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Ensuring the reliability and reduction of quality control costs by minimizing process variability

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Highlights

- Methodology of the planning the control while ensuring its reliability and minimizing costs.
- Maintaining the appropriate level of credibility of decisions.
- High variability of seat belts tensile strength.
- Definition of the scope of the acceptance control of belts tensile strength.

Abstract

This paper presents a method for planning the range of quality control while ensuring its reliability and minimizing costs. The method is dedicated to destructive inspection, in which the cost of performing the measurement is significant in relation to the cost of manufacturing a part or product. The methodology was divided into four main stages: (1) selection of the measurement system and definition of the inspection scope and sample size, (2) process control, (3) redefining the scope of control and (4) verification of control cost and reliability after sample size change. The article presents the results of applying the author's procedure to the process of evaluating seat belts in automotive industry. Belts are used in the process of controlling the final product, which is a seat belt anchor plate. This approach allowed to reduce the number of destroyed parts during control while maintaining the credibility of the decision based on the assessment. As a result of double-decreasing the sample size, the costs of seat belt quality control were reduced. Assuming an average of 40 seat belt deliveries per year, the material cost was reduced by 50%. Limiting the sample size to 15 pieces per delivery would reduce the cost of testing from by 45%. It was achieved maintaining the appropriate level of credibility of decisions made greater than 0.8.

Keywords
quality inspection, reliability, quality costs, sampling inspection

1. Introduction

The reliability of a technical object can be understood as the probability of the object achieving the specified requirements. It is closely related to durability, i.e. the ability of an object to maintain certain properties over time. Ensuring the right level of product reliability is one of the main tasks for the designer of the manufacturing process. Quality inspection located at various stages of this process is an instrument for assessing the degree to which product requirements are met. Nowadays, control becomes an integral part of the manufacturing process, which enables prompt product assessment and detection of nonconformities at the place of their occurrence. However, in many processes control is and for a long time will continue to be carried out in a traditional way, often with the use of relatively simple measuring instruments and with considerable human input [15].

Quality control, maintenance, warehousing and many other activities in the production process are ones that do not add value to the process, but are necessary when it comes to business [18]. Both manufacturers and customers want to have confidence that a product is defect-free. The basis of this trust

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is the reliability of quality control. Reliability of the control process could be understood through the prism of the variability of the measurement system, the probability of correct evaluation by a human and/or the human-machine system [7][13].

The reliability and cost of control are influenced by many factors. They include the location of control in the production process, the scope of control, applied measuring methods, the human factor and many others.

Quality control may be located: before the start of the process (control of materials, parts, semi-finished products), "first piece" control (only after obtaining a good so-called first piece, the process can be "released"), during the operation (operational control), or after the operation has been completed (before forwarding the product to the next operation or before sending it to the external recipient - acceptance sampling) [23][37].

The scope of control may include: all units (100% control), or some units –sampling inspection (the scope of control is planned using statistical rules).

Data for assessment can be obtained from measurements made with measuring instruments (control by variables) and presenting measurement results in the form of a specific numerical value in a given measurement unit or control by attributes. The latter can be obtained from organoleptic observation e.g. visually, tactilely or on the basis of comparison with a standard (e.g. by means of a test) and issuing, for example, a two-valued assessment: "conforming product" or "nonconforming product" (with only possibility to count different observation results).

With reference to the impact exerted on the controlled object, control can be non-destructive (e.g. dimensional control, X-ray examinations, ultrasound measurements, visual control) or destructive (e.g. strength tests).

The location of control, its scope and the method of data acquisition should take into account the capability of the process and the expected control effectiveness [20][39][1]. Capability of the process is most often perceived through the prism of the location and variability of statistics describing the process. For example, the higher it is, the smaller the scope of control application. In turn, the effectiveness of quality control is understood as the capability to perform correct assessment. Among many indicators that allow to express the effectiveness of quality control, one can indicate the magnitude of the so-called type I and II errors of assessment. Type I error means that a conforming product is regarded as nonconforming, and type II error - vice versa, that a nonconforming product is regarded as conforming [7]. It is quite common to claim that type II errors should particularly be avoided because their effects reach the customer. Indeed, such a situation can lead to significant, often immeasurable, losses associated with the loss of trust and prestige. However, type I errors, even though they do not go "outside" the enterprise, contribute to incurring additional and unnecessary costs related to scrapping or repairing a good product. The risk of committing type I errors can be considerable if employees conducting control are aware of high-quality requirements that final products need to meet, and at the same time control and assessment methods used by them do not give them the opportunity to make unambiguous assessments (not using measuring instruments, using standards that often make it difficult to perform an unambiguous assessment). In such a situation, they may have a tendency to perform too cautious assessments and frequently qualify conforming semi-finished products and/or final products as "nonconforming". In other words, striving to avoid type II error, consisting in a positive assessment of a "nonconforming" product, causes an increase in type I error, i.e. rejection of products which in fact meet requirements. This is associated with a significant and unjustified increase in the cost of control and, as a result, the cost of production [19][37].

Researchers deal with the issues of planning quality control processes referencing them to various aspects of the production process. For example, they address this problem in the context of production planning and scheduling. Porteus [28] was one of the first to consider the problem of production scheduling with regard to quality control aspects. In his works, he stresses that the effectiveness of the manufacturing process is closely related to the level of its quality. He developed a stochastic model that allows to determine optimal production batch sizes, with the assumed quality level of the manufacturing process, at which the risk that the process runs out of control is the lowest. Rosenblatt and Lee [30] proposed an approach that allows, among other things, to determine the optimal size of a production batch, taking into account the costs of process quality control. They indicated that activities related to process control are necessary in order to be able to detect the moment of its loss of stability to take corrective actions. It is also worth considering works by Tapiero [8], who presented a relationship between the level of quality and production costs, and by Fine, who developed a stochastic model of dynamic programming that allows to indicate the optimal level of production costs depending on various quality control strategies [9]. Parveen [26] analyzes the impact of process control and nonconforming product repairs in relation to three production scenarios. The presented approach allows to estimate the number of control activities in the aspect of production planning - Parveen's results show that the introduction of inspection in the production process results in larger batch sizes, yet ultimately leads to the reduction of total costs in the case of processes with a high level of nonconformance. Ho [17], on the other hand, presents a model of a sampling inspection plan for the customized assembly process with the number of nonconformities exceeding the acceptable values. The proposed model allows to plan production effectively, taking into account a specific level of production quality (defectiveness), with the assumed level of process efficiency and fixed assembly costs. The aforementioned research focuses primarily on discussing the benefits of appropriate quality control planning in the context of improving the quality of the manufacturing process and reducing the size of a production batch. Silva et all. implemented a quality control model in water quality analysis laboratories using control charts. The method of determining the technological reliability and stability of the treatment plant using the developed tool turned out to be an effective tool for detecting any instability of the results [25]. Novakovic [24] investigated the relationship between the quality control of hydraulic fluid pressure parameters and the operating pressure parameters of a gear pump. In the tests, he showed that the control of parameters allowed to increase the efficiency and reliability of the hydraulic system. It is emphasized that early detection of deviations of the liquid's primary materials allows for forecasting the quality of the entire system operation.

Another group of studies are those related to control planning in the context of quality costs. This research context also becomes an area for considering the profitability of process control. Clark and Tannock [8] proposed a quality cost model, taking into account manufacturing costs, the type and form of production, and control strategy. The authors presented a computer implemented model and its validation. The idea of the approach was presented on a practical example from industrial production in production cells. Duffuaa and Khan [9] developed product quality control planning strategies for multi-attribute assessment. For example, one of the models allows to determine the frequency of control with the assumption of minimizing the total cost of production. The problem of quality control planning was also tackled by Anily and Grosfeld-Nir [2] as well as Wang and Meng [38]. They developed theoretical models in which the validity of conducting control and its frequency depends on the size of a production batch, the level of control errors and the expected total cost. Vaghefi and Sarhangian [36] extended the proposed approaches with type II error in assessment and applied the model to a multi-stage production system. The model developed by the researchers allows, inter alia, to indicate the frequency of control and its cost at specific control points with reference to selected process parameters, such as: quality level and batch size. Toteva and Vasileva [35] present a decision model that allows to indicate the validity of control and its place and scope. The proposed decision rules connected with deciding whether to carry out control or whether it is unjustified, are a simple relationship between the loss caused by the occurrence of a defect and the cost of control in the entire process. Farooq and others [11] examine four scenarios of control operations in the aerosol cans production process: Scenario A - Double stage acceptance sampling strategy, Scenario B - Single stage acceptance sampling strategy, Scenario C - Single stage revised sampling strategy and Scenario D - No waterbath inspection strategy. Tambe introduced integrated planning between the three basic functions of workshop management - maintenance, production scheduling and quality. The methodology is based on the conditional reliability of components and its impact on system operation [33]. System operating costs (including the cost of quality control) were minimized by implementing an integrated approach based on these three pillars. In turn, Hanabli [16] proposed a new maintenance model that takes into account the impact of spare parts quality, lead time and quality control errors on the cost of production. The use of the model allowed to generate savings of up to 22% in maintenance costs. Cost of quality has also been of interest to Li [21] who developed a model and control plan for medical equipment, and then assessed its impact on its reliability and operation. The relationship which took into account time and financial outlays related to quality control was positive.

Another group of articles are those that describe the impact of human factor reliability on the control process and quality of the product. Aust and Pons [4] present a comparative analysis of the effectiveness and efficiency of human evaluation of aircraft parts in relation to the performance of optical systems. The results show that operator performance in screen-based inspection tasks was superior to automated inspection tasks. Human cognitive abilities, decision-making capabilities, versatility and ability to adapt to changing conditions contributed to this. The automated system surpassed operator control in consistency, availability and impartiality of the tasks performed. Gruszka and Gaspar [14] analyse the impact of the human factor on the quality of the finished product at individual stages of the production process, including quality control operations. In turn, Arcúrio and de Arruda [3] developed a coherent tool that serves as a guide for airports to assess human factor impact and risk at security checkpoints. Pereira and Souza [27] in their work raise the problem of control performed by a human in the process of maintenance and repair of aircraft engines. The authors analysed the checkpoints in the engine overhaul process and showed what factors have an impact on the result of the visual inspection. It also presents the most important actions related to each factor in order to reduce the risk of operational failures caused by human errors during the visual inspection.

An essential group of studies are those related to the so-called destructive control, i.e. one in which the assessment of a process or a batch of products, statistical in nature, causes the assessed object to be destroyed. An important problem considered in destructive control techniques is their relationship with the cost of such control, its frequency and the credibility of sample-based assessment [34]. The issue of the credibility of assessment is important as it influences the decision whether a batch of products can be accepted as conforming with requirements or whether it is entirely regarded as nonconforming with requirements [29]. In practice, it is often augmented by increasing the size of the sample subject to assessment and changing the acceptance limit number (Ac). Unfortunately, it is associated with an increase in control costs, and hence production costs [22][41][40]. A relatively low acceptance number (Ac) increases probability that a batch conforming with requirements will be rejected - inspection costs rise. Therefore, many researchers are looking for an effective practical method of sampling to minimize costs with the assumed level of reliability. For example, Son and Ryu [32] presented a sensitivity analysis and the results of comparing different methods of estimating reliability in determining the sample size and sampling time in one-shot processes. Shin et al. [31] proposed a control based on low-number samples, taking into account the expected quality level of one-shot processes. Nezhad and Nasab [10] introduced a sampling plan in which it is assumed that any defective component can be detected with a certain probability. The probability function model for the number of defective items in a batch was determined on the basis of Bayesian inference. Balamurali and Jun [6] developed multi-stage sampling plans. To assess the effectiveness of the inspection plan, measures determined from a model based on a Markov chain were used. In this way, optimal destructive control plans were obtained, taking into account the cost of assessment. In order to obtain an optimal sampling plan, various optimization criteria are taken into account. For example, Fernandez obtained an optimal acceptance plan for unit defects with limited consumer and producer risk [12][5].

The presented approaches show that in most works the search for the best control strategy with regard to a given criterion refers to defining its scope or place. The works consider various models which take into account, for example: the level of process quality expressed by capability indices, the way of planning production batches, and the effectiveness of assessment.

In the authors' opinion, there's a research gap regarding the problem of planning control for destructive assessment for which implementation time is unacceptable (with reference to technological operations) in relation to the minimization of its costs and the required credibility of decisions made. The guidelines that appear in the literature do not fully take into account the context related to a specific case: place, way, and purpose of control. The effects of decisions made and the resulting actions are also very important.

In this article, the authors presented an original approach to planning the range of quality control while ensuring its reliability and minimizing costs, which fills this gap. The method is dedicated to destructive inspection, in which the cost of performing the measurement is significant in relation to the cost of manufacturing a part or product.

The article is organized into 5 main chapters. Chapter 2 presents the author's methodology which was divided into four main stages. The next chapters present the results of applying the method on the example of seat belts control in an automotive industry enterprise. Belts are used in the process of controlling the final product, which is a seat belt anchor plate. The authors propose a methodical approach to planning the destructive tensile strength tests of anchor plates, taking into account the criterion of minimizing test costs while maintaining the expected level of assessment credibility and reliability. The methodology used in the paper can be successfully applied to other processes. In the end the authors present the conclusions from the research.

2. A method of minimizing the scope of control while maintaining its reliability

Quality control planning typically pursues two opposing goals: maximizing the reliability of the assessment over time while minimizing the total cost of the control. The methodology proposed by the authors allows rationalization of decision-making in relation to these two criteria. The procedure is particularly recommended by the authors in destructive testing, for which the cost of assessment is significant in relation to the cost of production.

The methodology was divided into 4 main stages:

Step 1: Selection of the measurement system and definition of the inspection scope and sample size

Goal: defining the measurement method and tools, measurement conditions, sample size and method of collecting parts for assessment

Tools: measurement system analysis procedures, sampling procedures.

Step 2: Process control

Goal: In this step, the control process should be conducted, taking into account the factors affecting its variability. Tools: The analysis of the control results can be carried out using appropriate statistical tests: analysis of variance ANOVA, Welch's test, Bartlett's test, Shapiro-Wilk's test, etc.

These statistical tools allow for the identification of relationships significant for the subject of the study.

Step 3: Redefining the scope of control

Goal: based on the results obtained in step 2nd, possibilities of minimizing the sample size at the assumed level of reliability are sought (power analysis of the tests used).

Tools: On the basis of the assessment of the process variability and the analysis of the assessment reliability, a decision on the scope of control is made – power analysis.

Step 4: Verification of control cost and reliability after sample size change

Goal: Evaluating the efficiency of changing the control scheme

Tools: Tools for economic analysis of control operation: material and tool costs, time and others.

3. Application of the methodology

The enterprise where the research was carried out conducts activity mainly based on the production and sale of parts ensuring safety in passenger cars - mainly seat belt anchor plates. They are produced in several dimensional variants. An illustrative photo of the part is presented in Fig. 1.

Fig.1. Illustrative photo of a seat belt anchor plate.

The part has three critical characteristics: (1) thickness, (2) corrosion resistance of the coating, and (3) tensile strength. The first feature depends on the supplier, the next one is tested in a salt spray chamber in accordance with the PN-EN ISO 9227 standard. The third one is controlled by assessing the force needed to break the part.

The tensile strength of an anchor plate is its critical feature. It is controlled in a destructive test carried out on a universal tensile strength test machine (Fig. 2).

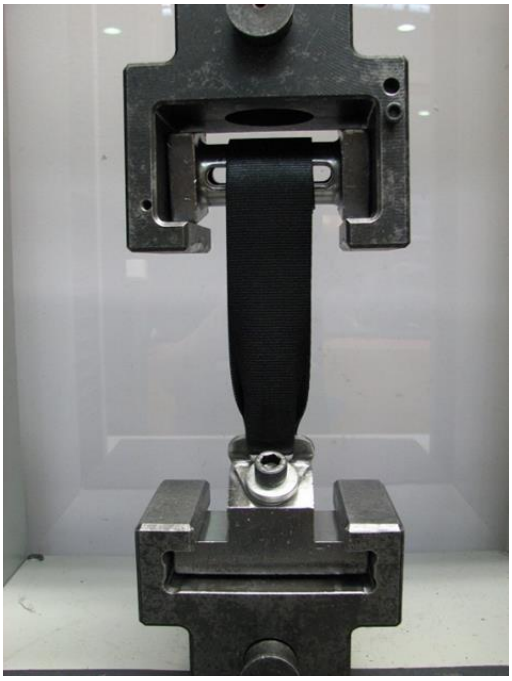


Fig. 2. Schematic diagram with an anchor plate on a universal tensile strength test machine where a belt can be seen.

Anchor plates are installed on the machine using the supplied seat belts, which determines tensile strength requirements for belts: the strength of belts used for the test should be greater than the strength of anchor plates. In a situation where this criterion is not met, it is not possible to properly control the strength of anchor plates.

Seat belts are delivered to the enterprise by various suppliers. So far, no acceptance control of deliveries has been carried out. The criterion of their acceptance was a certificate from the supplier confirming their compliance with the requirements. The enterprise voiced doubts about the quality and repeatability of the tensile strength of seat belts. It was pointed out that the high variability of the value of this feature as for seat belts may contribute to an incorrect assessment of the quality of anchor plates.

It was decided to undertake activities connected with the definition of the scope of the acceptance control of belts and the belt strength measurement system, maintaining the appropriate level of credibility of decisions taken and the criterion of minimizing control costs. The main purpose of belt delivery control is to ensure their homogeneity in terms of tensile strength. The activities carried out by the authors were conducted in accordance with the stages of the methodology.

As already mentioned, tensile strength is the critical characteristic of the supplied belts. It was decided that belts intended to be tested would be subjected to a static tensile test on a universal tensile strength test machine EU20 AMK10 manufactured by the German company VEB Werkstoffprüfmaschinen Leipzig. This machine is designed to test samples of all types of materials with a force range from 0 to 200 kN. A dedicated *tensile strength test* (TST) device was designed to fix belts on the machine (Fig. 3).

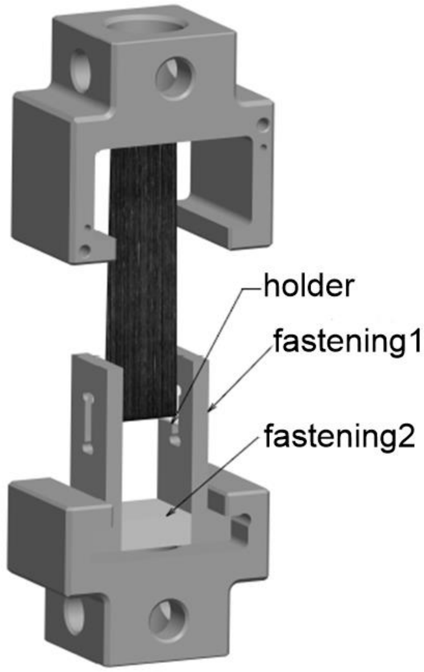


Fig. 3. 3D model of a device for tensile strength tests (TST device) of seat belts.

Four types of seat belts were selected for testing to assess their strength. The selection criterion was the frequency of using a given type of belts in the enterprise and the difference in the required strength. The list of requirements and necessary information for selected types of belts is presented in Table 1.

Table 1. List of seat belts selected for analysis

Product reference No.	Minimum strength requirement	Supplier's number	Sample size	Delivery number		
A	2.8 kN	1	30 pcs.	1	2	3
B	2.8 kN	2	30 pcs.	1	2	3
C	2.8 kN	1	30 pcs.	1	2	3
D	3.5 kN	1	30 pcs.	1	2	3

The sample size in the first test step was defined as 30 pieces for each type of belt. This decision was conditioned by the lack of knowledge about the type and parameters of the stochastic model for tensile strength. The Central Limit Theorem was used as the basis for indicating the sample size, which allows to adopt an assumption related to the theoretical probability model of the analyzed property, and consequently the use of adequate statistical inference techniques.

4. Results and discussion

After designing the tensile strength test of seat belts to determine the quality and homogeneity of deliveries, the planned tests were carried out. The evaluation of the distribution of the tensile strength measurement results for groups of belts is shown in box-and-whisker plots (Fig. 4).

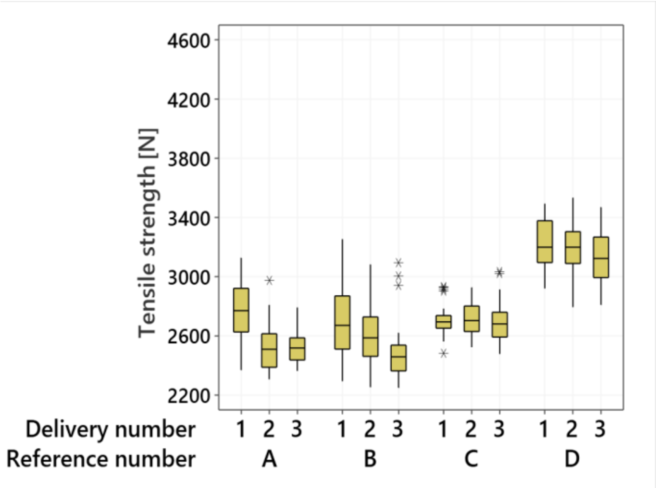


Fig. 4. Box-and-whisker plot of the tensile strength of seat belts diversified by reference number and delivery.

The authors observed a relatively high variability of the measurement results in individual groups for all four tested products.

For this reason, it was decided to perform an analysis of the causes that could contribute to the observed variability.

Fig. 5. Way of positioning a belt on the TST device in the pilot study

Observation of the measurement process allowed to indicate that the most likely source of variability is the way a belt is positioned on the TST device. The reason for it is that a belt is put on the TST device manually by an operator so that its sides are folded up in the place where it rests (Fig. 5a). Such a method of placing it in the measuring machine did not allow to ensure the repeatability of the measuring position and could contribute to the formation of a complex load condition. Therefore, it was decided to standardize the position of a belt at the place where it rests and abandon its folding (Fig. 5b).

To assess the effectiveness of the introduced changes, another 30 belts from the same deliveries as in the previous study were tested. As before, a preliminary analysis of the variability of the tensile strength measurements was performed and presented in box-and-whisker plots in groups (Fig. 6).

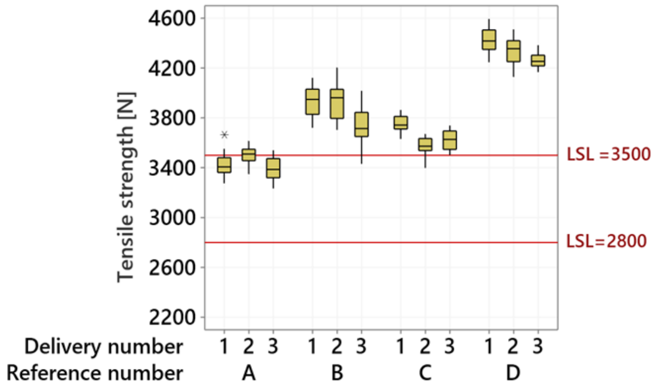


Fig. 6. Box-and-whisker plot with division into a belt and delivery number after eliminating the source of excessive variability (LSL – lower specification limit; 2800N concerns products ABC, 3500N concerns product D; * - outlier).

Repeated tests with unfolded belts confirmed the previous assumption that the way a belt is positioned largely influenced the results of the study. The results from each sample were characterized by higher tensile strength values by several dozen percent and lower sample dispersion by several dozen percent (Table 2).

As already described, the homogeneity of belt deliveries is a factor that significantly influences the final control result for the quality assessment of the manufactured anchor plates. The tensile strength of belts should not only be higher than the lower tolerance limit, but what is important, it should not significantly differ between consecutive deliveries.

Table 2. List of values of selected statistics for the test performed before and after changing the way of positioning a belt on the TST device.

Ref. no.	Delivery no.	Mean [N]		St. Deviation [N]		Min [N]		Max [N]	
		Before	After	Before	After	Before	After	Before	After
A	1	2770.2	3423.4	186	85.5	2368	3274	3127	3663
	2	2523.1	3500.1	151.6	69.3	2306	3348	2972	3615
	3	2517.2	3387.6	103	88.7	2363	3233	2792	3539
B	1	2727.5	3928.1	279.2	111.4	2294	3720	3253	4122
	2	2617.2	3930.2	220.7	136.4	2253	3703	3082	4204
	3	2492.2	3731.6	200.8	139.3	2249	3430	3093	4017
C	1	2706.6	3748.8	108.5	62.4	2482	3630	2930	3863
	2	2713.7	3576.1	107.7	62.9	2523	3398	2927	3670
	3	2693.6	3621.7	134.2	72	2477	3502	3035	3738
D	1	3214.1	4418.9	163.3	92.9	2920	4246	3493	4595
	2	3189.2	4341.1	172.6	104.6	2794	4129	3534	4511
	3	3123.4	4256.9	174	54.7	2809	4168	3469	4383

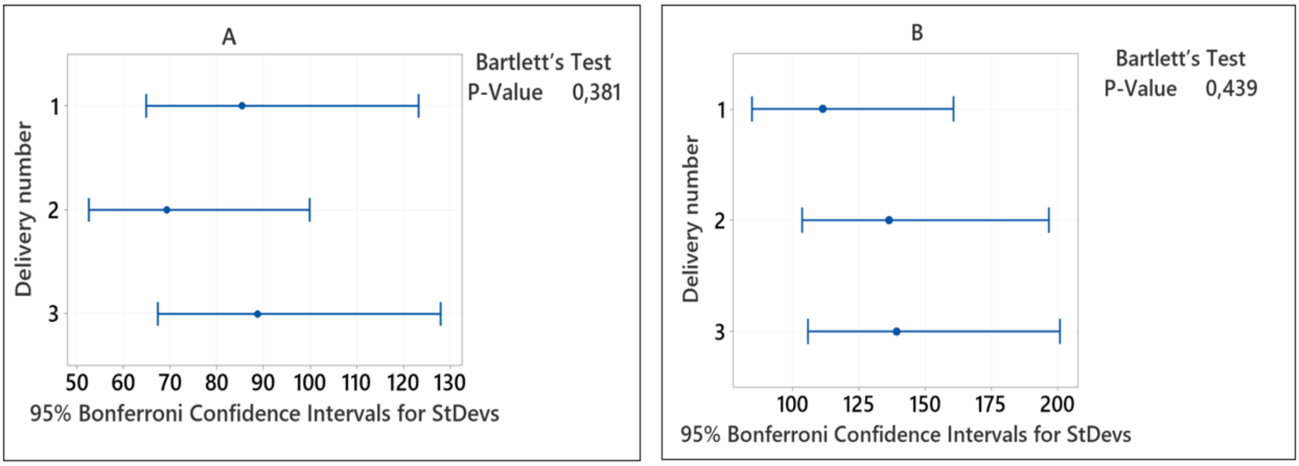
As already described, the homogeneity of belt deliveries is a factor that significantly influences the final control result for the quality assessment of the manufactured anchor plates. The tensile strength of belts should not only be higher than the lower tolerance limit, but what is important, it should not significantly differ between consecutive deliveries.

To compare the strength of belts between the selected deliveries within each product, it was decided to carry out the ANOVA test. In the first step, in accordance with the assumptions of the ANOVA test, it was verified whether strength distributions within deliveries are consistent with the normal distribution. For this purpose, the Ryan-Joiner test was performed. The test results showed the compliance of population distributions with the normal distribution ($p > 0.1$ level in each case) - Table 3.

Table 3. Ryan-Joiner test values and p-values for each group.

Product reference No.	Delivery number	Sample size	RJ statistic	p-value
A	1	30 pcs.	0.983	> 0.1
	2	30 pcs.	0.985	> 0.1
	3	30 pcs.	0.986	> 0.1
B	1	30 pcs.	0.974	> 0.1
	2	30 pcs.	0.985	> 0.1
	3	30 pcs.	0.994	> 0.1
C	1	30 pcs.	0.987	> 0.1
	2	30 pcs.	0.971	> 0.1
	3	30 pcs.	0.978	> 0.1
D	1	30 pcs.	0.989	> 0.1
	2	30 pcs.	0.986	> 0.1
	3	30 pcs.	0.989	> 0.1

The second assumption for the analysis of variance concerns the homogeneity of the variance of deliveries. In order to check it, Bartlett's test was used. The results are shown in Fig. 7.



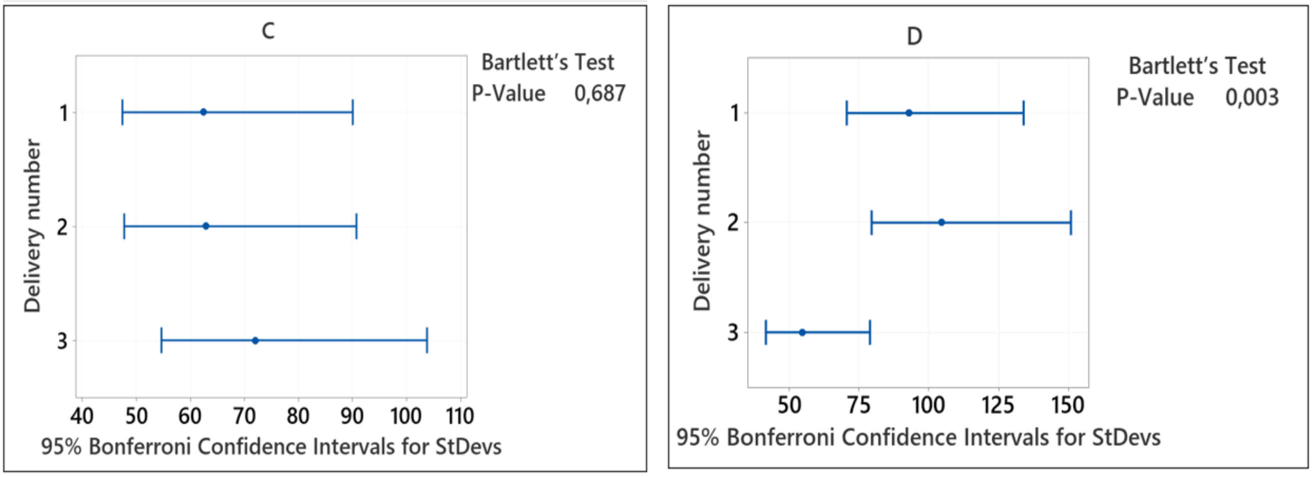


Fig. 7. Bartlett's test results for the analyzed products.

The results of Bartlett's tests indicate that only in the case of product D the variances are significantly different. For this reason, a classic analysis of variance was used for the first three products, and Welch's t-test for the above-mentioned one.

The results of the variance analysis for product A are presented in Table 4.

Table 4. Results of the analysis of variance for product A.

Source	df	Adj. SS	Adj. MS	F-value	p-value
Delivery No.	2	198082	99041	14.87	0.000
Error	87	579350	6659		
Total	89	777432			

The value of the test statistic and the associated p level indicate that the average tensile strengths for the analyzed three deliveries were homogenous. To find out which deliveries differed from each other, a post-hoc Tukey's test was carried out. Its results are presented in Table 5 and in Fig. 8.

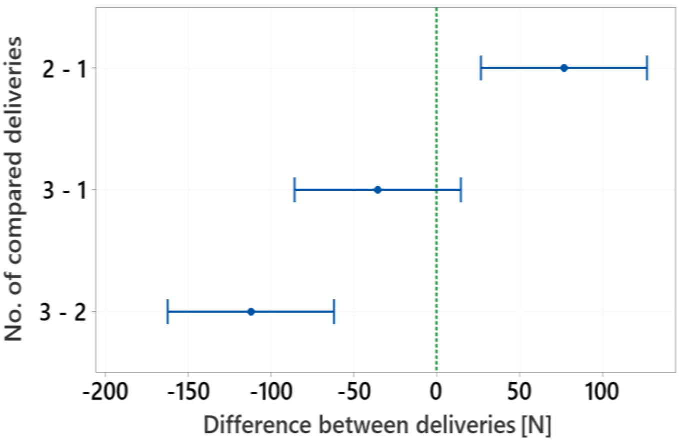


Fig. 8. Graphical presentation of Tukey's test results for product A (Tukey's Simultaneous 95% CIs for difference between deliveries) (If an interval does not contain zero, the corresponding means are significantly different).

Table 5. Statistics of the samples taken and the results of Tukey's test for product A.

No. of compared deliveries	Difference of Means	SE of Difference	95% CI	t-value	Adjusted p-value
2 - 1	76.7	21.1	(26.5; 126.9)	3.64	0.001
3 - 1	-35.8	21.1	(-86.0; 14.4)	-1.70	0.211
3 - 2	-112.5	21.1	(-162.7; -62.3)	-5.34	0.000

As can be seen, a delivery that differs significantly from the others in terms of tensile strength is delivery 2. What is important, the average value of the examined feature for delivery 1 and 3 is significantly lower than for delivery 2.

Similar results proving the heterogeneity of deliveries were also obtained for products B and C.

In the case of the first product, delivery 3 was characterized by significantly lower average tensile strength, and in the case of the second one, all three deliveries were significantly different from each other.

The results of Welch's test, which was carried out for product D for which the variance of the tensile strength of the analyzed deliveries was not homogeneous, are presented in Table 6.

Table 6. Welch's test results for belt D.

Source	df Numerator	df Denumerator	F-value	p-value
Delivery No.	2	53.1339	35.50	0.000

The value of the test statistic and the associated p level indicate that the average tensile strengths for the analyzed deliveries were not homogenous. To find out which deliveries differed from each other, the Games-Howell post-hoc test was carried out. Its results are presented in Table 7 and in Fig. 9.

Table 7. Statistics of the samples taken and results of Games-Howell test for product D.

No. of compared deliveries	Difference of Means	SE of Difference	95% CI	t-value	Adjusted p-value
2 - 1	-77.8	25.5	(-139.2; -16.4)	-3.05	0.010
3 - 1	-162.0	19.7	(-209.6; -114.4)	-8.23	0.000
3 - 2	-84.2	21.6	(-136.4; -31.9)	-3.90	0.001

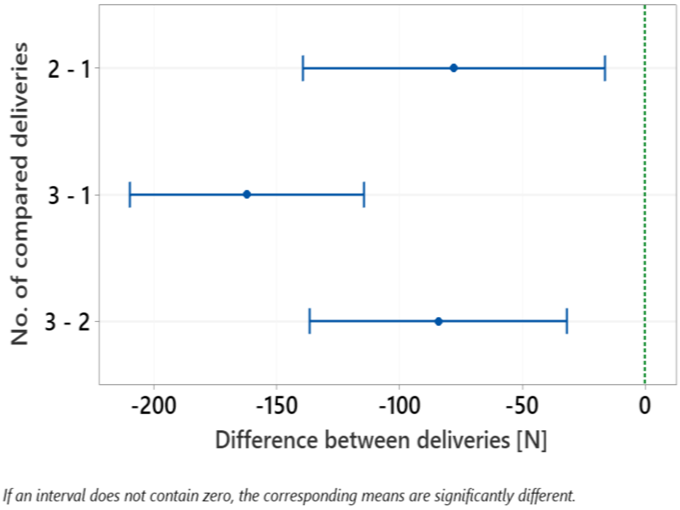


Fig. 9. Graphical presentation of the Games-Howell test results for product D (Games-Howell Simultaneous 95% CIs for difference between deliveries) (If an interval does not contain zero, the corresponding means are significantly different).

The results of the tests show that all 3 deliveries of product D significantly differed from each other in terms of tensile strength. Summarizing the stage of research and initial activities aimed at improving the control processes, it can be stated that after changing the method of positioning a belt, which limited the impact of human factor on measurement results, variability within individual deliveries decreased by 44% on average. With a relatively small variability and a sufficiently large sample, the tests tend to signal even a slight difference in tensile strength between deliveries as significant. From the point of view of the enterprise's interests, it may not be yet significant. For a given process, it was found that differences between deliveries exceeding 150 [N] should be considered as significant and proving the heterogeneity of deliveries. It is worth emphasizing once again that although the values of individual tensile strengths of seat belts met the requirements, the difference between deliveries causes problems during tensile strength tests of anchor plates, i.e. the product manufactured in the enterprise. It directly contributes to larger differences in the results of the strength tests of anchor plates.

It is worth noting that the credibility (reliability) of the decision about the homogeneity of deliveries of seat belts, measured by the power of the performed statistical tests with the significance level $\alpha = 0.05$ and for the difference between the averages of 150 [N] was very high and exceeded 0.95 for all four products.

4.1. Control costs Destructive control often exposes the enterprise to high assessment costs. In addition to time devoted to control and costs related to the controller's work and unused opportunities resulting from blocking the measuring device, there is also the cost of the damaged material. In this context, it is important not only to ensure the effectiveness but also the efficiency of this type of control.

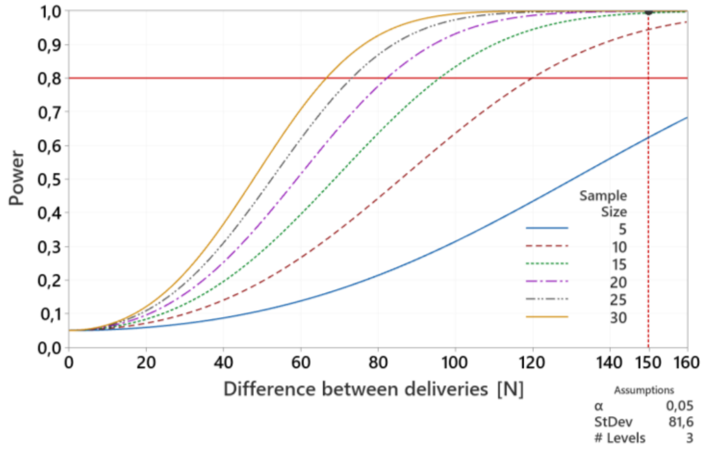
The quality control of individual deliveries of seat belts in the enterprise and the related costs include: preparation of belt samples for testing, i.e. cutting one-metre long strips (material cost), taking a TST device and placing it on a universal tensile strength test machine (cost independent of the number of tested samples), testing belt samples, i.e. placing the sample on the tested part and causing it to break. The enterprise uses 10 types of seat belts for strength tests. The average number of deliveries of all belts is approx. 40 per year. The performance of strength tests on seat belts involves two types of additional costs - material and man-hours of a test performer. The material cost for one sample is the cost of one metre of seat belts. In the case of a man-hour cost, it is divided into a fixed cost - independent of the number of tested samples - which consists of taking a TST device and installing it on a universal tensile strength test machine, and the variable cost of carrying out the test on one sample, hence completely dependent on the number of tested belt samples.

The cost of the material in the case of 40 deliveries per year and the sample size of 30 pieces is the cost of 1200 m of seat belts. In turn, the cost of quality control of individual deliveries expressed in man-hours is approximately 62.8 MHr.

Control costs that would be borne by the enterprise if the assumed sample size was to be kept turned out to be too high. This prompted the authors to analyze the possibility of their minimization while maintaining the acceptable level of credibility (reliability) of decisions made.

To minimize control costs, it was decided to reduce the sample size maintaining an appropriate level of credibility. It was established that the minimum allowable power value of the conducted homogeneity tests is 0.8. Fig. 10 shows the graphs of the dependence of the power of a test on the detected difference between the averages with different sample sizes for product A. It is clearly visible that for the assumed minimum difference in tensile strength between deliveries equal to 150 [N], it is possible to detect it at a 10-element test with a probability even above 0.9.

Fig. 10. Power of a test graph depending on the sample size



and the detected difference in average tensile strength between deliveries.

Similar tests were carried out for the remaining three products. Wishing to keep the same sample size for control, it was decided that for each product a sample of n = 15 would be taken. It was this sample size that made it possible to detect the required difference in tensile strength between deliveries with a probability greater than 0.8 for product B.

As a result of double-decreasing the sample size, the costs of seat belt quality control were reduced. Assuming, as before, an average of 40 seat belt deliveries per year, the material cost is reduced to 600 m of seat belts (a decrease by 50%). Limiting the sample size to 15 pieces per delivery would reduce the cost of testing from 62.8. MHr to 34.8 MHr (a decrease by 45%, times estimated basing on observations in company) - Table 8.

Table 8. Comparison of costs for seat belt homogeneity control before and after sample size reduction.

Number of samples	Test preparation time [MHr]	Test time [MHr]	Sum for 1 delivery [MHr]	Sum for 40 deliveries [MHr]
1	0.17	0.05	0.21	8.5
30	0.17	1.40	1.57	62.8
15	0.17	0.70	0.87	34.8

5. Conclusions

Destructive testing is the type of inspection that requires a particularly careful approach in the planning phase. Improper implementation of destructive testing in the manufacturing process may result in excessive costs or reduce the credibility of decisions made on its basis. The guidelines appearing in the literature do not fully take into account the context related to a specific case: the place, method and purpose of the control, as well as aspects related to its effectiveness.

The authors undertook activities related to the determination of the scope of acceptance control of the tensile strength of seat belts delivered to the company. They showed how important a systematic approach to the implementation of such activities is and proposed a methodology that can be successfully applied to other processes. The authors implement this methodical approach to planning the destructive tensile strength tests of anchor plates, taking into account the criterion of minimizing test costs while maintaining the expected level of assessment credibility and reliability.

Because the homogeneity of belt deliveries is a factor that significantly influences the final control result for the quality assessment of the manufactured anchor plates, the tensile strength of belts should not only be higher than the lower tolerance limit, but what is important, it should not significantly differ between consecutive deliveries. An additional advantage of the approach presented by the authors was the presentation of statistical methods enabling the assessment of the above-mentioned features - the quality and homogeneity of deliveries, taking into account the assumptions about the normality of the probability distribution and the homogeneity of variance.

In the analyzed case, it turned out that each of the suppliers supplied seat belts that met the quality requirements, but were not homogeneous when comparing different deliveries. However, it was found that the difference in average tensile strength between deliveries was statistically significant, but not significant for the company. The authors showed that assuming of an appropriate level from which this difference is considered significant and the level of reliability of the assessment measured by the power of the statistical test carried out, allows for the reasonable selection of the sample size that meets the specified criteria.

Combining this with restrictions on the cost of control enables the scope of control to be planned in such a way as to maintain an appropriate level of credibility of the decisions taken, while taking into account the criterion of minimizing control costs. This approach allowed to reduce the number of destroyed parts during control while maintaining the credibility of the decision based on the assessment. As a result of double-decreasing the sample size, the costs of seat belt quality control were reduced. Assuming an average of 40 seat belt deliveries per year, the material cost was reduced by 50%. Limiting the sample size to 15 pieces per delivery would reduce the cost of testing from by 45%. It was achieved maintaining the appropriate level of credibility of decisions made greater than 0.8.

The proposed methodology can be used by various enterprises in other branches of industry. Minimizing variability is one of the most important challenges in modern manufacturing companies. It has a significant impact on the increase in the quality of processes and products. at the same time giving a possibility to reduce the scope of applied quality control. The strength of the methodology is its focus on destructive control. In this type of inspection, the particular challenge is to reduce the number of parts assessed (destroyed) while maintaining the credibility of decisions made based on the results of the evaluation. Nevertheless, the methodology can be used in any form of quality control.

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