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Fuzzy Multi-criteria Decision Model to Support Product Quality Improvement

Dominika SIWIEC[1], Remigiusz GAWLIK[2], Andrzej PACANA[1]

[1] *Rzeszow University of Technology, Faculty of Mechanical Engineering and Aeronautics, Poland,*
[2] *Cracow University of Economics, Faculty of Economics and International Relations, Poland and North-West University, NWU Business School, South Africa*

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Abstract
Improving product quality while making decisions remains a challenge. The objective of this research was to develop a model that supports the precise enhancement of product quality through comprehensive analysis of possibilities, product incompatibilities, root causes, and recommended improvement actions. The model incorporated various tools and methods such as the SMARTER method, expert team selection, brainstorming, Ishikawa diagram, 5M+E rule, FAHP, and FTOPSIS methods. The study demonstrated that integrating quality management tools and decision-making methods into a unified model enables the accurate prioritization of activities for product quality management. This integrated approach represents the novelty of this research. The model was evaluated using a mechanical seal made of 410 alloy. The research findings can be valuable to enterprises seeking to enhance product quality at any stage of production, particularly for modified or new products.

Keywords
Production engineering; Decision support; Quality; FAHP; FTOPSIS; Multi-criteria decision making.

Introduction

The challenge of achieving the required product quality involves making precise decisions throughout the entire process of product quality management (Gawlik 2019 a, b, c; Pacana & Siwiec, 2022b). This challenge encompasses managing product quality by considering decisions related to product quality, potential incompatibilities, root causes, and necessary improvement actions. The accuracy of these decisions at each stage of product quality enhancement directly impacts the overall quality and customer satisfaction (Alt et al., 2019; Ostasz et al., 2022a; Pacana et al., 2020; Siwiec et al., 2021c, 2021d; Siwiec & Pacana, 2022). Initially, decisions are typically made after product quality control, often involving non-destructive testing (NDT) (Katunin et al., 2021; Krajewska-Śpiewak et al., 2021; Minutolo et al., 2019). However, these controls only identify incompatibilities and do not determine their root causes (Jarosińska & Berczyński, 2021; Khedmatgozar et al., 2021; Pacana & Siwiec, 2021a). Therefore, it becomes necessary to investigate and identify the root causes of these incompatibilities. The purpose of these investigations is to facilitate rational improvement actions aimed at eliminating or reducing future occurrences of incompatibilities (Naik, 2017; Ostasz et al., 2022b; Pacana et al., 2020; Ruszaj et al., 2016; Siwiec & Pacana, 2022). All actions and decisions aimed at achieving the desired product quality converge into a unified, multi-criteria process.

The literature review revealed that elementary quality management tools, particularly the Ishikawa diagram, have commonly been utilized (Pinho et al., 2021; Olejarz et al., 2022; Siwiec & Pacana, 2020; Wolniak, 2019). Various example studies (Chokkalingam et al., 2020; Gawlik 2019a; Luca & Luca, 2019; Siwiec & Pacana, 2021b; Sygut, 2017; Tegegne & Shing, 2013; Ulewicz, 2003) employed this diagram to identify potential causes of incompatibility in different contexts, such as products made from ductile iron (Ulewicz, 2003), welded pipes (Sygut, 2017), and au-

***Corresponding author**: Andrzej Pacana – Rzeszow University of Technology, Faculty of Mechanical Engineering and Aeronautics, al. Powstancow Warszawy 12, 35-959 Rzeszow, Poland, phone: +(4817) 865-13-90, e-mail: app@prz.edu.pl*

tomotive wheel bearings (Luca & Luca, 2019). The Ishikawa diagram was often combined with other quality management tools, notably the Pareto-Lorenz analysis. This combination helped identify incompatibilities in the automotive industry (Nugroho et al., 2017), production process defects like shrinkage (Chokkalingam et al., 2017), and issues related to alloy wheels (Chetan et al., 2015). Additionally, brainstorming was employed by authors such as Naik (2017), Pacana & Siwiec (2021a), and Sheth (2015) to generate causes of product incompatibility. Noteworthy studies applying quality management tools to improve product quality include Pacana & Siwiec (2021b, 2022a), which presented a model based on a new approach for classifying actions to stabilize industrial product quality. Furthermore, Pacana & Siwiec (2022c) and Siwiec & Pacana (2021a, 2020b) utilized the fuzzy analytic hierarchy process (FAHP) in conjunction with the Ishikawa diagram and the 5 Whys method.

The purpose of this study was to correlate well-known techniques for improving product quality, specifically heuristic techniques (Chokkalingam et al., 2020; Chokkalingam et al., 2017; Putman & Paulus, 2008). In this research, we aimed to address the following research questions:

- How can a large number of potential causes of product incompatibility be generated and categorized for subsequent advanced analysis?
- How can the most significant causes of product incompatibility (i.e., those with the greatest influence on its occurrence) be sequentially and effectively identified from a large pool of potential causes?
- How can the ranking of improvement actions be established with high precision, specifically tailored to address the most important causes of product incompatibility?

It was observed that classical quality management tools were utilized within the scope of these inquiries, such as those presented by Siwiec and Pacana (2021b), Tegegne and Shing (2013), and Ulewicz (2003). However, these tools were employed selectively during certain stages of the product quality management process. Furthermore, some of these tools are subjective in nature, as highlighted by Minutolo et al. (2019). Interestingly, no previous attention has been given to the integration of multicriteria decision methods (MCDM) (Parkan & Wu, 2000) throughout the entire quality management process, alongside conventional quality management tools.

Consequently, the objective of this research was to develop a model that combines MCDM techniques and quality management tools to facilitate precise decision-making regarding the causes of product incompatibility and recommended improvement actions. Thus, the following hypothesis was formulated:

Hypothesis 1. Combining quality management tools and decision methods into one cohesive model enables the precise determination of the sequence of activities that support product quality management. This is achieved by identifying, validating, and correlating the causes of incompatibility with the corresponding improvement actions.

The proposed approach to enhancing product quality has been recognized for its ability to address dynamic changes in customer expectations and support the development of enterprises, including those involved in Industry 4.0 and future factories (Sidhant & Bhushan, 2018). The model presented in this study is applicable not only to the improvement of newly developed products (including potential defect analysis) but also to modified products that require quality controls and decision-making to ensure stability. The research outcomes have the potential to contribute to the growth of companies and the implementation of more comprehensive future design and management strategies aimed at continuously improving product quality (Wolniak, 2019; Wotzka et al., 2021).

The model's effectiveness was verified through the examination of incompatibilities in casting products, specifically porosity clusters on an alloy 410 mechanical seal, which were identified through non-destructive testing (NDT) in the Polish industry. Importantly, the proposed methodology possesses a universal character, allowing it to be applied to analyse incompatibilities and their causes in any product, and it can be integrated with any product quality control system (Pacana & Siwiec, 2021b). Consequently, the model holds the potential to enhance product quality across various industries.

The Model

Motivation and conditions for model development

It has been observed that existing studies highlight challenges in achieving the desired level of product quality (Chokkalingam et al., 2020; Raji et al., 2018; Siekański & Borkowski, 2003; Siwiec & Pacana, 2021a; Tegegne & Shing, 2013). In order to effectively improve product quality, it is crucial to identify the root causes of incompatibility and determine appropriate improvement actions. Previous research has primarily relied on the use of quality management tools to support this process (Chetan et al., 2015; Sheth et al., 2015). Attempts have also been made to explore the combination of quality management tools and multi-criteria decision methods (Pacana & Siwiec, 2022b; Pacana & Siwiec, 2021b; Pacana & Siwiec, 2022a; Siwiec & Pacana, 2020, 2021a, 2022). However, these previous attempts lacked a unified method for precise verification and decision-making regarding overall product quality improvement. Consequently, this research gap serves as the motivation for the development of the proposed model, which aims to address this limitation.

Assumptions of the model

The assumptions for the model were derived from initial research conducted by Pacana and Siwiec (2021a, 2022b) as well as Siwiec and Pacana (2021a, 2021b, 2021c), and the specific conditions of the selected methods. The proposed methodology is expected to enable:

- effective identification of the main causes of the problem and improvement actions through fuzzy decision-making analysis using the fuzzy Saaty scale.
- inclusion of cause and improvement action weights (importance) in the model, based on assessments from a suitably selected team of experts (or even a single expert).
- the ability to analyze any number of causes and improvement actions.

After conducting a literature review and previous testing, the model incorporates a combination of quality management tools and multi-criteria decision methods, including:

- SMARTER method (Specific, Measurable, Achievable, Relevant or Realistic or Rewarding, Time-bound, Exciting or Evaluated, Recorded or Reward) (Lawlor & Hornyak, 2012);
- Method for selecting a team of experts (Kupraszewicz & Zółtowski, 2002; Pacana & Siwiec, 2021b);
- Brainstorming (BM) (Putman & Paulus, 2008);
- Causes-and-effects diagram (Ishikawa diagram or herringbone diagram) (Chokkalingam et al., 2017; Gawdzińska, 2011);
- FAHP method (Fuzzy Analytic Hierarchy Process) (Katunin et al., 2021; Pacana & Siwiec, 2021b; Siwiec & Pacana, 2021d);
- FTOPSIS method (Fuzzy Technique for Order of Preference by Similarity to Ideal Solution) (Jarosińska & Berczyński, 2021; Khedmatgozar et al., 2021; Minutolo et al., 2019).

The detailed characteristics of the model will be presented in the subsequent part of the study.

Model characteristics

The model is described based on the algorithm consisting of six main stages. The depiction of the model can be seen in Figure 1.

Stage 1: Determining the primary incompatibility and analysis objective

During this stage, the main incompatibility is examined, specifically the one that occurs most frequently or has significant costs or effects. The selection of the incompatibility is made by an entity such as an enterprise, expert, manager, or president, utilizing the model. A control sheet is employed for this purpose. Additionally, the analysis objective is determined based on the identified type of incompatibility.

The purpose is determined using the SMARTER method (Lawlor & Hornyak, 2012). The purpose includes key characteristics of noncompliance, such as the type of incompatibility, the product affected by the incompatibility, and the number of identified occurrences of this type of incompatibility (e.g., annually).

Stage 2: Selecting the team of experts

A team of experts is chosen to take on responsibilities throughout the process of improving product quality. The team should possess the necessary competencies and knowledge in the analysed problem area. The selection of the team is based on the method described in the study (Pacana & Siwiec, 2021b). The resulting number of qualified experts, denoted as T, determines the team size. It is beneficial to designate a team leader who has experience in coordinating team work to enhance the likelihood of achieving the goal.

Stage 3: Identifying the root cause of incompatibility

During this stage, the root cause of the incompatibility is identified. Brainstorming (BM) is conducted among the team of experts to pinpoint all the roots or places where the incompatibility occurs. In cases where there are numerous roots, the Pareto rule (20/80) can be applied, as demonstrated in the study (Hoła et al., 2018).

Stage 4: Identifying initial causes

The initial potential causes of the incompatibility are determined by addressing the question, "What has happened that caused the incompatibility?" Brainstorming (BM) is conducted for this purpose. The team leader records all the causes on a visible medium, such as a table. After 30 minutes, the BM session is

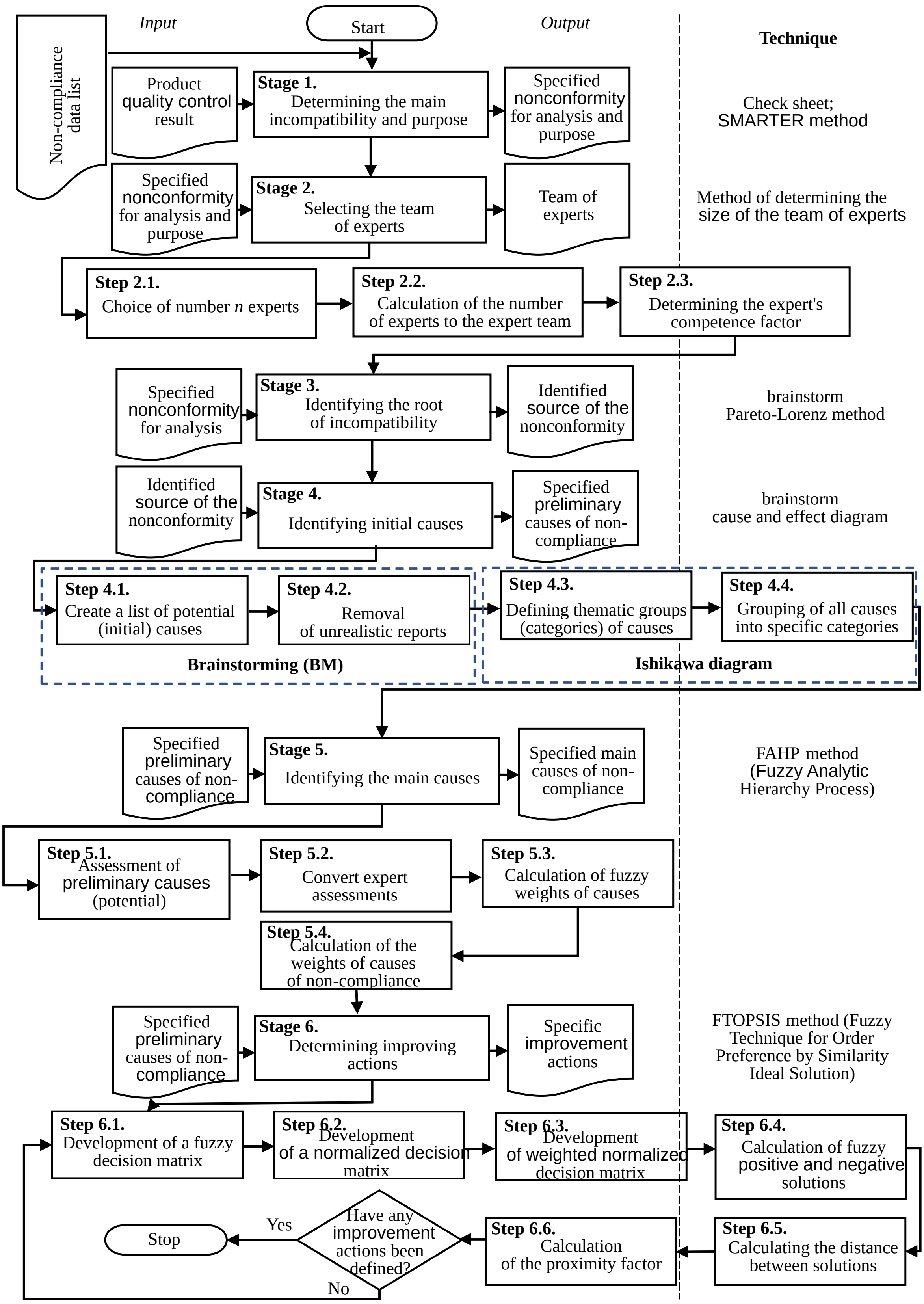

Fig. 1. Model for supporting quality improvement of products through rational decision making

concluded. The list of initial (potential) causes of incompatibility is then reviewed by the leader, eliminating unrealistic submissions. Thematic groups or categories of causes are established to facilitate systematic analysis. These categories are based on the 5M + E rule: Man, Method, Machine, Material, Measure, Management, and Environment (Chokkalingram et al., 2017). Additional categories, such as system, personnel, and suppliers, can also be included. All initial causes are grouped according to the designated categories and visualized on an Ishikawa diagram (Pacana & Siwiec, 2022a) to enhance understanding and guide further actions.

Stage 5: Identifying the main causes

The main causes of the incompatibility occurring in the analysed root are identified. This process is typically performed as the second step of brainstorming or by utilizing the Suzuki (ABCD) method. In the proposed model, the FAHP method is employed, integrated with causes-and-effect diagrams, brainstorming (BM), and multiple voting. This procedure involves five main steps.

In the first step, each expert on the team evaluates all the potential causes using the Saaty scale (Saaty, 1997). The Saaty scale assigns higher scores to causes that have a greater impact on the problem. These assessments are recorded on the Ishikawa diagram, and a summary list is created for each initial cause of incompatibility.

In the second step, the weight values are converted into combined values of cause weights using an algorithm for language variable conversion (1) (Katunin et al., 2021; Siwiec & Pacana, 2021a; Ulewicz et al., 2021):

$$\tilde{A}_{IJ}^{E} = \left(l_{ij}^{E}, m_{ij}^{E}, u_{ij}^{E}\right) \tag{1}$$

where: $l_{ij}^{E} = \text{Min}\left\{l_{ij}^{T}\right\} \forall T \in E$ is the minimum value on the left end, and $m_{ij}^{E} = \left\{m_{ij}^{T}\right\}^{\frac{1}{n}} \forall T \in E$ is the geometric mean of the median of all triangular Fuzzy Numbers, $u_{ij}^{E} = \text{Max}\left\{u_{ij}^{T}\right\} \forall T \in E$ is the minimum value on the right end, where: $\tilde{A}_{IJ}^{E}$ – the value obtained after multiple comparisons of the opinions of experts in relation to the i-th assessing element and the j-th assessing element; T – the T_{th} expert, where:

$$\tilde{a}_{ij} = \begin{cases} (1,\, 1,\, 1) & \text{if } \; i = j \\ (a_{ijl},\, a_{ijm},\, a_{iju}) & \text{if } \; j > i \\ \left(\dfrac{1}{a_{iju}},\, \dfrac{1}{a_{ijm}},\, \dfrac{1}{a_{ijl}}\right) & \text{if } \; j < i \end{cases}$$

In the third step, the relative fuzzy value of the weight of incompatibility causes is calculated by normalizing the average value in each row with the fuzzy geometric average value. This process determines the fuzzy value of the weights of incompatibility causes (Wotzka et al., 2021).

$$W_i = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}}{\sum\limits_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}} \tag{2}$$

where: $i, j = 1 \sim n$, a_{ij} – the Tringular Fuzzy Number located at row i and column j in the pariwise comparison matrix; W_i – the fuzzy weight of row i, where:

Step 1:

$$Z_i = \left[\prod_{j=1}^{n} \tilde{a}_{ij}\right]^{\frac{1}{n}}, \ \forall i$$

Step 2:

$$W_i = \frac{\left(\prod_{j=1}^{n} \tilde{a}_{ij}\right)^{\frac{1}{n}}}{\sum\limits_{i=1}^{n}\left(\prod_{j=1}^{n} \tilde{a}_{ij}\right)^{\frac{1}{n}}} = Z_i\left(Z_i \oplus \ldots \oplus Z_n\right)^{-1}$$

The sum of values for each row of the fuzzy matrix of pairwise comparisons $\tilde{A} = [\tilde{a}_{ij}]$ is determined. These values are calculated based on the fuzzy number calculation method.

In the fourth step, fuzzy weights are calculated as decimal weights of causes of incompatibility. Following the approach suggested by Kabir & Hasin (2011), Khorramrouz et al. (2019), and Liu et al. (2020), the COA (Center of Area) approach is used, as shown in formula (3):

$$w_i = \frac{a_{ijl} + a_{ijm} + a_{iju}}{3} \tag{3}$$

where: l, m, u – as in formula (1), $i, j = 1, 2, \ldots, n$.

The sum of all weights of incompatibility causes should be equal to 1 to verify the criteria. For this purpose, the weights need to be normalized using formula (4) based on the work of Chang (1996), Chen (2000), Lin (2020), and Tsai et al. (2020):

$$w_i^N = \frac{w_i}{w_{11} + w_{12} + \ldots + w_{ij}} \tag{4}$$

where: w_{ij} – weight of criterion, $i, j = 1, 2, \ldots, n$.

The main causes of incompatibility are selected based on the normalized weight values. The maximum value is chosen, representing the most important cause of the problem within each group of causes. Improvement actions are then determined for these main causes.

Stage 6. Determining improvement actions

In Stage 6, the focus is on determining the actions that will lead to improvements in addressing the identified root and main causes of incompatibility. The purpose related to the main causes of product incompatibility is established using the FTOPSIS method (Chang, 1996; Kusumawardani & Agintiara, 2015). This stage involves the following six main steps:

In the first step, the team identifies all possible improvement actions through brainstorming (BM), focusing on reducing or eliminating the main causes identified in the previous five stages of the model. A decision matrix (M_{ij}) is developed, involving the T-member team of experts selected in Stage 2. The team evaluates all improvement actions using the multiple voting technique and fuzzy scales. The assessments provided by the T^{th} expert for improvement action A_i and the group of main causes C_j are noted using formula (5) (Alt et al., 2019; Gawdzińska, 2011; Pacana et al., 2020):

$$\tilde{x}_{ij}^{k} = \left(a_{ij}^{k},\, b_{ij}^{k},\, c_{ij}^{k}\right) \tag{5}$$

In the second step of Stage 6, the assessments provided by the T-th expert are recorded in a combined matrix (M_{ij}^{c}), which represents a single decision matrix. This matrix is created by converting the language variables, as shown in formula (1), following the approach used in the fifth stage of the model (Basahel & Yaylan, 2016).

Next, a normalized fuzzy decision matrix is generated based on the combined decision matrix (M_{ij}^{c}). This matrix denoted as $\tilde{M}_{ij}^{c} = \left[\tilde{m}_{ij}^{c}\right]$ is specifically designed for assessing the improvement actions in terms of their benefits (where more is better) or costs (where less is better). The formulas (6–7) are used to construct this matrix.

In this approach, the decision regarding a group of improvement actions is made collectively by the team of experts, considering the fuzzy assessments provided by each expert (Alt et al., 2019; Peças et al., 2021). The normalized fuzzy decision matrix enables a comprehensive evaluation and comparison of the improvement actions, considering their benefits and costs:

for benefit improvement actions

$$\tilde{m}_{ij}^{c} = \left(\frac{a_{ij}}{c_j^{*}},\, \frac{b_{ij}}{c_j^{*}},\, \frac{c_{ij}}{c_j^{*}}\right) \quad \text{and} \quad \max_i c_j^{*} = \{c_{ij}\}, \tag{6}$$

for cost improvement actions

$$\tilde{m}_{ij}^{c} = \left(\frac{a_j^{-}}{c_{ij}},\, \frac{a_j^{-}}{b_{ij}},\, \frac{a_j^{-}}{a_{ij}}\right) \quad \text{and} \quad \min_i c_j^{-} = \{a_{ij}\}, \tag{7}$$

where: a, b, c – fuzzy numbers, i – main cause, $i = 1, 2, 3, \ldots, n$, j – improvement action, $j = 1, 2, 3, \ldots, n$.

In the third step of Stage 6, the matrix $\tilde{M}_{ij}^{w} = \left[\tilde{m}_{ij}^{w}\right]$ is developed based on the normalized fuzzy decision matrix $\tilde{M}_{ij}^{c}$. This matrix considers the importance of the main causes in the context of implementing the improvement actions. The weights for these causes are determined in the fifth stage of the model, as indicated in studies conducted by Jarosińska & Berczyński (2021) and Khedmatgozar et al. (2021).

Formula (8) is employed to calculate the weights in the matrix $\tilde{M}_{ij}^{w}$, allowing for the incorporation of the significance of the main causes. This weight calculation is a crucial step in the decision-making process, as it helps prioritize the improvement actions based on the importance of the underlying causes.

$$\tilde{m}_{ij}^{w} = \tilde{m}_{ij}^{c} \times \tilde{w}_{ij} \tag{8}$$

where: $\tilde{m}^{c}$ – values of normalized fuzzy decision matrix, $\tilde{w}$ – fuzzy weight value, i – improvement action, j – main cause, $i, j = 1, 2, 3, \ldots, n$.

In the fourth step of Stage 6, the fuzzy positive ideal solution (FPIS, A*) and the fuzzy negative ideal solution (FNIS, A–) are calculated. These calculations are essential for evaluating the performance of the improvement actions based on multiple criteria. The formulas (9–10) are used to determine these solutions, following studies conducted by Alt et al. (2019), Kabir & Hasin (2011), Khedmatgozar et al. (2021), and Saaty (1997):

$$A^{*} = \left(\tilde{m}_1^{w*}, \tilde{m}_2^{w*}, \ldots, \tilde{m}_n^{w*}\right) \quad \text{where: } \tilde{m}_j^{w*} = \max_i \{m_{ij3}\} \tag{9}$$

$$A^{-} = \left(\tilde{m}_1^{w-}, \tilde{m}_2^{w-}, \ldots, \tilde{m}_n^{w-}\right) \quad \text{where: } \tilde{m}_j^{w-} = \min_i \{m_{ij1}\}, \tag{10}$$

where: $\tilde{m}_n^{w*}$, $\tilde{m}_n^{w-}$ – weighted value of normalized fuzzy decision matrix, m_{ij3} – denotes the third value of the fuzzy number, m_{ij1} – denotes the first value of a fuzzy number.

In the fifth stage of the model, the distance between solutions is calculated based on the studies conducted by Basahel & Yaylan (2016). Formulas (11–12) are used for this purpose:

$$(\tilde{x}, \tilde{y}) = \sqrt{\frac{1}{3}\left[\left(a_1 - a_2\right)^2 + \left(b_1 - b_2\right)^2 + \left(c_1 - c_2\right)^2\right]} \tag{11}$$

$$d_i^* = \sum_{j=1}^{n} d\left(\tilde{m}_{ij}^w, \tilde{m}_j^{w*}\right), \qquad d_i^- = \sum_{j=1}^{n} d\left(\tilde{m}_{ij}^w, \tilde{m}_j^{w-}\right) \tag{12}$$

where: a, b, c – fuzzy numbers, $\tilde{m}_{ij}^w$ – values of weighted normalized fuzzy decision matrix, $\tilde{m}_n^{w*}$, $\tilde{m}_n^{w-}$ – values of weighted normalized fuzzy decision matrix.

In the sixth step, the proximity factor (CC_i) is estimated, representing the distance between solutions. This factor is calculated using formula (13) based on the studies by Jarosińska & Berczyński (2021), Khedmatgozar et al. (2021), and Ulewicz et al. (2021):

$$\mathrm{CC}_i = \frac{d_i^-}{d_i^- + d_i^*} \tag{13}$$

where: d_i^*, d_i^- – values of distance between solutions, $i = 1, 2, 3, \ldots, n$.

Then, a ranking is created based on the calculated values. The highest value corresponds to the most favorable improvement action for reducing or eliminating the incompatibility at the root.

Once the root of the incompatibility, the main causes of incompatibility, and the approach to preventing the main incompatibility have been determined, similar actions can be taken for other incompatibilities or their root causes. This marks the final stage of the model.

Key advantages of model

The advantages of the model have been determined based on preliminary research and a literature review, primarily focusing on heuristic techniques (Pacana & Siwiec, 2022a; Siwiec & Pacana, 2021b; Tegegne & Shing, 2013). The main advantages of the model include:

- the ability to provide a numerical measure of the importance of causes and ensure consistent and reproducible evaluation of causes (Hoła et al., 2018; Pacana et al., 2020; Radej et al., 2017; Siwiec & Pacana, 2021c; Ulewicz et al., 2021; Wolniak, 2019);
- reduction of subjectivity in expert assessments for determining causes of product incompatibility and identifying appropriate improvement actions through the use of triangular fuzzy numbers (Jarosińska & Berczyński, 2021; Pinho et al., 2021; Siwiec & Pacana, 2021c);
- simultaneous consideration of cause priorities (impact of causes on the occurrence of incompatibility) through numerical validation and the ability to make optimal expert choices (Lawlor & Hornyak, 2012; Putman & Paulus, 2008; Raji et al., 2018);
- proposition of an implementation process for decision-making supported by calculation results, which adds objectivity compared to qualitative decision-making approaches (Kabir & Hasin, 2011; Pacana & Siwiec, 2022a).

Additionally, using this model provides cost savings by focusing activities on addressing the most important cause and avoiding waste from taking inadequate or incorrectly defined actions.

Test of the model

The model was tested using a mechanical seal with a cluster of porosity, which was selected as it is a common defect in cast materials. Porosity refers to the presence of multiple small gas bubbles clustered together in a random geometric distribution (Pacana & Siwiec, 2021b). This porosity cluster negatively affects the strength and tightness of the product. For a mechanical seal, which is designed to handle heavy loads, this defect renders the product unfit for use. Figure 2 illustrates an example of this incompatibility.

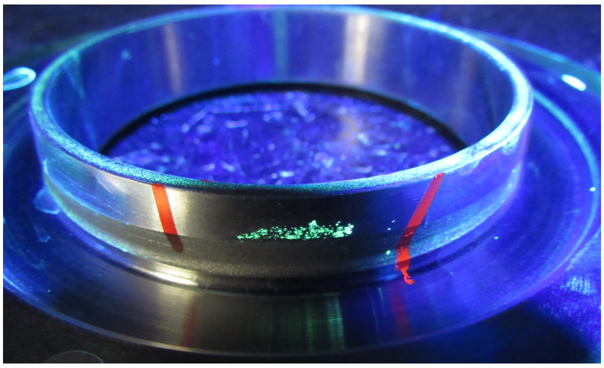

Fig. 2. Example of a porosity cluster on a mechanical seal

The characteristics of the mechanical seal and a detailed description of alloy 410 properties are presented in our study (Pacana & Siwiec, 2021b). Alloy 410 is a martensitic stainless steel known for its high strength and moderate resistance to heat and corrosion. In a company located in Poland, a porosity issue was identified in the mechanical seal made of 410 alloy through non-destructive testing (fluorescence method), as documented in (Pacana & Siwiec, 2021a, 2021b).

Stage 1: Determining the primary incompatibility and analysis objective

The objective was to improve the quality of the mechanical seal made from alloy 410 by precisely determining the source of incompatibility, initial causes, the main cause, and proposing improvement actions.

Stage 2: Selecting the team of experts

The team of experts was selected using a method described in (Kupraszewicz & Zółtowski, 2002; Pacana & Siwiec, 2021b) to analyze the porosity cluster in the mechanical seal made of 410 alloy. Initially, two experts were chosen based on their knowledge and experience related to the porosity cluster in mechanical seals. One expert was an employee working on the mechanical seal, and the other was responsible for performing NDT inspections. Each of these experts then identified four additional experts, with one expert being indicated twice. According to the authors of the study (Kupraszewicz & Zółtowski, 2002), an initial number of five experts is recommended.

The competencies of these experts were assessed, following the approach described in (Kupraszewicz & Zółtowski, 2002; Pacana & Siwiec, 2021b). The competency factor for each expert was calculated, and all experts ($T = N = 5$) were found to be competent in analyzing the problem of porosity clustering in the mechanical seal. The threshold value for the competency factor was set at greater than 0.60 (Pacana & Siwiec, 2021b). Experts whose competencies fell below this threshold would typically be excluded.

The group of preselected experts consisted of employees from the company involved in the study, including the quality control manager responsible for addressing the porosity cluster issue, the employee performing fluorescence tests and managing NDT inspections, an employee working in the production of the mechanical seal, and the authors of the article. From this group, a leader was selected using the described method, and the chosen leader was the NDT quality control manager.

Stage 3: Identifying the root cause of incompatibility

At this stage, a brainstorming session (BM) was conducted with the selected team of experts. It was determined that the porosity cluster in the mechanical seal was attributed to the reaction between dissolved gases in the liquid metal and certain components present in the liquid. When the temperature of the metal decreases, some of the dissolved gases are released from the solution. This occurs because they become trapped within the metal during solidification. Additionally, dissolved oxides often combine with carbon to form insoluble bubbles in both liquid and solidified metals. As a result, the porosity cluster forms as the gases evolve during the metal's solidification process. These conclusions are supported by a study conducted by Naro in 1999.

Stage 4: Identifying initial causes

This stage was initiated due to the root cause of incompatibility. Initially, a brainstorming method was used with a selected team of experts to identify the maximum number of potential causes for the porosity cluster on the mechanical seal. These causes arise from the evolution of gases from the metal during solidification. The list of initial causes included:

- significant nitrogen and hydrogen content in the arc atmosphere;
- significant sulfur content in the welded metal;
- too high clotting rate;
- metallurgical reactions involving the formation of gaseous reaction products;
- pouring overheated metal into the mold;
- casting structure (problems with ensuring directional solidification);
- metallurgical reactions involving the formation of gaseous reaction products;
- interaction of iron oxide with carbon, when releasing carbon monoxide and carbon dioxide;
- possibility of moisture in the coating;
- possibility of moisture in the flux, e.g., during automatic welding;
- rust on welded edges;
- rust formation on the wire;
- inadequate gas shield;
- electrode moisture;
- dirty form;
- wrong polarity;
- increased nitrogen content in liquid melt;
- high chrome content;
- employee mistakes;
- little experience of the employee;
- staff fatigue;
- staff stress;
- staff rush;
- distraction as a psychophysical state;
- no periodic training;
- no TPM (Total Productive Maintenance);
- lack of up-to-date procedures and instructions;
- inadequate number of controls during production;
- inadequate lighting of the production site;
- employees not motivated to supervise the correctness of the production process;

- impurities in the molding sand;
- water in the molding mass;
- strenuous working conditions causing distraction, e.g., noise;
- no standardized ongoing production controls.

The brainstorming process concluded within 30 minutes, resulting in the identification of 34 preliminary potential causes for porosity clusters. These identified causes have been confirmed by other authors who have examined porosity clusters in their studies (Naik, 2017; Sheth et al., 2015; Siwiec & Pacana, 2021a). Subsequently, causes such as dirty form, fatigue, stress, rush, and distraction as a psychophysical state were excluded as they were deemed unlikely to occur. Consequently, a total of 30 potential causes remained. Thematic groups were then established using the widely used 5M + E rule. All causes were subsequently grouped according to these categories, and a cause-and-effect diagram was developed (refer to Figure 3).

Following the development of the cause-and-effect diagram, the primary cause of the porosity cluster on the mechanical seal was determined. Typically, identifying the root cause is performed as the second stage of the brainstorming method (BM). However, in this study, the FAHP method (Fuzzy Analytic Hierarchy Process) was employed, which will be discussed further in the subsequent part of the study.

Stage 5: Identifying the main causes

The FAHP method was applied to determine the primary causes of the porosity cluster on the mechanical seal of the 410 alloy. This method was integrated with the cause-and-effect diagram and the brainstorming method (BM). The team of experts initially evaluated all potential causes of the porosity cluster, and their evaluations were recorded on the Ishikawa diagram (refer to Figure 3). These assessments were then combined using the conversion of language variables (formula 1). Based on the combined evaluations and formula (2), fuzzy weights for the causes of incompatibility were calculated for each category in the Ishikawa diagram. Subsequently, the weights of the incompatibility causes were calculated and normalized using formulas (3–4). The results of these calculations are presented in Table 1.

Calculations within the FAHP method can also be performed using computer programs such as Expert Choice or free M-AHP software (Yunus et al., 2013). Using the weighted values obtained, the primary causes of incompatibility were determined by selecting the maximum values within each category. In the analysed case, the main causes of porosity clusters in the mechanical seal were identified as follows:

- no periodic training (among young employees);
- electrode moisture;

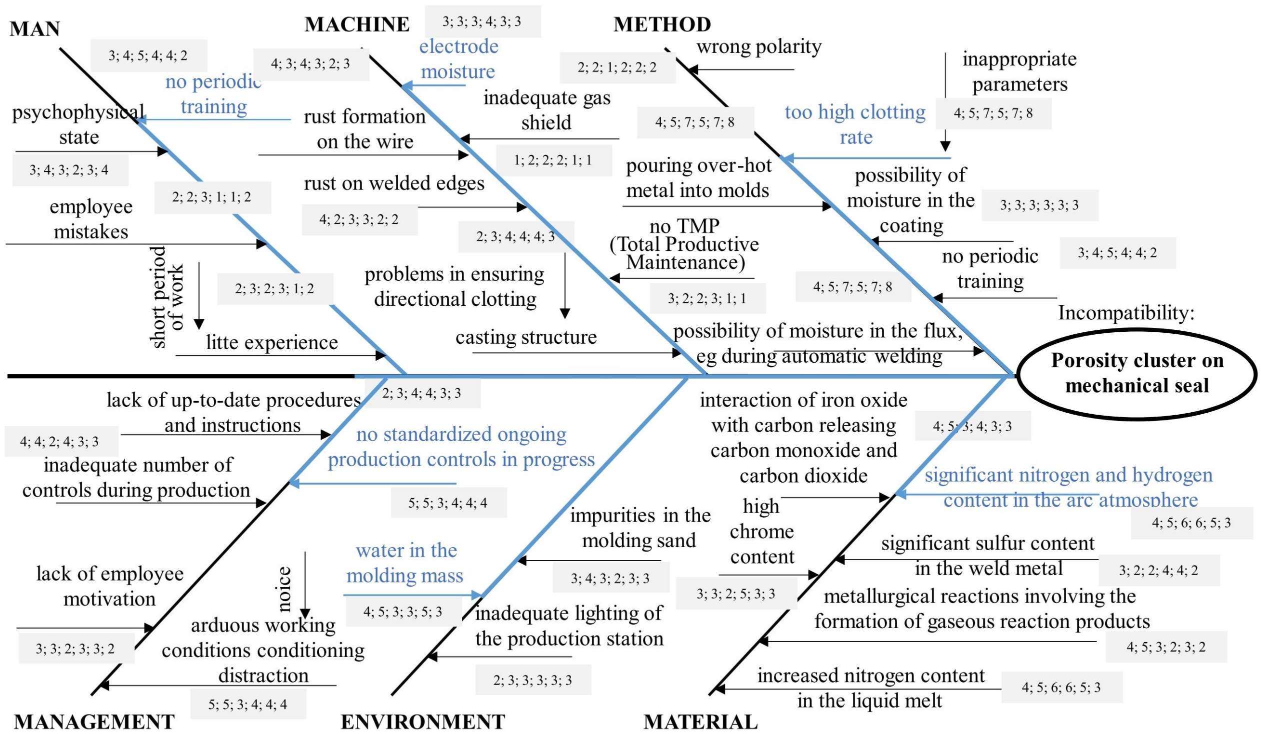

Fig. 3. Ishikawa diagram for problem of porosity cluster on mechanical seal considering assessments of team of experts

Table 1
Result after using the FAHP method

No. and category		Preliminary potential cause	Fuzzy Geom. Value (W_i)			Fuzzy Weights (w_i)				w_i^N
1	Man	employee mistakes	1.00	0.70	0.85	4.00;4.00;4.00 (0.25;0.25;0.25)	0.25	0.18	0.21	0.21
2		little experience of the employee	1.00	0.83	0.85		0.25	0.21	0.21	0.22
3		no periodic training	1.00	1.41	1.28		0.25	0.35	0.32	0.31
4		distraction as a psychophysical state	1.00	1.06	1.01		0.25	0.27	0.25	0.26
5	Machine	electrode moisture	1.74	1.19	1.11	5.22;5.20;5.09 (0.20;0.19;0.19)	0.34	0.23	0.21	0.26
6		rust formation on the wire	0.87	1.19	1.11		0.17	0.23	0.21	0.20
7		rust on welded edges	0.87	1.00	1.11		0.17	0.19	0.21	0.19
8		casting structure	0.87	1.25	1.11		0.17	0.24	0.21	0.21
9		inadequate gas shield	0.87	0.56	0.66		0.17	0.11	0.13	0.14
10	Method	no periodic training	0.70	1.17	1.19	7.79;7.79;7.80 (0.13;0.13;0.13)	0.09	0.15	0.15	0.13
11		wrong polarity	0.70	0.59	0.59		0.09	0.08	0.08	0.08
12		pouring overheated metal into the mold	1.40	1.55	1.59		0.18	0.20	0.20	0.19
13		too high clotting rate	2.10	1.92	1.78		0.27	0.25	0.23	0.25
14		possibility of moisture in the coating	1.40	0.96	0.79		0.18	0.12	0.10	0.13
15		possibility of moisture in the flux	0.70	0.88	0.93		0.09	0.11	0.12	0.11
16		no TPM (Total Productive Maintenance)	0.77	0.72	0.93		0.10	0.09	0.12	0.10
17	Management	lack of up-to-date procedures and instructions	0.87	1.15	1.12	5.22;5.34;5.14 (0.19;0.19;0.19)	0.17	0.22	0.21	0.20
18		inadequate number of controls	0.87	1.21	1.12		0.17	0.23	0.21	0.20
19		employees not motivated to supervise the correctness of the production process	0.87	0.97	0.89		0.17	0.18	0.17	0.17
20		strenuous working conditions causing distraction	0.87	0.49	0.67		0.17	0.09	0.13	0.13
21		no standardized ongoing production controls	1.74	1.52	1.34		0.34	0.28	0.26	0.29
22	Environ-ment	water in the molding mass	1.59	1.20	1.22	3.17;3.03;3.04 (0.33;0.33;0.31)	0.52	0.40	0.38	0.43
23		inadequate lighting of the production site	0.79	0.89	0.81		0.26	0.29	0.26	0.27
24		impurities in the molding sand	0.79	0.94	1.01		0.26	0.31	0.32	0.30
25	Material	interaction of iron oxide with carbon, when releasing carbon monoxide and carbon dioxide	1.59	1.07	1.00	6.35;6.10;6.03 (0.17;0.16;0.16)	0.26	0.18	0.16	0.20
26		high chrome content	0.79	0.93	1.00		0.13	0.15	0.16	0.15
27		significant nitrogen and hydrogen content in the arc atmosphere	0.79	0.93	1.00		0.13	0.15	0.16	0.15
28		significant sulfur content	0.79	0.83	0.84		0.13	0.14	0.13	0.13
29		metallurgical reactions involving the formation of gaseous reaction products	0.79	0.93	1.00		0.13	0.15	0.16	0.15
30		increased nitrogen content in liquid melt	1.59	1.41	1.17		0.26	0.23	0.18	0.23

- too high clotting rate (inappropriate parameters);
- no standardized ongoing production controls;
- water in the molding mass;
- increased nitrogen content in liquid melt.

The main causes identified from the previously developed Ishikawa diagram were highlighted (refer to Figure 4). The team of experts then proceeded to identify improvement actions aimed at reducing or

Table 2
Result from the FTOPSIS method

Main cause	No periodic training	Electrode moisture	Too high clotting rate	No standardized ongoing production controls	Water in the molding mass	Increased nitrogen content in the liquid melt
B/C	Benefit	Cost	Cost	Benefit	Cost	Cost
Weight	0.33;0.48;0.44	0.34;0.23;0.21	0.27;0.25;0.23	0.34;0.28;0.26	0.42;0.30;0.29	0.26;0.23;0.18
FPIS	0.15;0.35;0.44	0.07;0.01;0.21	0.07;0.10;0.23	0.19;0.24;0.26	0.11;0.13;0.29	0.29;0.07;0.12
FNIS	0.07;0.20;0.24	0.04;0.00;0.04	0.03;0.04;0.05	0.04.0.13;0.20	0.05;0.05;0.10	0.03;0.03;0.05
Distance between solutions for FPIS						
A1	0.00	0.01	0.07	0.11	0.09	0.03
A2	0.15	0.01	0.00	0.11	0.00	0.00
A3	0.20	0.10	0.11	0.00	0.12	0.08
A4	0.04	0.00	0.08	0.02	0.12	0.08
A5	0.11	0.00	0.07	0.04	0.03	0.09
Distance between solutions for FNIS						
A1	0.15	0.10	0.04	0.00	0.04	0.08
A2	0.00	0.10	0.11	0.03	0.12	0.09
A3	0.06	0.00	0.00	0.11	0.00	0.01
A4	0.13	0.10	0.04	0.13	0.01	0.01
A5	0.04	0.10	0.04	0.08	0.12	0.00

Calculation of the proximity factor (CCi)

Cause	d*	d-	Result	Ranking	Improvement actions
A1	0.31	0.40	0.56	2	Reduce the degree of nitrogen content in the liquid melt
A2	0.27	0.46	0.63	1	Reduce the rate of clotting
A3	0.62	0.18	0.22	4	Use well-dried coated electrodes and fluxes
A4	0.35	0.42	0.54	3	Select the appropriate frequency of ongoing production control

where: reducing the degree of nitrogen content in the liquid melt (A1); decrease in the rate of clotting (A2); use of well-dried coated electrodes and fluxes (A3); selecting the appropriate frequency of ongoing production control (A4); conducting periodic training (A5)

eliminating these main causes, which will be discussed in the subsequent stage.

Stage 6. Determining improvement actions

The proposed approach utilized the FTOPSIS method to determine improvements. As part of the brainstorming method, the team of experts identified improvement actions for the main causes of the porosity cluster on the mechanical seal. The identified actions are as follows:

- reducing the degree of nitrogen content in the liquid melt (A1);
- decreasing the rate of clotting (A2);
- using of well-dried coated electrodes and fluxes (A3);
- selecting the appropriate frequency of ongoing production control (A4);
- conducting periodic training (A5).

The next step involved the team of experts assessing all the improvement actions using the fuzzy Saaty scale. This assessment aimed to determine which actions would have the most significant impact in reducing or eliminating the root causes. Based on the expert evaluations and using formula (5), a combined decision matrix was created. Subsequently, a normalized decision matrix was developed from the combined decision matrix for the improvement actions. In this context, the experts evaluated the improvement actions in terms of cost and benefit categories. Specifically, they analysed whether increasing or decreasing the frequency of an action or adjusting the size of a parameter would be considered a benefit or a cost when aiming to reduce the main causes. Lower cost was considered better, while higher benefit was desired. Formula (6–7) were used to normalize the fuzzy decision matrix. The weights of the main causes of the porosity cluster were incorporated using formula (8). Next, following the FTOPSIS method and utilizing formulas (9–10), the fuzzy positive ideal solution (FPIS, A*) and the fuzzy negative ideal solution (FNIS, A-) were calculated. The distance between solutions was then computed using formulas (11–12). Based on this, the proximity factor (CCi) was determined using formula (13), as presented in Table 2.

Based on the generated ranking, the most beneficial improvement action selected was to reduce the clotting rate by testing and selecting the appropriate parameters for this process. According to the expert team, this action should be prioritized and implemented first. It is important to monitor and evaluate whether this action yields the expected result, such as a reduction in the presence of porosity clusters. Based on the observed outcomes, further corrective actions can be taken to enhance the production process of these products. The second priority improvement action identified was to decrease the nitrogen content during the liquid stage. Additionally, it was recommended to implement appropriate frequency of production control during the progress and ensure the use of well-dried coated electrodes and fluxes. These actions contribute to mitigating the porosity cluster issue and improving the overall production process.

Discussion

Enhancing product quality is a crucial objective for organizations (Pacana et al., 2023; Pacana et al., 2020; Pacana & Siwiec, 2022b). While heuristic techniques (Pacana & Siwiec, 2021a; Siwiec & Pacana, 2021b, 2021d) serve as fundamental tools, there is an ongoing search for more precise methods. The focus is primarily on tools that can support the entire process of improving product quality, starting from identifying incompatibility and determining the causes behind it, to identifying appropriate improvement actions (Bamford & Greatbanks, 2005).

The aim of the research was to develop a comprehensive model that supports the precise improvement of product quality through a detailed analysis of potential incompatibilities, causes of occurrence, and recommended improvement actions. The model was specifically tested using the mechanical seal of the 410 alloy, which frequently exhibited the issue of incompatibility in the form of porosity clusters. Upon testing the model, it was confirmed that combining quality management tools and decision methods in a unified and coherent model enables the accurate determination of a sequence of activities that support quality management. This includes identifying and validating the causes of incompatibility and correlating them with corresponding improvement actions. The combination of quality management tools and multi-criteria decision methods yielded several advantages, including:

- quantifying the importance of causes of incompatibility through numerical measures;
- ensuring a homogeneous and reproducible evaluation of root causes;
- reducing inconsistencies in expert assessments by implementing fuzzy decision methods;
- simultaneously considering the influence of root causes on the problem and determining appropriate corrective actions;
- supporting the computational and methodological aspects of expert decision-making in identifying causes of incompatibility and recommending improvement actions;
- implementing the model in the identification of problems (incompatibility) detected by various methods, including non-destructive and destructive testing;
- increasing enterprise profit through the implementation of suitable improvement actions;
- providing companies with informed decision-making capabilities;
- analyzing incompatibility problems and improvement actions with a properly selected team of experts or even by an individual expert;
- enhancing decision-making accuracy through teamwork among selected experts;
- categorizing causes and visualizing them in a straightforward manner, thereby standardizing the process of identifying root causes and corrective actions;
- organizing corrective actions in a ranked order, determining the most prioritized action to be taken.

The proposed model does have certain limitations. It requires complex calculations, but these calculations can be facilitated by using computer programs such as Excel. The selection of team members to address the problem is based on their self-assessment of qualifications, assuming that experts honestly and truthfully evaluate their own competence. The specific improvement actions may vary depending on the resources available to each enterprise. Therefore, the ranking of improvement actions in the final stage can be adjusted based on the specific needs and resources of the company, such as financial considerations. Nonetheless, the advantages of the model demonstrate its potential utility in enhancing product quality across different companies.

Future research efforts will focus on developing a computer program that supports the application of this model. Additionally, a dynamic decision platform is planned to be developed, enabling decision-making for various types of incompatibilities. This platform aims to collect information on different incompatibilities found in various products.

This research can serve as inspiration for other researchers, encouraging them to utilize the model for other products or services, as well as different incompatibilities or quality control challenges. The proposed research area holds the potential for new perspectives and insights from fields such as production engineering, mechanical engineering, management, and quality sciences. The outcomes of this research contribute to the stability and quality of materials and industrial products. Moreover, any manufacturing company can employ this model to improve their products.

Conclusions

The pro-quality model was developed to enhance product quality management. This model combines various quality management tools and fuzzy decision methods, including the SMARTER method, team selection method, brainstorming (BM), cause-and-effect diagram, FAHP method, and FTOPSIS method. The model was applied to address the issue of incompatibility (porosity cluster) in the mechanical seal made of the 410 alloy.

Initially, the purpose of improving the quality of the mechanical seal was determined using the SMARTER method. A five-person team of experts was selected to identify the source of incompatibility, initial causes, main cause, and improvement actions. Through brainstorming, the source of the porosity cluster was determined as gas release during solidification. Preliminary causes were identified and categorized using the 5M + E principle, visualized on the Ishikawa diagram.

The FAHP method was then employed to identify the main causes of non-compliance accurately. The calculations revealed that the main reasons were lack of periodic training, electrode humidity, excessive solidification rate due to inappropriate parameters, insufficient ongoing standardized production controls, water in the molding sand, and increased nitrogen content in the liquid alloy. Improvement actions were determined for these main causes using the FTOPSIS method. The top priority improvement action was reducing the clotting rate to minimize or eliminate the root causes. Additional improvement actions were proposed subsequently.

The model's effectiveness in determining and validating the causes of non-compliance and suggesting improvement actions demonstrates the value of combining quality management techniques and decision-making methods in a unified model.

This model serves as an inspiration for other researchers to further enhance and modify it, such as by incorporating artificial intelligence or other instruments, methods, and tools. Moreover, the practical application of this model is highly beneficial, as it can be employed for any product and combined with any quality control approach.

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