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DETERMINING THE RELIABILITY LEVEL BY COMBINING FMEA, FTA AND DEMATEL TOOLS

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ABSTRACT

The aim of the paper was to determine the level of reliability of a carousel type device. Considering the improvement of reliability, we decided to use the basic tools of FMEA and FTA. Using FMEA, we identified the most critical part of the equipment, namely welding (RPN=320). The proposed measure only solved the improvement of detection. Based on the FMEA analysis, we chose the TOP event for FTA - bad weld. The detected probability of peak event failure by quantitative FTA analysis was at the level of 0.58%. We identified the basic events leading to the TOP event, i.e. an allowed sonotrode, incorrect position of the membrane during sampling, short welding time and insufficient weld depth. Subsequently, reliability indicators were quantified. We achieved almost 100% availability values. Despite this, the aim was to find out a more comprehensive level of reliability and follow up findings from FMEA. We used the DEMATEL model and our own proposed economic model. Using the DEMATEL model, we found out that short welding time and an insufficient weld depth are the causative modes, that means, they significantly influence other failure modes and do so with a high significance. The creation of an economic evaluation model based on the quantification of direct costs for failure modes with the consequences of a certain number of defective products contributed to the fact that we again determined that the failure modes short welding time and insufficient depth are the modes with the highest priority for solving the bad weld event. The costs incurred as a result of their occurrence and as a result of the occurrence of downtime were the highest with these regimes. These models create space for us to more effectively design measures to improve the level of reliability and production quality, what is a prerequisite for ensuring a reduction in downtime, an increase in production quality and reliability, and an overall cost reduction. This also leads to an increase in the reputation of manufacturers.

Introduction

Many tools to assess production quality, reliability or safety are currently used to eliminate and evaluate production failure modes. Failure mode and effect analysis (FMEA) is one of the most used tools in different industries (Mutlu & Altuntas, 2019).

Today there an overwhelming number of different risk analyses techniques with acronyms such as FMEA (Failure Modes and Effects Analysis) and its extension FMECA (Failure Mode, Effects, and Criticality Analysis), DRBFM (Design Review by Failure Mode), FTA (Fault Tree Analysis) and its extension ETA (Event Tree Analysis), HAZOP (Hazard & Operability Studies), HACCP (Hazard Analysis and Critical Control Points) and What-if/Checklist are applied. However, the most used analysis techniques in the mechanical and electrical industry are FMEA and FTA (Cristea and Constantinescu, 2017).

In the past, FMEA and FTA methods were most used to identify the causes of failure modes. As a result, a reliability analysis can be performed through the interaction between FMEA and FTA tools for reliability or quality assessment of manufactured products in the production process (Cristea and Constantinescu, 2017).

FMEA is an inductive method. It usually gathers information about the consequences and effects of failures through interviews with experienced people and with different expertise, i.e. cross-functional groups (Tinga, 2013).

FTA is usually used as a deductive method. FTA identifies and analyses the potential causes, conditions and factors that contribute to the occurrence of an unidentified adverse serious incident (IEC 61025:2006 | Fault Tree Analysis (FTA), 2006). FTA method is used to analyse, assess, and graphically illustrate the hierarchical flow of potential incidents or situations that may negatively affect the system reliability and usability (IEC 61025:2006 | Fault Tree Analysis (FTA), 2006, p.11) (Mutlu and Altuntas, 2019).

Failure modes assessment for components needs a system approach where methods such as FMEA and FTA are helpful tools. However, FMEA as a bottom-up method lacks in directly identifying combinations of failure and effects. FTA on the other hand allows the free combination or separation of failure, effects, and external influences.

Table 1 presents the studies that considered the issue of combination of FMEA and FTA, or extended combination of methods and tools, where they formed the basis of the FMEA - FTA method. At the same time, Table 1 also contains the variant or result of using this combination.

The Decision Making Trial and Evaluation Laboratory (DEMATEL) model, developed by the Battelle Memorial Institute (Fontela, 1976), is a key technique in resolving problems associated with coupling relationships. It was initially applied to investigate complex world problems, including racial issues, starvation, environmental protection, and energy consumption (Kuzu, 2023; Zhang and Deng, 2019). The DEMATEL model can transform sophisticated systems into precise causal relationships in structure, so that the quantified extent of direct and/or indirect causality among coupled risk factors can be evaluated using matrix operations and mathematical theories to help find the core problem (Luthra et al., 2016; Strantzali and Aravossis, 2016).

Table 1.
Use of a combination of FMEA and FTA in scientific studies

Authors and Studies	Models Applied	Final Usage or Conclusion
Whiteley et al. (2016)	FTA - FMEA	Assessment of safety, manufacturing or reliability problems
Mutlu and Altuntas (2019)	FMEA – FTA - BIFPET	Improve the analysis performance
Held and Brönnimann, (2016)	FMEA - FTA	FTA utilized to analyze free combinations of failure modes, which FMEA does not allow.
Peeters et al. (2018)	FTA – FMEA	Criticality assessment of failure modes at both system and component level.
Sulaman et al. (2019)	FTA - FMEA	Improve the Quality. Comparison of FMEA and FTA.
Takahashi et al., (2021)	FMEA – FTA	Determination of causes of events (FMEA), causes of specific events (FTA)
Hong and Binbin (2009); Liu et al. (2013)	FMEA – FTA FTA - FMEA	Proposal for direct integration (i.e., FMEA to FTA) and backward integration (i.e., FTA to FMEA).
Renosori et al., (2023)	FTA – FMEA	Using FTA to identify defects and FMEA to reduce occurs.
Hidayat et al. (2018)	FTA – FMEA	Using FTA for determination of causes and then FMEA for improvements.
Jaiswal and Kaushik (2020)	FMEA – FTA	Utilize to quantify system reliability, availability, and maintainability.

Bujna et al. (2018) say that DEMATEL provided answers to better understand the linkages between individual failures by FMEA. In another study by Bujna et al. (2023a) used DEMATEL as a prediction tool to estimate the behavior of the PFMEA tool. Authors Cheshmberah et al. (2020) developed an integrated process model using Reality Charting, FMEA and DEMATEL to understand and implement RCFA effectively. Budiraharjo et al. (2023) proposed a new method of risk assessment, mainly in the risk evaluation stage, which complements other methods that are mainly used in the stages of risk identification and risk analysis such as Fault Tree Analysis (FTA), Failure Modes, Effects, and Analysis (FMEA), and Decision Making Trial and Evaluation Laboratory (DEMATEL).

Production losses are a big problem for many manufacturers. The consequences are not only economic, but also marketing. The possible loss of customers and reputation represents long-term consequences for organizations. Especially nowadays, in connection with the crisis, high inflation and in many countries even economic recession, it is particularly important to invest financial resources effectively. This also concerns the determination of the correct prioritization for the design of measures with the aim of increasing the reliability of the system and improving the quality of production. The aim of the paper is to establish the level of reliability of the production technology taking place on a carousel-type production line in the production of a plastic component. During the assessment, we will use the well-known connection of FMEA and FTA methods and calculate the level of reliability indicators. Following this, we will use additional models that will solve the level of reliability more comprehensively. The aim of the paper is to point out that it is not always possible to rely on the results of known methods.

Materials and Methods

Object of investigation

The product that is completed on the production line is a plastic component that serves as a cover of the pump motor in the urea tanks, so it is the cover of the AD-blue liquid pump. It is a component made from ABS material with a certain proportion of glass fibers. The component has a specific shape and must meet high requirements, especially for tightness, as it is surrounded by an aggressive liquid and electronic components are stored inside, the short circuit of which can have fatal consequences. At the same time, high dimensional accuracy is required from the component, mainly since the fluid travels through the component under high pressure. However, the component must not only withstand high pressure and aggressive fluid, but it must also withstand operation for a sufficiently long time. Overall, after leaving the production line, the component is composed of itself, of the O-ring that is mounted on it, of another plastic component that aims to hold the O-ring, of the so-called "dust cap", i.e. from the cap to prevent dirt from getting into the component and the last part, the membrane, which is ultrasonically welded to the component and must be perfectly tight (Fig. 1). All these components are assembled on the plastic part on the production line that is the subject of our investigation.

Legend: 1 dust cap, 2 membrane, 3 O-ring, 4 seal retainer

Figure 1. Assembled part - Cover of the AD-blue liquid pump

Characteristics of the device

The device is a semi-automated production line of the carousel type. It is necessary for the device to function that some operations be performed by the operator. The function of this equipment is to test and prepare a plastic component so that it can be assembled with another plastic part. The device has a total of 8 not only assembly but also control stations. The whole device operates under a program that has been refined over the years to avoid as many errors as possible and the organization was able to avoid customer's complaints. The device (Fig. 2 and 3) has two conveyor belts, one for loading semi-finished products and the other for output of finished products.

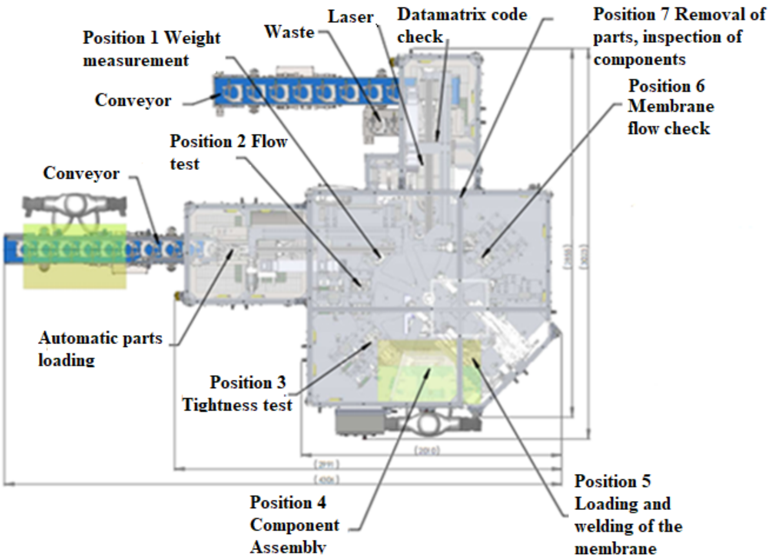

Figure 2. Observed device for the production of cover of the AD-blue liquid pump

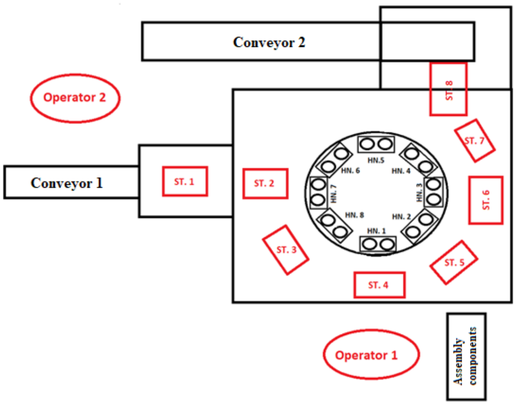

Figure 3. Scheme of the device the production of cover of the AD-blue liquid pump

FMEA analysis

FMEA procedure:

– structural analysis - sequence number of the operation, name of the process and who is responsible for it, function of the process and its characteristics.

– risk analysis - where the failure mode manifests itself, severity of the failure mode – S (according to the criteria prescribed for each FMEA, for each failure mode from 1-10), root cause, occurrence – O (according to the criteria prescribed for each FMEA, for each failure mode from 1-10), failure mode detection, each step inspection, detectability – D (according to the criteria prescribed for each FMEA, for each failure mode from 1-10 - in our case, each value will be the same and determined as 3, as the device will automatically lock and mark the non-conforming product as non-conforming and discard it) (Bujna et al., 2023a).

In Figure 4 we can see the matrix for determining the level of RPN.

Severity Závažnosť		Occurrence Výskyt 1	2-3	4-5	6-7	8-10	Detection Detekcia
	1	L	L	L	L	L	1
		L	L	L	L	L	2-4
		L	L	L	L	L	5-6
		L	L	L	L	L	7-10
	2-3	L	L	L	L	L	1
		L	L	L	L	L	2-4
		L	L	L	L	M	5-6
		L	L	L	L	M	7-10
	4-6	L	L	L	L	M	1
		L	L	L	M	M	2-4
		L	L	L	M	H	5-6
		L	L	M	M	H	7-10
	7-8	L	L	M	M	H	1
		L	L	M	H	H	2-4
		L	M	M	H	H	5-6
		L	M	H	H	H	7-10
	9-10	L	L	M	H	H	1
		L	L	H	H	H	2-4
		L	M	H	H	H	5-6
		L	H	H	H	H	7-10

Figure 4. Determining the qualitative level of risk

The RPN is calculated based on the product of criteria S, O and D (formula 1)

$$RPN = S.O.D \tag{1}$$

FTA

The FTA analysis procedure is as follows:

– System selection – based on FMEA.
– Determining the causes of undesirable states and system activities - determining the rough scope of analyses. Subsequently, the lower levels are determined, which gradually lead to the required lowest level, thus we reach the primary events.
– Construction of the fault tree - it is created by using standard symbols (Fig. 5).
– Making a quantitative analysis - the required data, suitable for quantitative analysis, are the intensity of repairs, the intensity of faults, the probability of occurrence of types of fault conditions (Bujna et al., 2023b).
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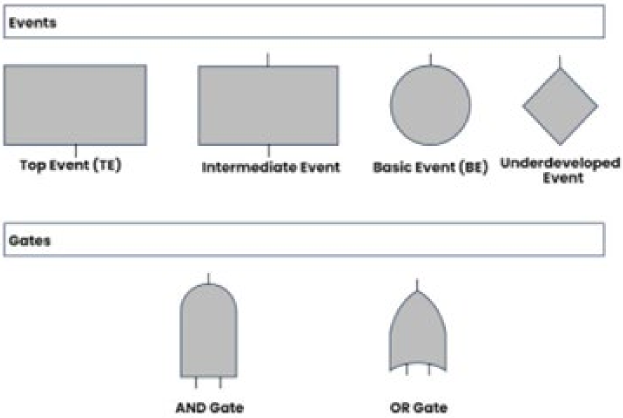

Figure 5. Symbols used in the fault tree

The following relations are used to determine the probability of the occurrence of a top event within the quantitative analysis of FTA. Formula 2 for the AND gate and formula 3 for the OR gate.

$$P(G) = \prod_{i=1}^{n} P(A_i) \tag{2}$$

$$P(G) = 1 - \prod_{i=1}^{n}(1 - P(A_i)) \tag{3}$$

By using formula 2, we determine the probability for transient events in the FTA method, and then by using formula 3, we calculate the probability of failure of the top event (Bujna et al., 2023b).

Determination of reliability indicators

Mean time between failure MTBF

$$MTBF = \frac{t_p}{n} = \frac{\sum_{i=1}^{n} t_{pi}}{n} \text{ (h)} \tag{4}$$

where:
tp – the cumulative operating time, (h)
n – number of outages caused by failures.

Failure rate λ

$$\Lambda = \frac{1}{MTBF} \text{ (h}^{-1}\text{)} \tag{5}$$

Mean time to repair MTTR

$$MTTR = \frac{t_{op}}{n} \text{ (h)} \tag{6}$$

where:
top – cumulative downtime due to item failure, (h)
n – number of failures.

Availability A

$$A = \frac{MTBF}{MTBF+MTTR} \quad (7)$$

Based on the quantification of reliability indicators, the overall availability of the machine is evaluated (Bujna et al., 2020).

DEMATEL procedure

The DEMATEL method is performed in 6 steps, each of which has its own rationale. The steps are as follows:

Generation of the direct relational matrix. When assessing the relations between factors, experts indicate the direct relation on a factor using a numerical scale where they are graded from 0 - no influence, 1 - very low influence, 2 - low influence, 3 - medium influence, 4 - medium influence, 5 - high influence and 6 - very high influence. The respondents are asked to evaluate the direct influence or strength of the relationship between any two criteria (binary relation) in a matrix form. An $n \times n$ matrix A_y is derived from the y^{th} expert's response. The $x_{ij}(y)$ represents the degree of influence of criterion CR_i on CR_j, which then forms the influence matrix A_y. Suppose k is the number of respondents consulted, the average matrix Z is found by averaging the scores of all the respondents as shown in equation (formula 8).

$$Z = \frac{1}{k}\sum_{m-1}^{k} X_{ij}^{m} \quad kde\ 1 \leq m \leq k \quad (8)$$

Calculate the normalized initial direct relation matrix *(D)*. Normalize the initial direct-relation matrix *(D)* so that each element in matrix *D* falls between zero and one. Using the average matrix *Z*, the normalized initial direct matrix *(D)* can be obtained using equations (9 and 10).

$$D = \frac{Z}{S}\ kde\ 0\ \leq každý\ element\ z\ D \leq 1 \quad (9)$$

$$S = \frac{1}{\max\left(\sum_{j=1}^{n} z_{ij}, \sum_{i=1}^{n} z_{ij}\right)} \quad (10)$$

Calculate the total relation matrix *(T)*. Using a normalized relation matrix, a total relation matrix is calculated by summing the direct influences and all the indirect influences in what is referred to as the identity matrix (formula 11).

$$T = \sum_{n=1}^{\infty} D^{i} = D + D^{2} + D^{3} + \cdots + D^{n} = \frac{D(I-D^{n})}{(I-D)} = \frac{D(I-D^{\infty})}{(I-D)} = \frac{D}{(I-D)} = (DI-D)^{-1} \quad (11)$$

Calculate the sum of rows and columns. Determine row (R_i) and column (C_j) sums for each row(i) and column(j) from the total relation matrix (T) as given in equations 12 a 13. (Ullah et al., 2021).

$$R_i = \sum_{i=1}^{n} Tij \forall i \quad (12)$$

$$C_j = \sum_{j=1}^{n} Tij \forall j \quad (13)$$

Determine the overall prominence and the net effect. Using equations 14 and 15, calculate the overall prominence (P_i) and the net effect (E_i) of factor i. The value of prominence corresponds to the value of P_i. So, the larger the value of P_i, the greater will be the overall prominence of factor i in terms of its overall relationship with other criteria. If E_i greater than 0, then factor i is a net cause or starting point of other criteria. Similarly, if E_i less than 0, then factor i is a net effect of other criteria.

$$P_i = \left[R_i + C_j \ i = j\right] \quad (14)$$

$$E_i = \left[R_i + C_j \ i = j\right] \quad (15)$$

A threshold value *(α)* must be set up to filter out the negligible effects in the total relation matrix *(T)* and keep the complexity of the system at a manageable level for explaining the structural relationships between the criteria. If the value is too low, the resultant digraph will be too complex to show the essential information for proper decision-making. Similarly, if the value is too high, many criteria will emerge and be presented as independent criteria without exhibiting any other criteria. (Ullah et al., 2021)

Creating an economic model

Creation of an optimal model for the economic evaluation of costs that arise due to the emergence of failure modes and the number of defective products. We will distinguish between internal and external costs. Internal are those that arise in production and external are those that will only be revealed by the customer.

We will create our own proposal by using the correct formulas according to the available costs. This evaluation will be part of the final interpretations to achieve improvement of the evaluated problem.

Results

FMEA

Before the final creation of the FMEA, we created a functional and structural analysis of the FMEA (Tab. 2). The first form contained the operation numbers of the given production process. All production operations are part of the Carousel type production line.

Table 2.
FMEA functional and structural analysis

N. op.	System function	Process function assurance method	Requirement/characteristic
1	Ensuring the correctness of the delivered component	Recognition of the part by using the camera	Recognition of the part by using signs on the surface
1	Ensuring the delivery of a complete and dimensionally correct part	Weight control	Checking whether the weight of the part is within the tolerances
2	Verification of sufficient flow rate	Channel flow rate testing	Control of flow rate sufficiency or insufficiency
3	Checking the tightness of the component	Checking the tightness	Checking the tightness of the component according to the required value
4	Mounting the O-ring on the part	Mounting the O-ring	Manual mounting to ensure tightness
4	Mounting the dust cap on the part	Mounting the dust cap	Manual mounting to prevent dirt in the parts
4	Mounting the seal retainer on the part	Mounting the seal retainer	Manual mounting to retain the O-ring
5	Removal of the membrane	Removal of the membrane by the suction cup	Removal with sufficient vacuum to remove and hold
5	Placing the membrane on the part	Membrane deposition by using vacuum	Placing the membrane to the correct position
5	Membrane welding	Welding with an ultrasonic welder	Welding the membrane to the part
6	Permeability control	Membrane permeability control by using a flow rate sensor	Comparison of the permeability with the allowed value
6	Pushing the seal retainer	Pushing the seal retainer with a weight	Pushing to the specified position
7	Component inspection	Control of the presence of the seal holder by using a camera	Checking presence and correct position
7	Burning datamatrix code	Burning the code into the plastic surface	Burning datamatrix code and reading it

Each station has its own designation; a different operation or a different control is performed at each station (Tab. 2 and 3). Some stations have multiple tasks, others only one task. In the final FMEA form, the identified failure modes for the tasks of all operations are displayed.

Table 3.
Final FMEA analysis completed by proposal of actions

N.	S	Failure mode / unfulfilled requirement	Causes	Current method of prevention	O	Current method of detection	D	AP	RPN	CH
1	1	The customer receives the wrong item	The wrong part entered into the line	Control by camera	1	Control by camera	3	**L**	3	
1	1	Incorrectly marked part	Defect in the injection process	Control by camera	1	Control by camera	3	**L**	3	
1	7	Incomplete part	Defect in the injection	Weight control	3	Weight control	3	**L**	63	SC

N.	S	Failure mode / unfulfilled requirement	Causes	Current method of prevention	O	Current method of detection	D	AP	RPN	CH
			process	with a pre-set tolerance		with a pre-set tolerance				
1	7	The part is dimensionally different	Defect in the injection process	Weight control with a pre-set tolerance	4	Weight control with a pre-set tolerance	3	**M**	84	SC
2	7	Too much flow rate	The part is not completely sprayed	Flow test with strict tolerance	3	Flow test with strict tolerance	3	**L**	63	SC
2	7	Too little flow rate	The part is over sprayed	Flow test with strict tolerance	4	Flow test with strict tolerance	3	**M**	84	SC
3	7	The part is leaking	The part contains leaks through which air escapes	Tightness test with strict tolerance	3	Tightness test with strict tolerance	3	**L**	63	SC
4	6	Insufficient tightness	The operator did not insert the O-ring	Control by camera	3	Control by camera	3	**L**	54	SC
4	6	NOK installation	The operator inserted more O-rings	Control by camera	3	Control by camera	3	**L**	54	SC
4	6	Leakage into the channel	The operator inserted the O-ring incorrectly	Control by camera	3	Control by camera	3	**L**	54	SC
4	6	Impurities in parts	The operator did not install the dust cap	Control by camera	3	Control by camera	3	**L**	54	
4	6	NOK installation	The operator installed the dust cap incorrectly	Control by camera	3	Control by camera	3	**L**	54	
4	6	Non-functionality of the part	The operator did not insert the seal retainer	Control by camera	3	Control by camera	3	**L**	54	
4	6	NOK installation	The operator inserted the seal retainer incorrectly	Control by camera	3	Control by camera	3	**L**	54	
5	7	Non-functionality of the part	The suction cup did not remove and hold the membrane	Permeability control	5	Permeability control	3	**M**	105	SC
5	8	Electronic defect	The vacuum does not place the membrane on the part	Permeability control	3	Permeability control	3	**L**	72	SC
5	8	Electronic defect	The machine inserted more membranes into the part	Permeability control	3	Permeability control	3	**L**	72	SC
5	8	Electronic defect	The welding machine insufficiently welded the membrane to the part	Optical control	5	Optical control	8	**H**	320	SC
5	8	Electronic defect	The welding machine welded the membrane into the wrong position	Optical control	5	Optical control	8	**H**	320	SC
6	8	Electronic defect	Damaged membrane during welding	Permeability control	3	Permeability control	3	**L**	72	SC
6	8	Electronic defect	Incorrect type of membrane during montage	Permeability control	1	Permeability control	3	**L**	24	SC
6	8	Electronic defect	More membranes inserted into the part	Permeability control	1	Permeability control	3	**L**	24	SC
6	6	NOK installation	Incorrectly inserted seal retainer by the operator	Control by camera	3	Control by camera	3	**L**	54	SC

N.	S	Failure mode / unfulfilled requirement	Causes	Current method of prevention	O	Current method of detection	D	AP	RPN	CH
7	6	NOK installation	Non-insertion of the seal retainer during the montage by the operator	Control by camera	3	Control by camera	3	**L**	54	SC
7	6	Leakage	Non-insertion of the seal retainer during the montage by the operator	Control by camera	3	Control by camera	3	**L**	54	SC
7	1	Non-ability to identify the part	Insufficiently burned data matrix	Control by camera	5	Control by camera	3	**L**	15	
7	1	Non-ability to identify the part	Unreadable data matrix due to the defect at the part	Control by camera	5	Control by camera	3	**L**	15	
7	1	A NOK part can be marked as OK	Error burning to a part in the system	Control by camera	1	Control by camera	3	**L**	3	

The most critical parts according to the RPN number were 2 and both relate to ultrasonic welding. Specifically, it is the ultrasonic welding process, where high-risk failure modes can occur. The first failure mode is that the membrane will be welded to the wrong position with a high RPN of 320 points. The inspection of the position of the weld was mainly problematic, because this inspection was performed visually - by the operator. We had to assign a detection number of 8 for this check. As a measure to eliminate this failure mode, we propose to add a camera to sense the membrane position, which would reduce our detection number value to 3 and avoid the problem of insufficient tracking of bad pieces, and the RPN number would be reduced to 120 (Tab. 4).

The FMEA specifically determined the possibility of defects arising from insufficient welding of the membrane to the part and welding of the membrane in the wrong position. We can therefore merge these 2 defects into one whole and determine these failure modes as a defect - a bad weld. By optimizing the FMEA, we solved the risk reduction, but the measures were aimed at improving the detection of the defect so that it does not get to the customer. The measures did not solve the internal consequences and the reduction of frequency.

Table 4.
Optimized FMEA after applying the action proposal

N.	PFMEA Preventive action	PFMEA Detection action	Responsible	Completion date	Status	S	O	D	Ch	AP	RPN
5	Action needed	Adding a sensor for control of the weld depth	Team FMEA	30.4.2023	In progress	8	5	3	SC	M	120
5	Action needed	Adding a camera for control the weld position	Team FMEA	30.4.2023	In progress	8	5	3	SC	M	120

FTA

The FMEA specifically determined the possibility of failure modes arising from insufficient welding of the membrane to the part and welding of the membrane in the wrong position. We merged these 2 failure modes within the FTA into the TOP event as a failure - wrong weld, or the occurrence of a wrong weld on the membrane.

Description of the monitored event - 2 events can occur: – 1. the membrane will not be inserted in the correct position and will therefore be welded outside its determined place; - 2. insufficiently welded membrane – the weld will not be deep enough.

We have established circumstances that will not be included in the analysis.

This is about: non-insertion of the membrane into the part, insertion of more membranes into the part, insertion of a wrong membrane into the part, damage of the welding machine, curvature of the welding machine.

We have established the physical boundaries of the system - station number 5, we only deal with removing the membrane, putting the membrane on the part and welding it.

We have described the considered states of the system - there are 2 variants in the case of a bad weld, namely insufficient welding of the membrane to the part - this means that it will not be welded deep enough and there is a risk of it falling off during manipulation or contact with liquid. The second variant – the wrong position of the membrane, there is a risk that the weld was sufficient, but the membrane was not welded precisely enough and thus a part of it may leak.

<u>Qualitative analysis of FTA</u>

1. System analysis: Station number 5 consists of 3 processes, those processes and therefore the parts are: removing the membrane, inserting the membrane and welding the membrane. The suction cup has a role to take away membrane. The suction cup takesaway the membrane by using a vacuum. Then the robotic arm, which moves the suction cup to the position where the vacuum is then inserted and released again, and the last part is the ultrasonic welder, the movement of which is provided by the servo motor, which moves this welder along the robotic arm.

   Main parts:
   - robotic arm – a bearing part of the suction cup and welding machine,
   - welding machine,
   - suction cup,
   - servo motor,
   - vacuum.
2. Determining the causes of undesirable conditions:
   Undesired condition: incorrect position of the membrane
   Failure: incorrect position when removing the membrane

   Undesired condition: incorrect weld position
   Failure: enabled sonotrode

   Undesirable condition: insufficient welding of the membrane to the part

Failure: Short welding time, insufficient weld depth

The graphical result of the qualitative analysis is the creation of a fault tree (Fig. 6), which logically and systematically takes into account the links between failure modes.

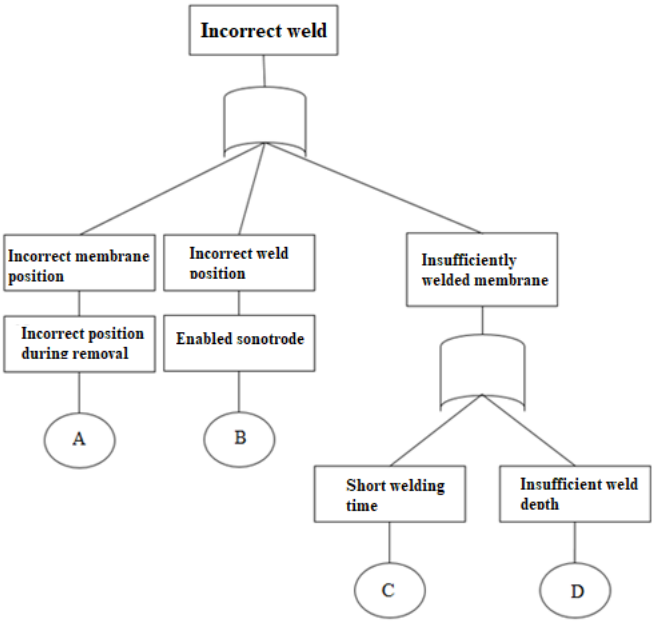

Figure 6. Fault tree

Quantitative analysis of FTA

For quantitative analysis, we needed to determine the frequency of occurrence of failure modes per million units produced. Based on this, we determined the probability of failure modes (Tab. 5).

Table 5.
Frequency of failure modes for quantitative analysis of FTA

Basic events	nn_i	$P(x)_i$
A – enabled sonotrode	1	0.000001
B – incorrect position during removal	19	0.00002
C – short welding time	289	0.000289
D – insufficient weld depth	289	0.000289

Legend: nn_i – the number of defective products, $P(x)_i$ - failure probability of the i-th mode.

Based on Table 10 and taking into account formulas 2 and 3, the probability for transient events was determined P_{AB} a P_{CD}.

$$PAB = 1 - [(1 - PA).(1 - PB)] = 1 - (1 - 0.000001).(1 - 0.00002) = 0.000020$$

$$PCD = 1 - [(1 - PC).(1 - PD)] = 1 - (1 - 0.000289).(1 - 0.000289) = 0.005778$$

Subsequently, the probability of failure of the TOP event "Bad weld" was calculated.

$$PABCD = 1 - [(1 - PAB).(1 - PCD)] = 1 - (1 - 0.000020).(1 - 0.005778) = 0.005797 \cong 0.58\,\%$$

Determination of reliability indicators

We determined the number of failure modes identified in the fault tree in terms of 1 000 000 manufactured products. This served as the basis not only for the quantitative analysis of the FTA, but also for the calculation of reliability indicators. The norm in the device is stated at 260 manufactured pieces per hour, so the device produces a million pieces in 3847 working hours. Table 6 shows the frequency of failure modes and downtime caused by one failure mode.

A: downtime: 0.25 h – production interruption time, of which repair time is 0.083 h;
B: downtime: 0.33 h – production interruption time, of which repair time is 0.167 h;
C: no downtime, nothing needs to be replaced or repaired, it is just a component defect, the part is thrown into the trash - when changing from C to D – 0.03 h – production interruption time;
D: no downtime, nothing needs to be replaced or repaired, it is just a component defect, the part is thrown into the trash - when changing from D to C - 0.03 h - production interruption time.

For failure mode A, the total downtime is 15 minutes, which is the production interruption time, 10 minutes for calling the maintenance worker, the arrive of the maintenance worker and preparing the tools, etc. The total repair time on the device by the maintenance worker is 5 minutes. After the repair, the device starts up and production continues.

For B, the total downtime is 20 minutes, which is the production interruption time, 10 minutes for calling the maintenance worker, the arrive of the maintenance worker and preparing the tools, etc.

The total repair time on the device by the maintenance worker is 10 minutes. After the repair, the device starts up and production continues.

In case of C and D, there is no downtime, nothing needs to be replaced, it is a random defect, when it is discovered, the faulty part is thrown away. The welding time is limited by the PLC device, which, when it does not reach the required time, evaluates the part as NOK and goes to waste. There are two options for welding, 1. welding according to time and 2. welding according to depth. We either weld to a certain depth, which is controlled by the movement of the servomotor, or for a time, which controls the length of the welding. Therefore, the same waste is generated in both C and D. The only downtime is when this function is changed in the PLC - while welding was done in such a way that we focus only on the welding time and that is our control parameter, and we want to transfer it to the welding depth and have that as our control parameter. This operation takes a maximum of 2 minutes; it is only a transfer of the control parameter on the control panel. Thus, the repair time is zero (clicking through the control panel).

Table 6.
Failure modes identified in the fault tree and their downtime

Failure mode	nn_i	$P(x)_i$	$MTTR_{1nni}$ (h)	$MTTR_{nni}$ (h)
A – enabled sonotrode	1	0.00000	0.25000	0.25000
B – incorrect position during removal	19	0.00002	0.33000	6.27000
C – short welding time	289	0.00029	0.03333	9.63333
D – insufficient weld depth	289	0.00029	0.03333	9.63333
Σ	598			25.78667

Legend: nn_i – number of defective products, $P(x)_i$ - failure probability of i-th mode, $MTTR_{1nni}$ - downtime for 1 defective product of i-th failure mode, $MTTR_{nni}$ – total downtime of i-th failure mode.

Table 7.
Calculations of complex reliability indicators

Failure mode	MTBF (h)	λ	MTTRi (h)	A
All failure modes	6.43	0.16	0.04	1.00
A – enabled sonotrode	3847	0.00026	0.25	0.999935
B – incorrect position during removal	202.4737	0.004939	0.33	0.999914
C – short welding time	13.31142	0.075123	0.033333	0.999991
D – insufficient weld depth	13.31142	0.075123	0.033333	0.999991

In Table 11 reliability indicators are set. Based on them, we can conclude that the device is highly reliable in terms of the selected failure modes, as we achieved high availability values (almost 100%). Nevertheless, we decided to examine the reliability of the device in more detail, because the given indicators work only with frequencies and consequences expressed by downtimes.

Applying the DEMATEL method

The DEMATEL method was applied based on chapter 3.5. First, a direct impact matrix was generated based on the team's assessment. The assessment team evaluated the impact between individual modes A, B, C and D determined by FMEA and FTA analysis. These values created the given matrix (Tab. 8).

Table 8.
Direct-relation matrix Z

FM	A	B	C	D	Σ
A	0	0	5	5	10
B	0	0	1	1	2
C	0	0	0	6	6
D	0	0	6	0	6
Σ	0	0	**12**	**12**	

To determine the normalized direct influence matrix D, the sum of the values in both rows and columns was determined in Table 13. From them, max. value (12) and S was calculated.

$$S = \frac{1}{\max(\sum_{j=1}^{n} z_{ij}, \sum_{i=1}^{n} z_{ij}} = \frac{1}{12} = 0{,}0833$$

These values created the given matrix (Tab. 14). Subsequently, each value in the matrix was calculated according to formulas 9 and 10 for the calculation of normalized values and entered in Table 9.

Table 9.
Normalized direct-relation matrix D

FM	A	B	C	D
A	0	0	0.416667	0.416667
B	0	0	0.083333	0.083333
C	0	0	0	0.5
D	0	0	0.5	0

A matrix of total influence (T) was constructed according to formula 11. First, we created an inverse matrix (tab. 10).

Table 10.
Inverse matrix I as an auxiliary matrix for the determination of the total-relation matrix

FM	A	B	C	D
A	1	0	0	0
B	0	1	0	0
C	0	0	1	0
D	0	0	0	1

We created the auxiliary I-D matrix shown in Table 11.

Table 11.
Auxiliary matrix I-D as an auxiliary matrix for determination of the total-relation matrix

FM	A	B	C	D
A	1	0	-0.41667	-0.41667
B	0	1	-0.08333	-0.08333
C	0	0	1	-0.5
D	0	0	-0.5	1

Then, based on formula 11 and using the inverse function in MS EXCEL, we created a second auxiliary matrix, the inverse I-D. We presented the values in Table 12.

Table 12.
Auxiliary matrix inverse I-D as an auxiliary matrix for determination of the total-relation matrix

FM	A	B	C	D
A	1	0	0.833333	0.833333
B	0	1	0.166667	0.166667
C	0	0	1.333333	0.666667
D	0	0	0.666667	1.333333

Finally, with the mmult function in MS Excel, we obtained the values for the resulting matrix of the overall impact (Tab. 13). This function works based on formula 11.

Table 13.
Total-relation matrix T

FM	A	B	C	D
A	0	0	0.833333	0.833333
B	0	0	0.166667	0.166667
C	0	0	0.333333	0.666667
D	0	0	0.666667	0.333333

We created a matrix of influential relationships based on formulas 12 and 13 (tab. 14).

Table 14.
Matrix of influential relations for final DEMATEL digraph creation

FM	R_i	C_j	P_i	E_i
A	1.666667	0	1.666667	-1.66667
B	0.333333	0	0.333333	-0.33333
C	1	2	3	1
D	1	2	3	1
Σ			2	0

Based on Table 14, we created a graphic representation of the DEMATEL digraph (Fig. 7).

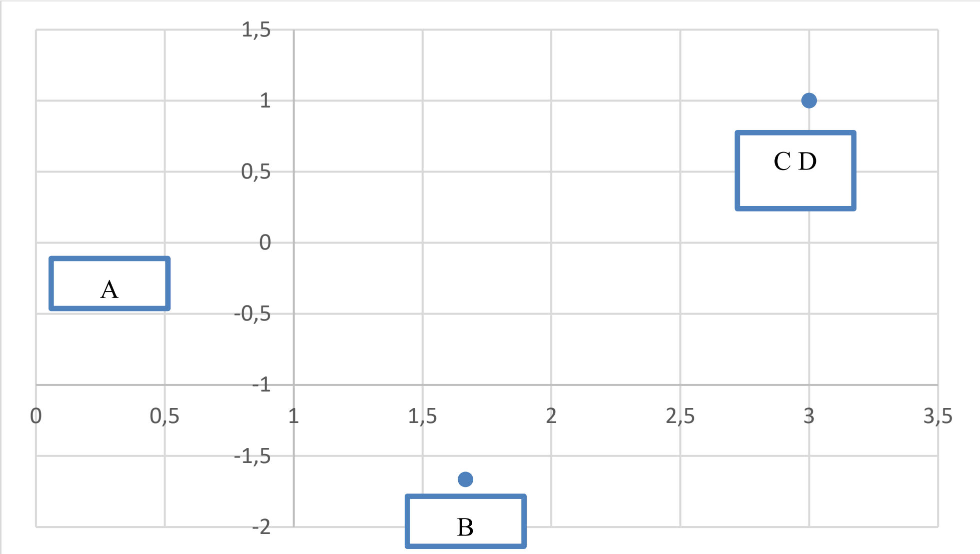

Figure 7. DEMATEL digraph for assessment the relation of failure modes

Interpretation of the results of the DEMATEL model

Failure modes short welding time (C) and insufficient welding depth (D) are causative modes, it means, they significantly affect other failure modes and, moreover, with high significance.

The failure mode enabled sonotrode (A) is relatively independent. It is a regime that is causal, but of a low significance.

The failure mode incorrect position during removal (B) is influenced by other failure modes with high significance. It often arises as an effect of these regimes.

Models of economic evaluation

The economic evaluation was based on the information about frequency and downtime from Table 5, while the direct costs of 1 failure mode were not calculated. Therefore, a new evaluation methodology was created. It was based on the fact that 1 000 000 products (n) were produced in 3 847 hours (t). During this time, 598 defective products (nn) were identified. The total downtime was calculated at 25.79 hours (MTTRnn). We decided to start from the fact that for a defect discovered in production, for each failure mode for one defective product, the calculated damage is 1.95 euros (we will mark it as INi). For a defect discovered by the customer, the calculated loss is EUR 101.95 (ENi) per a defective product for all failure modes. The proportion of revealed products in production and at the customer is in the ratio 3:7. In tab. 15, this ratio is taken into account and the number of defective products for a given time is determined.

Table 15.
The number of detected defective products per million manufactured pieces in production and at the customer

Failure mode	nn_i	nni_i	nne_e
A – enabled sonotrode	1	0.3	0.7
B – incorrect position during removal	19	5.7	13.3
C – short welding time	289	86.7	202.3
D – insufficient weld depth	289	86.7	202.3
Σ	598	179.4	418.6

Legend: nn_i – number of defective products, nni_i - the number of defective products identified in production, nne_i - the number of defective products identified by the customer.

We calculated the total internal costs (IN) spent on defective products in production by multiplying the number of all defective products in production, the costs of such a product, and the proportion of these products (formula 13). According to Table 2, factor E (external dispenser plate feed rate) contributes most significantly to reducing the probability of a top event G failure. The following factors are F (external dispenser cooling), AL (incorrect set tray setting), D (external dispenser plate break).

$$IN = nni_i \,.\, IN_i \,.\, 0{,}3 \tag{16}$$

$IN = 179{,}4 \,.\, 1{,}95 \,.\, 0{,}3 = 104{,}95$ (€)

From this, the internal costs (IN1nn) for one defective product are (formula 17):

$$IN_{1nn} = IN_i \,.\, 0{,}3 \tag{17}$$

$IN_{1nn} = 1{,}95 \,.\, 0{,}3 = 0{,}585$ (€)

Similarly, we determined the external costs (EN) spent on solving defects that occurred at the customer (formula 18).

$$EN = nne_i \,.\, EN_i \,.\, 0{,}7 \tag{18}$$

$EN = 418{,}6 \,.\, 101{,}95 \,.\, 0{,}7 = 29\,873{,}39$ (€)

From this, the external costs (EN1nn) for one defective product are (formula 19):

$$EN_{1nn} = EN_i \,.\, 0{,}3 \tag{19}$$

$EN_{1nn} = 101{,}95 \,.\, 0{,}3 = 71{,}355$ (€)

Similarly, we determined the costs for the individual failure modes shown in Table 20.

Subsequently, we tried to calculate the costs for 1 production hour in total (N1h). We created the formula (20):

$$N_{1h} = \frac{IN+EN}{t} = \frac{104{,}95+29873{,}39}{3847} = 7{,}78\ (€\cdot h^{-1}) \tag{20}$$

We calculated costs of 1 hour of downtime (N1hp) according to formula 18.

$$N_{1hp} = \frac{IN+EN}{\sum_{i=1}^{n} MTTR_{nni}} = \frac{104{,}95+29873{,}39}{25{,}79} = 1161{,}0\ (€\cdot h^{-1}) \quad (21)$$

Following formula 21, we calculate the cost (formula 22) for the duration of total downtime for each Npi failure mode. We entered these values in Table 16.

$$N_{pi} = N_{1hp} \,.\, MTTR_{nni}\ (€) \quad (22)$$

Table 16.
Final calculated costs for individual failure modes

Failure mode	n	$Nnni_i$ (€)	$Nnne_i$ (€)	Nnn_i (€)	N_{pi} (€)
A – enabled sonotrode	1	1.02	289.62	290.64	290.27
B – incorrect position during removal	19	1.39	7263.68	7265.07	7280.017
C – short welding time	289	32.39	11160.04	11192.43	11185.14
D – insufficient weld depth	289	32.39	11160.04	11192.43	11185.14
Σ	598	67.18	29873.39	29940.57	29940.57

Legend: n – number of defective products, Nnnii – cost of i-th failure mode in production, Nnnei – cost of i-th failure mode in case of customer complaint, Nnni – total cost of i-th failure mode, Npi – cost of total downtime of the i-th failure mode.

Based on Table 16, we can conclude that the highest costs are achieved due to failure modes C – short welding time and D – insufficient weld depth. From this point of view, they are therefore a priority for solving the basic problem, which was defined as an incorrect weld. This means that despite the low probability of a top event failure and the high availability of the device, very high costs were created. For this we provide suggestions for improvement.

There is insufficient control of the manufactured components at the station, so as a suggestion for improvement, we set the addition of a camera to check the shape and position of the weld on the membrane.

There is insufficient control of the manufactured components at the station, so as a suggestion for improvement, we set the addition of a camera to check the shape and position of the weld on the membrane. Therefore, as a proposal to improve the production line, we suggest adding a sensor that will control the depth of the weld.

By using the DEMATEL method, we came to the conclusion that it is necessary to monitor the above-mentioned failure modes, short welding time and insufficient weld depth.

Discussion

Schenkelberg (2015) claims that reliability can be defined as a special attribute that can be used to describe the reliability of a component or part. Essentially this means that the component consistently performs the required function over time and under certain conditions so that business objectives and customer requirements are met. Therefore, the subject of the article is related to this concept, where the main goal in the production organization was to meet the business goals and customer requirements with a device that will be reliable and able to function as planned, in order to be able to supply such quantities as the customer requires.

Bloch and Geitner (2024) claims that to prevent the product failures that may occur in the first place during operation, we can detect them already in the prototyping phase, by using, for example, a failure mode and effects analysis, FMEA method and FTA fault tree analysis. Just because of this, in the paper we decided to use FMEA failure analysis and fault tree analysis tools, and we also added the quantification of reliability indicators and the DEMATEL matrix to describe the links between individual modes.

Bujna et al. (2023a) used DEMATEL as a prediction tool regarding the use of PFMEA optimization in the production process to improve production quality. However, it is also possible to use these tools when determining the reliability of the device. It is only about whether we use FMEA with a focus on process or device. Alternatively, we can use it to solve both the process and the device, that is, to solve the quality of production, as well as to solve reliability.

Nguyen et al. (2016) and Bujna (2023b) used the ERPN (Extended Risk Number) model to quantify the consequences of internal defects and external claims. We did not base the article on direct costs, because we could not directly calculate the costs for one mode of failure and its consequences. Therefore, we had to create our own model of economic evaluation, which was adapted to data from production. It is possible that many production organizations have it set up similarly.

Many of the authors mentioned in Table 1 used their proposed combination of methods and tools to create a theoretical model. We solved a real problem in practice and demonstrated real data when solving the given models and tools.

Conclusions and summary

The aim of the paper was to determine and increase the reliability of the selected technical system. We chose a carousel type device as a technical system and therefore the object of investigation.

With the help of FMEA analysis, we found out that the most critical part of the device is welding - removing the membrane and welding the membrane. The FMEA led us to identify the biggest risk and by using its analysis, we determined the places where the top event of a bad weld occurs, which we solve in the FTA. By constructing a fault tree and subsequent quantification, we found a relatively low probability of failure of this event. This was confirmed also by the subsequent determination of the reliability indicator, where very high values of device availability were achieved. Therefore, we looked for other reliability solution options that would demonstrate the weak points of the device that FMEA identified for us in the first step.

By using the DEMATEL model, we found that short welding time and insufficient weld depth are the causative modes, that is, they significantly influence other failure modes and do so with high significance. The creation of an economic evaluation model based on the quantification of indirect costs for failure modes with the consequences of a certain number of defective products contributed to the fact that we again determined that the failure modes short welding time and insufficient depth are the modes with the highest priority for solving the bad weld event. The costs incurred as a result of their occurrence and as a result of the occurrence of downtime were the highest in these modes and quantified the consequence on the level of production losses expressed in economic terms, despite of good reliability indicators and a low level of probability of failure. Following this, measures were proposed.

The result of the article is a model where the connection was created, or FMEA, FTA and DEMATEL model. For the model, we created our own proposal of an economic model, which was not only an economic evaluation, but a full part of the model, which identified critical points for improving the reliability of the whole device and reducing production losses.

Conflicts of Interest: The authors declare no conflict of interest.

Authors Contribution: The entire article is the work of the first author, Marián Bujna. Miroslav Prístavka, Chia Kuang Lee, Zuzana Strápeková, Krzysztof Kapela and Zoran Malicevic participated in the interpretations, Chia Kuang Lee and Marián Bujna participated in the evaluation of the DEMATEL analysis and Marián Bujna worked on the quantitative analysis calculations.

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References

Bloch, H., & Geitner, F. (1994). *Machinery Failure Analysis and Troubleshooting: Practical Machinery ... - Heinz P. Bloch, Fred K. Geitner* - (4th ed.). Butterworth-Heinemann.

Budiraharjo, R., Sarno, R., Wijaya, D. R., Prasetyo, H. N., & Waspada, I. (2023). IMARA: A New Approach to Multi-Attribute Risk Assessment Based on Event Data Weighting (Case Study in a Container Terminal). *IEEE Access*, *11*, 62292–62306. https://doi.org/10.1109/ACCESS.2023.3287781.

Bujna, M., Kotus, M., & Matušeková, E. (2018). Using the DEMATEL model for the FMEA risk analysis. *Sciendo*, *1*(1), 550–557. https://doi.org/10.2478/czoto-2019-0070

Bujna, M., Lee, C. K., Kadnár, M., Korenko, M., & Baláži, J. (2023a). New Possibilities of Using DEMATEL and ERPN in the New PFMEA Hybrid Model. *Applied Sciences 2023, Vol. 13, Page 3627*, *13*(6), 3627. https://doi.org/10.3390/APP13063627

Bujna, M., Prístavka, M., & Čičo, P. (2020). *Spoľahlivosť technických systémov* (1st ed.). SUA Nitra.

Bujna, M., Prístavka, M., Lee, C. K., Borusiewicz, A., Samociuk, W., Beloev, I., Malaga-Toboła, U., Pahang, M., Abdullah, A.-S., Tun, P., Yaakob, K., Kuantan, D., & Makmur, M. (2023b). Reducing the Probability of Failure in Manufacturing Equipment by Quantitative FTA Analysis. *Agricultural engineering*, *27*(1), 255–272. https://doi.org/10.2478/agriceng-2023-0019.

Cheshmberah, M., Naderizadeh, A., Shafaghat, A., & Nokabadi, M. K. (2020). An integrated process model for root cause failure analysis based on reality charting, FMEA and dematel. *International Journal of Data and Network Science*, *4*(2), 225–236. https://doi.org/10.5267/j.ijdns.2019.12.003.

Cristea, G., & Constantinescu, D. M. (2017). A comparative critical study between FMEA and FTA risk analysis methods. *IOP Conference Series: Materials Science and Engineering*, *252*(1), 012046. https://doi.org/10.1088/1757-899X/252/1/012046.

Fontela, E. ; G. (1976). *The DEMATEL observer*. Battelle Geneva Research Center,. https://scholar.google.com/scholar?hl=sk&as_sdt=0%2C5&q=E+Fontela%2C+A+Gabus+DEMATEL+1976&btnG.

Held, M., & Brönnimann, R. (2016). Safe cell, safe battery? Battery fire investigation using FMEA, FTA and practical experiments. *Microelectronics Reliability*, *64*, 705-710. https://doi.org/10.1016/J.MICROREL.2016.07.051.

Hidayat, A. A., Kholil, M., Hendri, & Suhaeri. (2018). The Implementation of FTA (Fault Tree Analysis) and FMEA (Failure Mode And Effect Analysis) Methods to Improve the Quality of Jumbo Roll Products. *IOP Conference Series: Materials Science and Engineering*, *453*(1), 012019. https://doi.org/10.1088/1757-899X/453/1/012019.

Hong, Z., & Binbin, L. (2009). Integrated analysis of software FMEA and FTA. *Proceedings - 2009 International Conference on Information Technology and Computer Science, ITCS 2009*, *2*, 184–187. https://doi.org/10.1109/ITCS.2009.254.

IEC 61025:2006 | Fault tree analysis (FTA). (2006). International Electrotechnical Commission Sign in | Create Account. https://webstore.iec.ch/publication/4311

Jaiswal, Y., & Kaushik, R. (2020). Optimization of Critical Factors of Northern Railway Network using TISM and DEMATEL. *Article in International Journal of Innovative Technology and Exploring Engineering*, *9*, 2278–3075. https://doi.org/10.35940/ijitee.F3502.049620

Kuzu, A. C. (2023). Application of fuzzy DEMATEL approach in maritime transportation: A risk analysis of anchor loss. *Ocean Engineering*, *273*, 113786. https://doi.org/10.1016/J.OCEANENG.2023.113786.

Liu, C. T., Hwang, S. L., & Lin, I. K. (2013). Safety Analysis of Combined FMEA and FTA with Computer Software Assistance – Take Photovoltaic Plant for Example. *IFAC Proceedings Volumes*, *46*(9), 2151–2155. https://doi.org/10.3182/20130619-3-RU-3018.00370.

Luthra, S., Govindan, K., Kharb, R. K., & Mangla, S. K. (2016). Evaluating the enablers in solar power developments in the current scenario using fuzzy DEMATEL: An Indian perspective. *Renewable and Sustainable Energy Reviews*, *63*, 379–397. https://doi.org/10.1016/J.RSER.2016.04.041.

Mutlu, N. G., & Altuntas, S. (2019). Risk analysis for occupational safety and health in the textile industry: Integration of FMEA, FTA, and BIFPET methods. *International Journal of Industrial Ergonomics*, *72*, 222–240. https://doi.org/10.1016/J.ERGON.2019.05.013

Nguyen, T. L., Shu, M. H., & Hsu, B. M. (2016). Extended FMEA for sustainable manufacturing: An empirical study in the non-woven fabrics industry. *Sustainability (Switzerland)*, *8*(9). https://doi.org/10.3390/su8090939.

Peeters, J. F. W., Basten, R. J. I., & Tinga, T. (2018). Improving failure analysis efficiency by combining FTA and FMEA in a recursive manner. *Reliability Engineering & System Safety*, *172*, 36–44. https://doi.org/10.1016/J.RESS.2017.11.024.

Renosori, P., Oemar, H., & Fauziah, S. R. (2023). Combination of FTA and FMEA methods to improve efficiency in the manufacturing company. *Acta Logistica*, *10*(3), 487–495. https://doi.org/10.22306/AL.V10I3.422.

Schenkelberg, F. (2015). Fourteen ways to learn reliability engineering. *Proceedings - Annual Reliability and Maintainability Symposium*, *2015-May*. https://doi.org/10.1109/RAMS.2015.7105187.

Strantzali, E., & Aravossis, K. (2016). Decision making in renewable energy investments: A review. *Renewable and Sustainable Energy Reviews*, *55*, 885–898. https://doi.org/10.1016/J.RSER.2015.11.021.

Sulaman, S. M., Beer, A., Felderer, M., & Höst, M. (2019). Comparison of the FMEA and STPA safety analysis methods–a case study. *Software Quality Journal*, *27*(1), 349-387. https://doi.org/10.1007/S11219-017-9396-0/TABLES/8.

Takahashi, M., Anang, Y., & Watanabe, Y. (2021). A Safety Analysis Method for Control Software in Coordination with FMEA and FTA. *Information 2021, Vol. 12, Page 79*, *12*(2), 79. https://doi.org/10.3390/INFO12020079.

Tinga, T. (2013). *Principles of loads and failure mechanisms. Applications in maintenance, reliability and design.* https://doi.org/10.1007/978-1-4471-4917-0.

Ullah, F., Sepasgozar, S. M. E., Jamaluddin Thaheem, M., Cynthia Wang, C., & Imran, M. (2021). It's all about perceptions: A DEMATEL approach to exploring user perceptions of real estate online platforms. *Ain Shams Engineering Journal*, *12*(4), 4297-4317. https://doi.org/10.1016/J.ASEJ.2021.04.023.

Whiteley, M., Dunnett, S., & Jackson, L. (2016). Failure Mode and Effect Analysis, and Fault Tree Analysis of Polymer Electrolyte Membrane Fuel Cells. *International Journal of Hydrogen Energy*, *41*(2), 1187-1202. https://doi.org/10.1016/J.IJHYDENE.2015.11.007

Zhang, W., & Deng, Y. (2019). Combining conflicting evidence using the DEMATEL method. *Soft Computing*, *23*(17), 8207-8216. https://doi.org/10.1007/S00500-018-3455-8/TABLES/4

OKREŚLANIE POZIOMU NIEZAWODNOŚCI POPRZEZ POŁĄCZENIE NARZĘDZI FMEA, FTA I DEMATEL

Streszczenie. Celem artykułu było określenie poziomu niezawodności urządzenia typu karuzela. Biorąc pod uwagę poprawę niezawodności, postanowiliśmy wykorzystać podstawowe narzędzia FMEA i FTA. Za pomocą FMEA zidentyfikowaliśmy najbardziej krytyczną część urządzenia, a mianowicie spawanie (RPN = 320). Proponowany środek rozwiązał jedynie problem poprawy wykrywania. Na podstawie analizy FMEA wybraliśmy zdarzenie TOP dla FTA - zły spaw. Wykryte prawdopodobieństwo awarii zdarzenia szczytowego za pomocą ilościowej analizy FTA wyniosło 0,58%. Zidentyfikowaliśmy podstawowe zdarzenia prowadzące do zdarzenia TOP, tj. dozwolona sonotroda, nieprawidłowe położenie membrany podczas pobierania próbek, krótki czas spawania i niewystarczająca głębokość spawania. Następnie dokonano ilościowej oceny wskaźników niezawodności. Odkryliśmy, że urządzenie jest bardzo niezawodne, ponieważ osiągnęliśmy prawie 100% wartości dostępności. Pomimo tego celem było znalezienie bardziej kompleksowego poziomu niezawodności i dalszych ustaleń z FMEA. Wykorzystaliśmy model DEMATEL i nasz własny proponowany model ekonomiczny. Korzystając z modelu DEMATEL, odkryliśmy, że krótki czas spawania i niewystarczająca głębokość spoiny są trybami przyczynowymi, co oznacza, że znacząco wpływają na inne tryby awarii i robią to z dużym znaczeniem. Stworzenie modelu oceny ekonomicznej opartego na kwantyfikacji bezpośrednich kosztów trybów awarii z konsekwencjami określonej liczby wadliwych produktów przyczyniło się do faktu, że ponownie ustaliliśmy, że tryby awarii krótki czas spawania i niewystarczająca głębokość są trybami o najwyższym priorytecie dla rozwiązania złego zdarzenia spawalniczego. Koszty poniesione w wyniku ich wystąpienia i w wyniku wystąpienia przestoju były najwyższe w tych reżimach. Modele te stwarzają nam przestrzeń do skuteczniejszego projektowania środków w celu poprawy poziomu niezawodności i jakości produkcji, co jest warunkiem wstępnym zapewnienia skrócenia przestojów, zwiększenia jakości i niezawodności produkcji oraz ogólnej redukcji kosztów. Prowadzi to również do wzrostu reputacji producentów.

Słowa kluczowe: niezawodność, FMEA; FTA; DEMATEL, przestój, model ekonomiczny