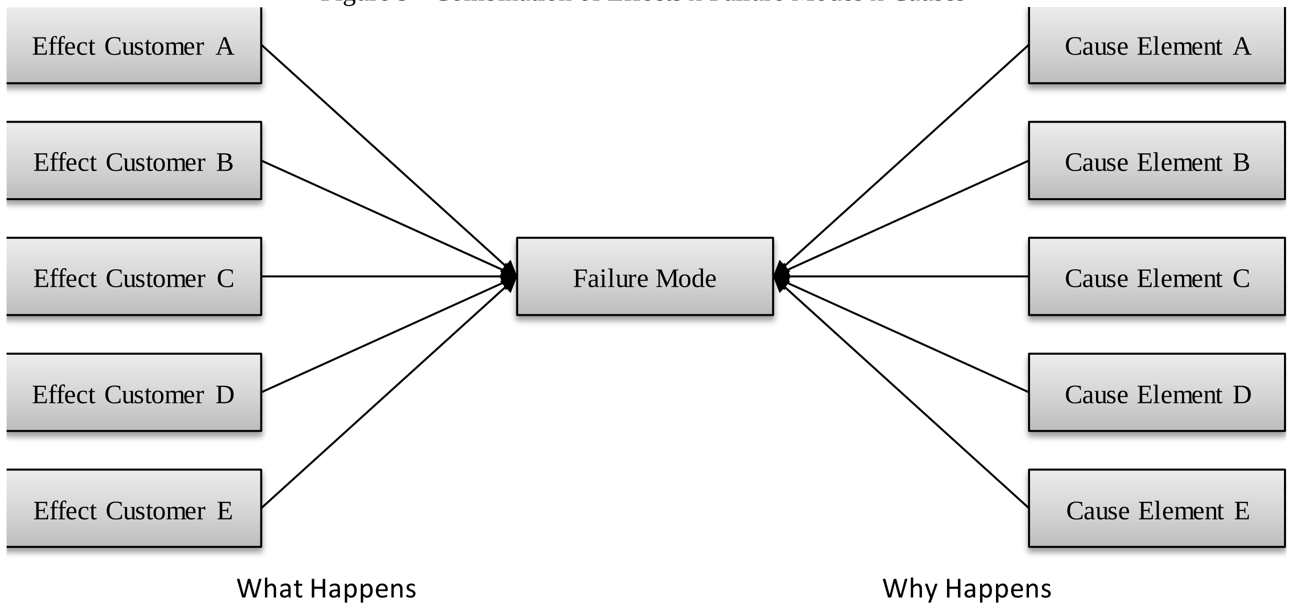
$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1j} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2j} \\ a_{31} & a_{32} & a_{33} & \cdots & a_{3j} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & a_{i3} & \cdots & a_{ij} \end{bmatrix} \quad , a_{ij} \in \{0;1\} \,\Big|\, \sum_{j=1}^{n} a_{ij} = 1 \qquad (1)$$

Failure Cause

Failure Modes

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1j} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2j} \\ a_{31} & a_{32} & a_{33} & \cdots & a_{3j} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & a_{i3} & \cdots & a_{ij} \end{bmatrix} \quad , a_{ij} \in \{0;1\} \qquad (2)$$

Figure 9 - Combination of Effects x Failure Modes x Causes

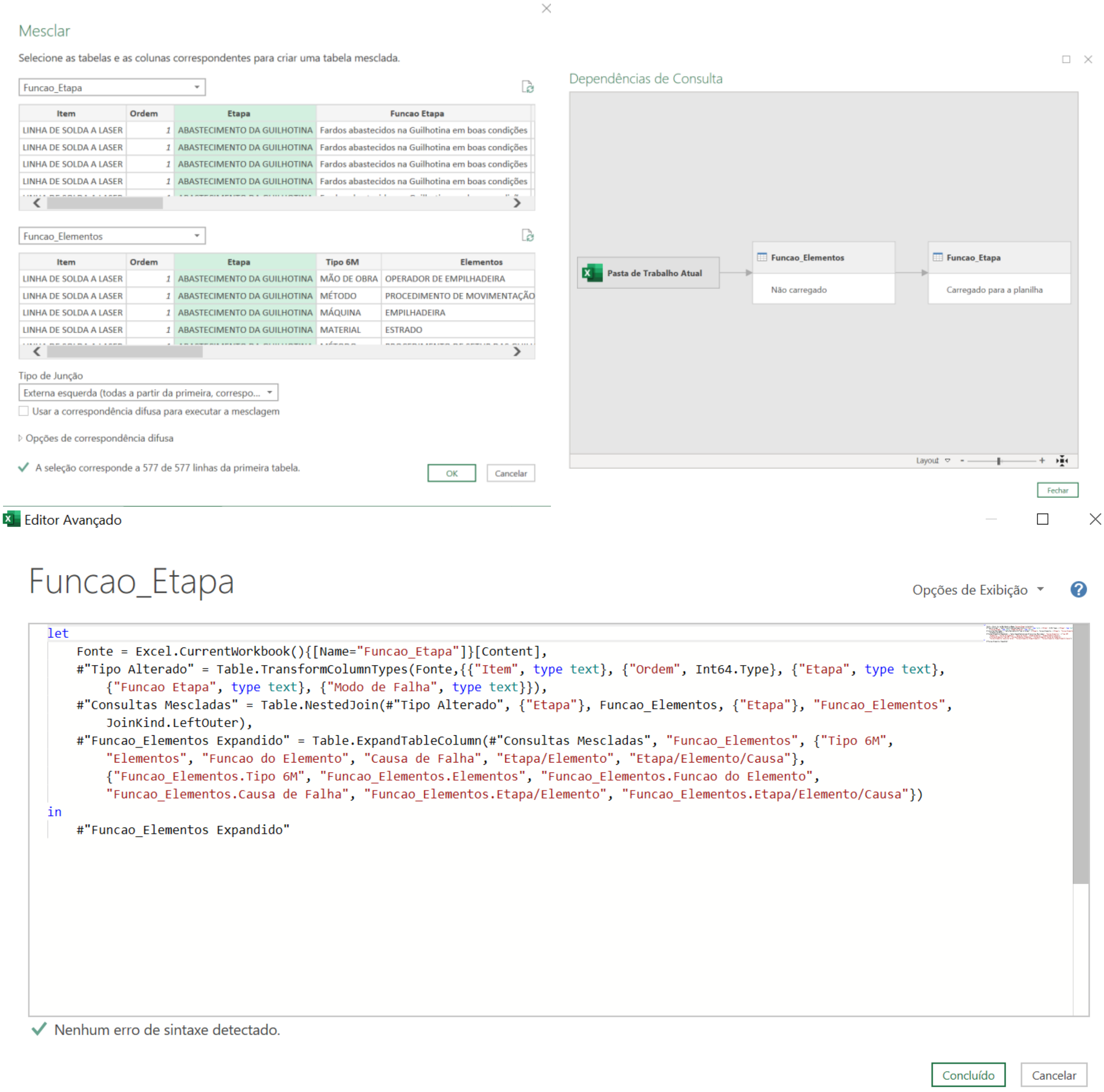


Source: Prepared by the authors (2024)

To perform the combinations in Excel® software, the Power Query® module was used to enable the use of query features. The tables "Functions of Stages" and "Functions of Elements" were combined, considering the Stage as the central element. The "Functions of Stages" table is the main table, and all elements of the Stage are combined considering a "Left Outer Join," so that the stages are not repeated, and the elements of each stage are combined. This is a "Many-to-Many" combination feature, which is not possible using other features of the applied software. Figure 10 illustrates these steps. After constructing the table with the relationships of stages and their elements, it is possible to combine the analyses of Failure Mode x Effects on different customers and the relationship of Failure Mode x Causes. Formulas were used to cross-reference the Failure Modes with the Effects and their Causes to obtain a table that defines the process stages, their failure modes, the corresponding elements, the expected effects on the customers defined for the study, and if there is a correlation between the Cause and the Failure Mode.

Once the Failure Analysis is completed, the next step is Risk Analysis. In this step, the tables with the Severity, Occurrence, and Detection scores defined in the first step are used by the experts to assess the risks associated with the Failure Modes. For Severity, the most serious effect perceived by different customers is considered (AIAG & VDA, 2019). Detection requires evaluating the types of controls used to identify the failure mode or cause of failure (AIAG & VDA, 2019), and in the Occurrence analysis, the potential for the cause to materialize is quantified without considering detection controls. This score is relative and may not reflect the actual occurrence. Factors such as historical data, field experience, data from a similar previous project, best practices, and the implementation of error-proofing solutions are examples of characteristics considered by experts for this type of assessment (AIAG & VDA, 2019). With the scores established, the table from Figure 11 is used to determine the Action Priority, classifying risks as High (H), Medium (M), and Low (L).

Figure 10 - Modeling the Failure Chain in Power Query®



Source: Prepared by the authors (2024)

The next step in completing the FMEA AIAG & VDA analysis is Optimization. In this step, the team of experts reviews the failure mode and their causes and establishes actions that can reduce the risk (Frunza; Radu Rusu; Pop, 2020). Actions should be proposed in such a way as to decrease the likelihood of occurrence of a cause or increase the ability to detect a failure mode or its causes, in that order of priority (AIAG & VDA, 2019). Figure 12 provides examples of actions for prevention and detection controls. In step seven, all information and analyses are documented properly.

Figure 11 - Action Priority Table

S	O	D	PA	S	O	D	PA	S	O	D	PA	S	O	D	PA
9-10	8-10	7-10	H	7-8	8-10	7-10	H	4-6	8-10	7-10	H	2-3	8-10	7-10	M
		5-6	H			5-6	H			5-6	H			5-6	M
		2-4	H			2-4	H			2-4	M			2-4	L
		1	H			1	H			1	M			1	L
	6-7	7-10	H		6-7	7-10	H		6-7	7-10	M		6-7	7-10	L
		5-6	H			5-6	H			5-6	M			5-6	L
		2-4	H			2-4	H			2-4	M			2-4	L
		1	H			1	M			1	L			1	L
	4-5	7-10	H		4-5	7-10	H		4-5	7-10	M		4-5	7-10	L
		5-6	H			5-6	M			5-6	L			5-6	L
		2-4	H			2-4	M			2-4	L			2-4	L
		1	M			1	M			1	L			1	L
	2-3	7-10	H		2-3	7-10	M		2-3	7-10	L		2-3	7-10	L
		5-6	M			5-6	M			5-6	L			5-6	L
		2-4	L			2-4	L			2-4	L			2-4	L
		1	L			1	L			1	L			1	L
	1	1-10	L		1	1-10	L		1	1-10	L		1	1-10	L
												1	1-10	1-10	L

Source: Adapted from AIAG & VDA, (2019); Sun; Yeh; Pai, (2022)

Figure 12 - Recommended Actions for Reducing Failure Probabilities

Control Type	Example
Prevention (aims to reduce occurrence)	Machine operation using both hands – bimanual
	The next part cannot be assembled (Poka Yoke)
	Shape-dependent positioning
	Equipment maintenance
	Operator maintenance
	Work instructions/Visual aids
	Machine controls
	First part release
Detection Controls (aims to increase the ability to detect the presence of a cause or failure mode)	Visual inspection
	Visual inspection using a checklist
	Optical inspection with a camera system
	Optical testing with a limit sample
	Attribute testing with "pass/fail"
	Dimensional verification with a caliper
	Random inspection
	Torque monitoring
	Applied load monitoring
	Final function inspection

Source: Adapted from AIAG & VDA, (2019)

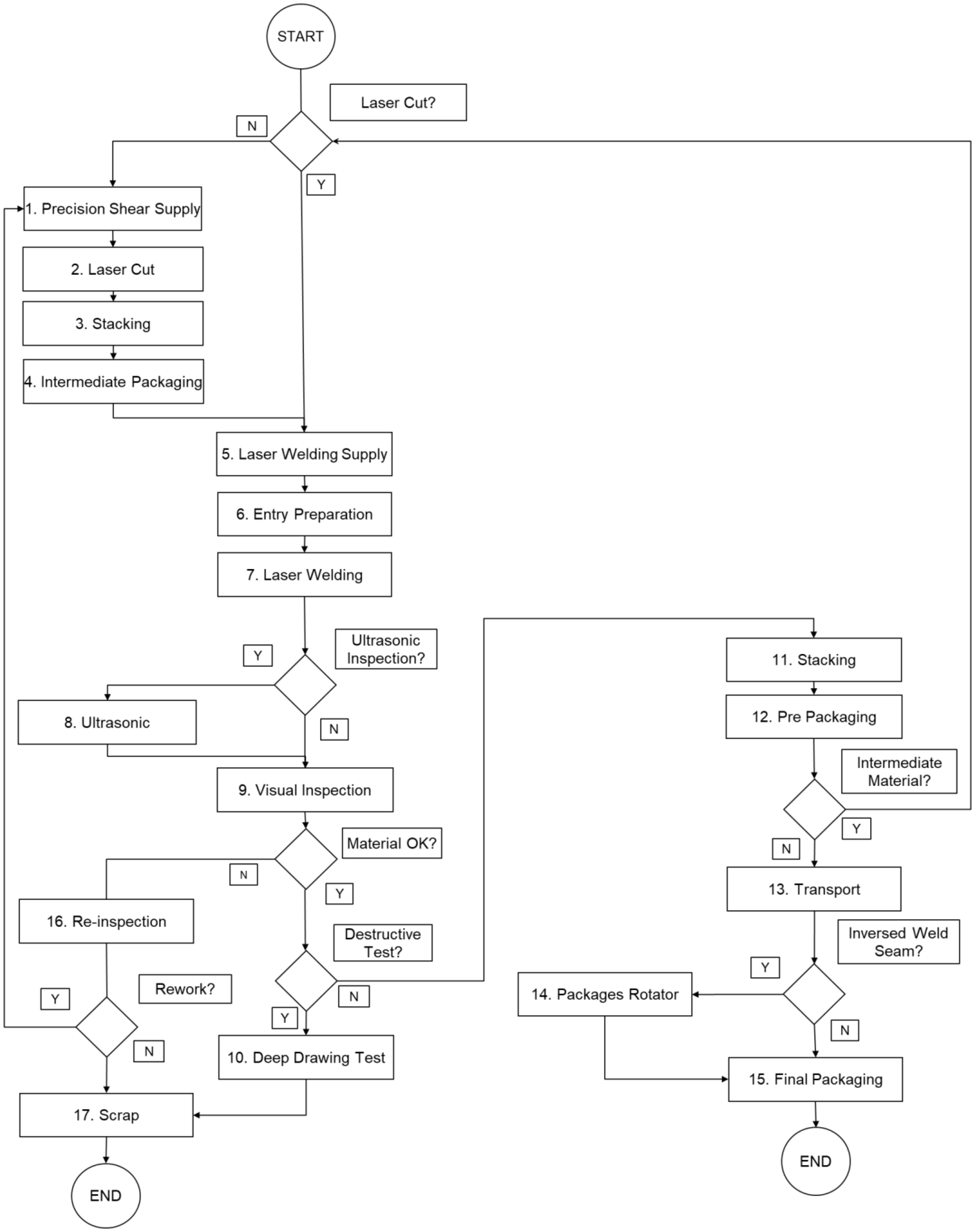
3. Results

The proposed framework was applied to a Laser Welding Process for Flat Steel to evaluate its failure modes and respective causes. Using the approach proposed by AIAG & VDA for FMEA application, it was possible to systematically establish a process analysis due to its structuring by functions and the Failure Chain. The process flowchart was defined as shown in Figure 13, with all the steps of the laser welding process specified. The Process Item to be studied was defined as the “LASER WELDING LINE.” Based on the process flowchart, the process stages were identified along with the process item and by applying the Six M analysis to each step, its elements were mapped. Following these analyses, the functions of the items, stages, and elements of the process were defined, and the respective correlations were established in the methodological procedure to enable risk analysis.

Each risk was assessed using the criteria defined for occurrence, detection, and severity, generating the necessary data for determining the Action Priority (AP), and consolidating the steps of the AIAG & VDA FMEA approach. Considering the Six M's, and the respective functions of the process, stages, and elements, 327 distinct failures of the Laser Welding Process were identified with their respective causes, composed of a combination of 58 risk factors and 97 potential causes. Compared to the original FMEA study, which consists of 63 items, a more comprehensive view of the process was achieved.

After the AIAG & VDA FMEA analysis, using the Action Priority criterion, 19 failure modes were classified as high priority, 135 as medium priority, and the remaining 173 failure modes were classified as low priority. Among the 19 high-priority failure modes, Figure 14 illustrates those that demand the improvement team's attention to adopt preventive actions to avoid occurrence or improve the detection capability of the process. For a better understanding, Figure 15 describes the mentioned risk factors, except for the 'Planar defect inspection failure' mode, which is associated with a deficiency in the ultrasonic inspection system that may affect the detection of defects related to the general weld geometry.

Figure 13 - Laser Welding Process Flowchart



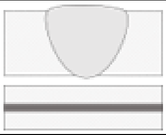
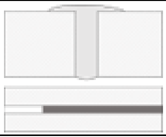
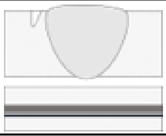
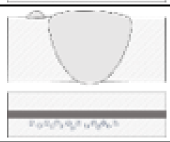
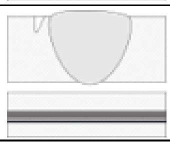
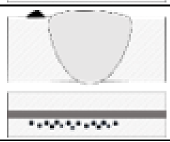
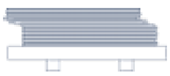
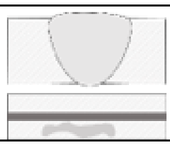
Source: Prepared by the authors (2024)

Figure 14 - Failure Modes with High Priority AP score

1. Failure Effect (FE) [Plant]	1. Failure Effect (FE) [Shipping Plant]	1. Failure Effect (FE) [Final Customer]	2. Process Step Failure Mode (FM)	3. Work Element Failure Cause (FC)
Steel scrap above expected	Parts do not allow assembly	No perceptible effect	Incorrect cut	Part out of position during cutting. Irregular cut
Surface appearance not suitable for use	Painting failures on parts	Poor appearance	Scratches from Laser Cutting	Incorrect entry stack height in guillotine
Surface appearance not suitable for use	Painting failures on parts	Poor appearance	Scratches from Guillotine	Not stacking parts correctly
Surface appearance not suitable for use	Painting failures on parts	Poor appearance	Scratches from Guillotine	Allowing damage to parts during transport
Weld geometry inadequate	Parts do not allow assembly	No perceptible effect	Incorrect Laser Welding Setup Preparation	Not preparing parts correctly for welding
Surface appearance not suitable for use	Painting failures on parts	Poor appearance	Welding splatter	Inadequate laser for welding
Surface appearance not suitable for use	Painting failures on parts	Poor appearance	Welding splatter	Left and right parts not driven correctly
Surface appearance not suitable for use	Painting failures on parts	Poor appearance	Welding splatter	Inadequate welding adjustments and inspection error
Surface appearance not suitable for use	Painting failures on parts	Poor appearance	Welding splatter	Z-axis adjustment out of position
Surface appearance not suitable for use	Painting failures on parts	Poor appearance	Scratches from Welding	Inadequate welding adjustments and inspection error
Surface appearance not suitable for use	Painting failures on parts	Poor appearance	Scratches from Welding	Left and right parts not in correct position on welding wheel
Surface appearance not suitable for use	Painting failures on parts	Poor appearance	Scratches from Welding	Parts misaligned on welding wheel
Surface appearance not suitable for use	Painting failures on parts	Poor appearance	Scratches from Welding	Inadequate weld seam cooling
Surface appearance not suitable for use	Painting failures on parts	Poor appearance	Dirty Plate Welding	Left and right parts not in correct position on welding wheel
Weld geometry inadequate	Parts do not allow assembly	No perceptible effect	Planar defect inspection failure	Interrupted electronic circuit
Weld geometry inadequate	Parts do not allow assembly	No perceptible effect	Planar defect inspection failure	Incorrect ultrasound reading of weld seam
Irregular stacking	Painting failures on parts	No perceptible effect	Parts shifted on pre-packaging pallet	Inadequate pre-packaging method
Irregular stacking	Painting failures on parts	No perceptible effect	Parts shifted on final packaging pallet	Tapes and seals not properly fixed
Surface appearance not suitable for use	Painting failures on parts	Poor appearance	White rust	Allowing damage to parts during transport

Source: Prepared by the authors (2024)

Figure 15 - Failure Modes Description

Failure Mode	Representation	Description
Weld OK		
Incorrect cut		Improper contact of the Strip Edges
Scratches from Laser Cutting		scratches on the sheet surface affecting the superficial appearance caused in the guillotine
Welding splatter		Solidified metal splatters near the weld seam during the welding process affecting the superficial appearance
Scratches from Laser Welding		scratches on the sheet surface affecting the superficial appearance caused in the laser machine
Dirty Plate Welding		Accumulated dirt on the surface of the sheet affecting the surface appearance.
Parts shifted on pre-packaging pallet		Misaligned parts in intermediate packaging with a risk of physical damage such as dents and scratches
Parts shifted on final packaging pallet		Misaligned parts in final packaging with a risk of physical damage such as dents and scratches
White rust		White zinc corrosion on the sheet surface affecting the appearance

Source: Prepared by the authors (2024)

4. Conclusion

The approach recommended by AIAG & VDA for the FMEA technique establishes a systematic method for process evaluation, facilitating specialists in creating a comprehensive mapping, despite its complex structure.

In the context of the analyzed process, using the action priority criteria, 19 failure modes were classified as high priority, 135 as medium priority, and the remaining 173 failure modes were classified as low priority. To reduce risk, since aspects related to severity concern the potential impacts of failure effects perceived by the manufacturing plant, assembly, or end user, it is not feasible to adopt actions in the manufacturing process that could reduce the potential risk, as it is intrinsically linked to the part design and its function. Failure effects manifest in the presence of a failure mode, which is the central element of the failure theory, defined as the way the process can lead to the product not being shipped, and the failure causes indicate why the failure mode might occur. Considering these issues, since there is no action capable of reducing the impact or severity of the failure, reducing the potential impact of the failure can be achieved through preventive controls that mitigate the causes, reducing the probability of occurrences, or by developing more effective systems for detecting causes or failure modes.

Thus, for the studied process, it is recommended to increase the detection capacity of the failure mode associated with Incorrect cut, Scratches from Laser Cutting, Scratches from Guillotine, Incorrect Laser Welding Setup Preparation, Welding splatter, Scratches from Welding, Dirty Plate Welding, Planar defect inspection failure, Parts shifted on pre-packaging pallet, Parts shifted on final packaging pallet and White rust, so that the production process can react to the failure with minimal non-conformities, preventing the failure mode from affecting the customer. On the other hand, alternatives to block Part out of position during cutting (Irregular cut), Incorrect entry stack height in guillotine, Not stacking parts correctly, Allowing damage to parts during transport, Not preparing parts correctly for welding, Inadequate laser for welding, Left and right parts not driven correctly, Inadequate welding adjustments and inspection error, Z-axis adjustment out of position, Left and right parts not in correct position on welding wheel, Parts misaligned on welding wheel, Inadequate weld seam cooling, Interrupted electronic circuit, Incorrect ultrasound reading of weld seam, Inadequate pre-packaging method and Tapes and seals not properly fixed are the most viable actions and should be prioritized, as they are causes of different failure modes. Reducing the occurrence of these causes will decrease the incidence of failure modes, with special attention to Allowing damage to parts during transport, Inadequate welding adjustments and inspection error and, Left and right parts not in correct position on welding wheel since they are causes of two distinct failure modes, each with a high AP.

Thus, the general objective of proposing a methodological procedure for the use of the FMEA technique, harmonized between AIAG and VDA, applied to industrial processes without the need for commercial software, has been met. The FMEA AIAG & VDA still strongly relies on specialists for process analysis. This research was limited to applying the approach to the use of Excel® for Microsoft 365 due to the need for the Power Query® module and matrix functions. Future research is recommended to enhance the FMEA analysis to highlighting and prioritizing failure causes that could be responsible for different failure modes.

REFERENCES

AIAG & VDA. **Manual FMEA**. Southfield: Automotive Industry Action Group, 2019.

ANACKOVSKI, Filip; KUZMANOV, Ivo; PASIC, Roberto. Action Priority in new FMEA as factor for Resources Management in Risk Reduction. **International Journal of Scientific & Engineering Research**, [*s. l.*], v. 12, n. 4, 2021. Disponível em: http://www.ijser.org.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ISO 9001:2015**. [*S. l.*]: Associação Brasileira de Normas Técnicas, 2015.

CHIN, Kwai Sang; CHAN, Allen; YANG, Jian Bo. Development of a fuzzy FMEA based product design system. **International Journal of Advanced Manufacturing Technology**, [*s. l.*], v. 36, n. 7–8, p. 633–649, 2008.

FRUNZA, Gabriela; RADU RUSU, Cristina Gabriela; POP, Ioan Mircea. Study regarding the application of the FMEA (failure modes and effects analysis) method to improve food safety in food services. **Scientific Papers. Series D. Animal Science**, [*s. l.*], v. Vol. LXIII, n. Issue 2, p. 360–369, 2020.

GRIGG, Nigel P. Redefining quality in terms of value, risk and cost: a literature review. **International Journal of Quality & Reliability Management**, [*s. l.*], v. 38, n. 5, p. 1065–1089, 2021. Disponível em: https://www.emerald.com/insight/content/doi/10.1108/IJQRM-06-2020-0209/full/html.

GUEORGUIEV, Tzvetelin; KOKALAROV, Miroslav; SAKAKUSHEV, Boris. Recent Trends in FMEA Methodology. *In*: , 2020. **2020 7th International Conference on Energy Efficiency and Agricultural Engineering, EE and AE 2020 - Proceedings**. [*S. l.*]: Institute of Electrical and Electronics Engineers Inc., 2020.

HARPSTER, Richard A. AIAG VDA and SAE J1739 DFMEA Methods, Similarities, Differences and Impact on the Auto Industry. *In*: , 2022. **2022 Annual Reliability and Maintainability**

Symposium (RAMS). [*S. l.*]: IEEE, 2022. p. 1–6. Disponível em: https://ieeexplore.ieee.org/document/9893956/.

HUANG, Jia *et al.* Failure mode and effect analysis improvement: A systematic literature review and future research agenda. **Reliability Engineering & System Safety**, [*s. l.*], v. 199, p. 106885, 2020. Disponível em: https://linkinghub.elsevier.com/retrieve/pii/S095183201930105X.

ISLAM, Md. Ariful; TEDFORD, J.D.; HAEMMERLE, E. Managing operational risks in Small- and Medium-sized Enterprises (SMEs) engaged in manufacturing - an integrated approach. **International Journal of Technology, Policy and Management**, [*s. l.*], v. 8, n. 4, p. 420, 2008. Disponível em: http://www.inderscience.com/link.php?id=20167.

KLUSE, Christopher. A critical analysis of the AIAG-VDA FMEA; does the newly released AIAG-VDA method offer improvements over the former AIAG method?. **Journal of Management and Engineering Integration**, [*s. l.*], v. 13, n. 1, p. 71–85, 2020. Disponível em: https://soar.wichita.edu/handle/10057/24747. Acesso em: 13 jul. 2024.

LEOPOULOS, V. N.; KIRYTOPOULOS, K. A.; MALANDRAKIS, C. Risk management for SMEs: Tools to use and how. **Production Planning & Control**, [*s. l.*], v. 17, n. 3, p. 322–332, 2006. Disponível em: https://www.tandfonline.com/doi/full/10.1080/09537280500285136.

LEOPOULOS, V.; KIRYTOPOULOS, K.; VOULGARIDOU, D. A model for risk identification in ERP system processes. *In*: , 2006, Southampton, UK. **Risk Analysis V: Simulation and Hazard Mitigation**. Southampton, UK: WIT Press, 2006. p. 143–152.

MONFORTE, Priscila Morcelli; OLIVEIRA, Ualison Rébula; ROCHA, Henrique Martins. Failure Mapping Process: An Applied Study in a Shipyard Facility. **Brazilian Journal of Operations & Production Management**, [*s. l.*], v. 12, n. 1, p. 124, 2015. Disponível em: https://bjopm.emnuvens.com.br/bjopm/article/view/V12N1A12.

OLIVEIRA, Fernando Ailton Castellani de; BRANDALISE, Nilson. Evaluation of costs and reworks in the tires recovery process by the Monte Carlo Method: case study. **Independent Journal of Management & Production**, [*s. l.*], v. 11, n. 7, p. 2925–2942, 2020. Disponível em: http://www.ijmp.jor.br/index.php/ijmp/article/view/1087.

OZKOK, Murat. Risk assessment in ship hull structure production using fmea. **Journal of Marine Science and Technology (Taiwan)**, [*s. l.*], v. 22, n. 2, p. 173–185, 2014. Disponível em: https://jmstt.ntou.edu.tw/journal/vol22/iss2/8. Acesso em: 2 jul. 2022.

PLINTA, Dariusz; GOLINSKA, Ewa; DULINA, Ľuboslav. Practical Application of the New Approach To FMEA Method according to AIAG and VDA Reference Manual. **Communications - Scientific letters of the University of Zilina**, [*s. l.*], v. 23, n. 4, p. B325–B335, 2021. Disponível em: http://komunikacie.uniza.sk/doi/10.26552/com.C.2021.4.B325-B335.html.

SUN, Jia Jeng; YEH, Tsu Ming; PAI, Fan Yun. Application of Monte Carlo Simulation to Study the Probability of Confidence Level under the PFMEA's Action Priority. **Mathematics**, [*s. l.*], v. 10, n. 15, 2022.

THURNES, Christian M. *et al.* Using TRIZ to Invent Failures – Concept and Application to go Beyond Traditional FMEA. **Procedia Engineering**, [*s. l.*], v. 131, p. 426–450, 2015. Disponível em: https://linkinghub.elsevier.com/retrieve/pii/S1877705815043313.