PRO-QUALITY METHOD IMPROVING INDUSTRIAL PRODUCTS TOWARD SUSTAINABLE DEVELOPMENT WITH CRITERIA OF CIRCULAR ECONOMY

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Abstract

Improving product sustainability is challenging in times of climate change. The research aimed to develop a method for sustainable product development in a circular economy. The SMARTER method was used to determine analysis objectives and select a team of experts. Quality levels were analyzed for selected products to identify incompatibilities, which were then analyzed sequentially to determine possible causes using brainstorming, Ishikawa diagrams, and multiple voting. The correlation matrix was used to analyze indirect causes impacting the environment. The main causes were selected based on their negative impact on the environment and degree of influence on the problem. The proposed method aims to improve product quality and customer satisfaction while promoting sustainable product development.

Keywords: Quality, sustainable development, circular economy, quality engineering, mechanical engineering

1. INTRODUCTION

Product quality improvement is crucial for enterprise development, but in today's climate change era, environmental considerations cannot be ignored [1]. While quality management techniques are commonly used for product analysis, they do not simultaneously verify causes of incompatibility and their environmental impact. Despite the popularity of these techniques, the lack of an integrated method remains an open problem in the literature. Various methods have been proposed for analyzing potential causes and effects of product incompatibilities. The Ishikawa diagram [2] and the Pareto-Lorenz method [3] have been used separately and in combination [2]. Universal models that incorporate quality management tools, multiple decision methods, and machine learning methods, such as the Naive Bayes Classifier (NBC), have also been developed [4] to analyze industrial product quality and predict development direction. The lack of methods for simultaneously improving product quality and reducing their impact on the natural environment was recognized as a research gap. This led to the development of a method to promote sustainable development and circular economy (CE). The inclusion of circular economy criteria in the method allows for improvement activities focused on resource regeneration, waste reduction, and increased product usability. This approach can lead to a reduction of carbon dioxide emissions and depletion of natural resources [5]. A method test was conducted on the porosity cluster found on the mechanical seal of the 410 alloy. The proposed method of sustainable quality improvement has a broad range of applications not only in machine production [6] but also in various other industries, including electronic [7], metal [8], military [9], construction [10], and biotechnological [11]. Additionally, this approach can serve as a basis for further development of data analysis methods, both parametric [12] and non-parametric [13,14].

2. METHOD

A method was developed to improve product quality while promoting sustainable development and circular economy. It includes improving product quality and reducing negative impact on the environment. The method involves four stages, shown in **Figure 1**.

Stage 1. The subject of research is chosen by an expert, who may consider the most frequently occurring defects on products and the potential negative impact of production on the environment. Catalogues of products with the number of incompatibilities of the same type are useful for this purpose. The Pareto-Lorenz analysis can be used for a large number of different types of incompatibility, as demonstrated in [3]. The research subject is not limited. The expert sets the purpose of the investigation, which should focus on improving product quality while considering sustainable development and circular economy principles. The SMARTER method can be used to define the research purpose precisely [15].

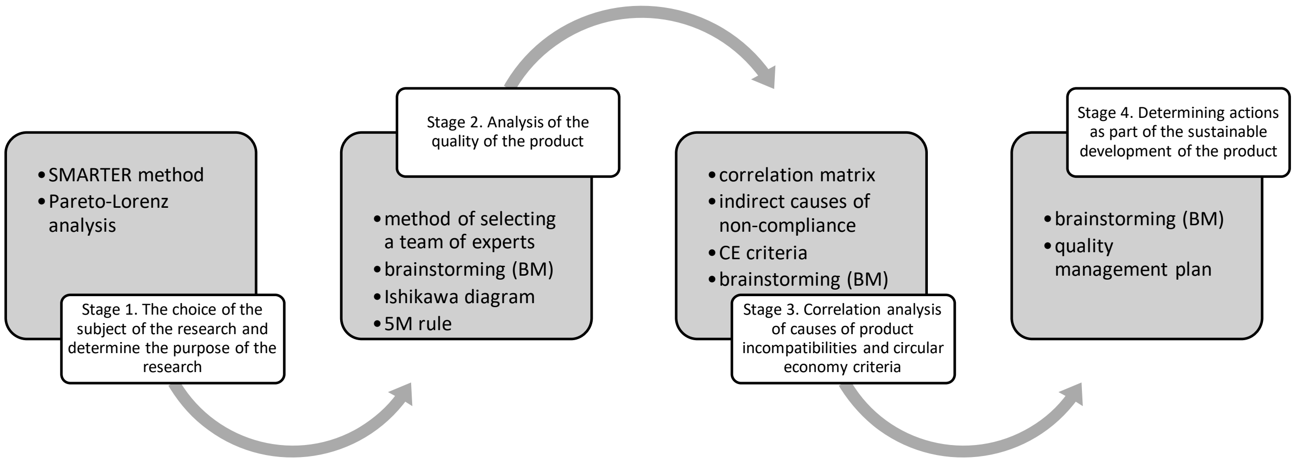

Figure 1 Scheme of stages of proposed method and tools supporting its realization

Stage 2. The team responsible for making the analysis and achieving the purpose of the research should consist of competent individuals who have knowledge about the problem. The way of selecting the team of experts is shown in the literature, e.g., [16]. A team of experts can use brainstorming (BM) [17] to determine potential causes of problems in product quality. All potential causes should be noted in a visible place, such as a table, and an Ishikawa diagram should be developed using the 5M rule (man, machine, material, management, environmental work) to categorize each potential cause on the diagram. During brainstorming, the team of experts assesses all potential causes to select the indirect causes with a significant impact on the problem. The Ishikawa diagram is used to note down the assessments of causes on a three-point scale: 1st score for negligible impact, 2nd score for moderate impact, and 3rd score for a very significant impact. Only the causes with a score of 3 are subjected to further analysis [18].

Stage 3. Correlation analysis of causes of product incompatibilities and circular economy criteria. The correlation analysis is performed to identify the main causes of the problem, which will have the greatest possible impact on the occurrence of non-conformity and at the same time have an impact on the environment. According to the idea of a circular economy, actions as part of the elimination or reduction of incompatibilities should allow the regeneration of resources, minimalization of waste, or increase the usability of products (including materials and components) [5]. At this stage, the analysis of correlation is performed by using indirect causes (from stage 2) and the sustainable and circular economy criteria. The main criteria of circular economy that correspond to the problem analyzed are determined by using brainstorming among the team of experts and based on the subject of literature [19]. In the proposed correlation matrix $A = [a_{ij}]_{n \times m}$, it is necessary to include *i*-th indirect causes for incompatibility of the product (selected in the second stage of method) and *j*-th criteria of circular economy, where *n* – number of indirect causes, *m* – number of circular economy criteria. Correlated causes are further analyzed, and improvement activities are proposed based on sustainable development principles.

Stage 4. Determining actions for sustainable product development. Main causes of incompatibility are analyzed based on CE criteria identified in the previous stage. Low-cost and easily achievable actions are recommended to be taken first. Brainstorming (BM) is used to rank the causes and determine the priority of actions. A management plan with objectives, responsibilities, deadlines, and costs is proposed. Improvement actions are monitored and analyzed for continuous improvement. The method is based on [20].

3. TEST OF METHOD

The method test consisted of four stages. The investigation subject was the incompatibility of a mechanical seal from 410 alloy identified by non-destructive fluorescent method testing. The incompatibility was a porosity cluster, shown in **Figure 2**. The aim of the research was to improve the quality of the mechanical seal made of 410 alloy by eliminating or reducing the occurrence of a porosity cluster, which is one of the most common incompatibilities. This was important to contribute to the sustainable development of the product by reducing waste and unusability. The research was carried out in accordance with the circular economy rules. In the second stage, the quality analysis of the mechanical seal with a porosity cluster was done by a team of experts using the Ishikawa diagram with the 5M rule (man, machine, material, management, and environmental of work). The potential causes were generated during brainstorming (BM) and evaluated by the team. Assessments were awarded on a scale from 1 to 3 and observed on the Ishikawa diagram (see **Figure 3**). The team of experts was selected according to the method shown in [4].

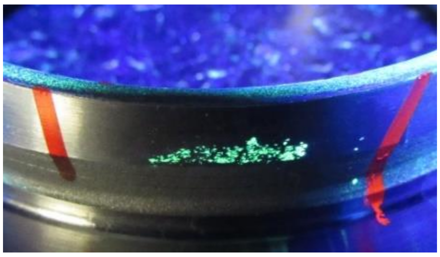

Figure 2 Example of a cluster of porosity

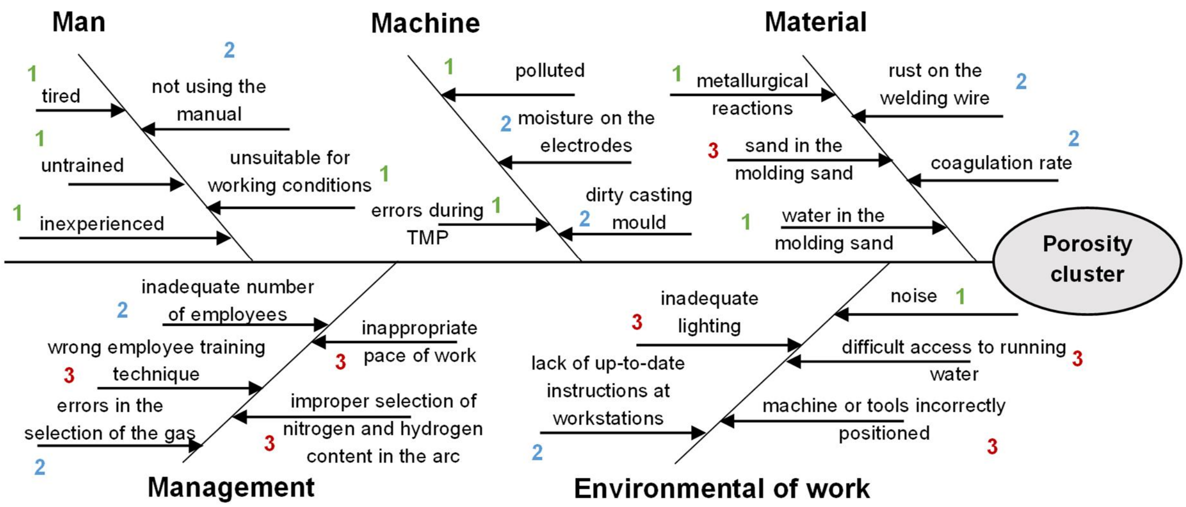

Figure 3 Ishikawa diagram and assessments of potential causes according to its impact on occurrence the incompatibility

The analysis showed that the indirect causes are: incorrect employee training techniques, inappropriate pace of work, inappropriate selection of nitrogen and hydrogen content in the arc, inadequate lighting, difficult direct access to running water, inappropriate positioning of the machine or tools, and sand in the molding sand. These reasons were probably the most influential in the formation of the porosity cluster.

Table 1 Correlation of indirect causes of incompatibilities and circular economy criteria

		Circular economy criteria							
		J1	**J2**	**J3**	**J4**	**J5**	**J6**	**J7**	**J8**
Indirect causes of incompatibility	**I1**				+	+	+		
	I2				+	+	+		
	I3	+		+	+		+	+	+
	I4	+							
	I5							+	
	I6				+		+		
	I7				+		+		

where: I1-incorrect employee training technique, I2-inappropriate pace of work, I3-inappropriate selection of nitrogen and hydrogen content in the arc, I4-inappropriate lighting, I5-difficult direct access to running water, I6-improper setting of the machine or tools, I7-sand in the molding sand;

J1-low energy consumption, J2-recyclability, J3-negligible emission of harmful gases, J4-small number of machine or tool settings, J5-small workforce threshold, J6-high employee learning rate, J7-low consumption of natural resources, J8-no waste toxicity.

The purpose of the third stage was to determine the potential environmental impact of the causes identified in the second stage. An analysis was conducted to correlate the indirect causes of the mechanical seal quality issue with circular economy (CE) criteria selected based on the literature, such as [5,10,11]. The selected criteria were low energy consumption, recyclability, negligible emission of harmful gases, small number of machine or tool settings, small workforce threshold, high employee learning rate, low consumption of natural resources, and no waste toxicity. Selected indirect causes and CE criteria were summarized in the correlation matrix [illegible], after which the team of experts determined the correlations between them, as shown in **Table 1**. Causes correlated with CE criteria are considered to be the main causes of the problem. On the basis of these correlations, improvement actions are proposed in accordance with the principles of sustainable product development. This is carried out in accordance with the concept proposed in the fourth stage of the method, where the main reasons were the following:

- (I1) incorrect employee training technique, and (I2) inappropriate pace of work, therefore, as part of eliminating these causes in accordance with the CE criteria, it is proposed to provide:
  - (J4) small number of machine or tool settings;
  - (J5) small workforce threshold;
  - (J6) high employee learning rate;
- (I3) inappropriate selection of nitrogen and hydrogen content in the arc, where, according to the CE criteria, it is proposed to ensure that when working with these gases:
  - (J1) low energy consumption;
  - (J3) negligible emission of harmful gases;
  - (J4) small number of machine or tool settings;
  - (J6) high employee learning rate;
  - (J7) low consumption of natural resources;
  - (J8) no waste toxicity.
- (I4) inappropriate lighting, therefore, in order to eliminate this cause, in accordance with the CE criteria, it was assumed that the following should be ensured at the same time:
  - (J1) low energy consumption;

- (I5) difficult direct access to running water, the reduction of which should take into account the possibility of:
  - (J7) low consumption of natural resources;
- (I6) improper setting of the machine or tools, and (I7) sand in the molding sand; therefore, according to the CE criteria, it was assumed that it would be good to eliminate these causes:
  - (J4) small number of machine or tool settings;
  - (J6) achieve a high learning rate of workers working with the machine or tools.

The team of experts determined that the sequence of actions should start with the least demanding root causes, i.e. (I4), (I5), (I6) and (I7). After they are completed, actions should be taken for the remaining root causes, e.g. (I1), (I2), and (I3). After implementing these actions, it is good to monitor them. This is the last step of the method.

4. DISCUSSION AND CONSLUSION

The objective of the research was to develop a method that supports improving the quality of industrial products to promote sustainable development and circular economy, considering the difficult task of caring for the natural environment while achieving the expected product quality. The developed method was the combination of techniques, i.e.: SMARTER method, brainstorming (BM), method of selection, team of experts, Ishikawa diagram, 5M rule, multiple voting, and correlation matrix. The method aimed to identify and eliminate the key causes of non-compliance in products, aligning with sustainable development and circular economy. It was tested on a mechanical seal made of 410 alloy, where a porosity cluster was found through non-destructive fluorescent testing. The research team started by defining the research purpose and selecting a group of experts through brainstorming. They then used the Ishikawa diagram and the 5M principle to group all potential causes. Finally, indirect causes that had the greatest impact on the formation of a porosity cluster were determined through multiple votes. The analysis focused on verifying the correlation between indirect causes and sustainability criteria, leading to the determination of the main causes with the greatest negative impact on the environment. The next step involved developing a direction for product improvement in the context of sustainable development. The main benefits of the proposed method are:

- Focusing on improving product quality and caring for the natural environment.
- Practical implementation of sustainable development for industrial products.
- Sequential and consistent assessment of the causes of incompatibility in products, to propose ways to eliminate them in accordance with sustainable development activities.

Future research will extend the proposed method to multi-criteria decision support techniques to verify a larger number of incompatibility reasons, while incorporating sustainable development and circular economy criteria. The method is suitable for any product, particularly industrial ones in manufacturing enterprises, to improve product quality and reduce negative impact on the environment.

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