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Using the Design of Experimental Method for Problem-Solving of Noisy Parts in the Automotive Industry

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ABSTRACT

This paper explores and presents the importance and application of the Design of Experiments (DOE) method in scientific and industrial research. It analysed the theoretical foundations of the method in detail and then illustrated concrete examples as well as benefits of its use in an automotive environment. The introduction outlined the key principles and objectives of the DOE method, including optimisation of experimental processes and minimisation of variability of results. The publication focused on the significant impact of this method in improving the efficiency of experiments and achieving reliable and reproducible results. The practical part of the paper presented concrete examples of the application of the DOE method in the automotive industry. Through this case study, it was highlighted how the DOE method enables the systematic investigation of the influence of different factors on experimental results, leading to a better understanding of the phenomena under investigation and an increase in process efficiency. Emphasis was also placed on the practical aspects of using the DOE method, including the design of experimental plans and the analysis of the data obtained. The case study outlined the challenges and benefits that can arise when implementing this method and presents new perspectives for future research in statistical experimental analysis. Overall, this research paper can be considered an important resource for researchers and practitioners seeking effective methods for planning and conducting experiments to achieve significant research results in various disciplines.

Keywords: DOE, experiment planning, automotive.

INTRODUCTION

Today, when competitiveness and efficiency play a key role in scientific research and industries, it is essential to look for systematic and innovative approaches to process optimisation [1, 2] In this context, the DOE method occupies an exceptional place as a powerful tool for planning and analysing experiments to obtain as much information as possible with a minimum number of experiments. DOE, also known as Statistical Design of Experiments, provides a systematic framework for conducting experiments, allowing the identification of key influences of factors and their interactions on the system under study. This method goes beyond traditional single factor experiments by allowing the investigation of complex relationships between many factors at once, significantly saving time cost and resources [3]. The DOE methodology is also used in a few fields, for example, for wire EDM [4], or for experiments on metal matrix composites for automotive or aerospace applications [5]. The design of experiments method has also been used in a few studies and engineering applications to optimise appropriate parameters and their combinations, leading to valuable results for many fields [5, 6, 7]. This paper presents in detail the use of the DOE method in experimental planning and optimisation in the context of automotive applications [8, 9]. The basic principles of the method, experimental design techniques and the benefits that this systematic and statistically based methodology brings to the decision-making process were explored. Specific examples of the application of the DOE method in a real industrial environment were also analysed. The aim of the paper was to provide a comprehensive view of the application of the DOE method and to illustrate its impact on optimisation processes, innovation and achieving competitive advantage in the current industrial environment. Final reflections were directed towards future perspectives and challenges associated with this methodological approach in the context of a rapidly changing industrial environment. This may also include the use of simulation techniques, which may lead to an acceleration of the whole design process and verification of the results obtained [10, 11, 12].

BASIC METHODOLOGY

The DOE or Design of Experiments method is a method of planned experiments. It is used most often when there is a concern that a process (or some of its parts) is affected by more than one predictor variable, or factor [5]. The aim of the method is to perform experiments on a small number of samples, the variations of which are given by a complete factorial design. The smallest number of experiments that are performed in the DOE method is 4. For a more complex problem with many inputs, a high number of experiments may be required. These cases tend to be more challenging, but if there is a need to obtain a large amount of information in the output, it is also advisable to choose the planned experiments method. Experimentation means changing the standard working conditions. The aim of this change is to find more appropriate working practices as well as to obtain more accurate and detailed information about the processes, services, or characteristics of the product under study [13].

The experimental design specifies 3 basic characteristics, the so-called 3Ps:

- the total number of trials of which the experiment is composed,
- the conditions for the execution of each experiment,
- the order in which each experiment will be performed.

The most common approaches to the DOE method are:

- the classical approach to DOE – examining all options,
- statistical approach to DOE – it deals with only a part or segment of all possible variations.

In common practice, the statistical method of planned experiments is most often used. As it was mentioned below, this statistical method was pioneered by the Japanese mathematician Genichi Taguchi, who was dedicated to the application of statistics to improve the quality of processes and products. The main benefits of the planned experiments method:

- reduction in the number of non-conforming processes or products,
- reducing the cost of claims and mistakes,
- improving product and process development, increasing quality,
- reducing quality problems in production,
- higher customer satisfaction [14, 15, 16].

DOE procedure

Experiment planning is, like many other tools, governed by the well-known PDCA (Plan-Do-Check-Act) cycle (Figure 1). This cycle was first described by W. Edwards Deming, which is why the PDCA cycle is sometimes referred to as the “Deming cycle”. The goal of the PDCA cycle is to help improve the process in a clear and efficient way. As it was mentioned at the beginning, this cycle is divided into four parts:

The planning of the experiment can be divided into the following sub-phases:

- analysis and planning of the experiment.
- experiment design.
- conducting the experiment.
- analysis of the experimental results.
- conclusions and possible decisions about the next experiment [17, 18].

A CASE STUDY ON THE APPLICATION OF DOE IN PRACTICE

Why do companies address the noise made by parts? Customer requirements and specifications are very strict in this respect, and they are all focused on the comfort of vehicle users. Noise levels, spectra and frequencies are a highly monitored parameter for all components that move in some way. Measurements are carried out in laboratories on individual products as well as on finished vehicles. In some cases, the requirements are so demanding that they can only be achieved at a disproportionately high cost,

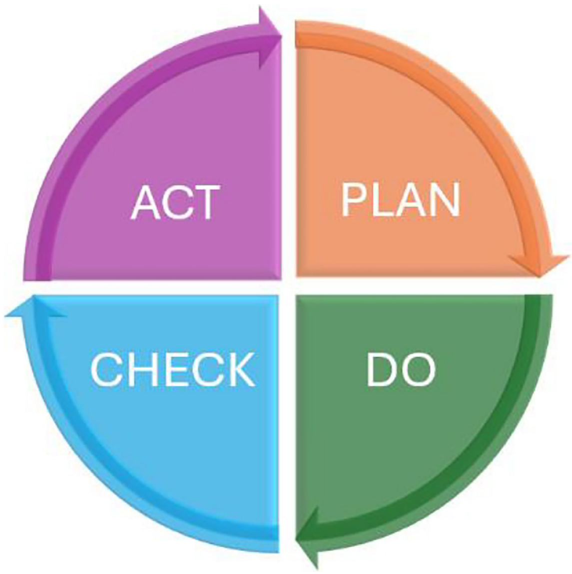

Figure 1. PDCA circle diagram

which is of course passed on to the end customer, i.e. in the final price of the car. It is certainly worth considering whether it might sometimes be more efficient to discount requirements in some areas and use resources more effectively to address other problems. This whole situation has been exacerbated by the advent of increasingly mainstream electric cars. The reason for this is simple: when conventional internal combustion cars are in operation, some of the noise is hidden behind the noise generated by the internal combustion engine itself. With electric cars, this noise is eliminated, and the greater demands are placed on the products [19].

Practical application of the DOE method for the 5th Door Actuator

The 5th Door Actuator product was selected due to the detection of noisy pieces in the production line. Due to the high production volume of this product, it was necessary to immediately start looking for the root cause of the problem and ensure it was eliminated in order to supply customers with products that met their specifications.

Selection of appropriate factors for the application of the DOE method

For the correct application of the DOE method, it is essential to thoroughly analyse the entire process and take into account all potential causes of the defect. In this case, it is reporting from internal quality about a high increase of noisy parts on the assembly line. After verifying this information, a team of internal specialists was convened from the responsible departments: development, production management, quality, technology, project management, maintenance management and production planning. After explaining the identified issue of increased noise for the 5th Door Actuator part, the IF/NOT method was applied. This method is very useful for simplifying the description of the problem and clarifying under what circumstances the problem occurs. An initial analysis using the IF/THEN method clarified the circumstances of the problems and applied another team method, the Ishikawa diagram. All

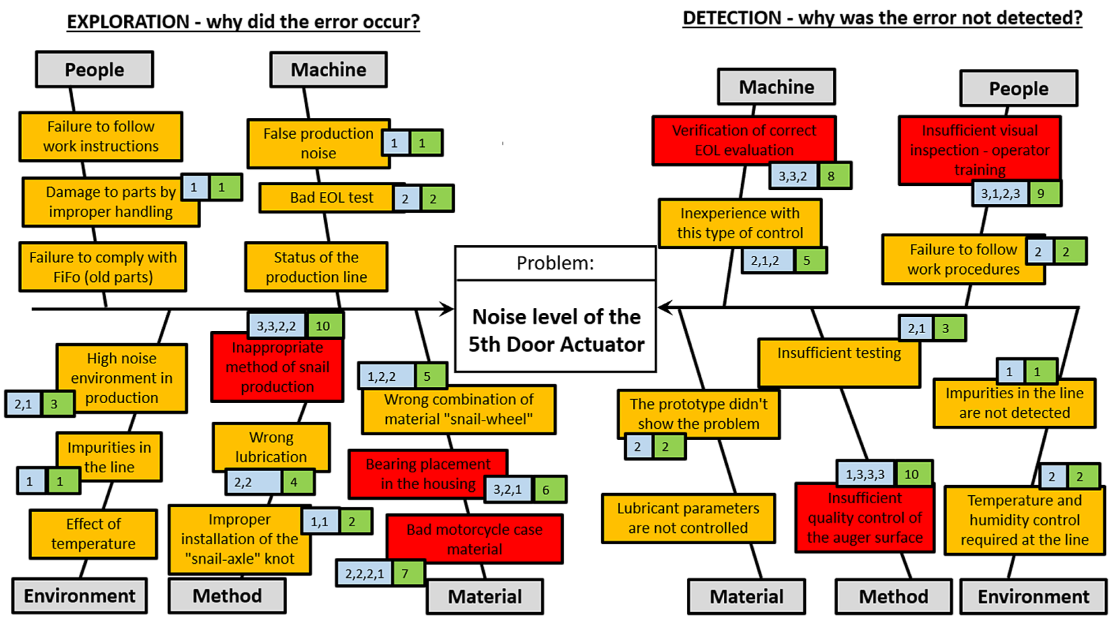

Figure 2. Ishikawa diagram for the 5th Door Actuator

possible potential causes were first defined and entered the Ishikawa diagram. Next, the causes that seemed most likely to the team of experts were selected. The scoring method was used for this selection. Each team member was assigned a total of 6 points. These allocated points were to be assigned at his discretion to the causes he thought might be root causes. Each member had 6 points for the left and 6 points for the right side of the diagram. The constructed Ishikawa diagram for the problem at hand is shown in Figure 2.

Adding up the votes of all the points awarded on the left side of the diagram, it was found that the following 3 aspects contribute most to the problem of increased noise level of the Door 5 Actuator:

- inappropriate method of snail production,
- bearing in the housing,
- bad material of the motor case.

The right part of the Ishikawa diagram justified why defects were not detected in the prototype phase of the project. Again, 3 probable causes were selected for evaluation:

- verification of correct EOL evaluation,
- insufficient visual inspection – operator training,
- insufficient quality control of the auger surface.

Selection of levels of defined factors

The team of internal specialists, with the same composition as when the Ishikawa diagram was drawn up, reconvened to clearly define the main factors that will be emphasised in the application of the DOE method. The team agreed to use the data from the left side of the Ishikawa diagram because they concluded that the most likely propagation of sound is from the enclosure, which serves as a sounding board and carries around noise from internal components that are in contact with it. The main factors and their levels are described in Table 1. Data from Table 1 served as input variables. The total number of experiments to be performed was calculated by substituting into formula (1):

$$n = 2^k = 2^3 = 8 \quad (1)$$

Minitab statistical software was used to create the factorial test plan. The tests and their combinations resulting from Table 1 were conducted according to the full factorial design described in Table 2. In order to maximise objectivity, all factors were calculated in Minitab.

Description of DOE outputs

To properly evaluate DOE, it is necessary to know which outcome factors were observed and how they were measured. The values of the output factors were recorded in a modified Table 3, which was used to construct the full factor schedule. A right hand column was added to this table to record the response.

The most important measured output from the DOE is the noise level emitted by the Door

Table 1. Main noise manifestation factors, including their levels

Factor	Level -1	Level +1
Motor case material	PP/EPDM	POM
Adding an ”O” ring to the motor bearing	With a ring	Without ring
Adjusting the shape or surface of the worm	Shrinking	Polished surface

Table 2. Full factorial plan

Selected experiment	Motor case material	Adding an ”O” ring to the motor bearing	Adjusting the shape or surface of the worm
1	-	-	-
2	+	-	-
3	-	+	-
4	+	+	-
5	-	-	+
6	+	-	+
7	-	+	+
8	+	+	+

Table 3. Full factorial plan including response

Selected experiment	Motor case material	Adding an "O" ring to the motor bearing	Adjusting the shape or surface of the worm	Response (Yn)
1	-	-	-	y1
2	+	-	-	y2
3	-	+	-	y3
4	+	+	-	y4
5	-	-	+	y5
6	+	-	+	y6
7	-	+	+	y7
8	+	+	+	y8

Actuator 5. This measured noise level must be within the limits set by the customer specification and 45 dBA is stated as the maximum accepted value. This is because passenger comfort would be reduced when closing the 5th door lid with a noisy actuator.

For a part to be designated as i.O. (German for "in Ordnung", or in order), the noise level must be within a maximum of 45 dBA. Anything over this limit is discarded as a non-conforming product. These non-conforming parts are then analysed by the quality department. The higher the noise limit exceeded, the easier the analysis is. Noises just above the limit cause the greatest problem.

Analysis of factor effects

Individual effects were determined by adding or subtracting the response for each selected factor based on the assigned sign of the factor level and dividing the sum or difference by n/2, where n indicates the number of experiments.

The Pareto diagram (Figure 3) below was constructed in the Minitab statistical software. The diagram shows the statistical significance of the individual factors. The dashed line in the graph indicates p-value < α. Factors not exceeding this red line have been removed from the model and it is recommended to proceed only with factors exceeding the dashed line. A line through the normal-probability effects plot below shows the normal distribution function. The factors that are close to or directly on the line are considered as unimportant. Conversely, the further away a factor is from the line, it is referred to as important. In this case, the graph shows that all factors closely surround the green line, except for factor C. This evaluation corresponds to the graph

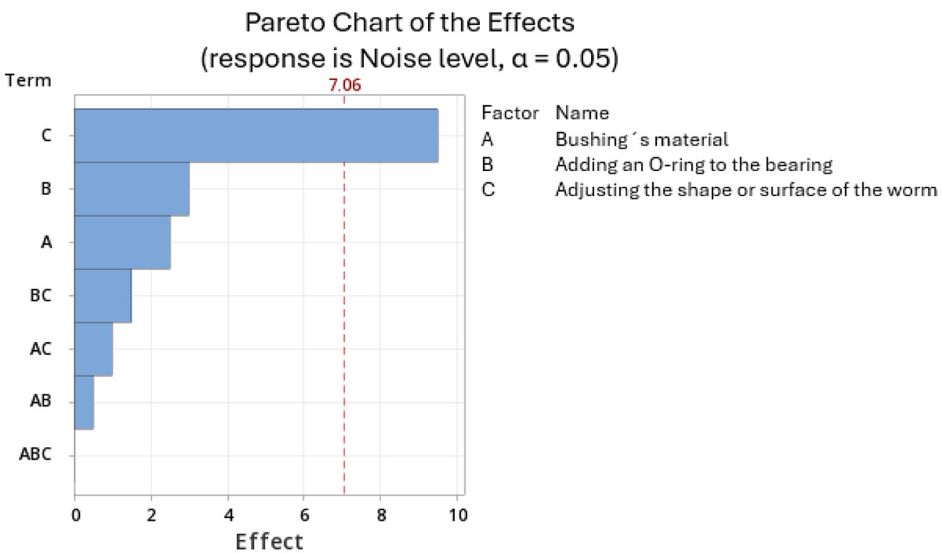

Figure 3. Pareto diagram of the 5th Door Actuator from Minitab

shown in Figure 4, where factor C exceeded p-value and can therefore be considered as the only significant factor.

Evaluation of the analysis, identification of problems and bottlenecks

Partial evaluation of the results of the DOE method for the Door Actuator 5

To test the theory that the material of the motor housing, the motor bearing and its housing or the shape of the worm is responsible for the increased noise of the part, the method of planned experiments was applied. Prior to this application, the output factors and their levels had to be determined. The evaluation of the application of the DOE method was carried out using Minitab statistical software. In evaluating the Minitab outputs, it was found that the measured values mostly exceeded the customer specification and were therefore above the 45 dBA limit. The only factor that confirmed a positive effect on improving the noise problem was the modification of the auger shape, which the company focused on and began to investigate the possibility of deploying this modification in series production (Figure 5). Further testing led the team to conclude that adding shrinkage to the auger proved to be the best option. This solution is also easy to apply to mass production. A very interesting moment occurred during the testing of the shrinking on the snail, when a second round of brainstorming was necessary. The idea was put forward that if the internal parts inside the Actuator 5 door covers are generating noise, perhaps it would be better to "keep"

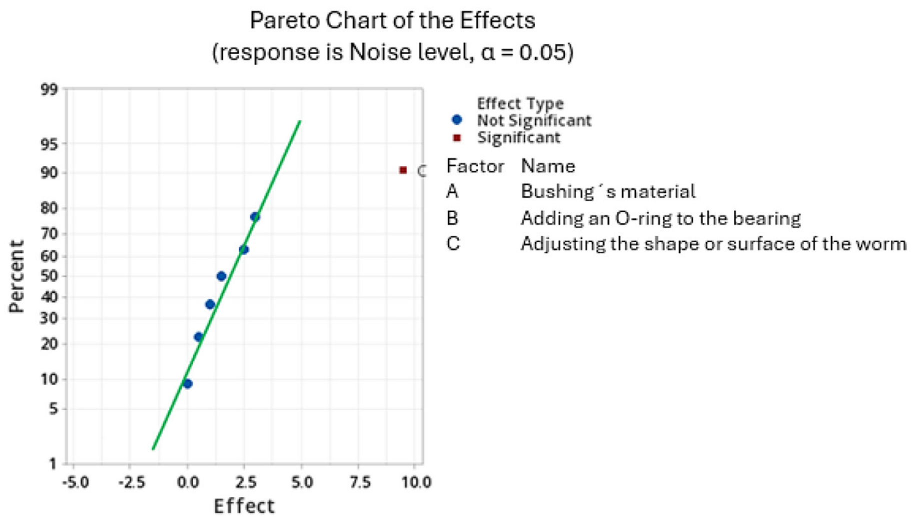

Figure 4. Normal probability plot of all effects

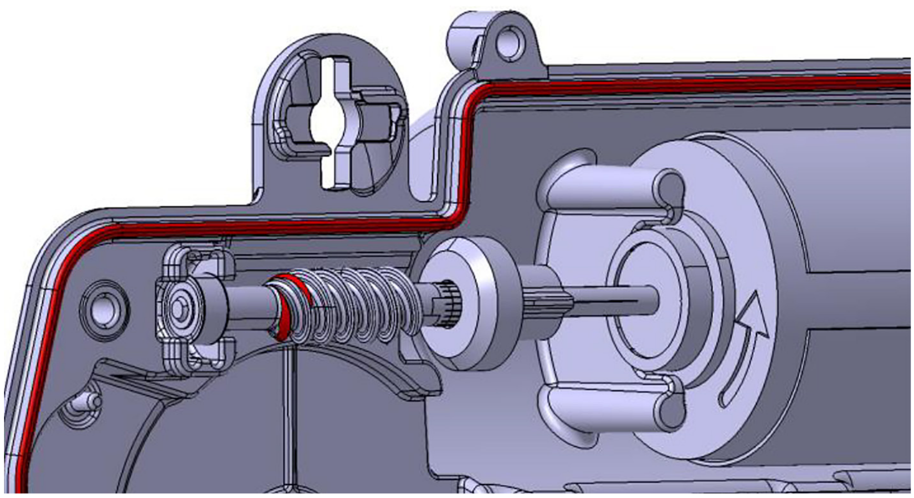

Figure 5. Detail of the shrinkage on the worm and the peripheral seal

this generated noise inside the covers and not let it out through the joint between the covers. Therefore, an acoustic measurement experiment was attempted using an auger with a shrink fit and a plastic gasket was applied between the top and bottom covers. The result was an even greater reduction of 2 dBA in the Actuator's acoustic performance. This resulted in an average sound level of 39–40 dBA, which is below or just at the customer's accepted value (40 dBA). The ideal value is lower than the accepted value to provide a margin. This margin is necessary due to the manufacturing tolerances of all components that go into the part being measured.

Practical demonstration of the execution of the planned experiment of the 5th Door Actuator

This section will describe how one of the experiments was carried out in practice, specifically the combination of factors highlighted in blue in Table 4.

Before the practical execution of the experiment itself, it was necessary to build a setup containing the required variables according to Table 4. The next step was the preparation of the equipment necessary for the proper execution of the experiment; in this case, it was the preparation of the shockless chamber and installation of the test fixture with the scanning microphone inside the chamber, setup and connection of the laboratory power supply as well as calibration of the measurement software, which was custom developed at the Technical University of Ostrava.

Figure 6 shows the location of the Door 5 Actuator in the measuring fixture, to which the scanning microphone is fixedly attached in a defined position and the entire fixture is located in the shockless chamber. The measured data from the shockless chamber were evaluated directly in the software. The second option is to import the measured data into Excel, where it is possible to work with them

Table 4. Combination of factors of the practical experiment of the Door 5 Actuator

Factor	Level -1	Level +1
Bushing´s material	PP/EPDM	POM
Adding an O-ring to the bearing	With ring	Without ring
Adjusting the shape or surface of the worm	Chamfer	Polishing

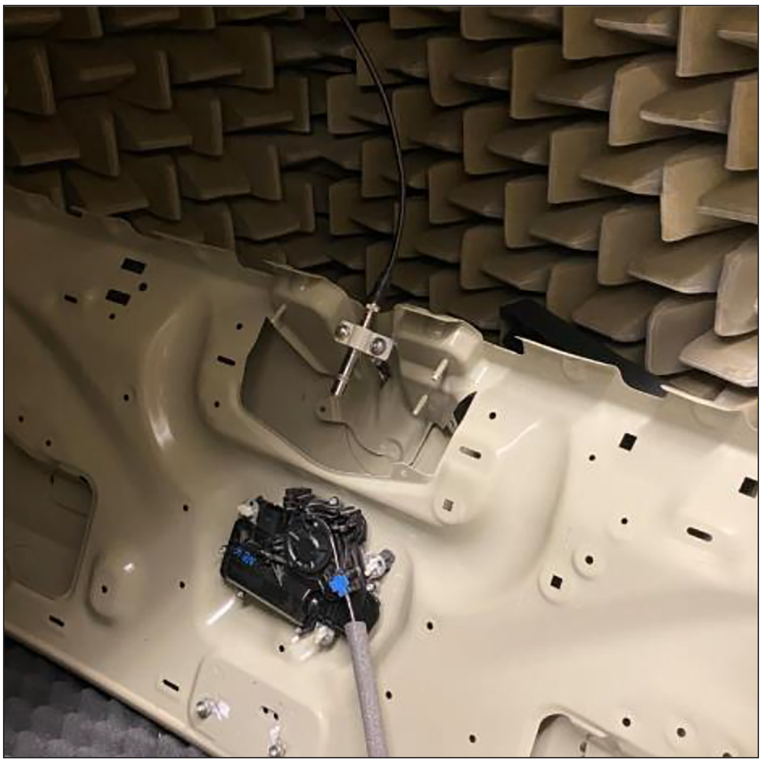

Figure 6. 5th door actuator in the shockless chamber

further, making various comparisons. Similarly, a great advantage of Excel is that by adjusting the individual measured values, the influence of these parameters on the result can be modelled in real time. This method is very often used in practice.

A comparison of the plots of the stock condition and the modified part shown in Figure 7 clearly shows the effect of the improvement. By further successive experiments according to Table 4, it was found that the addition of shrinkage on the worm has the greatest effect, the other factors are not as significant and do not have a significant effect on the final result.

RESULTS AND DISCUSSION

On the basis of the data above, the main factors contributing to the problem of increased noise level of Door Actuator 5 were identified using the JE/NENÍ and Ishikawa diagram methods. A full factorial plan was developed for testing using the DOE method, which was further evaluated to identify the factors that contribute most to the problem at hand.

The correctness of the optimisation of these identified factors was verified in the practical part, where the graph in Figure 7 clearly shows the improvement compared to the previous situation. The original condition had an average measured value of 50 dBA, the part after analysis and adjustment showed an average measured value of 41 dBA.

Elimination of the above-mentioned problem has significant economic implications for the company, as it is no longer necessary to monitor the noise level of 100% of the production, but only randomly, which means an increase in the production stroke of the line. It also eliminates the high cost of reworking non-conforming parts, which was necessary for the original condition of the parts.

In the practical part of the article, the work with the selected factors and their evaluation was presented. Furthermore, the equipment necessary for the evaluation of noise problems, such as the shockless chamber and the measurement software, was also presented in this section.

From the results described above, it can be said that the use of the design of experiment method provides a structured and statistically based approach to experimental design and analysis, which leads to an increase in the reproducibility of results and the credibility of the findings obtained.

CONCLUSIONS

In this paper, the results of authors' study on the use of the design of experiment method to address the problem of noise in automotive components were presented. On the basis of the

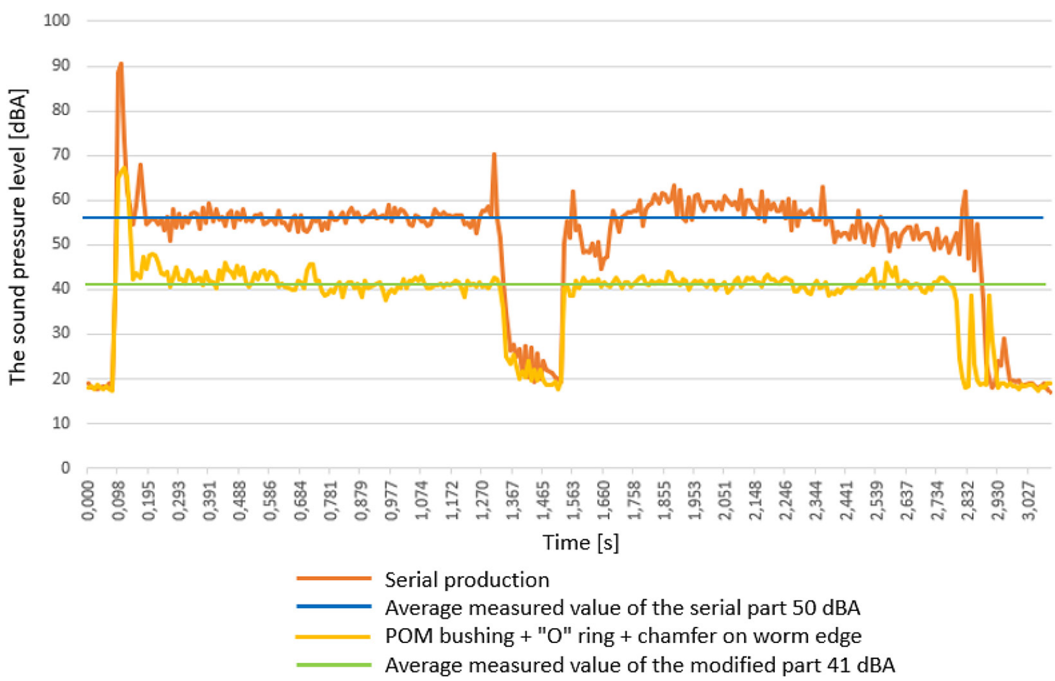

Figure 7. Comparison of measured values of Door Actuator 5

conducted experiments and analyses, several important conclusions were drawn:

Key factors affecting the occurrence of noise in automotive components have been identified, including factors related to manufacturing, materials, design and assembly. Using the DOE method, it was possible to systematically investigate these factors and their interactions, allowing us to identify the optimum conditions for noise minimisation.

Another conclusion is that the application of the DOE method has resulted in significant economic and time savings. The number of experiments required was minimised while maximizing the efficiency of experimental space utilisation, which allowed achieving the desired results with minimal cost and time. These outcomes further translated into significant improvements in the economics of manufacturing the analysed part.

The study also highlighted the practical application of the DOE method in the automotive industry and demonstrated its ability to effectively address real-world product quality and performance issues.

In the current competitive environment of the automotive industry, it is essential to use these modern methods such as DOE as they have a major impact on speeding up the problem analysis process and reducing costs.

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REFERENCES

1. Šajdlerová I., Schindlerová V., Kratochvíl J. Potential and limits of overall equipment effectiveness in the total productivity management. online. Advances in Science and Technology Research Journal. 2020; 14(2): 19–26. https://doi.org/10.12913/22998624/113617 (Accessed: 18.03.2024)
2. Turečková K., Martinát S., Nevima J., Varadzin F. The impact of brownfields on residential property values in post-industrial communities: A study from the eastern part of the Czech Republic. Land. 2022; 11(6): 1–21. Available from: https://www.mdpi.com/2073-445X/11/6/804 (Accessed: 18.03.2024)
3. Kučerová L., Burdová K., Marková V., Zálabský J., Ťavodová M. Using the design of experiments methodology to evaluate the heat treatment of additively manufactured maraging steel. Journal of Materials Research and Technology. 2023, 26(September–October 2023), 8688–8703. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2238785423022433 (Accessed: 18.03.2024)
4. Dhobe M., Chopde I., Gogte C. Optimization of wire electro discharge machining parameters for improving surface finish of cryo-treated tool steel using DOE. Materials and Manufacturing Processes. 2014; 29(11–12): 1381–1386. Available from: http://www.tandfonline.com/doi/abs/ 10.1080/10426914.2014.930890 (Accessed: 18.03.2024)
5. Aabid A., Murtuza M., Khan S, Baig M. Optimization of dry sliding wear behavior of aluminium-based hybrid MMC's using experimental and DOE methods. Journal of Materials Research and Technology. 2022; 16(January–February 2022), 743–763. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2238785421014484 (Accessed: 18.03.2024)
6. Anjum M., Khan M., Hassan S., Mahmood A., Qureshi H., Gidlund M. RSSI fingerprinting-based localization using machine learning in LoRa Networks. IEEE Internet of Things Magazine. 2020; 3(4): 53–59. Available from: https://ieeexplore.ieee.org/document/9319633/ (Accessed: 18.03.2024)
7. Afzal A., Aabid A., Khan A., Afghan Khan S., Rajak U., Nath Verma T., Kumar R. Response surface analysis, clustering, and random forest regression of pressure in suddenly expanded high-speed aerodynamic flows. Aerospace Science and Technology, 2020; 107(December 2020), 1–18. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1270963820310002 (Accessed: 18.03.2024)
8. Aabid A., Hrairi M., Ali J. Optimization of composite patch repair for center-cracked rectangular plate using design of experiments method. Materials Today: Proceedings, 2020; 27(2), 1713–1719. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2214785320324214 (Accessed: 18.03.2024)
9. Prabhu P., Prabhu D., Rao P. Analysis of Garcinia indica Choisy extract as eco-friendly corrosion inhibitor for aluminum in phosphoric acid using the design of experiment. Journal of Materials Research and Technology, 2020; 9(3): 3622–3631. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2238785420301496 (Accessed: 18.03.2024)
10. Sujová E., Bambura R., Vysloužilová D., Koleda P. Use of the digital twin concept to optimize the production process of engine blocks manufacturing. Production Engineering Archives. 2023; 29(2): 168–174. Available from: https://www.sciendo.com/article/10.30657/

pea.2023.29.20 (Accessed: 18.03.2024)

11. Šproch F., Schindlerová V., Šajdlerová I. Using 3D printing technology in prototype production to control the dimensions of complexly shaped products. Manufacturing Technology, 2020; 20(3): 385–393. Available from: https://journalmt.com/doi/10.21062/mft.2020.061.html (Accessed: 18.03.2024)
12. Schindlerová V., Šajdlerová I. Use of the dynamic simulation to reduce handling complexity in the manufacturing process. Advances in Science and Technology Research Journal, 2020; 14(1): 81–88. Available from: http://www.journalssystem.com/astrj/use-of-the-dynamic-simulati on-to-reduce-handling-complexity-in-the-manufacturing,113616,0,2.html (Accessed: 18.03.2024)
13. Tošenovský J. Planning experiments. Ostrava VSB Technical University of Ostrava, 2012. (in Czech)
14. Montgomery D. Design and Analysis of Experiments. Eighth edition. USA: John Wiley & Sons, Inc., 2013.
15. Antony J. Design of Experiments for Engineers and Scientists. Second edition. Elsevier Ltd., 2014.
16. Eriksson L, Johansson E, Kettaneh-Wold N, Wikström C, Wold S. Design of Experiments. Principles and Applications. 3rd. rev. and enlarged ed. Umetrics Academy, 2008.
17. Zichová J. Experiment planning and predictive multivariate analysis. Praha: Karolinum, 2007. (in Czech)
18. Jarošová E. Design of experiments and their analysis. Praha: Czech Society for Quality, 2007. (in Czech)
19. Sýkora, V. Using the DOE Method for Problem-solving of Noisy Parts in Automotive: Diploma’s Thesis. Ostrava: VSB Technical University of Ostrava. Faculty of Mechanical Engineering. Department of Mechanical Technology, Thesis Head: Schindlerova, V. 2023. (in Czech)