Determining The Probability of Failure Modes by Fault Tree Analysis

Marián Bujna, Chia Kuang Lee, Miroslav Prístavka,
Mitko Nikolov, Todor Delikostov, Adrian Gula

Abstract: *The aim of the paper was to analyze the failure modes in the manufacturing part of the company in the production of products. To achieve this aim, we decided to use the FTA analytical methods - the fault tree method and the FMEA method. We analyzed the CNC milling machine HOLZHER 7120. We constructed a graphical representation of the fault trees for the object under study and a comprehensive fault tree. We used the FTA method to calculate the probability of occurrence of the basic events leading to the failure of the top event. The results of the FTA method served as the basis for the application of the FMEA method. We used the FMEA method to find out the causes of failures resulting from the FTA method, the probability of their occurrence, their effect, and the probability of detecting the failures. We rated the failure probability factors, the impact of failure occurrence, and the probability of detection using a numerical scale from 1 to 10 with an assigned meaning for each level. By multiplying the ratings of these factors, we obtained the overall RPN. Based on the results of the FMEA method, we determined measure suggestions for factors with RPN values greater than 30. The results of this work serve as a tool for the company to improve product quality, reduce defects, increase reliability, and influence economic results. In addition, the findings of this work are applicable to other companies, manufacturing or non-manufacturing.*

Keywords: *Reliability. Production machines. Fault tree. Probability of occurrence. FMEA. Measures.*

INTRODUCTION

Continuous improvement of machine reliability is one of the most important tasks of the industrial sectors. Reliability is defined as the probability that a given entity or system will be able to perform its intended functions over a specified time interval under specified operating conditions. In other words, reliability is the ability of a system not to fail (Patil et al. 2013).

The world demands increased performance of products and systems while reducing costs. The requirement to minimize the probability of failures, whether these failures only increase costs or seriously threaten public safety, places a greater emphasis on reliability and safety. The formal body of knowledge developed to analyze and minimize such failures is applicable to nearly all engineering disciplines and provides a rich and diverse context in which reliability considerations arise (Breneman et al., 2022).

FTA is an analytical technique where an adverse event is predefined (usually followed by a system or subsystem) and the system is then examined in the context of its environment and underlying operations to identify all possible combinations of events that could lead to the occurrence of the predefined events. The term 'baseline event' refers to the circumstances that precede an undesired event, such as component hardware failure, human error, environmental factors, or any other related circumstances. This event is predominantly referred to in the literature as a "TOP event". The fault tree produces a graphical representation of the logical relationship between undesirable events and underlying faults. The FTA provides a logical output for easily understanding the question of how a failure can occur, which is as important to enterprises as understanding how a system can operate. This technique is also suitable for use with complicated systems and finding faults in a process while it is running using graphical models based on a branching diagram (Mishra, 2018)

Each event is analysed by asking a question. "Why did this happen?" The answer to this question represents the root causes of the negative event and their interplay. This logical process continues until all potential causes are identified. During this process, a tree diagram is used to record the events uncovered. The branches of the tree diagram stop once all events leading up to the negative event have been completed and thus cannot be developed further. (Pan, 2022)

FMEA defines the concept of "failure modes" and identifies potential or actual defects or errors in the design of a product or process, focusing on those that affect the customer or end user. "Failure effects" are the consequences of a product or system function failure as perceived by the user. The consequences of failure can be described in terms of what the end user may see or experience. Examining the consequences of identified failures is called consequence analysis. FMEA prioritizes failures according to severity, frequency, and detectability. Severity is the severity of the consequences of the failure. Frequency describes how often the failure occurs (Siemens, 2016). FMEA methods and FTA fault tree analysis can be used to improve reliability (Bujna et al., 2023a; Bujna et al., 2023b; Carlson, 2012; Mandal et al., n.d.; Markulik et al., 2021; Yazdi, n.d.).

The aim of this paper is to analyze the failure modes in the manufacturing part of the company. The analyses will be applied to the production technology running on a CNC milling machine HOLZHER EcoMaster 7120. A main undesirable event (TOP event) will be determined, which will then be characterized, and the possible causes of the event will be identified. These are analysed in the fault tree. The generated fault tree will be the basis for the quantitative calculation of the probability of the failure mode of the top event and the individual branches of the fault tree. In the FMEA analysis, based on the identification of vulnerabilities, we will propose measures to reduce the occurrences of failure modes. We predict an increase in reliability and overall production quality.

MATERIALS AND METHODS

Production process:

The first step is to transfer the material using a forklift from the warehouse. After the material is received in the production hall, the worker at the cutting centre opens the production order, places the material on the machine's workbench and starts production using the program. The cutting centre will divide the material into the necessary parts and can itself design the efficient use of the remaining large material for the remaining parts, if possible. This process is repeated until all parts are cut. Some of these are then machined on a CNC mill where holes are drilled. The milling machine works on the principle of the TwinCAM 32 software. The last step is then to glue the edges of the boards. Despite the computer support, this task requires care in positioning and selecting the right parts for edge banding.

Object of evaluation: CNC milling machine HOLZHER EcoMaster 7120 (figure 1):

CNC milling machine (Figure 1) with worktable with integrated vacuum system for workpiece clamping. It is driven by a vacuum pump. Particularly suitable for small and medium-sized companies. It covers all tasks required by furniture commissions and offers a wide range of woodworking options. The milling machine is equipped with TwinCAM 32 software for CAD data, which can of course be loaded and supports the dxf format. Individual commands can be combined into a single block so that they can be executed with a single mouse click. The milling machine has a double drilling spindle for horizontal drilling and an adapter for vertical drilling. The vector axis has a range of 0-360 degrees (Hoechsmann, 2003).

Fig. 1 CNC milling machine HOLZHER EcoMaster 7120

FTA procedure (figure 2):

1. Identification of the top event to be analyzed.
2. Starting with the top event, identify possible causes or failure modes that may lead to the identified event.
3. Identify the causes for each failure mode.
4. Sequential identification of undesirable failure modes as the system continues to the next lower level of the system. Events found at the lowest level are called baseline events. The detection of "cascading" faults in operation leads to the highest event (Fuchs, Valis, 2004).

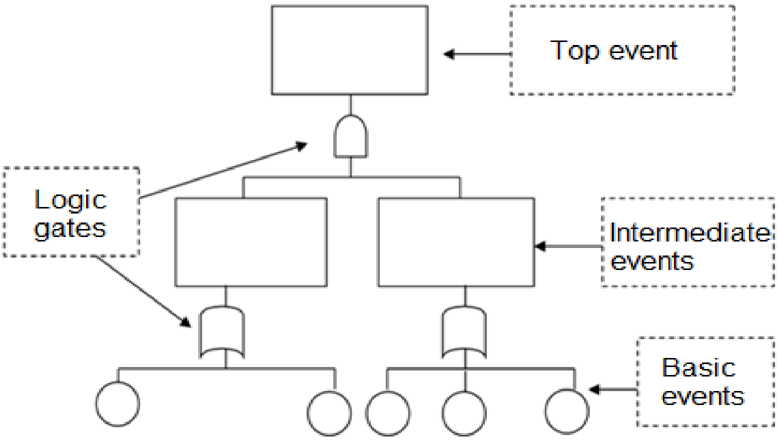

Fig. 2 Schematic of the fault tree with description (Bujna, Čičo, Kotus, 2018)

The fifth point is the quantitative FTA analysis - calculating the probability of a top event occurring:

If a probability of occurrence can be assigned to the base event, the probability of the top event can be calculated. For the quantification of individual events to be reliable, it must be shown that the input events at each level are necessary and sufficient for the occurrence of the output events, otherwise probabilistic analysis cannot be performed (Fuchs, Valis, 2004)

We proceed by using known relationships to sequentially determine the probability of events from the lowest level to the top event. From the bottom, we progressively traverse all the logical gates of the fault tree (Figures 3 and 4) and, according to their type, determine the probability of occurrence of the events that are logically defined by these gates. To calculate the probability for the OR gate we use formula 1 and for the ANDgate we use formula 2 (Vintr, 2015).

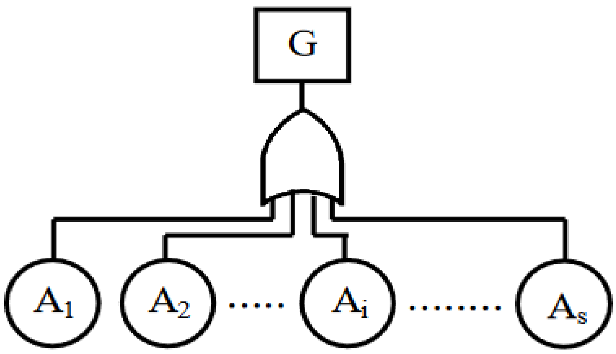

Fig. 3 Example of an OR logic gate

$$P = 1 - \prod_{i=1}^{i=s}[1 - P(Ai)] \quad (1)$$

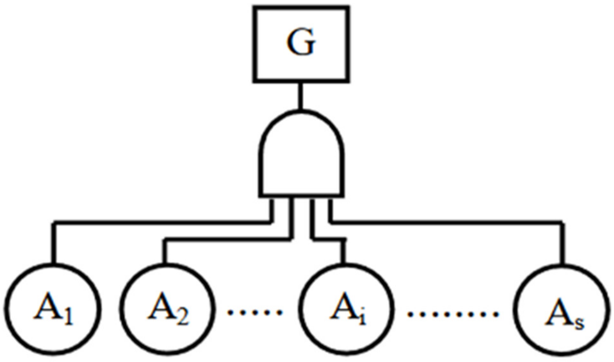

Fig. 4 Example of an AND logic gate

$$P = \prod_{i=1}^{i=s} P(Ai) \quad (2)$$

Creation of a FMEA:
– Identification of causes, consequences and determining the method of control.
– Determination of severity of consequences, occurrence of failures and detection - according to IATF 16 949: 2016.
– Calculation of RPN (formula 3) – RPN = S.O.D (3)
– Where: S -Severity, O – Occurrence, D - Detection.
– The suggestion of measures.

RESULTS

We constructed a quantitative fault tree (figure 5).

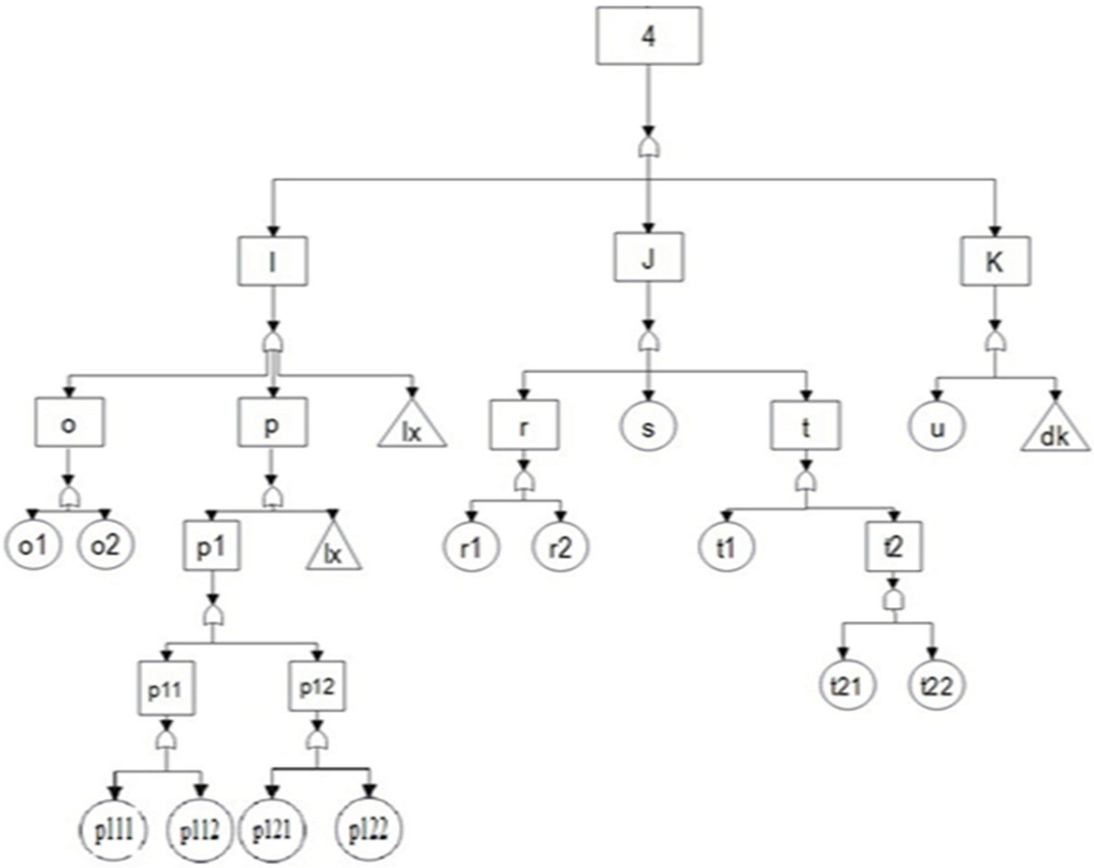

Fig. 5 Fault tree of CNC milling machine

We determined the probability of occurrence of the basic events by considering the logic gates of the transition events. By deductive analysis, we went from the probability of occurrence of the base events to the probability of failure of the top event.

Table 1 *Fault tree failure probability table for CNC milling machine*

Mark	Failure mode	P	Gate
3	Failure on CNC milling machine HOLZHER EcoMaster 7120	0.0273	TU
I	Production operator	0.0114	Failure on CNC
o	OHS	0.0050	Production operator I 0.0273
o1	Incorrect fixing of material	0.0025	Incorrect fixing 0.0114
o2	Incorrect placement of material	0.0025	o 0,0050
p	Incorrect setting	0.0045	
lx	Laxity – transfer	0.0010	Incorrect positioning p
p1	Expertise	0.0035	0,0045
p11	Incorrect parameters	0.0010	Expertise p1
p12	Incorrect tool	0.0025	0,0035
p111	Incorrect machining speed	0.0005	Incorrect parameter p11
p112	X and Y axes wrongly selected	0.0005	0,0010
p121	Wear tool	0.0015	Incorrect tool p12
p122	Unsuitable type	0.0010	0,0025
lx	Laxity - transfer	0.0010	
J	Technical failure	0.0056	
r	Oil leakage	0.0026	Technical failure J
r1	Damaged seal	0.0025	Oil leakage r 0.0056
r2	Oil pan	0.0001	0,0026
s	Chuck failure	0.0020	
t	Motor failure	0.0010	
t1	Engine gear failure	0.0010	Motor failure t
t2	Damaged power supply	0.0001	0.0010
t21	Damaged power cables	0.0001	Damaged power supply t2
t22	Fault in the electric current	0.0001	0.0001
K	Software faults	0.0105	
u	Inability to load material part	0.0030	Software faults K
dk	Mistake in documentation - transfer	0.0075	0.0105

The probability of failure due to a failure on the CNC mill is 0.0273.

After creating Table 1 with the notation of the probability values found by the FTA method, we were able to determine which events occur most frequently in the enterprise. We decided to focus on those in order to eliminate them or to propose measures to eliminate or minimize them. To do this, a more detailed analysis of them was necessary.

This analysis includes measures that should lead to the reduction of the level of risk or its elimination or reduction to an acceptable level. The output of this method is a worksheet (Table 2).

By linking the FMEA method to the FTA method, we have achieved more accurate data that form the basis for designing measures that will help reduce negative impacts on the product during its development process.

We have identified the RPN value of 30 (inclusive) as a guideline for determining the need for applying measures. We considered failures below this value to be insignificant and decided not to propose any measures to correct them.

Table 2 *Worksheet of the FMEA*

CNC fréza HOLZHER EcoMaster 7120								
FM	**Effect**	**S**	**Cause**	**O**	**Detection**	**D**	**RPN**	**Measures**
Incorrect parameters	Defective product	7	Poor expertise	6	Knowledge test	5	210	Staff retraining
			Laxity	4	Supervisor inspection	6	168	Review of the pay system
Incorrect tool	Material damage	8	Incorrect knife type	2	Retraining	3	48	Sorting and labelling of tools
Oil leakage	Gearbox damage	8	Laxity	5	Retraining	3	120	Reassessment of the remuneration system
			Seal failure	4	Visual check	8	256	Replacement of seals at oil change
Chuck failure	Material release	9	Wearing quick-release coupling	5	Load check	6	270	Weekly load c
Incorrect documentation	Defective production	3	Human factor	3	ceck	2	18	No action

The CNC mill (Table 2) exhibited five failures with high RPNs. They are chuck failure (270), oil leakage (256), poorly set parameters with two causes: poor expertise (210), laxity (168) and laxity in wrong tool selection (120).

Suggestions for improvement

- Suggestion for improvement for negligent staff attitude.
  - In the suggestions for improvement for the CNC milling machine based on the FMEA method, laxity is consistently found twice as a cause of failure. For this cause of failure, we propose the same measure, namely, reviewing the reward or salary system by recording the error rate from the production manager, who evaluates and assesses the character of the error that occurred and submits the documents to the administrative department that generates the salary.
- Suggestion for improvement for incorrect parameter setting.
  - The most common cause of this failure is poor employee proficiency. Therefore, we suggest retraining the knowledge of the employees, but given the relatively simple products, internal retraining in regular annual cycles will also suffice.
- Suggestion for improvement due to incorrect selection of tools.
  - To eliminate this cause of failure, we suggest simply marking the type of tool and the location where the tool is to be stored. This will help especially during time stress situations, reduce failures due to inattention, and will also make checking tool wear clearer. There are several solutions, whether based on pictograms, colour coding, various stickers or others.
- Oil leakage improvement suggestion.
  - This cause is important because we rate its consequence as high (8), as it may damage the gearbox, which would then make production impossible by enforced downtime that would only end when this fault is corrected. Thus, I suggest, as in the case of a banding or cutting center, the preventive measure of a monthly cycle of checking the seal set, which tends to be the most common cause of oil leakage. It is therefore necessary to have sufficient gaskets in stock for possible replacement.
- Suggestion for improving chuck failure.
  - In the event of a chuck failure, immediate replacement of the chuck that is showing an inability to properly clamp the workpiece is required. In this case, we are talking about an immediate danger to the health or life of the workers. The cause of chuck failure most often appears to be high wear on the quick-release screw. I therefore suggest immediate replacement of the damaged machine part, a regular weekly check of the wear rate of this component and a chuck load check.

CONCLUSION A DISCUSSION

The fusion of FTA and FMEA methods is very popular nowadays. According to Professor Mahmood Shafiee (2019), this is mainly due to the benefits that this combination offers. By performing FTA analysis, we can determine the specific failures that lead to the failure of the selected top event. By connecting the FMEA method with the follow-up of the FTA method, we are able to identify the impact of these failures on the top event. The fault tree nodes serve as the initial distribution of the system components, and these serve as the starting points for the creation of the FMEA method.

The authors Kai Pan et al (2022) argue that negative analysis trees and fault trees are excellent tools for problem solving. They can be used to prevent the occurrence of failures or to detect them, but they are most used as an investigation tool to analyse accidents and identify failures. We confirm this idea, but also add that a fault tree requires perfect knowledge of the system. Every single unanalyzed event will significantly affect the correct execution of the quantitative analysis, especially if the results obtained from the analysis will be used in the next FMEA assessment of the system. The MTBF needs to be kept as high as possible to make the system more reliable. This can be achieved by optimizing preventive maintenance.

Authors G. Cristea and D. M. Constantinescu (2017) argue that the FMEA method generally provides a library of all possible failures and their consequences, while the FTA allows a detailed analysis of the logical and temporal links leading to the failure, captured from the top of the tree. Using these two complementary methods provides deeper information than using the methods alone. Also in our research, we used FTA to quantitatively calculate the probability of occurrence of all events by taking into account logical relationships and links and used this probability in the FMEA analysis to determine the probability of occurrence criterion.

We used the FTA method to identify the causes that can lead to the failure of the manufacturing process. We calculated the probability of failure (Section 3.2), which later served as the basis for constructing the FMEA method.

The failure of the CNC milling machine (Table 6) reached a probability of failure occurrence value of 0.021.

We decided to further address these problematic factors in the FMEA method. By applying this method to the factors, we achieved the identification of the impact of these failures on the overall quality of the product, the likelihood of their occurrence and detection in the manufacturing process, and the total amount of the risk level (RPN) they pose to the product.

For the HOLZHER CNC milling machine (Table 11), we identified five causes with high RPNs. These are: material loosening due to chuck failure (270), gearbox damage by oil leakage (256), poorly set parameters caused by poorly set parameters (210) and employee laxity (168), and poorly selected tooling again caused by employee laxity (120).

We believe that the ingestion of FTA and FMEA methods is sufficient to determine the level of reliability. Based on the interconnection of these methods, we have proposed measures that lead to an increase in the reliability of the objects and technical systems addressed.

REFERENCES

[1] Breneman, J., et al. 2022. Introduction to reliability engineering. 3. vyd. Hoboken: Jon Wiley & Sons, Inc. 607 p.

[2] Bujna, M., Lee, Chia, K., Kadnár, M., Korenko, M.,Baláži, J., 2023(a). New Possibilities of Using DEMATEL and ERPN in the New PFMEA Hybrid Model. In. Applied Sciences, 13(6), 3627.

[3] Bujna, M., Prístavka, M., Lee, C., et al. 2023(b). Reducing the probability of failure in manufacturing equipment by quantitative FTA analysis. In. Agricultural Engineering, 27(1), 255-272.

[4] Carlson, C., 2012. Effective FMEAs: achieving safe, reliable, and economical products and processes using failure mode and effects analysis. Vol. 1. John Wiley & Sons, 2012.

[5] Cristea, G., Constantinescu, DM., 2017. A comparative critical study between FMEA and FTA risk analysis methods [online]. In. IOP Conference Series: Materials Science and Engineering.

Vol. 252. No. 1. IOP Publishing, 2017. Dostupné na: https://www.researchgate.net/publication/320579551_A_comparative_critical_study_between_FMEA_and_FTA_risk_analysis_methods

[6] Mandal, S., Maiti, J., 2014. Risk analysis using FMEA: Fuzzy similarity value and possibility theory based approach. In. Expert Systems with Applications Elsevier. Vol 41, Issue 7, Pages 3527-3537

[7] Markulik, Š., Šolc, M., et al. 2021. Application of FTA analysis for calculation of the probability of the failure of the pressure leaching process. In. Applied Sciences, 11(15), 6731. https://doi.org/10.3390/app11156731

[8] Krishna, B. Misra, 2008. Handbook of Performability Engineering. London: Springer Verlag. 1412 s. ISBN 978-1-84800-130-5

[9] Pan, K., 2022. Towards a Systematic Description of Fault Tree Analysis Studies Using Informetric Mapping [online]. In Sustainbility, vol 14. Dostupné na: https://www.mdpi.com/2071-1050/14/18/11430

[10] Patil, R., Bhimgonda et al., 2013. An Overview Of Fault Tree Analysis (Fta) Method For Reliability Analysis [online]. In: Journal of Engineeing Research and Studies. Dostupné na: https://www.researchgate.net/publication/281065262

[11] Siemens, Product Lifecycle Managment Software Inc. 2016. How to conduct a failure modes and effects analysis (FMEA) [online]. Dostupné na: https://polarion.plm.automation.siemens.com/hubfs/Docs/Guides_and_Manuals/Siemens-PLM-Polarion-How-to-conduct-a-failure-modes-and-effects-analysis-FMEA-wp-60071-A3.pdf

[12] Shafiee, M., et al. 2019. An Integrated FTA-FMEA Model for Risk Analysis of Engineering Systems: A Case Study of Subsea Blowout Preventers [online]. In Applied sciences. Dostupné na: https://www.mdpi.com/2076-3417/9/6/1192

[13] Yazdi, M., 2017. Hybrid probabilistic risk assessment using fuzzy FTA and fuzzy AHP in a process industry. Journal of Failure Analysis and Prevention 17 (2017): 756-764.

CONTACTS

Marián Bujna, Institute of Construction and Engineering Technologies, Faculty of Engineering, Slovak University of Agriculture in Nitra, Tr. A. Hlinku 2, 949 76 Nitra, Slovak Republic, marian.bujna@uniag.sk

Lee Chia Kuang, Faculty of Industrial Management, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, 26300, Kuantan, Pahang Darul Makmur, Malaysia, chia@umpsa.edu.my

Miroslav Prístavka, Institute of Construction and Engineering Technologies, Faculty of Engineering, Slovak University of Agriculture in Nitra, Tr. A. Hlinku 2, 949 76 Nitra, Slovak Republic, miroslav.prístavka@uniag.sk

Mitko Nikolov, Department of Repair and Reliability, Agrarian and Industrial Faculty, University of Ruse, 8, Studentska Str., 7017 Ruse, Bulgaria, e-mail: mnikolov@uni-ruse.bg

Todor Delikostov, Department of Repair and Reliability, Agrarian and Industrial Faculty, University of Ruse, 8, Studentska Str., 7017 Ruse, Bulgaria, e-mail: delikostov@uni-ruse.bg

Adrián Gula, TF I-KBI den, student at Faculty of Engineering, Slovak University of Agriculture in Nitra, Tr. A. Hlinku 2, 949 76 Nitra, Slovak Republic, xgula@uniag.sk