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Synergistic method for quality and cost improvement of cast products

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Abstract

The foundry industry is an important component of the economy on which other progressive industries depend. The reliability of the products it manufactures is determined by the technologies used, but, most importantly, it ensures the expected level of quality. The purpose of the article is to develop a synergistic quality-cost model for the improvement of casting products. The model is based on an integral methodological configuration that makes it possible to determine the level of relevance of the causes of casting nonconformity in the quality-cost context. The model integrates techniques such as the Pareto-Lorenz diagram, ranking, brainwriting, Ishikawa diagram, Likert rating scale, and matrix diagram. Verification of the method by its implication in the manufacturing process of a gearbox casting is performed. The model makes it possible to identify quality-cost relationships between key categories of problem causes and major product nonconformities. The main causes of the loss of quality stability of the analyzed product are found to be low quality of molding sand, poor technical condition of foundry equipment (too infrequent repairs and overhauls), and ineffective quality control. Carrying out the analysis made it possible to develop appropriate improvement measures. It is proposed to implement changes in the casting process, implement the TPM method, conduct periodic training, develop job instructions, implement a control system, and provide supervision of employees. Further research directions will concern the implications of the method within the other positions in the casting company and its development towards automation of analysis.

Introduction

An analysis of the global economy and the development trends that are occurring testifies to the ever-increasing contribution of foundry engineering, understood as a technique for manufacturing metal products. This trend is related to the global increase in the level of industrialization, the constant search for the most efficient solutions for final products, the reduction of electric energy consumption, as well as an increased awareness of the need to protect the environment (Miskinis, 2021; Siwiec & Pacana, 2021; Staniszewska, Klimecka-Tatar & Obrecht, 2021).

Foundry is a part of the industry that links metallurgy with the technology of manufacturing and shaping machine and equipment parts. The relevance of foundry within the global economy is a result of the industry's interconnectedness with other key manufacturing industries, that is, the automotive, aerospace or defense, and shipbuilding industries, which are buyers of finished castings that are components for the manufacture of final products (Shi et al., 2021; Pacana & Czerwińska, 2023). This demonstrates the foundry industry's extensive capabilities regarding the casting alloys used and the manufacturing technologies employed, as well as its interdisciplinary nature. As a result, the foundry industry is recognized as a strategic industry for many industries (Stawowy & Duda, 2012; Ulewicz, 2014).

The high quality of the implementation of a special process, such as casting, is associated with certain technological parameters that can affect the quality of the finished product. The main difficulty occurring during the casting production process is the impossibility of simultaneously exercising control over all factors of the technological process. The implementation of production in casting technology is fraught with many difficulties (Czerwińska & Pacana, 2019).

One of the key aspects related to the management of a foundry enterprise today is the drive to improve product quality. Activities implemented by managers are increasingly directed not so much to the study of the manufacturing process after its finalization with the implementation of analyses of the occurring casting nonconformities, but, increasingly, these activities are extended to the detailed prediction of undesirable events and their analysis. The availability of a number of quality management tools and methods makes it possible to reduce the occurrence of nonconformities even before the production process begins (Skotnicka-Zasadzień, Wolniak & Zasadzień, 2017). Another reason that encourages such an approach is the desire to reduce the level of potential costs associated with implementing full inspection (100% quality control) of a given batch of manufactured casting products (Ulewicz & Novy, 2019). While the desire to reduce costs prompts change, importantly, controlling the entire process with all its component parts can be a lengthy and labor-intensive activity with no measurable results. For a foundry company, it should be most important to identify those products that, within the entire manufacturing process, bring the greatest number of nonconformities. Precisely studying these determinants will not only enable efficient improvement of the quality level of the cast product, but also implement improvement activities in an efficient manner (Klimecka-Tatar & Niciejewska, 2021; Wolniak & Skotnicka-Zasadzień, 2014).

Due to the constant demands of customers and very high competition in the market, foundry companies are looking for a variety of solutions to convince customers by producing products of the highest possible quality (Ulewicz & Blašková, 2018; Biadacz, 2024). For this reason, the purpose of this article is to develop a synergistic quality-cost model for improving casting products. The model is based on an integral methodological configuration that makes it possible to determine the level of relevance of the causes of casting nonconformities in the quality-cost context. The model coherently combines such techniques as the Pareto diagram correlated with the ABC principle, ranking, brainwriting, Ishikawa diagram (5M+E), five-point Likert rating scale, and matrix diagram.

The issue addressed in this study is of key importance in improving the technological, managerial, and economic spheres of foundry enterprises. The developed synergistic method can significantly affect the improvement of the way of quality management in manufacturing enterprises (Marković et al., 2021) to the improvement of cast parts in the automotive industry (Godzsák & Gácsi, 2013), aerospace industry (Goroshko, Royzman & Pietraszek, 2014), as well as mining industry (Li et al., 2023), where the wear and tear of machinery significantly affect the safety of workers. The implication of the method significantly determines the implementation of improvement activities in accordance with the concept of continuous improvement (Torielli et al., 2011). The results obtained during the implementation of quality-cost analyses can be useful in processes of an analogous nature with the use of foundry methods (Sajid et al., 2018), including particularly demanding implementation of high-quality die casting (Jorstad & Apelian, 2008; Uyan et al., 2023).

Method

The method of quality and cost improvement of products was developed to improve and stabilize the manufacturing process of products. The idea of this method refers to the identification and solution of critical problems, i.e., problems (product nonconformities) with the greatest adverse impact on the quality stability of the process and, at the same time, generating the greatest costs. A review of the literature and empirical tests of quality improvement methods made it possible to develop a method based on a structured analysis of the main causes of problems in terms of quality and cost. The method is a sequential integration of such methods and techniques as the Pareto Lorenz diagram correlated with the ABC method, non-verbal brainstorming (Brainwriting), Ishikawa diagram (according to the 5M+E

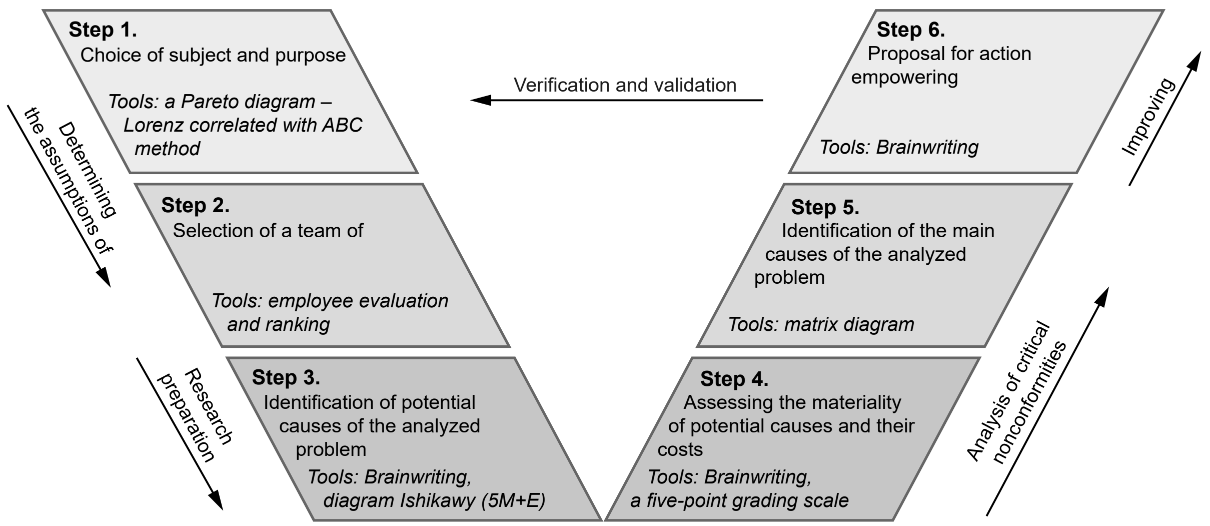

Figure 1. Concept of the quality-cost method of product improvement

principle), balanced five-step evaluation scale, and matrix diagram. The method was divided into logical stages of implementation, as shown in Figure 1.

Step 1. Selection of the subject and purpose of the study. The subject and purpose of the study are determined by the subject authorized to do so (i.e., the expert). Due to the specifics of the developed method, it can be a product that has lost its quality stability or a specific type of nonconformity (the most severe in its consequences or the most frequent). The selection should be guided by the frequency of nonconformities and the cost to the enterprise of doing so. The selection can be made based on catalogs and records of nonconformities created in the enterprise (Demian & Demian, 2010; Sütővá & Grzincic, 2013) or using supporting tools, for example, the Pareto Lorenz diagram correlated with the ABC method (Caban, 2020; Ostasz, Czerwińska & Pacana, 2020). After this, the subject (the expert) determines whether the purpose of the study is adequate for the current needs of the company. The method was developed to pursue objectives related to:

- analysis of quality problems concerning the identification of critical nonconformities,
- analysis of the causes of the occurrence of critical nonconformities (root causes of the problem),
- proposing appropriate corrective actions.

In addition, the objective should consider the customer's requirements in relation to the subject of the study.

Step 2. Selection of the expert team. The members of the working team should have a broad knowledge of the subject under study, as well as of the production process and technology in which the product is produced to achieve the goal. The selection of the composition of the expert team should be implemented based on the issues presented in the study, among others (Pacana et al., 2014).

Step 3. Identification of potential causes of the problem under consideration. The task of the work team members in this step is to identify all potential causes of the problem under consideration. It is important to list a significant number of potential causes of the problem. This process should be supported by non-verbal (written) brainstorming, which makes it possible to obtain a large number of suggestions for solving the problem in a short period of time and, at the same time, the written form avoids the tensions and conflicts that happen in classical brainstorming (Heslin, 2009). Next, the brainwriting facilitator should visualize and logically group the generated potential causes. A supporting tool is an Ishikawa diagram (following the 5M+E rule) (Pacana & Czerwińska, 2019; McDermott, Antony & Sony, 2022).

Step 4. Evaluate the significance of potential causes and their costs. The potential causes of the qualitative problem under consideration should be evaluated with regard to the significance of their impact on the origin of the problem and their impact on the costs caused by the problem. The evaluation is carried out by experts using a Likert scale of 1 to 5, arranged in order from total rejection to total acceptance (Tanujaya, Prahmana & Mumu, 2022). When applied to the method, this means: 1 signifies the cause affects the problem to a very small degree/the cause generates very small costs, while 5 denotes the cause causes the problem to a very large degree/the cause generates very large costs. Assessments can be made using brainwriting (Heslin, 2009). The resulting assessments should be noted on an Ishikawa diagram. If the legibility of the diagram is lost, the assessments should be placed in a summary table.

Step 5. Identification of the main causes of the analyzed problem. In the proposed approach, the identified main causes of the analyzed problem have a significant impact simultaneously on the occurrence of a serious quality problem and incurring significant costs. To identify the causes with the greatest impact on quality and production costs, a matrix diagram should be used (Pacana & Czerwińska, 2020). Individual causes are located in the area of the diagram based on the ratings given to them. The causes belonging to the critical area are the root causes.

Step 6. Proposed improvement actions. With regard to the identified root causes, corrective and preventive actions should be developed immediately. Effective actions will increase the level of product quality and significantly reduce production costs. Improvement actions should be developed using brainwriting (Ponsignon, Kleinhans & Bressolles, 2019).

Results and discussion

The test of the synergistic method of quality and cost analysis was performed at one of the foundries located in the southeastern part of Poland. The test concerned production data across six months in 2022.

According to the proposed method, the first step was to select the subject of the research and then determine the purpose of the research. The expert used the nonconformity register operating in the company. A gearbox casting, which had lost its quality stability due to design changes, was considered the subject of the study. According to the nonconformity register, the most frequently identified defects in the casting were sand inclusions and near-surface gasification occurring simultaneously. Figure 2 shows the subject of the study and an example of a nonconformity.

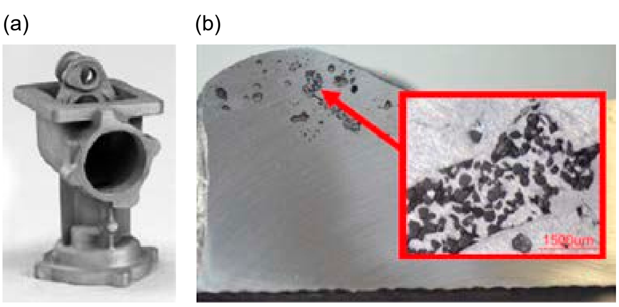

Figure 2. Visualization of (a) the model of the gearbox under analysis and (b) the most common nonconformity

The purpose of the research was specified in relation to the selected research subject. The objective was considered to be the identification of the main causes of sand inclusions and near-surface gasification in gearbox castings. At the same time, those with the greatest impact on the occurrence of nonconformities and time-generating significant costs were considered the main nonconformities.

In the next step, the members of the expert team were selected. The team consisted of the chief technologist, product quality control manager, and production manager. The expert team carried out the next steps of the method. Members of the expert team identified potential causes of sand inclusions and near-surface gasification. The potential causes of the problem were listed during a brainwriting session, and the result was recorded and organized on an Ishikawa diagram according to the 5M + E principle (i.e., man, machine, material, method, management, and environment). The result is shown in Figure 3.

To assess the relevance of the potential causes of the problem and their costs, the expert team used a five-point rating scale. Ratings were given during brainwriting on pre-prepared sheets. The final ratings of the potential causes were created as an average of the ratings made by the individual experts rounded to the whole part. All potential causes placed within the Ishikawa diagram were evaluated. The result of this step is shown in Table 1.

In the final step, in order to better understand the degree of importance of the potential causes of the problem in terms of the loss of product quality and the incurred costs associated with the occurrence of these causes, the results of the assessment were graphically presented. A matrix diagram was used to outline the critical area. Displaying the data on a four-quadrant grid of activities visually provides information to analyze the distribution of critical nonconformities. Figure 4 shows the graphical result of the analyses. The critical area within the matrix is a box indicating the main causes of the quality problem. In the matrix, the critical area is marked with a dashed line.

After evaluating the potential causes of sand inclusions and near-surface gasification within the analyzed gearbox model in the critical field, five main causes of the problem were detected. These causes were categorized as material, machine, and management and were given as: R1, too little compactability of the molding sand; R2, too many lumps in the molding sand; R3, a large number of inactive fractions in the molding sand; R4, too infrequent

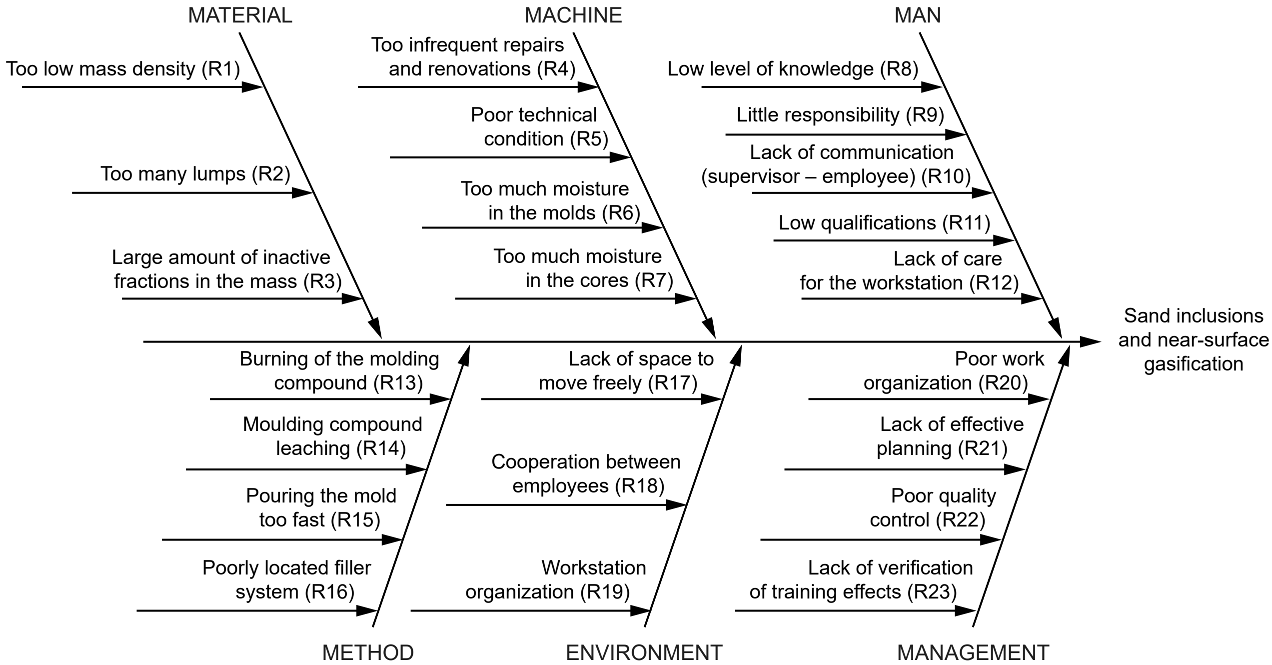

Figure 3. Ishikawa diagram for the problem of sand inclusions and surface gasification in casting

Table 1. Degree of importance of potential causes along with the cost of their presence

Area of occurrence	Potential cause number	Assessment of the impact of potential causes on the analyzed non-compliance	Assessment of the level of costs incurred, presence of potential causes of the problem
Material	R1	4	4
	R2	5	4
	R3	5	3
Machine	R4	3	4
	R5	3	5
	R6	4	2
	R7	4	2
Man	R8	5	2
	R9	3	1
	R10	3	2
	R11	5	2
	R12	4	2
Method	R13	2	3
	R14	4	2
	R15	4	1
	R16	1	5
Environment	R17	2	2
	R18	2	2
	R19	2	2
Management	R20	2	1
	R21	1	1
	R22	4	3
	R23	1	2

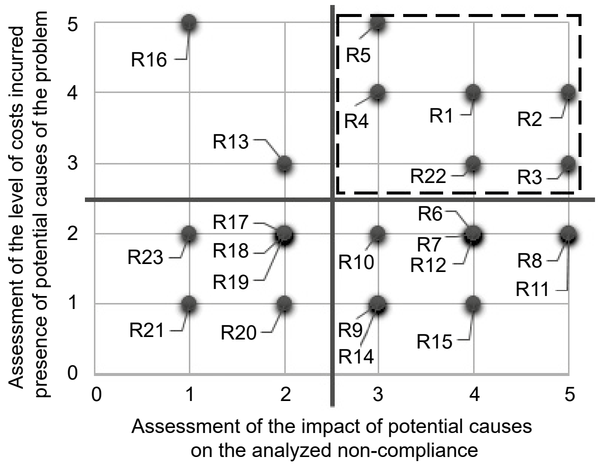

Figure 4. Result of the impact of potential causes on the creation of the analyzed nonconformity in terms of quality and cost

repairs and overhauls; R5, poor technical condition; R22, ineffective quality control.

With regard to the identified main causes of sand inclusions and near-surface outgassing in finished gearbox castings, improvement measures, i.e., corrective and preventive actions, were plotted. The experts identified the following actions:

- ensure uniform mold compaction;
- increase the compactability and, consequently, the plasticity of the molding sand;
- reduce the amount of inactive dust fractions (due to the reduction of dust content, the amount of lumps in the mass will also be reduced) and improve the efficiency of molding sand regeneration;

- reduce the pouring time, improve the distribution of metal through the pour;
- control casting temperature;
- implement the total productive maintenance (TPM) method, with the goal of achieving maximum efficiency in machine utilization and employee involvement;
- develop job instructions within the foundry department;
- train employees in the foundry department;
- implement a control system, and ensure constant supervision of employees.

The measures proposed by the experts were the result of brainwriting sessions. The indicated activities are aimed at improving the quality of castings (ensuring the quality stability of the product) while reducing the costs incurred by the company related to complaints, repairs, and disposal of nonconforming products.

The results of the analysis contribute to the achievement of a wide spectrum of benefits in the technological, managerial, qualitative, and cost contexts. The application of the synergistic model enables improvements in the implemented manufacturing processes, increases the efficiency of management and supervision methods, and increases the level of reliability of the machinery park. Additional benefits include an increase in the economics of the production process and an expansion of markets and customer base.

Summary and conclusion

Currently, in a globalized reality, foundry companies wishing to maintain an established position in the market should conduct conscious and mature management of quality and realized processes. The ability of the organization to promptly adapt and effectively implement processes (while maintaining the expected level of products) to changing market requirements is one of the key aspects in the context of competitiveness. Therefore, the purpose of this article was to develop a synergistic model of quality and cost improvement of cast products. The model is based on an integral methodological configuration that allows for the determination of the level of significance of the causes of casting nonconformity in the quality-cost context. The model coherently combines such techniques as the Pareto diagram correlated with the ABC principle, ranking, brainwriting, Ishikawa diagram (5M+E), five-point Likert rating scale, and matrix diagram.

Verification of the created model through its implications within the manufacturing process, in terms of a gearbox casting used in light vehicles, was performed. The course of action established in the model makes it possible to determine the quality-cost relationships that occur between the key categories of problem causes and the main product nonconformities. A reliable test of the synergistic model to support quality management confirmed the fact that conducting casting quality loss analyses with its use makes it possible to identify the critical causes of the most serious product nonconformity. The main reasons for the loss of quality stability of the gearbox were found to be a low density of the molding sand, a large number of lumps from the molding sand, a large number of inactive fractions in the molding sand, infrequent repairs and overhauls, poor technical condition, and ineffective quality control. The performance of the analyses made it possible to develop appropriate improvement measures within the studied process. It was proposed that changes be implemented in the casting process, the TPM method be executed, periodic training courses ending with a knowledge test be conducted, and job instructions be developed. An additional improvement measure was the implementation of a control system and the provision of constant supervision of employees.

The developed method of quality and cost improvement of foundry products is a useful tool aimed at foundry enterprises, which supports monitoring and maintaining an appropriate level of quality. Future research directions will concern the implications of the developed model within the other jobs in the foundry company. Further work on the model will be concerned with its development towards automation.

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