THE EVALUATION OF THE SIGNIFICANCE OF FACTORS AND THEIR INTERACTIONS FOR THE MAGNITUDE OF IMPACT ENERGY OF CONVEYOR BELTS

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Abstract

The paper is aimed at the experimental testing of the impact energy of conveyor belts in terms of their resistance to puncture using the Design of Experiment (DOE) method. The plan of the experiment consists of selecting a response i.e., the analysed impact energy, defining selected factors: A – impact height; B – hammer weight; and C – impactor type, designing and implementing the experiment, and evaluating the significance of the effects of the individual factors and their interactions using a t-test, which is expressed in the output by means of the p-value. The Pareto chart and the normal probability plot were used to evaluate the effects of the individual factors and their interactions on impact energy. The experiment was evaluated using a regression model by means of which the input and output variables were determined. The obtained regression model presents a complete three-factor experiment comprising the main factors and the interactions between them. The analysis showed that the three main factors A, B, C, and their first-order interactions AB and BC have a statistically significant effect on the response i.e., the output value of the impact energy.

Keywords: DOE, impact energy, conveyor belts

1. INTRODUCTION

For customers, quality becomes a key decisive factor when choosing from a range of products, services, and so on [1]. Quality of conveyor belts guarantees their operational reliability and a long service life. The evaluation of quality of conveyor belts by applying the method of Principal Component Analysis (PCA) and a cluster analysis was discussed in an article [2]. An important quality factor is the advanced technology for the production of conveyor belts described in [3] in terms of the potential reengineering of the logistic and technological processes. The Design of Experiment (DOE) method was applied to the evaluation of conveyor belts produced by a Slovak manufacturer, which has produced conveyor belts in compliance with the European and globally applicable standards, as well as national standards and specifications. This method was also applied to the testing of conveyor belts described in a paper [4]. The DOE method is used to test and optimise processes, products or services. It facilitates the systematic planning and selection of factors, which may be further analysed based on data obtained from a process running in modified conditions. Experiments are generally conducted with the aim of identifying the factors with potential effects or optimising certain effects. In the case of the optimisation, experimental data are used to create an estimated model i.e., an equation describing a functional correlation between the output characteristics and the input factors [5].

All of the values that a factor can assume are referred to as the factor level [6,7]. When planning an experiment, 2 levels are normally used (the two-level factorial experiment). They are usually referred to as the first (low) level and the second (high) level [8]. In a brief (encoded) form, they are substituted with symbols +1 and –1. The conversion of the original value of x_0 factor into an encoded variable x_c may be carried out using the following equation:

$$x_c = \frac{x_0 - \frac{x_{max}+x_{min}}{2}}{\frac{x_{max}-x_{min}}{2}}, \tag{1}$$

wherein x_{max} is high level and x_{min} is the low level of the factor.

The stage of experiment planning and execution is followed by identifying the impact (effects) of the individual factors on the response. The impact of a factor is defined as a change in the response caused by a change in the factor level. If the factor is one of the main factors, it is referred to as the main effect of the factor.

The main effect of a factor $E_f(F)$ may be calculated by applying a number of methods. In a 2^k factor experiment, the effect of factor F may be estimated as a difference between the average values of the response at the high and low levels of the factor [9], while the following equation is applied:

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

wherein: $\bar{y}_{F+}$ is the average value of the response at the high level of the factor F; $\bar{y}_{F-}$ 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 influential parameter that often occurs in a factorial experiment is an interaction. It is the influential parameter for which the effect of one factor on the response depends on another factor or multiple other factors [6]. There are two-factor interactions (first-order interactions), three-factor interactions (second-order interactions) and interactions of higher orders.

The aim of this work is to assess the factors that influence the impact energy. This energy is essential in the development of conveyor belt damage [10,11]. Research in this area is important to increase the service life of the components of traction and load-bearing components in belt transport. The benefit is knowing the effects of operating factors. The monitored hammer weights, impact heights, and selected impactors simulating the shape of the transported material correspond to the operating conditions, but experimental research for such set intervals is expensive and time-consuming. Therefore, the use of the DOE method is crucial for further research in this area.

2. EXPERIMENT DESIGN AND EVALUATION

The experiment was designed based on the results of previous measurements conducted within the experiments aimed at the evaluation of the dynamic impact loading. In the designed experiment, the effects of 3 factors (Table 1) were analysed. The factors included the hammer weight (Factor A), the impact height (Factor B) and the hammer impactor type (Factor C). The goal was to identify the factor or the interactions between the factors with a significant effect on the response i.e., the magnitude of the impact energy E_{Pr} [J] acting on the conveyor belt, type P 2000/4 8+4, after the hammer impacted the belt.

Table 1 List of input factors and their levels

Factors \ Level		Low level (–1)	High level (+1)
A	**Hammer weight [kg]**	50	100
B	**Impact height [m]**	0.2	1.4
C	**Hammer impactor type [-]**	sphere	pyramid

The tested belts were rubber-textile belts with a 4-ply polyamide carcass of the strength of 2,000 $N.mm^{-1}$ and with the 8 mm top cover layer and the 4 mm bottom cover layer. During the experiments conducted on the test equipment [12] that is available at the Institute of Logistics and Transport of the Technical University of Košice, tested belt sample didn't exhibit any puncture.

The experiment was designed as a full three-factor experiment with two levels, without repetitions and with interactions, while the number of all potential runs was 2^3 – 8 experiments. The values of the individual factors and the responses in all of the experiments are listed in Table 2. The values of the response were experimentally identified values of the impact energy based on experimental measurements.

A graphical representation of the experiment, in the form of a cube plot, is shown in Figure 1, while the values in the corners are the values of the selected response for the individual combinations of factors.

Table 2 Design of the experiment with the input and output values

Run	A [kg]	B [m]	C [-]	E_{Pr} [J]
1	50	0.2	Sphere	74.1
2	100	0.2	Sphere	134.4
3	50	1.4	Sphere	469.4
4	100	1.4	Sphere	912.5
5	50	0.2	Pyramid	85.3
6	100	0.2	Pyramid	133.4
7	50	1.4	Pyramid	544.5
8	100	1.4	Pyramid	979.0

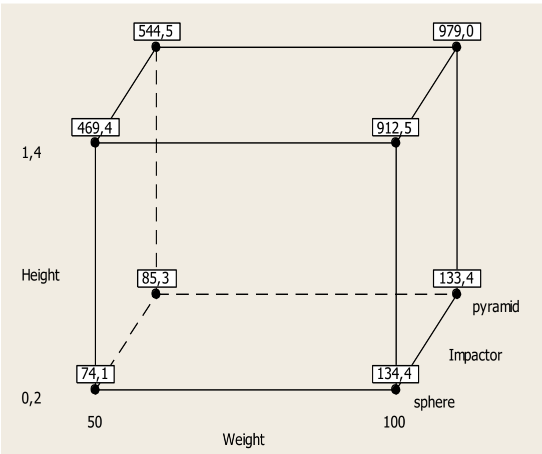


Figure 1 Graphical representation of the experiment in the form of a cube plot

The analysis of the effects of the factors indicated that the impact energy acting on the conveyor belt after the hammer impacted the conveyor belt was of the greatest magnitude when all the three factors were set to the high level. Table 4 clearly shows that Factor B (impact height) and Factor A (hammer weight) had the greatest effects on the magnitude of the impact energy. Factor C (impactor type) had the lowest effect. The significance of the individual factors or the interactions between them was tested using a t-test and by calculating the p-value.

Table 4 The main effects of the factors on the response

Factors	A	B	C
$\bar{y}_{-}$ (low level)	293.3	106.8	397.6
$\bar{y}_{+}$ (high level)	539.8	726.4	435.6
Effects of factors	246.5	619.6	37.9

The significance of the effects may be assessed graphically, while in this type of the assessment of the significance of the effects and their interactions, a Pareto chart (Figure 2) and a normal probability graph (Figure 3) are typically used. The Pareto chart shows the factors and interactions with statistically significant effects on the impact energy, with a significance level α=0.05. The Pareto analysis indicated that only the first-order AC interaction had no statistically significant effect on the response.

The factors and interactions with no effect lie near the drawn line (Figure 3). The factors and interactions located outside the drawn line are regarded as significant. The graphs (Figures 2 and 3) indicate that the hammer impact height (Factor B), the hammer weight (Factor A), the impactor type (Factor C), and the AB and BC interactions had statistically significant effects on the response.

The graphs of the interactions (Figure 4) revealed important interactions between the factors. If the drawn lines are parallel, no interaction between the factors exists or it is insignificant. The interaction between the analysed factors increases with an increasing angle between the lines. There were significant interactions between Factors A and B and between Factors B and C. No significant interaction existed between Factors A and C.

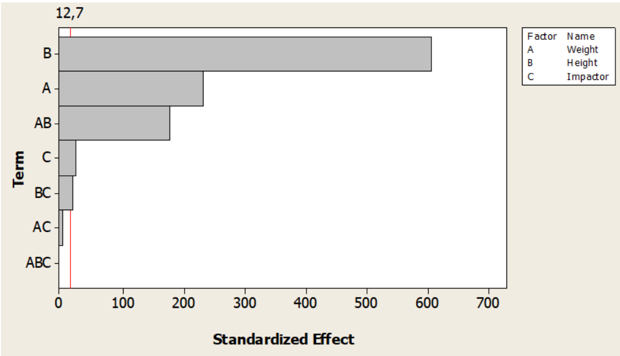


Figure 2 Pareto chart of the significance of factors and interactions

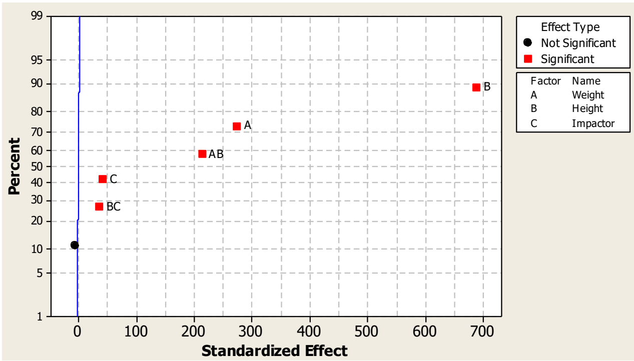


Figure 3 Normal probability plot of the significance of factors and interactions

The model of the full three-factor experiment comprising the main factors and all two-factor interactions is described by the following equation:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \varepsilon, \quad (3)$$

wherein y is the response; x_1, x_2, x_3, $x_1 x_2$ to $x_2 x_3$ are the values of Factors A, B and C and the interactions between the relevant two factors (e.g. $x_1 x_2$ represents the AB interaction).

The point estimate of the regression model is:

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \hat{\beta}_3 x_3 + \hat{\beta}_{12} x_1 x_2 + \hat{\beta}_{13} x_1 x_3 + \hat{\beta}_{23} x_2 x_3, \quad (4)$$

wherein $\hat{\beta}_0$,$\hat{\beta}_1$, to $\hat{\beta}_{23}$ are the estimated coefficients of the regression model, which may also be calculated using the effects [9]. The values of all model coefficients are listed in Table 5.

The value of the coefficient of determination R^2_{adj} = 99.9% indicates that the identified regression model explains the experimental results in 100%.

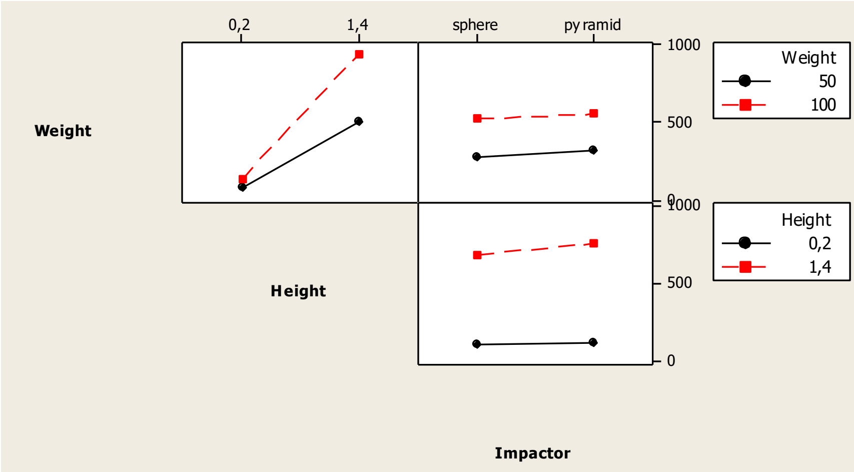
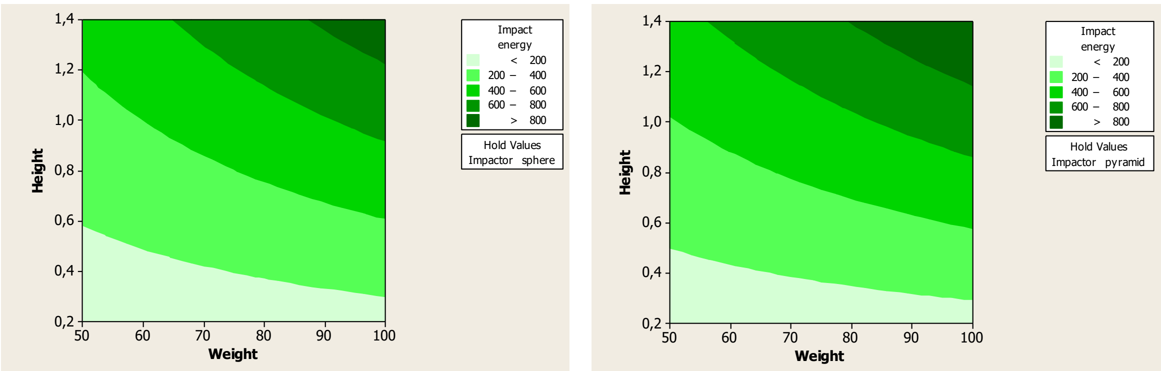


Figure 4 Interaction plot of the main effects

Table 5 The coefficients of point estimates of the regression model

Coefficient	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_3$	$\hat{\beta}_{12}$	$\hat{\beta}_{13}$	$\hat{\beta}_{23}$
Value	416.6	123.3	309.8	18.9	96.2	-2.6	16.4
p-value	0.001	0.002	0.001	0.015	0.003	0.109	0.017



a) Response values for the spherical impactor   b) Response values for the pyramidal impactor

Figure 5 Contour plots of impact energy

The use of contour plots (Figure 5) facilitates the visualisation of the response values. The graphs may be used to compare the values of the analysed response for the given factors. These graphs show how the response variable relates to the two factors (hammer weight and impact height) for each impactor type. Since the graphs only visualise two factors, another factor is maintained at a constant level. As a result, the graphs for the individual impactor types were obtained. The points of the contour plots with equal responses are linked to form the contour lines with constant values. The darkest green (or grey) zone indicates the contour where the response is the highest. The maximum impact energy of 979 J is reached with a hammer weight of 100 kg, an impact height of 1.4 m, and the pyramidal impactor. Based on the comparison of the values of the analysed response, it may be concluded that the values of impact energy were higher with the use of the pyramidal impactor than those observed with the spherical impactor. The pyramidal shape simulates a sharp-edged shape of a transported material that damages conveyor belts to a greater extent.

3. CONCLUSION

Puncture resistance of conveyor belts, or their ability to absorb the impact energy through the deformation work without damaging the conveyor belts, is one of the most important parameters of reliability of belt conveyance systems in the transport of materials. It is therefore very important to know the factors that affect the value of the impact energy without damaging the conveyor belt.

The DOE method was applied to confirm the effects of three input factors (impact height, hammer weight and impactor type) on the impact energy value. A statistically significant effect on the response was observed for the impact height (Factor B), hammer weight (Factor A), impactor type (Factor C), as well as the two-factor interactions AB and BC.

The original results will influence the future direction of research on this issue. Thanks to the DOE method, attention will be paid to the identified significant factors, while the obtained experimental data will be further subjected to mathematical modelling and simulations of impact processes of individual qualities of rubber-textile belts. This will bring about possibilities to increase the service life of these belts and, finally, to save the costs of this most expensive component of belt transport. However, the use of steel-cord belts, which were not the subject of research in this work, is questionable.

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REFERENCES

[1] ANDREJIOVÁ, M. GRINČOVÁ, A., KIMÁKOVÁ, Z. Application of multi-criteria decision-making methods for the conveyor belt selection in practice. *Transport & Logistics: the International Journal.* 2023, vol. 23, pp. 20-31.

[2] GRUJIĆ, M. et al. Using principal components analysis and clustering analysis to assess the similarity between conveyor belts. *TTEM Journal: Technics Technologies Education Management*. 2012, vol. 7, pp. 4-10.

[3] TARABA, V. Logistical and technological reengineering of the combined four-cylinder line for the production of conveyor belts (in Slovak). *Acta Montanistica Slovaca*. 2010, vol. 15, pp. 4-8.

[4] ANDREJIOVÁ, M., GRINČOVÁ, A., MARASOVÁ, Jr., D. The use of DOE method in the evaluation of conveyor belt impact resistance. *Transport & Logistics: the International Journal.* 2023, vol. 23, pp. 95-105.

[5] KUČEROVÁ, M. Determining the levels of input factors in the wire tempering process by the DOE method (in Slovak). *Transfer inovácií*. 2012, vol. 14, pp. 159-163.

[6] HORNÍKOVÁ, A. *Designing and Evaluating Application Experiments* (in Slovak). Bratislava: Iura Edition, 2009.

[7] TEREK, M., HRNČIAROVÁ, Ľ. *Statistical Quality Management* (in Slovak). Bratislava: Edícia Ekonómia, 2004.

[8] MILLER, I. *DOE. Assisted Experiment Design and Analysis by MINITAB®* (in Czech). Praha: Interquality, 2010.

[9] MONTGOMERY, D.C. *Design and Analysis of Experiments*. New York: J. Wiley, 2002.

[10] BORTNOWSKI, P., KAWALEC, W., KRÓL, R., OZDOBA, M. Types and causes of damage to the conveyor belt – Review, classification and mutual relations. *Engineering Failure Analysis*. 2022, vol. 140, pp. 1-23.

[11] ANDREJIOVÁ, M., GRINČOVÁ, A. Classification of impact damage on a rubber-textile conveyor belt using Naive-Bayes methodology. *Wear*. 2018, vol. 414-415, pp. 59-67.

[12] GRINČOVÁ, A., ANDREJIOVÁ, M., GRENDEL, P. Application the renewal theory to determining the models of the optimal lifetime for conveyor belts. *Applied Mechanics and Materials*. 2014, vol. 683, pp. 97-101.