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PRACTICAL USEFULNESS OF THE MONTE-CARLO METHOD IN PROCESSES OF THE AUTOMOTIVE INDUSTRY

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ABSTRACT

Post-pandemic (COVID-19) and amidst raw material shortages (due to war of Russia-Ukraine), there's a push to analyze stored data to enhance quality management through scientific methods, leading to better forecasting and reduced waste. Understanding manufacturing processes and machine operations is crucial for meaningful data analysis. The study reviews relevant literature, presents research results, and demonstrates the method's practicality in manufacturing, concluding with a discussion of findings.

In the Otto engines of subject of research, camshafts control valves to manage air for shafts of the intake and exhaust. The cams, made from wear-resistant chromium alloy steel, are crucial for valve operation.

ANOVA (F-test) and regression analysis were used with Minitab to test hypotheses and analyze data, confirming significant differences between batches and the impact of energy levels on hardness depth. The Monte-Carlo method, involving random sampling, was also applied to model outcomes and probabilities. Regression analysis showed differences in data series averages, while the Monte-Carlo method helped determine optimal energy levels for induction hardening. The study found that adjusting energy levels ensure all products meet the required hardness depth, reducing the rejection rate significantly. This highlights the methods' value in optimizing production processes and minimizing scraps.

KEYWORDS: automotive industry, Monte-Carlo method, process development, regression analysis, scrap-reduction

1. Introduction

The previous study (Hugyi, 2022) points out the differences between Industry 4.0 and Industry 5.0, but also the synergies that can be derived from their interfaces. Following the pandemic that has transformed our recent years and the scarcity of raw materials, partly caused by the war in our environment, these tangible and intangible resource problems seem to have stabilised somewhat. This may also give them a reason to start analysing those data sets, once stored or manually recorded, and to assess the added value they can add to the business – helping to raise quality management to a new level by applying scientific methods. All this should lead to more accurate forecasting and scrap reduction.

It is not insignificant that the interpretation and analysis of the relationships between data make the most sense when the underlying reasons are known, i.e., when the manufacturing processes and the logical operating mechanisms of the machines involved are familiar.

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2. Literature Review

The four-stroke engine was invented by Nikolaus August Otto (1832-1891). In internal combustion engines, the camshafts, or more accurately the elements on them called the cams, move the valves so that air is drawn in and the combustion products can be emitted. Upon the turn of the cam of the rotating shaft to the valve lifter, the valve opens due to the pressure. When the cam is turned, the respective spring returns the valve to its initial position. The mentioned cams, which ensure the control of the motion of the valves, belong to a group of cold-forming tool steels made of a chromium alloy with an immense wear resistance. This material is usually used for the production of parts where, in terms of use, they are subject to severe stress, pressure and abrasion. It is used for the production of bearings and other pressure and friction resistant components that are subjected to high stress, and with a suitable procedure, it can be achieved that their service life is adjusted to the requirements of the application (Owunna & Ikpe, 2021).

In this instance, our focus will be on the double overhead camshaft (DOHC) engine, given that our customer-side component is utilised in such a unit. This configuration represents the optimal solution for increasing speed, as all structural components of the camshaft, with the exception of the valves, exhibit a circular motion, thereby eliminating the generation of mass forces. For this arrangement to be most efficient, it is essential that the mixture formation and combustion of the gases occur with the utmost rapidity and precision (Sudheer & Raghunatha, 2018).

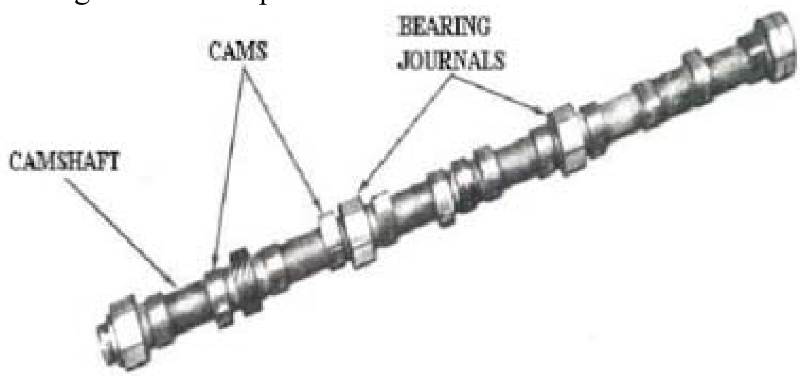

Figure no. 1: *Detail of a camshaft*
(Source: Sudheer & Raghunatha, 2018)

Two main parts of the above-mentioned lifting lobes are distinguished: the nose and the base, which are affected by induction hardening in different ways due to the principle of the hysteresis effect. In this article, the values of induction hardening for the **base side** of the lobe, as visualized in Figure no. 1 and Figure no. 2, are analyzed.

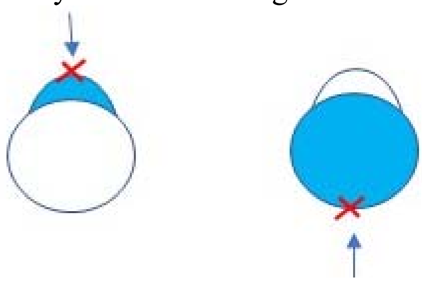

Figure no. 2: *Main portions of the lobe: nose (left) and base (right): measurement points marked red "X"*
(Source: Author's research)

The following regression analysis and the Monte-Carlo method are used to investigate the manufacturing process of the induction hardening process. Above all, a production equipment is required that with an optimised cycle time ensures stable quality in mass production, in consistency with the principles of stability and reliability, for which regular machine maintenance is also an essential prerequisite.

In a nutshell on induction hardening: if you place an electrically conductive metal in an alternating current coil, the magnetic field will generate an eddy current. Joule heat is produced by this vortex which then heats the metal. In addition, when it comes to magnetizable metals, the loss of magnetization can result in heat generation, which expedites the heating (Laleh et al., 2023).

Our aim is to achieve significant savings in the production process under study by using the methods mentioned above.

3. Material and Method

ANOVA (F-test) was used with a 5% significance level. The Minitab program was enlisted for assistance. The null hypothesis, which states that three batches are from the same set, and the counter hypothesis, which posits that one of the three batches is from a different set, were tested. The counter hypothesis was affirmed. Consequently, the null hypothesis was dismissed as the P-value was below the defined confidence level (alpha = 0.05).

The statistical method of regression analysis was also used to examine the measured data in relation to hardness depth, with Minitab also being used.

Thanks to R-sq, insight is gained into the extent to which reality is depicted by the formula. It is just an estimate that acts as guidance and is therefore insufficient on its own. Despite an undefined goodness-of-fit level it is believed by some that an R-sq value above 70% is fairly good. The error rate of the total standard deviation is indicated by the R-sq value. A smaller error results in a greater R-sq. The equation of the abstract line is regarded to be accurate if 90% of the points are within the confidence limits. In this particular instance, R-sq (adj) is greater 90%, it is precisely 97,8%, this indicates that the error is lower than 10%. The null hypothesis is dismissed again, because the value of P is lower than the confidence level defined above (alpha = 0.05).i.e. changes in the level of energy have an impact on the training depth (Ntumi, 2021).

The scatter diagram shows the confidence interval (CI) marked with the dashed green line around the regression line. The regression equation estimates the mean of the data points based on the sample, consequently, the mean range of a manifold becomes known, but its location is not known to me. The prediction interval (PI), on the other hand, specifies the spectrum in which certain points in the manifold about the regression line will fall.

In addition to the above, the Monte-Carlo method was also used by me. Bera & Pokorádi (2015) call Monte-Carlo methods those numerical methods of solving mathematical models using random set modelling and their statistical evaluation, including their characteristics. The approach is used broadly to the possible outcomes of differential events and their probabilities for system inducing parameters with a few parametric uncertainties (Bera & Pokorádi, 2015).

The point of the Monte-Carlo method is to choose a value at random for each uncertain induced parameter based on the probability distribution. The benefit of the approach is that by simply solving the random numbers quickly and easily, the questions can be answered (Bera & Pokorádi, 2015).

It is paramount to review the fit of the data before implementing the Monte-Carlo method. The objective of the goodness-of-fit test is to determine at a set confidence level if the probability variable out of which the statistical sample is taken can be a distribution outlined by a specific distribution function F(x). This distribution can be discrete or continuous, uniform or normal (Hanka, 2022).

The fitting test was based on the Kolmogorov test. The Kolmogorov test is applied to check whether the distribution function of a given probability variable ξ with a continuous distribution is a given function F(x) or not. Firstly, the empirical distribution function of the examined probability variable ξ is created, marked by Fn(x) for n number of observations, i.e., a statistical sample of n elements. The empirical distribution function value at a given location x is the relative frequency of values less than x. So, Fn (x) has a jump of magnitude xi |n for each ξi element of the sample, where xi is the number of observations of a specific value (Hanka, 2022).

The point of the Monte-Carlo method is consciously applying randomness similarly to gambling, hence the name. Monte-Carlo algorithms are all about performing calculations and modelling by generating random numbers a large number of times and they are substituted in the mathematical model (Hanka, 2022).

4. Results

In this chapter, the importance of these two methods mentioned above is discussed, and they are illustrated below. The following result is shown by the study carried out using the regression analysis method.

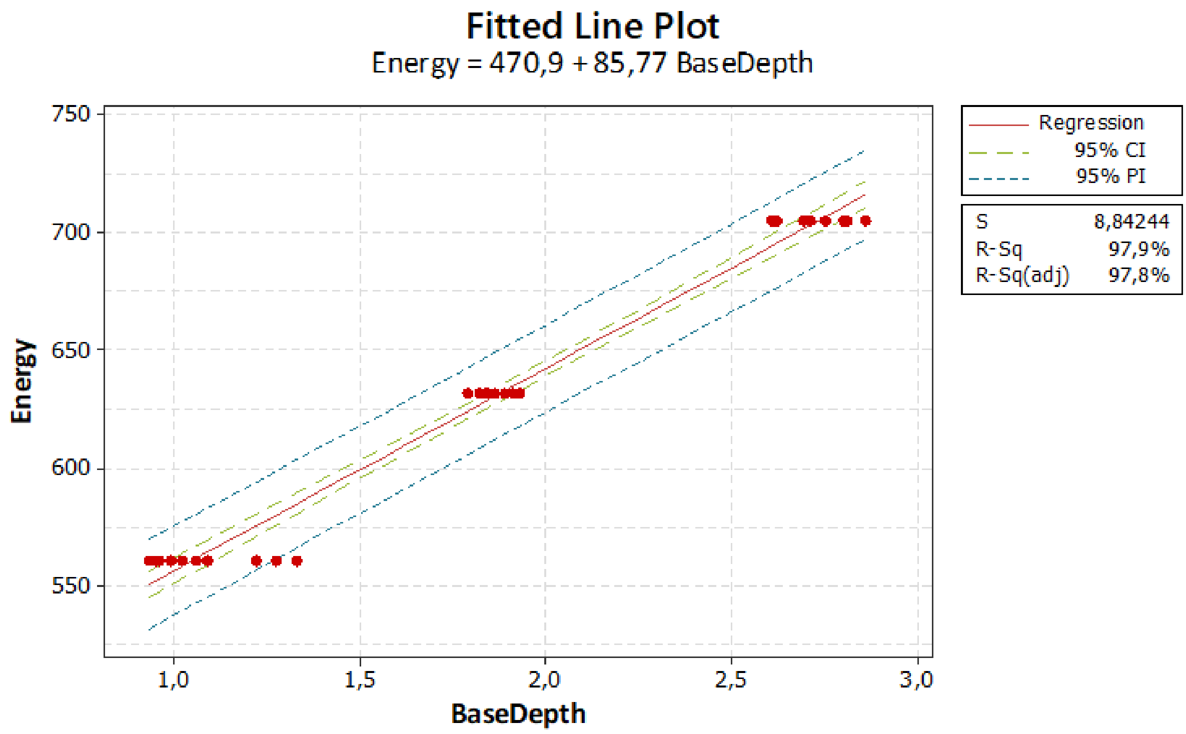

Figure no. 3: *Regression analysis (using Minitab): Hardness Depth of Base side of the lobe*
(Source: Author's research)

To calculate the base side hardness depth and to work out the required energy level, the following formula is used:

$$\text{Energy level} = 470{,}9 + 85{,}77x\ BHD \quad (1)$$

where BHD means the hardness depth-value of base side of the lobe. Energy level must be adjusted on the given production-machine. The value of the 'Energy level' has no unit, since it is a unique machine-specific parameter that can be adjusted by employee of the production company in interest of getting the desired products.

Overall, it can be stated that a difference was shown by the averages of the compared data series, and the good results were achieved with the resulting equation regarding base side of the lobe. Additionally, it is essential to emphasize that the material properties limit the possibilities and that the results will not vary equally across each segment, since, for example, indefinite hardening of a material cannot happen and, as mentioned before, various elements, including mechanical components, will also influence the effectiveness of our process, so that in general, in all cases and for all ranges, the data obtained from more complex statistical tests are not necessarily valid and need to be taken with a grain of salt. There is a range where the values vary in a quasi-linear fashion, while in other ranges the data may even smooth out. This is why this formula has essence and value-add in the case of my study.

The goodness of fit of the data was assessed using the Kolmogorov test. This involves calculating the maximum difference between the theoretical and empirical distributions, which in this case is determined to be 0.143. Utilizing this value, the test-statistic is computed as 1.197. Given that this test-statistic is less than the critical z-value of 1.36 at a 95% confidence level, the null hypothesis is accepted. Consequently, the conditions are deemed appropriate to proceed with the Monte Carlo method.

The hardness depth value was determined using the regression analysis method. Detailed below are the hardness depth values for the induction hardening of the lifting cam (base side) utilising the Monte-Carlo method. The next paragraphs show the result of 100 simulations on the evolution of hardness depth.

In this case, the appropriate hardness depth of the cams is 1.3 mm and 2.3 mm, considering the extent of further operations to remove the material in the manufacturing procedures, and lattermost, the demands and needs of the clients. In case of first scenario merely 22% of the products were within the required limit following the induction hardening. The production machine which is responsible for induction heat-treatment process allows us to adjust the energy level between: 450-850 value. Using these settings, the production would have a 78% rejection rate which is highly unsatisfactory considering its inefficiency and non-economical nature. As such, the energy level needs to be optimised during the production process.

By fitting the hardness depth (mm) values (between 1.3 mm and 2.3 mm) into the related formula (hardness depth, base) in this chapter above, the required levels of energy can be recognized, using which, if the Monte-Carlo method is repeated, all (100%) the hardness depth values in the series of 100 simulations will fall within the required limit. In this scenario, the lower and upper energy levels are as follows: 583 and 668 as they are visible on the Figure no. 4.

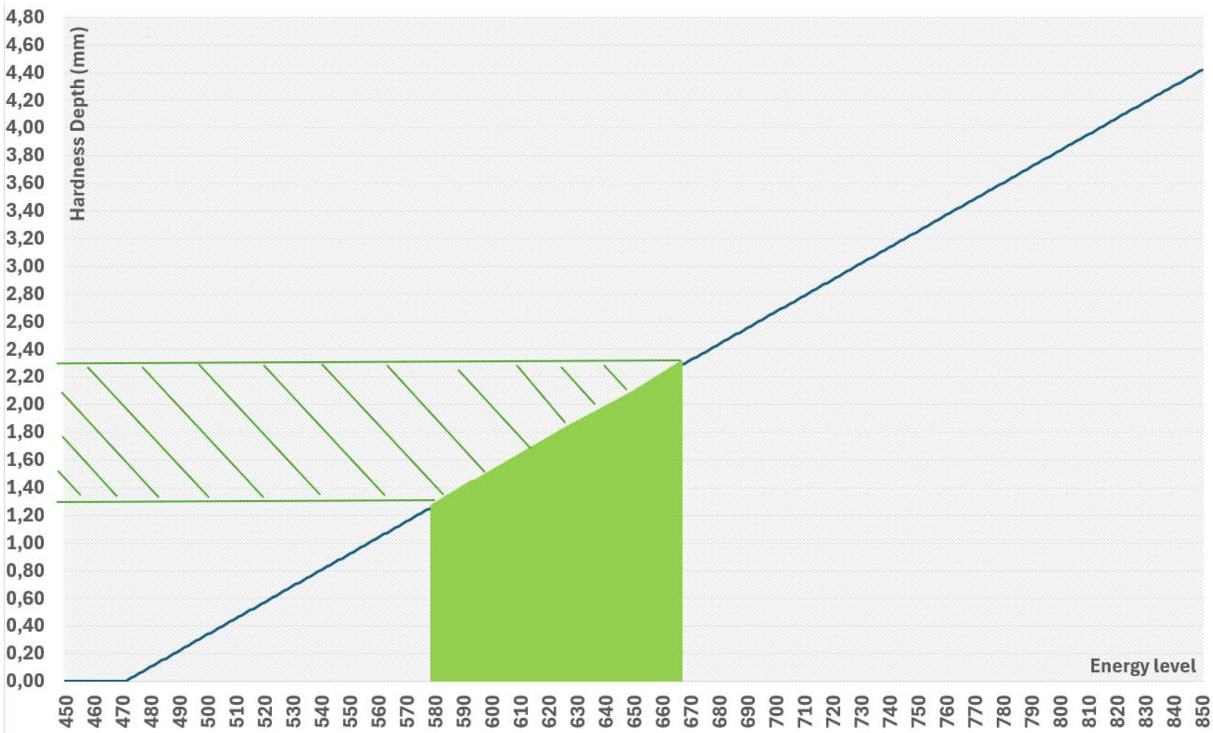

Figure no. 4: *Result of 100 simulations of the evolution of hardness depth on the base side of the Lobe, OK 100%, NOK: 0%*
(Source: Author's research)

Essentially, Figure no. 4 is representing the correlation between hardness depth of base side of the Lobe and Energy level of the relevant heat-treatment production-machine as well.

5. Conclusion

Using regression analysis and the Monte-Carlo method, the connection between the parameters and the rejection rate as a function of the application of the parameters were determined. When any type of change is detected (e.g. criteria, customer requirements, production machine), the respective tests have to be reconducted. It is insufficient to merely identify the desired value; rather, it is essential to conduct sampling and analysis of both overaged and underaged bits in order to reach accurate conclusions, as has been done here. Since the raw material is prone to change in its structure and its characteristics so it is pivotal to do the control-check of the results of heat treatment in mass production regularly. It can be concluded that by using the Monte-Carlo method, in light of correlation of the data, the required results, their proportions, and whether or not they are expected to be within the desired interval can be predicted.

Furthermore, it is also a very useful method to define the tolerance of the process parameters of a given machine, i.e. the upper and lower limits of the relevant process parameter(s), which is the 'Energy level' here, in order to achieve the aim, which can be used to minimise the amount of scrap or, more importantly for the stakeholders, the cost of scrap.

This clearly demonstrates the importance and usefulness of the method described, considering the background mentioned above. It is also a great way to reduce quality costs.

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