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THE USE OF DOE METHOD IN THE EVALUATION OF CONVEYOR BELT IMPACT RESISTANCE

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Abstract:

Belt conveyors are efficient conveyance systems that are used for the transportation of bulk materials across all industries. One of the basic components of these conveyors is a conveyor belt. This component is of crucial importance, since damage to the belt may lead to unexpected and long-lasting interruptions in the production. In the present article, the impact resistance of selected conveyor belts is evaluated by applying the Design of Experiments method.

Key words:

conveyor belts, impact force, DOE method.

1 INTRODUCTION

The transportation of mineral raw materials plays an important role in the mining processes of mining companies. A belt conveyor is as important part of that transportation process (Andrejiova, 2015). At present, the belt conveyor is the most common type of conveyor and it is used primarily in the mining industry, as well as in other industries. The basic structural component of a belt conveyor is the conveyor belt (Bajda, 2022), (Marasova, 2023).

As a result of the operational conditions and continuous contact with the transported materials, these conveyor belts eventually become damaged. However, the proper usage of the belts may efficiently extend their service life (Bortnowski, Kawalec, 2022). Numerous articles have explored the classification of belt damage and the methods used to detect it. The proper

monitoring of conveyor belts is a key precondition for the continuous utilisation of these belts. Article (Bortnowski, Krol, 2022) describes the algorithms that are used for the detection of potential damage to conveyor belts. The authors of papers (Zhang a, 2021), (Zhang b, 2021) and (Zhu, 2023) applied deep learning to detect the failures of conveyor belts. Furthermore, in paper (Kirjanów, 2021), the authors presented an approach to the classification of conveyor belt damage based on artificial intelligence, through the implementation of a 2-layer neural network.

Detailed investigations into conveyor belts in real-life operations indicate the strong impact of wear and damage, which is caused by a dynamic impact load, on the conveyor belt's service life. This topic has been explored by many authors. For the purpose of studying the effects of the impact process, the authors of article (Grincova, 2016) conducted theoretical, experimental and numerical analyses, including the identification of the degree of damage to the cover layers and the internal carcass of the conveyor belt. Numerical modelling was carried out using basic statistical methods and a multiple regression analysis (Grincova, 2016). Article (Grincova, 2015) presents the results of an experimental and regression analysis of the dynamic effects of impact forces on a system comprised of a conveyor belt with its support system, as well as a system without the support system.

Article (Ambrisko, 2023) presents research into the energy balance of conveyor belts exposed to impact processes. The focus of that research was the measurement of the conveyor belt's resistance to punctures, the impact process, and the effects of changes in the drop height on the tensile and impact forces. Testing of the conveyor belt's impact resistance was also described by the authors of articles (Król, 2017), (Bajda, 2015).

The authors of article (Ambrisko, 2022) used data on the tensile load of rubber test specimens in a conveyor belt that was used in the transport industry, with the aim of identifying a correlation between the tensile properties and the hardness of the rubber cover layers of the belt.

The conveyor belts that were subjected to the testing described in the present article were obtained from the facility in a steel-making enterprise.

2 METHODS AND METHODOLOGY

2.1 Conveyor belts

The conveyor belt is a component that continuously circulates around the terminal pulleys. During the circulation, the belt serves two functions: the carrying and the traction functions. As a carrying component, it carries materials along its transport length. At the same time, it overcomes the resistance to motion – it is therefore also a traction component of the belt conveyor. The basic structural components of the conveyor belt are the protective rubber selvage, the carcass, and the cover layers. The thickness of the cover layers is affected by the properties of the transported material (Fig. 1).

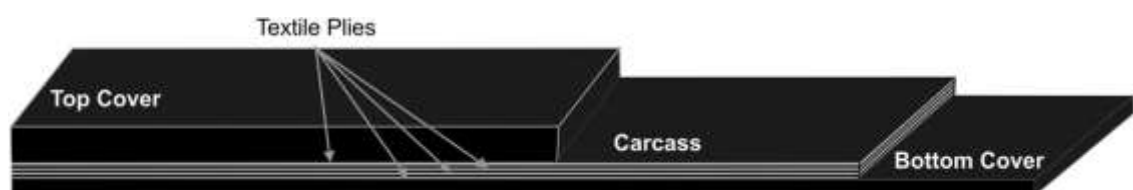


Fig.1 Basic components of the conveyor belt

Source: (Authors)

2.2 DOE method

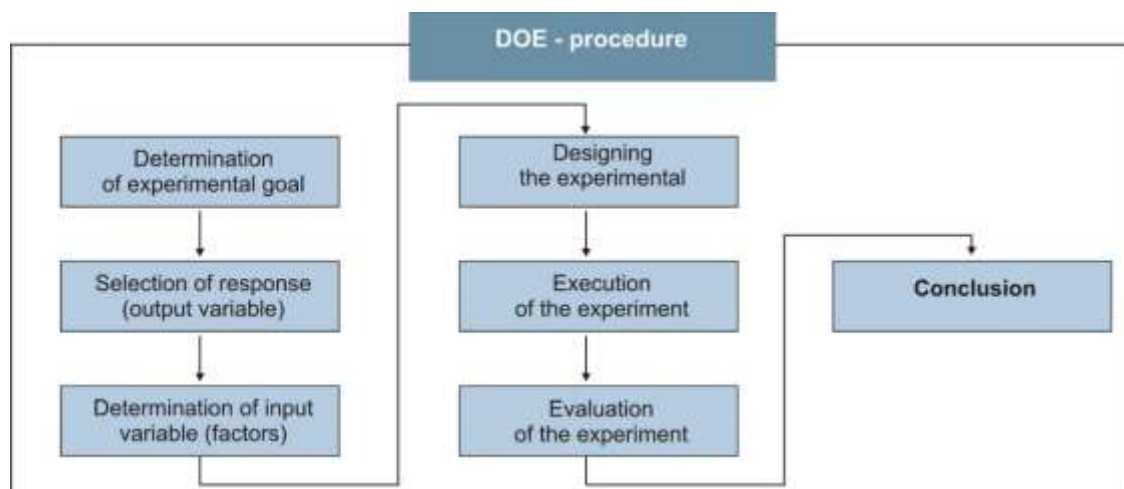
The Design of Experiments (DOE) method facilitates understanding and improving technological and laboratory processes. The variable that represents the experiment output is referred to as the response (the output variable – response). The inputs (input variables) that are manipulated in order to assess their effects on the response are referred to as the factors.

A planned experiment is conducted in compliance with a design prepared in advance. The design determines the number of experiment trials to be conducted, the conditions in which the individual trials are to be carried out, as well as the order of the trials.

When planning experiments, the following basic principles should be respected:

- The replication principle – repetition of an experiment with the same factor levels (detection of potential measurement inaccuracies, and hence increasing the reliability of the conclusions);
- The randomisation principle – execution of the individual trials in a randomised sequence;
- The blocking principle – arranging the trials so that they form relatively homogeneous blocks (the blocks are formed while considering the identifiable processes).

The procedure and steps of a designed experiment are shown in Fig. 2.

**Fig.2** DOE procedure

Source: (Authors)

The experiment in which the effects of k -factors on the response are examined is referred to as the k -factorial experiment. In general, the factors may have various numbers of levels; however, only two, or a maximum of three, levels are typically designed. Such experiments are then referred to 2^k or 3^k experiments, wherein k is the number of factors. This number also corresponds to the number of trials that must be carried out in the designed experiment.

Setting a factor to a certain value is referred to as the factor level (Hornikova, 2009), (Terek, 2004). When designing an experiment, two levels are typically applied (the 2-level

experiment). The levels are typically referred to as the low (minus) level and the high (plus) level. They may be coded as +1 (or “+”) and -1 (or “-”).

The planning and execution of the experiment is followed by the determination of the impact (effects) of the individual factors on the response. The effect of the factor is defined as the change in the response caused by the change in the factor level. If any of the main factors is analysed, its effect is referred to as the main effect of the factor. The main effect of the factor may be calculated by applying several methods. In a 2^k factorial experiment, the effect of factor F may be estimated as the difference between the effect at the “+” and “-” levels; it is the difference in the average values of the response at the low and high levels of the factor (Montgomery, 2002), (Antony, 2003). The following equation applies:

$$E_f(F) = \bar{y}_{F+} - \bar{y}_{F-} = \frac{1}{2^{k-1}n} [\sum y_{F+} - \sum y_{F-}] \tag{1}$$

wherein \bar{y}_{F+} is the average value of the response at the high level; \bar{y}_{F-} is the average value of the response at the low level of factor F; k is the number of factors; and n is the number of repetitions.

Another type of effect that often occurs in factorial experiments is the interaction. It is the effect in which the impact of one factor on the response depends on another factor or on a group of factors. There are 2-factor interactions (first-order interactions), 3-factor interactions (second-order interaction) and interactions of higher orders.

Designing the experiment, as well as data processing and evaluation, is carried out primarily in the Minitab environment (Miller, 2010).

3 RESULTS

In the present experiment, the effects of four factors were examined: the weight of the falling load (Factor A), the hammer drop height (Factor B), the conveyor belt type (Factor C) and the impactor type (Factor D). The purpose was to identify the factor, or the interactions of factors, that significantly affects the magnitude of the impact force F_i [kN] that is exerted at the impact of the load onto the conveyor belt (Response Y).

3.1 Data characteristics

The experiment was carried out using two types of conveyor belts: P 630/3 and P 2000/4. Those were rubber-textile conveyor belts with a strength of 630 and 2,000 N.mm with 3 and 4 textile plies. The minimum hammer drop height was determined as 0.6 m, and the maximum height was 1.6 m. The minimum hammer weight was 50 kg, and the maximum weight was 80 kg. The tests were conducted with two types of impactors (spherical and pyramidal) without the support system (Table 1).

Tab. 1 Input factors and their levels

Factor level	Hammer weight[kg] A	Hammer drop height [m] B	Conveyor belt type C	Impactor type D
Low (-)	50	0.6	CB1 (P630/3)	Sphere (S)

High (+) 80 1.6 CB1 (P2000/4) Pyramid (P)
 Source: Authors

In the full 4-factor experiment, it is possible to conduct $2^4=16$ trials. They are listed in Table 2 together with the values of the individual factors and Response Y.

Tab. 2 Design of the full factorial experiment with four factors and the interactions between them

No.	Trial	A [kg]	B [m]	C	D	Y [kN]
1	(1)	50	0.6	CB1	Sphere	5.285
2	a	80	0.6	CB1	Sphere	10.500
3	b	50	1.6	CB1	Sphere	11.509
4	ab	80	1.6	CB1	Sphere	20.635
5	c	50	0.6	CB2	Sphere	7.333
6	ac	80	0.6	CB2	Sphere	11.810
7	bc	50	1.6	CB2	Sphere	15.435
8	abc	80	1.6	CB2	Sphere	22.176
9	d	50	0.6	CB1	Pyramid	5.916
10	ad	80	0.6	CB1	Pyramid	10.872
11	bd	50	1.6	CB1	Pyramid	11.553
12	abd	80	1.6	CB1	Pyramid	20.886
13	cd	50	0.6	CB2	Pyramid	7.736
14	acd	80	0.6	CB2	Pyramid	13.187
15	bcd	50	1.6	CB2	Pyramid	15.613
16	abcd	80	1.6	CB2	Pyramid	25.286

Source: Authors

The graphical representation of the experiment in the form of a cubic graph is shown in Fig. 3. The values in the corners are the values of the response in the individual trials.

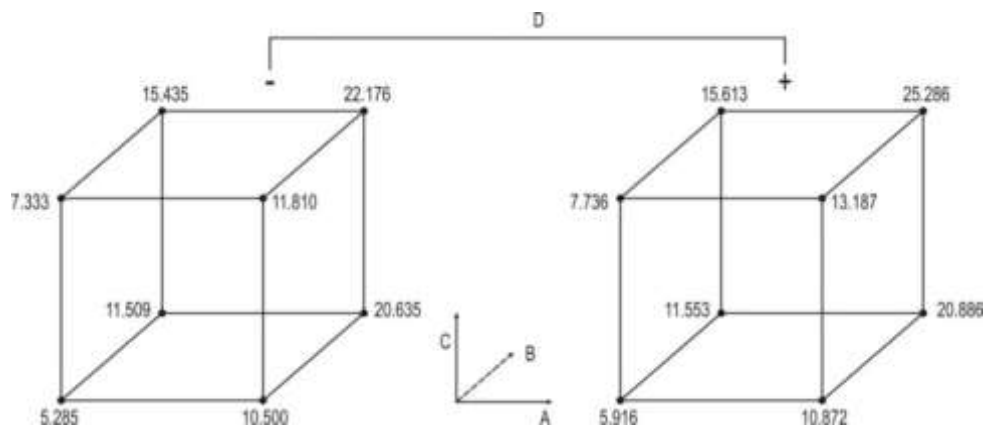


Fig.3 Graphical representation of the experiment in the form of a cubic graph
 Source: (Authors)

In the case of the 2^4 full 2-factor experiment, the main effect of Factor A may be calculated using the following equation (Montgomery, 2002):

$$E_f(A) = \bar{y}_{A+} - \bar{y}_{A-} = \frac{1}{8} [\sum y_{A+} - \sum y_{A-}] = \frac{1}{8} [a + ab + ac + abc + ad + abd + acd + abcd - (1) - b - c - d - bc - bd - cd - bcd]. \tag{2}$$

The same procedure was applied to identify the main effects of Factors B, C and D. The estimates of the effects of interactions between Factors A and B was calculated using the following equation:

$$E_f(AB) = \frac{1}{2} [\bar{y}_{A+B+} - \bar{y}_{A-B+} - (\bar{y}_{A+B-} - \bar{y}_{A-B-})], \tag{3}$$

wherein \bar{y}_{A+B+} , \bar{y}_{A-B+} , \bar{y}_{A+B-} and \bar{y}_{A-B-} represent the average of the results in the combinations of levels A^+B^+ , A^-B^+ , A^+B^- and A^-B^- . The main effects of the factors are listed in Tab. 3.

Tab. 3 Main effects of the factors for the factorial design with four factors

	A	B	C	D
\bar{y}_- (Low)	10.0475	9.0799	12.1445	13.0853
\bar{y}_+ (High)	16.9190	17.8866	14.8220	13.8811
Effects of factors	6.8715	8.8067	2.6775	0.7958

Source: Authors

The graphical representation of the main effects of all the factors is shown in Fig. 4. The plots facilitated determining the optimal level of the factor setting depending on the second factor. The analysis showed that the strongest analysed impact force exerted at the impact of the load onto the conveyor was achieved when all four factors were set on the high level.

The effects of all main factors (A, B, C and D) and the second-order interactions (AB, AC, AD, BC, BD and CD) are listed in the following output from Minitab software (Miller, 2010):

Term	Effect	Coef	SE	Coef	T	P
Constant		13.4833	0.1579	85.38	0.000	
A	6.8715	3.4358	0.1579	21.75	0.000*	
B	8.8067	4.4034	0.1579	27.88	0.000*	
C	2.6775	1.3388	0.1579	8.48	0.000*	
D	0.7958	0.3979	0.1579	2.52	0.053	
A*B	1.8468	0.9234	0.1579	5.85	0.002*	
A*C	-0.2860	-0.1430	0.1579	-0.91	0.407	
A*D	0.4818	0.2409	0.1579	1.53	0.188	
B*C	0.8043	0.4021	0.1579	2.55	0.052	
B*D	0.1000	0.0500	0.1579	0.32	0.764	
C*D	0.4713	0.2356	0.1579	1.49	0.196	

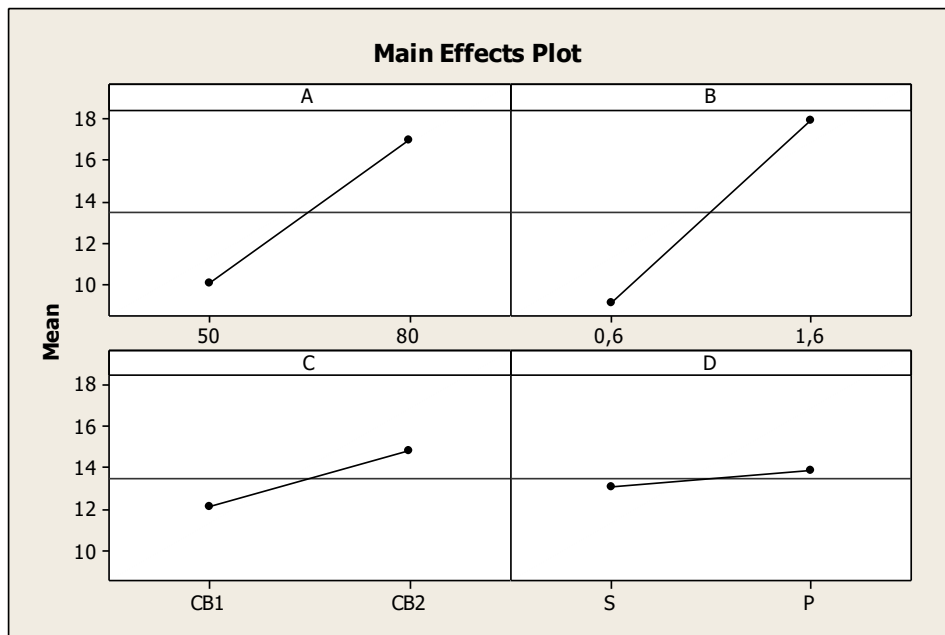


Fig.4 Graphical representation of the main effects for the 2⁴ experiment
 Source: (Minitab output)

The outputs from the software and from Table 3 show that Factor B (hammer drop height) and Factor A (hammer weight) had the strongest effects on the analysed response. Factor D (impactor type) had a very negligible effect. Significance of the individual effects of the factors or their interactions was tested using the t-test and through the identification of the p-value. The analysis showed that three main factors A, B and C, and the AB interaction had the statistically significant effects on the response, i.e. on the output value of the impact force.

The evaluation of the effects of the individual factors and their interactions was carried out using the Pareto chart (Fig. 5).

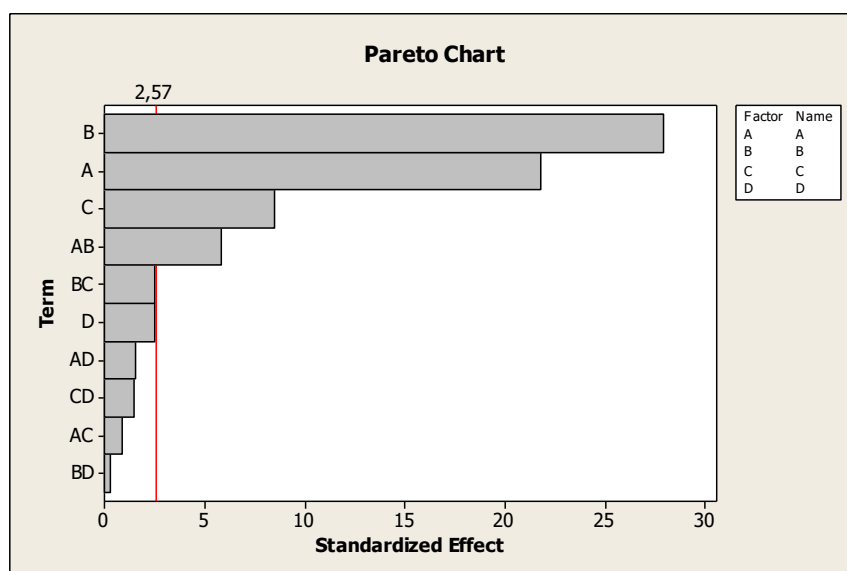


Fig.5 Pareto chart
 Source: (Minitab output)

The model of the full 4-factor experiment, which contains the main factors and all 2-level interactions, was calculated using the following equation:

$$y = \beta_0 + \beta_1x_1 + \beta_2x_2 + \beta_3x_3 + \beta_4x_4 + \beta_{12}x_1x_2 + \beta_{13}x_1x_3 + \beta_{14}x_1x_4 + \beta_{23}x_2x_3 + \beta_{24}x_2x_4 + \beta_{34}x_3x_4 + \varepsilon, \tag{4}$$

wherein y is the response; x_1, x_2, x_3, x_4 , and x_1x_2 to x_3x_4 are the values of Factors A, B, C and D and the interactions between the respective two factors (e.g. x_1x_2 represents the AB interaction). The point estimates of the model parameters are listed in Tab. 4.

Tab. 4 Point estimates of the coefficients of the regression model for the 24th experiment

	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_3$	$\hat{\beta}_4$	$\hat{\beta}_{12}$	$\hat{\beta}_{13}$	$\hat{\beta}_{14}$	$\hat{\beta}_{23}$	$\hat{\beta}_{24}$	$\hat{\beta}_{34}$
Value	3.483	3.436	4.403	1.339	0.398	0.923	- 0.143	0.241	0.402	0.050	0.236
p-value	0.000*	0.000*	0.000*	0.000*	0.053	0.002*	0.407	0.188	0.052	0.764	0.196

Source: Authors

The statistical significance of the individual factors and interactions was evaluated on the basis of the p-value, which represents the lowest possible level of significance α , at which the null hypothesis may still be rejected. The rule applied to the decision on accepting or rejecting the null hypothesis is as follows: if the $p - value < \alpha$, then the null hypothesis is rejected at the significance level α . The analysis showed that the effects of three factors – A, B and C, and of the AB interaction were statistically significant.

The reduced regression model was as follows:

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1x_1 + \hat{\beta}_2x_2 + \hat{\beta}_3x_3 + \hat{\beta}_{12}x_1x_2, \tag{5}$$

$$\hat{y} = 13,483 + 3,436x_1 + 4,403x_2 + 1,339x_3 + 0,923x_1x_2. \tag{6}$$

The value of the adjusted coefficient of determination R_{adj}^2 was 97.70%. This means that the identified regression model explains the experimental results in almost 98%.

The observed (empirical) and the estimated (theoretical) values facilitated the calculation of the residuals $e_i = y_i - \hat{y}_i$. In the correct model, the residuals meet the requirement of independence, normality and constant dispersion. The plot of residuals versus the estimated values is shown in Fig. 6 and the normal probability plot is shown in Fig. 7.

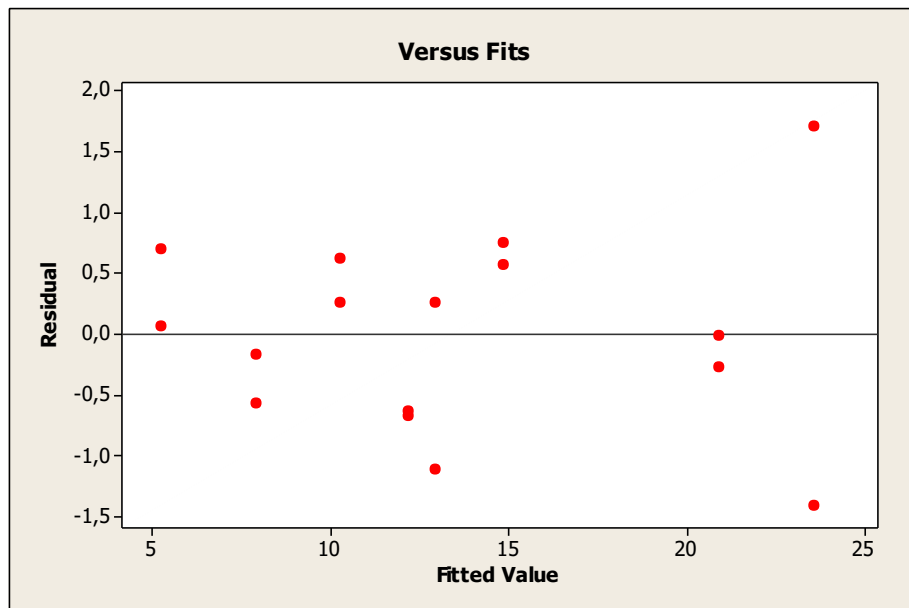


Fig.6 Residual plot
Source: (Minitab output)

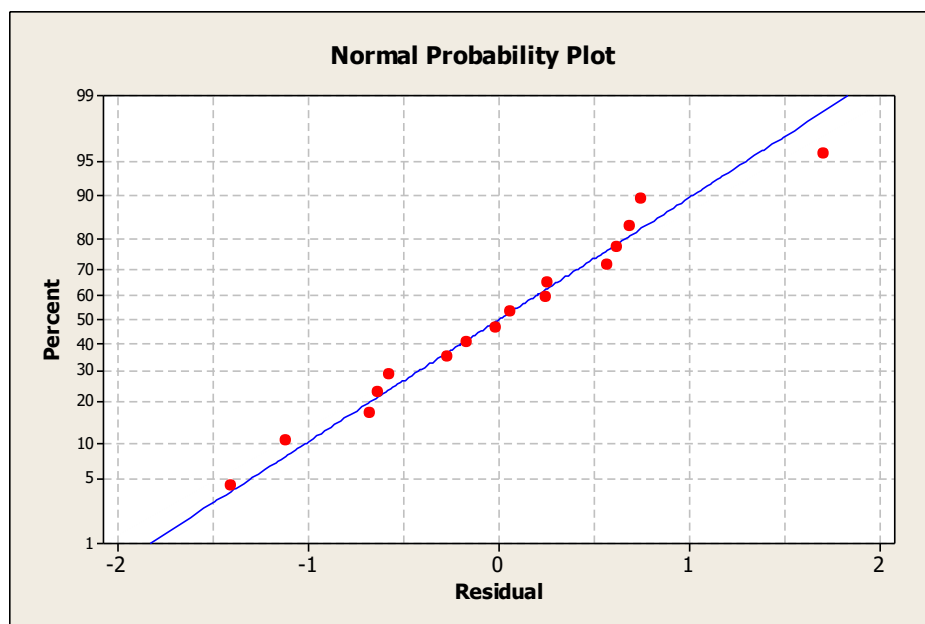


Fig.7 Normal probability plot of residuals
Source: (Minitab output)

Fig. 8 shows the contour plot, which is shown as the region with main factors (A – hammer weight; B – hammer drop height) on the axes, while the constant values of the response variable are shown as the lines. The lines in the contour plot are slightly curved, which proves the existence of a weak interaction between those factors.

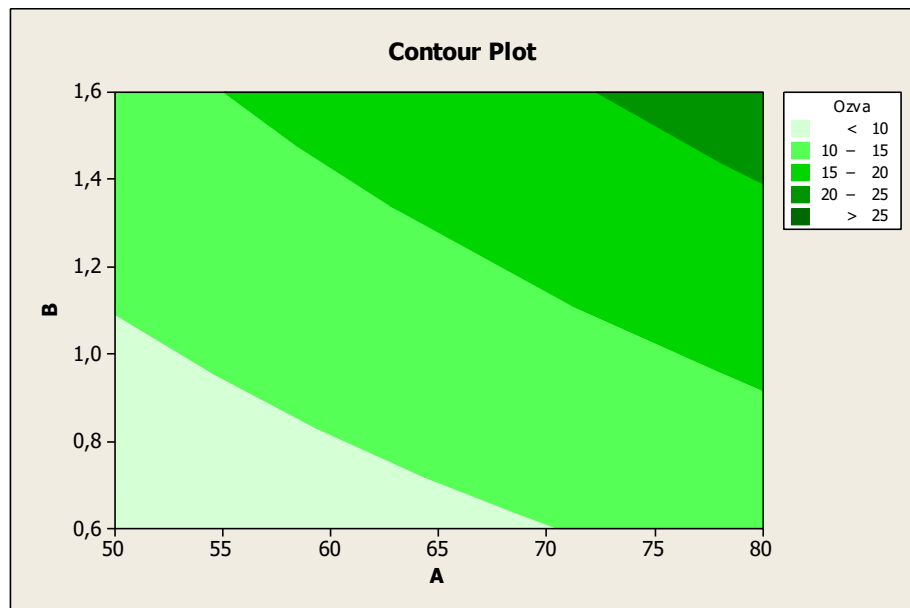


Fig.8 Contour plot
Source: (Minitab output)

4 CONCLUSIONS

Understanding the factors, i.e. the parameters, that affect the wear of conveyor belts during their utilisation is important not only for their users, but also for the manufacturers. The application of the DOE method confirmed the significant effect of the drop height and the hammer weight, as well as the interactions between them. The use of the DOE method is appropriate in experiments with multiple factors, since it facilitates identifying the factors that significantly affect the response. This method is of great importance in the process of designing and the effective execution of experiments, while the procedure applied in this method facilitates a reduction in the number of required tests. This may eventually result in a shorter duration of the experiment, as well as a reduction in the costs and the consumption of materials.

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