Checkpoint Efficiency Analysis Method

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Abstract. The use of multifaceted quality analyses contributes to increasing the efficiency of production processes and quality control as part of maintaining competitiveness. The aim of the study was to identify an integrally configured method for analysing the effectiveness of control points in the context of their ranking in terms of given variables. Verification of the model was carried out against the production process of an aluminium casting. The obtained ranking of the detection methods indicated the MT method as the most effective, which was influenced by the significant detection of critical non-conformities. The study observed little difference between the performance parameters of visual inspection and endoscopic testing, which is largely due to the detection of non-conformities of lower significance and the relatively low cost of testing. Further work will relate to the implementation of the model against other processes carried out in the company.

Introduction

One of the key challenges currently facing manufacturing enterprises is the increasing level of market competitiveness. Such conditions force business units to comprehensively meet the changing demands of buyers while ensuring a significant level of flexibility of the processes implemented [1-3]. Both the volatility of demand and the challenges relating to shorter product and technology life cycles, expectations of shorter lead times, satisfactory product quality levels result in the quality of manufacturing processes and systems being the basic parameters for assessing the effectiveness of an organisation's functioning [4-6].

Within the scope of the issue of functioning of production systems, the basic problem of the performed processes is the management and use of all necessary resources to produce the final product from the supplied raw materials [7, 8]. Consequently, it is possible to define the reliability of a production process by the ability of the production system to completely fulfil the production plan by producing fully valuable final products under specified operational conditions and within a specified time frame. Operational conditions include: the correct functioning of machinery, production equipment and maintenance and logistical support infrastructure, information flows (along with measures for their correct execution), decision-making processes, the human factor, and also include the possibility of internal and external risks [9]. A comprehensive reliability analysis should include an assessment of all facets of production systems in the context of their efficiency, including in particular the assessment of quality control activities.

When considering efficiency, reference should be made to the concept of efficiency of action, which is defined on the level of praxeology. In this aspect, the actions undertaken have the attribute of efficiency only when they are characterised by effectiveness, advantageousness and economy [10]. The term construction of efficiency determinants is based on the specification of the relationship between objective, effect and input. An important point is that beneficence indicates the absolute advantage of a system, while economy indicates the relative advantage. A review of the literature indicates that efficiency is usually equated with effectiveness. However, according to [11, 12], special attention should be paid to the difference in the interpretation of these two concepts, as 'efficiency is concerned with getting things done in the right way, while effectiveness is concerned with getting the right things done. According to the theory of efficient action, in a strict sense efficiency corresponds to economy. Within economic reality, the desired state is a combination of efficiency, economy and expediency. Therefore, it is possible to take actions that are efficient but not economical, or actions that are efficient and yet will be economically damaging or beneficial [13].

An analysis of the literature shows that manufacturing companies tend to focus on introducing quality engineering activities [14-16] or implementing mixed quality and reliability engineering approaches [17-19] to improve efficiency. By limiting improvement activities to quality engineering activities and the combined approach of quality engineering and reliability, the achievable benefits of implementing a multidimensional approach are neglected. Which may be due to:

- the lack of guidance relating to the correlation between the quality intactness of production systems and operational variables,
- lack of data and information necessary to implement a multidimensional assessment of the intactness of production systems,
- lack of awareness among managers of the benefits of a combined approach to assessing the performance of production systems.

The common ground for both approaches to organisational management and quality assurance is an effectively implemented quality control process. For this reason, the main objective of the study is to propose an integrally configured method for the multidimensional analysis of the effectiveness of control points, taking into account the established criteria. The method is based on the integration of selected diagnostic tests from the non-destructive testing (NDT) group with a cycle of analyses relating to the effectiveness and cost, time and reliability of checkpoints. The method allows the total effectiveness of the checkpoints to be indicated together with their ranking.

The proposed method, which falls under the category of organizational methods [20-22], plays a significant role in enhancing product quality across various industries. Its impact extends to sectors such as energy [23-25], machinery manufacturing [26,27], including heavy-duty machinery [28-30], and military equipment [31-33]. These changes have substantial implications for the applied technologies in these domains, encompassing special coatings [34-36], modified functional and technological layers [37], as well as the methods employed for their application [38] and modification [39,40], alongside the selection of suitable substrate materials [41-43]. Implementing such extensive changes across multiple areas necessitates a meticulous approach, utilizing supporting methodologies such as experimental design [44,45], even with non-classical approaches [46,47]. The analytical microscopic techniques [48] as well as image analysis [49] further enhance the efficacy of the implementation process. These methodologies enable researchers and practitioners to gain in-depth insights into the materials, surfaces, and processes involved, facilitating comprehensive improvements. The benefits of the proposed method manifest in numerous ways. Firstly, it contributes to a significant reduction in the wear rate of machine parts [50,51], leading to enhanced durability and longevity. Additionally, it enhances the fatigue resistance of welded joints [52-54] and separation membranes [55-57], thereby improving their performance under demanding operational conditions. The combined impact of these improvements enhances the overall reliability and efficiency of the systems. By integrating the proposed method into the existing production systems, organizations can achieve notable advancements in product quality. Furthermore, by addressing potential failure scenarios and their consequences [58-60], it enables the development of proactive strategies to minimize risks and optimize operations. The integration of these changes also fosters a more sustainable approach, reducing environmental impact and promoting responsible practices.

Checkpoint Efficiency Analysis Method

The proposed method is divided into three areas: test preparation, analysis of checkpoint indications and analysis of total effectiveness in the context of checkpoint rankings. With the implementation of sequential control (diagnostic-analytical), the method enables research in an area broader than passive control. Fig.1 shows the assumptions of the method.

Stage 1 – selection of the research subject, team of experts and definition of the research objective

Due to the specifics of the detection tests applied in the method, the selection of the test subject should concern the production system within which the production of ferromagnetic alloy castings is realised. The non-destructive tests assumed in the method make it impossible to detect products made of non-ferromagnetic metals and non-metals.

The appointment of an appropriate expert team is a necessary step for the successful implementation of the developed method. The members of the expert team should have a broad knowledge of the object of testing and of the process within which it is produced, as well as experience in carrying out NDT tests included in the method.

The aim of the model's implication should be to improve the selected production process in terms of the quality of manufactured products and optimisation in terms of the selection of inspection methods, their distribution and frequency of application according to the Kaizen concept.

Stage 2 – visual, ultrasonic, endoscopic, magnetic-powder testing

Visual inspection is carried out as part of the initial visual inspection. Preparation includes a thorough familiarisation with the product (e.g. shape, geometry, type of object, material, mass, surface condition). The visual inspection and evaluation of the object informs the identification or not of discontinuities in the object under examination. Identified discontinuities are classified by specifying their number, the severity of the discontinuity, their type, their size and their designation [61,62].

Ultrasonic testing belongs to the volumetric testing group. They consist of introducing ultrasonic waves into the product, which are reflected by the discontinuities, scattered and deflected at the edges of the discontinuities. The test makes it possible to detect cracks, collapses, delaminations, porosity, penetration leaks and other discontinuities within components. The method can also be used to measure the thickness of objects [63,64].

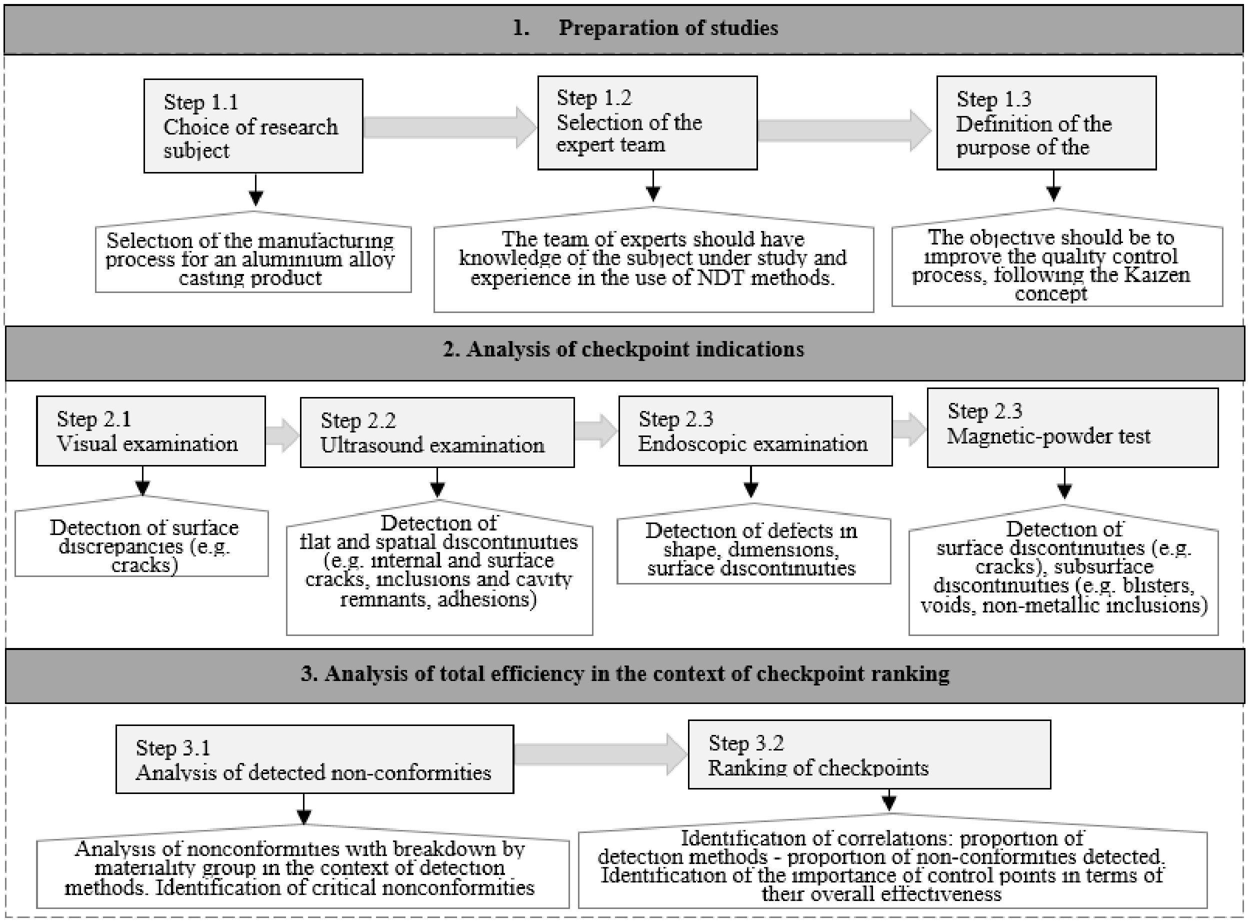

Fig.1. *Concept of the checkpoint efficiency analysis method*

Endoscopic examinations are based on viewing the internal areas of products using apparatuses that allow the supply of light and optics. A variety of equipment is used for this purpose (e.g. inspection mirrors, magnifying glasses, joint meters, microscopes and video endoscopes). Testing allows the identification of discrepancies caused by dimensional deviations, shape defects, surface discontinuities or operational damage [65,66].

Magnetic-powder testing - when a non-conformity occurs, magnetic flux scattering takes place and the magnetic powder is rearranged in this area. With this method, narrow and shallow subsurface and surface discontinuities of up to about 2 mm can be detected. The magnetic flux source in yoke testing (for hard-to-reach or small object testing) or current generators. The test material used takes the form of oil or water suspensions or coloured or fluorescent dry magnetic powders [67].

Stage 3 – analysis of detected inconsistencies, ranking of control points

After collecting data such as the type of nonconformity detected, the percentage, the cumulative value of the nonconformity, the assignment to one of three groups indicating the frequency of occurrence, and the indication of the detection method under which they were identified. A Pareto-Lorenz diagram taking into account the ABC principle is constructed. This activity allows the correlation between non-conformities and the type of quality control to be analysed in terms of effectiveness, time and cost of the test implementation and the possibility of immediate repair of the detection device. In this step, the type of correlation is identified, which is based on ranks. Table 1 shows the formulae used in the analysis.

The main idea of this stage is to rank the inspection points from the most to the least effective (in terms of the set variables), i.e. to rank the NDT methods. This will enable the optimisation of the quality control process within the production process under study.

Table 1. *Formulas used to identify the correlations analysed*

No.	Correlation studied	Design and markings
1.	Checkpoint efficiency – relationship between frequency of non-compliance and frequency of inspection methods	$S = CN \cdot (1 - F)$ (1) where: S – checkpoint effectiveness, CN – non-compliance detection rate, F – control method frequency
2.	Cost effectiveness – relationship between checkpoint efficiency and the cost of a unit detection	$EK = S \cdot (1 - K)$ (2) where: EK – checkpoint cost effectiveness, S – checkpoint efficiency, K – unit detection cost
3.	Time effectiveness – relationship between checkpoint efficiency and time to complete a unit detection	$EC = S \cdot (1 - Cz)$ (3) where: EC – checkpoint time efficiency, S – checkpoint effectiveness, Cz – unit detection time
4.	Overall effectiveness – relationship between the efficiency, cost, time per unit detection and reparability of the detection device	$\mathrm{E} = \mathrm{S} \cdot \mathrm{K} \cdot \mathrm{Cz}$ (4) where: E – total efficiency, S – checkpoint efficiency, K – unit detection cost, Cz – unit test execution time

The developed method of analysing the effectiveness of control points makes use of the diversity and complementarity of NDT methods and techniques and quality analysis. The aim of the synergic linking of activities is to optimise the number of inspection points, their distribution (incoming inspection, inter-operational inspection, final inspection) and detection frequency (random inspection, 100% inspection). The method promotes a reduction in the level of diagnostic uncertainty through a step-by-step approach to the detection tests carried out and an increase in the efficiency of quality control throughout the production process.

Verification and Test of the Method

Verification of the universal checkpoint efficiency analysis model was carried out for a production process that had lost the quality stability of the manufactured products. The selected process is implemented in a foundry company located in the south-eastern part of Poland. The test covered production data from 4 months of the year 2021.

Stage 1 – selection of the research subject, team of experts and definition of the research objective

Verification of the method was carried out by means of its implication to the production process of the casting responsible for the water jet inlet used within engine and car technology. The product, with dimensions of 1330 x 600 x 420 and a weight of 66 kg, is cast in AlSi7Mg0.3 alloy. A model of the tested product is shown in Fig. 2.

The company observed a decrease in the quality level of the jet inlet casting after the implementation of reorganisation measures and structural changes to the casting.

Expert team members were selected for their skills and knowledge of the process and detection testing. The following were appointed to the team: a quality control manager, an NDT specialist, a quality control employee and a claims specialist.

The aim of applying the model to the process presented was to propose a course of action for assessing the level of overall efficiency of the individual inspection points, thus optimising the entire quality control process in terms of their efficiency, time and cost effectiveness and the reparability of the machines and detection equipment used.

Stage 2 – visual (VT), ultrasonic (UT), endoscopic (IVT), magnetic-powder (MT) inspection

Quality control of the waterjet inlet production process is carried out in accordance with the control plan. The quality control plan for the production process of the waterjet inlet has been developed taking into account the key parameters of the product, which are specified by the customer and standards and reflected in the technological documentation. The control plan includes information on the location and number of quality gates (preliminary, inter-operational and final control) along with an indication of detection methods (visual, ultrasound, endoscopic, magnetic-powder) after specific technological operations. The plan also contains information on the scope of controlled characteristics: name of product, scope of control, names of measuring and detection instrumentation, measuring/verification method, expected values with parameter tolerance, standards, specified sample sizes, testing frequency, relevant regulations and standards.

The detection results of the indicated methods within the control points were the input data of step 3 of the method.

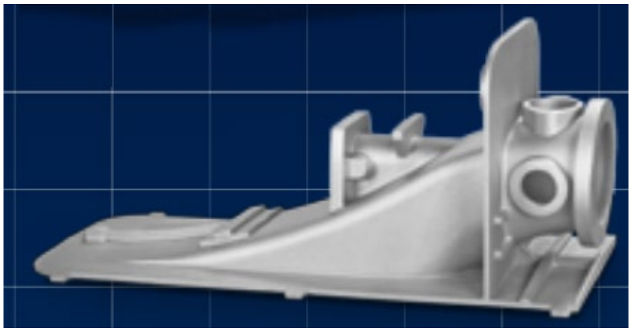

Fig.2. *Water jet inlet model*

Stage 3 – analysis of the detected non-conformities, ranking of control points

In order to identify the correlation between the incidence of quality control during waterjet inlet detection and the proportion of identified non-conformities, a Pareto-Lorenz diagram taking into account the ABC principle was drawn up, showing the critical non-conformities (occurring in the waterjet inlet in terms of their incidence). The resulting diagram is shown in Fig.3.

In Fig.3, the types of incompatibility have the following designations: 1) Presence of shrinkage cavities, 2) Presence of oxides, 3) Presence of rows, 4) Cracks, 5) Edge spalling, 6) Porosity, 7) Blistering, 8) Sintering, 9) Underfilling, 10) Scratching. The diagram also includes the type of detection method that is most likely to detect a particular non-conformity.

The critical non-conformities of waterjet inlet castings, from group "A", are three of the ten listed, i.e. presence of shrinkage cavities, presence of oxides, presence of ripples. These account for 84.7% of the quality problems identified. Further non-conformities from group "A" are detected using ultrasonic and magnetic-powder testing.

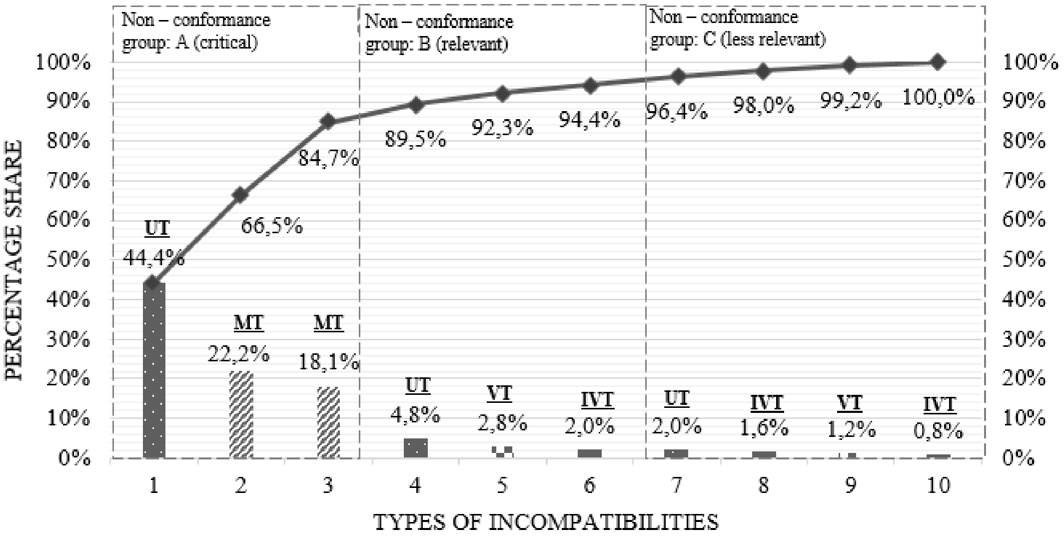

Fig.3. *Pareto-Lorenz diagram taking into account the ABC principle of casting incompatibility*

The results of the analyses of the occurrence of quality control points in the identification of casting non-conformities and the proportion of identified non-conformities by these detection methods are included in Table 2.

Table 2. *Types and number of waterjet inlet casting incompatibilities*

Method used at the checkpoint	**Contribution of the control method to the detection of non-compliance**	**Detection of non-compliance by inspection method**
Visual inspection (VT)	20.0%	4.0%
Ultrasound examination (UT)	30.0%	51.2%
Endoscopic examination (IVT)	30.0%	4.4%
Magnetic-powder testing (MT)	20.0%	40.3%

Table 3. *Checkpoint ranking*

Parameter	**Value achieved by individual checkpoints**	**Ranking**
Effectiveness of checkpoints	• $S_{VT} = 80.0\% \cdot 4.0\% = 3.2\%$ (5) • $S_{UT} = 70.0\% \cdot 51.2\% = 35.8\%$ (6) • $S_{IVT} = 70.0\% \cdot 4.4\% = 3.1\%$ (7) • $S_{MT} = 80.0\% \cdot 40.3\% = 32.3\%$ (8)	UT > MT > VT >IVT (9)
Cost-effectiveness of checkpoints	• $EK_{VT} = 3.2\% \cdot 93.0\% = 3.0\%$ (10) • $EK_{UT} = 35.8\% \cdot 31.9\% = 11.7\%$ (11) • $EK_{IVT} = 3.1\% \cdot 87.5\% = 2.7\%$ (12) • $EK_{MT} = 32.3\% \cdot 62.8\% = 20.3\%$ (13)	MT >UT> VT >IVT (14)
Time efficiency of checkpoints	• $EC_{VT} = 3.2\% \cdot 84.2\% = 2.7\%$ (15) • $EC_{UT} = 35.8\% \cdot 79.9\% = 28.6\%$ (16) • $EC_{IVT} = 3.1\% \cdot 45.1\% = 1.4\%$ (17) • $EC_{MT} = 32.3\% \cdot 50.6\% = 16.3\%$ (18)	UT >MT> VT >IVT (19)
Total efficiency of checkpoints	• $E_{VT} = 3.2\% \cdot 93.7\% \cdot 84.2\% = 2.53\%$ (20) • $E_{UT} = 35.8\% \cdot 31.9\% \cdot 79.9\% = 9.14\%$ (21) • $E_{IVT} = 3.1\% \cdot 87.5\% \cdot 45.1\% = 1.23\%$ (22) • $E_{MT} = 32.3\% \cdot 62.8\% \cdot 50.6\% = 10.25\%$ (23)	MT>UT> VT >IVT (24)

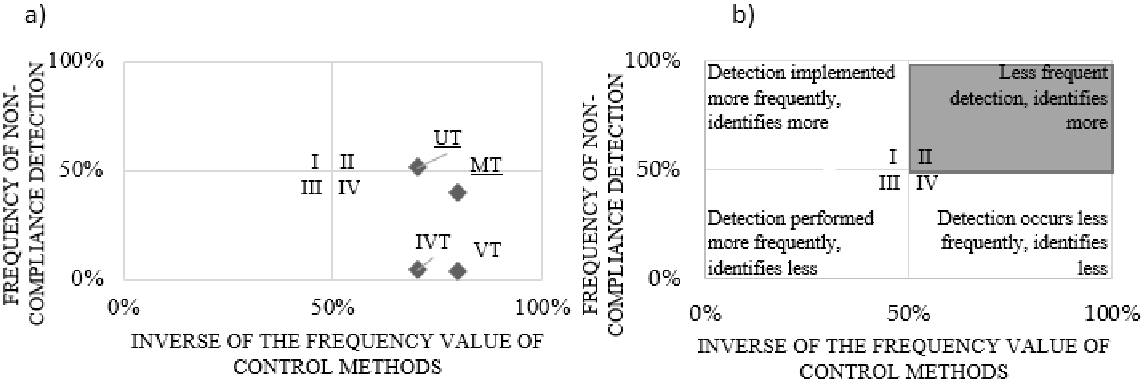

Fig.4. *Matrix diagram indicating (a) effectiveness - relationship between frequency of non-compliance identification and frequency of checkpoint occurrence (b) interpretation of the diagram*

The quality control method most frequently involved in the detection of workpiece nonconformities (3 out of 10 cases) was ultrasound and endoscopic inspection, while the method identifying the most nonconformities is ultrasound (51.2%).

The results of the correlation analysis of the effectiveness of the method (Table 2) are presented in a matrix diagram (Fig. 4). In the diagram, the quadrant in which the individual detection methods should be located is shaded. In order to realise the objective function: the more the better, the function values on the X-axis are expressed as (1-Frequency of control methods).

The location of the control points within the defined planes of the matrix diagram indicates that the control points are located in the 2nd and 4th quadrant. This positioning indicates:

- II quadrant - methods with relatively infrequent detection identifying relatively many nonconformities (ultrasonic method),
- IV quadrant - methods with relatively infrequent detection identifying relatively few nonconformities (magnetic-powder method, visual examination, endoscopic examination).

Parameters such as efficiency, cost-effectiveness, time-effectiveness and total checkpoint efficiency are shown in Table 3.

According to series (9) and (19), the control point with the highest efficiency and at the same time the highest time efficiency is the control point within which ultrasonic detection takes place. The high level of efficiency of the UT method is influenced by the significant level of identification of critical casting non-conformities, while in terms of time efficiency the determinant is the automation of detection by the UT method. The MT method test shows the highest level of cost-effectiveness and the highest level of overall efficiency. The checkpoint within which the endoscopic examination is implemented shows the lowest performance of the analysed indicators. However, this test is necessary due to the complex geometry of the product and thus the lack of possibility for effective detection.

The presented concept of checkpoint efficiency analysis is not only concerned with the identification of a group of critical nonconformities, but also allows the monitoring of the total checkpoint efficiency level. Such an approach makes it possible to identify the detection methods with the highest level of efficiency (i.e. those occurring relatively rarely and detecting a significant number of nonconformities with particular emphasis on critical defects). The proposed method also makes it possible to optimise the placement of checkpoints and the frequency of their use, taking into account the cost and time of detection. Checkpoints with low cost-effectiveness can, for example, be transformed into 100 per cent inspection.

Conclusions

Continuous supervision and monitoring of the processes carried out in a production enterprise, together with quality control, are the key to success for any organisation wishing to maintain a competitive position in an ever-changing market. The aim of the developed method is to propose an integrally configured, multidimensional analysis of the effectiveness of control points, taking into account the assumed criteria.

The checkpoint efficiency analysis method presented in the study allows for the ranking of detection methods in terms of effectiveness, cost efficiency, time efficiency, total efficiency. This makes it possible to manage quality by improving checkpoints through their optimisation, relocation, application of selective control, which influences the maintenance of stability of the production process. As part of the study, a model test was carried out. By verifying the model against the waterjet inlet production process and the quality control points within it, it was shown that the magnetic powder method has the highest level of cost efficiency and the highest level of overall efficiency - thus representing a key control point influencing the level of product quality. The endoscopic test, on the other hand, shows the lowest performance of the indicators analysed. However, this testing is necessary due to the complex geometry of the product and thus the inability of other detection methods to detect it effectively.

Due to the ever-increasing requirements for quality, price, reliability and the relatively short period of time in which components are available on the automitiv market, the issue is important and topical.

Further research directions will concern the implementation of a model for the pro-quality analysis of the company's casting processes, the aim of which is to ensure a high level of product quality while reducing process times and ensuring cost optimisation.

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