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Fuzzy Method to Improve Products and Processes Considering the Approach of Sustainable Development (FQE-SD Method)

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Abstract: Assumptions of the concept of sustainable development should include actions towards the development of modern, well-managed enterprises. However, making decisions in this area is difficult as it often results from subjective assessments of environmental problems. Hence, there is a motivation to develop a method of analysing the search for solutions to environmental problems that supports decisions in the area of improving the quality of products or processes while considering their impacts on the natural environment. In view of the specification of this problem, it was considered that this method should be conducted in a fuzzy decision environment. This method is called FQE-SD (fuzzy qualitatively environmentally sustainable development). This method integrated, in a hybrid way, the selected tools or elements of qualitative and multi-criteria decision methods, i.e., using the SMARTER method, brainstorming (BM), a method to select the team of experts, the Pareto-Lorenz analysis, the fuzzy QE-FMEA method, and the fuzzy AHP method. The main contribution of the FQE-SD method is its hybrid methodology, which supports: (i) a coherent and objective approach during the identification, analyses, and ranking of the causes of incompatibility of products or processes and (ii) the realization of the sustainable development of products or processes. The method was tested using the magnetic-powder test (MT). This control was carried out for producers of an outer bearing made fromAMS6470 steel. The results of this work confirmed the practical possibilities of applying the FQE-SD method. This method can also be applied to other production situations, if appropriate assumptions are made.

Keywords: quality; sustainable development; risk management; fuzzy decision environment; fuzzy QE-FMEA; production engineering; mechanical engineering

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1. Introduction

In order for enterprises to increase their competitiveness they should implement the effective management of selected elements in the process of product development [1–3]. These elements have the potential to satisfy customer expectations and environmental requirements [2,4,5], as well as influence technical requirements, thus leading to the creation of innovative products [6,7] and possibly the development of ideal product alternatives [8–10]. The management of the quality of products and processes is recognised as the main element supporting issues of sustainable development [11,12]. Quality management is understood as rules or values that target customer satisfaction, but it also contributes to continuous product improvement and decision making based on acquired data in order to process resources into functional products [13,14]. Therefore, sustainable development in terms of meeting customer requirements contributes to environmental sustainability and, therefore, is an important customer value and societal expectations inform stakeholders and customers [15,16].

Hence, the activities of companies that apply product quality management practices should be taken into consideration when determining environmental requirements for products [17,18]. As shown by the authors of [19,20], during the design of environmental sustainability guidelines, popular methods of quality management are increasingly integrated, such as quality function development (QFD) [21,22] or analysis of causes and effects of defects (FMEA) [23,24]. In addition, according to the authors of [17,19], other quality tools can be an integral part of sustainable development because they are designed to meet customers' expectations. As a review of the literature on the subject shows, despite the fact that there are studies in this area, such an approach to the sustainable development of products is not a common practice [19,25].

For example, in article [26], a decision support model based on the concept of product life cycle assessment (LCA) and eco-design was developed. This model supports solving problems occurring during the development of products that address to the whole cycle of the product life. However, the authors of article [8], in order to promote the sustainable design of products, combined a selection of techniques, that is, FMEA, QFD, TRIZ (theory of innovative problem solving), LCA, and fuzzy TOPSIS (fuzzy technique for order of preference by similarity to ideal solution). This research was based on the design of a simple safety valve, where FMEA was used to analyse valve failure. Then, customers' expectations and environmental requirements were combined in the QFD method, in which the results were analysed using the TRIZ method. Furthermore, using the FTOPSIS method, the ranking of the product criteria was completed based on the prototype. The authors of article [27] combined the Kano model, the QFD for the environment, and the TRIZ method. The authors of article [23] developed a method of fuzzy qualitative environmental analysis of hazards to improve products and processes (Fuzzy QE-FMEA). In this method, it was possible to simultaneously analyse qualitative environmental hazards. As part of this research, new assessment data sheets for indicators using the FMEA method were developed, and these assessments were created in a fuzzy decision environment. Furthermore, according to the same rules, a datasheet of assessments of the impacts on the natural environment was developed. In turn, the authors of article [28] developed a model of making decisions to support decision makers in the assessment and improvement in product design. In the model, the combined standard project "iF" and multicriteria methods of making decisions, i.e., DEMATEL (decision making trial and evaluation laboratory method) [29], were used to determine relations between important attributes, and then VIKOR (multicriteria optimisation and compromise solution) [30] was used to determine the level of assessment of product attributes and product designs. Finally, the network relationship map was used to determine possibilities to determine the impacts of different strategies of improvement. Another example is shown in the study [22], in which the QFD-CE (quality function development customer expectations) method was developed to design new products or improve existing products on the market. The novelty of this method is that it determines design goals, not only based on customers' expectations, but also considering impacts on the natural environment.

A summary of the review of the literature on the subject is presented in Table 1.

Table 1. Summary of literature review.

Category	LCA	FMEA	QFD	TRIZ	FTOPSIS	Kano Model	Saaty Scale	DEMATEL	VIKOR	Relationship Map
Eco-design	[8,26]	[8]	[8,27]	[8,27]	[8]	[27]	-	-	-	-
analysis and reduction in threats to product improvement	-	[23,29]	[22]	-	-	-	[23]	[28,29]	[28]	[28]

Based on the literature review, it was shown that different instruments to improve product quality were used, and these analyses included assessments of quality and impacts on the natural environment. These instruments mainly referred to improving products based on the basis of customers' requirements and impacts on the natural environment. However, no method of product improvement has been found that would allow qualitative and environmental analysis and validation of causes of incompatibility of products or processes while reducing inconsistency and also the subjectivity in the evaluation of these causes. This was considered a research gap. This gap is assumed to be filled in our study. Hence, the aim of this study was to develop a fuzzy method for the sustainable development of product and process improvement (FQE-SD method). As part of the research, the following hypothesis was adopted:

Hypothesis 1. *The improvement in products and processes according to sustainable development rules is possible by conducting an analysis followed by ranking the causes of incompatibilities in view of their impacts on quality and the natural environment, and their risk in terms of occurrence.*

The originality of the FQE-SD method is its integration of selected elements in the management of quality for the effective realization of sustainable development principles and, simultaneously, aspirations for the development of high-quality products and processes. The novelty of the FQE-SD method is its qualitative environmental analysis and sequential and coherent approach to the causes of incompatibility between products and processes. While it is possible to determine the causes that have the most negative impacts on product quality and the environment using one method, it is recommended to use a hybrid approach that is based on more than one method and to integrate the obtained results in order to support informed final decision making. Other benefits of hybrid methods include:

- The possibility of integrating the importance of criteria expressed in a subjective and objective way;
- The possibility of applying fuzzy logic to reduce uncertainty and inconsistency in preferences.

In addition, according to the author of article [7], the use of HMCDM (hybrid multi-criteria decision making) in the area of sustainable development allows for achieving much better results in making decisions for various problems.

2. Materials and Methods

2.1. Motivation and General Concept of the FQE-SD Method

Establishing the quality of products and processes is a key aspect of successful companies [31,32]. However, in the era of climate changes, it is inevitable to strive to improve products and processes further from the perspective of sustainable development. Despite this, the implementation of sustainable development practices is not yet popular in enterprises, and the main goal is to meet customer satisfaction [26,33,34]. Moreover, making decisions regarding impacts to the environment is difficult and imprecise, which results in subjective assessments of problems in the case of predicting impacts on the natural environment [35,36]. The motivation of this research was to develop a method that supports making decisions in the area of quality improvement considering impacts on the natural environment. It refers to developing a method to support improvement in the environmental sustainability of products and processes, and this method operates in a fuzzy decision-making environment. The result of using this method is the ability to focus improvement activities on the most important quality and environmental issues of products or processes. This method is called FQE-SD (fuzzy qualitatively environmentally sustainable development), where "F—fuzzy", "Q—quality", "E—environment", and "SD—sustainable development". The general concept of the FQE-SD method is shown in Figure 1.

The idea of developing this method stems from the need to simultaneously analyse the causes of incompatibilities of products and processes in the qualitative and environmental areas with an analysis that is objective and coherent. It was assumed that coherence and precision in decision making will be achieved as part of using fuzzy decision making [37,38]. The method of this approach relies on a sequential and coherent analysis of any incompatibility of a product. Finally, it is possible to determine the main causes of incompatibility, which, to the largest degree have an impact on the occurrence of a defect.

Figure 1. General concept of the fuzzy qualitatively environmentally sustainable development method. Own study.

The novelty of the FQE-SD method is its methodology, which was developed in a hybrid way, i.e., it combines (integrates) different techniques in a coherent manner [28,39,40]. In this case, the method mainly consists of the integration of selected elements of known quality management methods. These methods are used for the effective realisation of the idea of sustainable development and, simultaneously, aspirations for high-quality products or processes. The selected elements of these methods were indicators from the FMEA method. The FMEA method is the analysis of the causes and effects of defects. This method is based on the main indicators (i.e., probability of occurrence, detectability, and importance for customers) determined according to the risk values calculated. According to the risk values, it is possible to make decisions about improvement actions. The FMEA analysis is recommended to analyse any design defects in the process or product. In this approach, these indicators were quality (importance of incompatibility causes) [41] and the probability of the occurrence of incompatibility causes [24]. In addition, it is proposed to include an indicator of the impact on the natural environment [23], and then combine this indicator with the qualitative indicator to simultaneously determine the effects of the qualitative–environmental causes of the incompatibilities of products or processes. As part of our previous research, the fuzzy QE-FMEA method was developed [23] with data sheets for selecting assessments in triangular fuzzy numbers. Their use was adopted in the FQE-SD method, and then calculations were carried out as part of the popular fuzzy analytic hierarchy process (FAHP) method [42]. The purpose of using fuzzy numbers was to reduce inconsistencies and uncertainties in expert assessments. A detailed description of the assumptions adopted and the developed procedure of the FQE-SD method is presented in the following section.

2.2. Assumptions of the FQE-SD Method

After a literature review of the subject, the assumptions of the FQE-SD method were assumed. These assumptions were the following:

- The product or process analysis is unlimited, but it is necessary to use adequate data sheets [15,43];
- Incompatibility means not meeting requirements for the product or process [44];
- Potential causes are those which may, however, not necessarily result in the occurrence of incompatibility of the product or process [32];
- The main causes are those that have the greatest impacts on the incompatibility of the product or process [36];

- Quality (Q) refers to the effect of a potential cause on the product or process incompatibility; it also refers to the impacts of the incompatibility on the use of the product or process [23];
- Environmental impact (E) refers to the negative impacts of the potential causes of incompatibility of a product or process [2,23,45];
- The probability of occurrence of the cause of incompatibility (P) is the probability of a potential cause occurring in the area of the analysed incompatibility of the product or process [24];
- The weight of potential causes in terms of quality and environment (w^{QE}) is calculated on the basis of the ratings assigned to these causes in triangular fuzzy numbers, which simultaneously concern quality (Q) and environmental impact (E) [2,23];
- Assessments of quality effects and environmental impacts are awarded in triangular fuzzy numbers adequately for the product or process in accordance with the developed safety data sheets, and then integrated in the FAHP method [46].

The adopted assumptions provided the basis for developing the proposed method of environmentally sustainable improvement in the quality of products and processes, functioning in a fuzzy decision-making environment (FQE-SD).

2.3. Procedure of the FQE-SD Method

The qualitative–environmental method of improving products or processes operating in a fuzzy decision-making environment was developed (FQE-SD, fuzzy qualitatively environmentally sustainable development). This method was initiated in a hybrid way by combining selected tools or elements of qualitative methods and decision methods, i.e., using the SMARTER method (S—specific, M—measurable, A—achievable, R—relevant or realistic or reward, T—"based on timeline" or timebound, E—exciting or evaluated, and R—recorded or reward) [47], brainstorming (BM) [48], a method of selecting a team of experts [43], rule form Pareto–Lorenz analysis [49,50], the fuzzy QE-FMEA method [23], and the fuzzy AHP method (fuzzy analytic hierarchy process) [51,52]. The choice of these instruments was justified at the various stages of the method, which was developed in nine main stages (Figure 2).

- Stage 1. Selection of the subject of research and determination of the purpose of research

Initially, it is necessary to select the subject of research. The choice is made by the entity (expert) realizing the proposed method. The expert is selected in terms of expert competence. In the proposed approach, the subject of research should be the main incompatibility that it occurs the most often or generates the largest waste. This incompatibility should be determined based on the catalogue of incompatibility, which is often realised by enterprise. This incompatibility should refer to the product or process. In the case of products, these incompatibilities can include, e.g., functionality, reliability, or technology. Decisions about the selection of products can result from, e.g., the introduction of a new product, the modification of product parts, or using other technologies with a product. In the case of process, incompatibilities can refer to the realisation of requirements of construction or important impacts on the production process, e.g., processing parameters or measurement and control measures. The Pareto–Lorenz analysis, as presented in studies, e.g., [49,53], is useful in the selection of the main incompatibility.

Then, for the selected research study, the aim of the analysis is determined. In this case, the aim is to determine the ranking of environmentally sustainable improvement actions of the product (or process). The SMARTER method is helpful in determining the goal. The approach to using this method in order to determine the goal is presented in studies, e.g., [47].

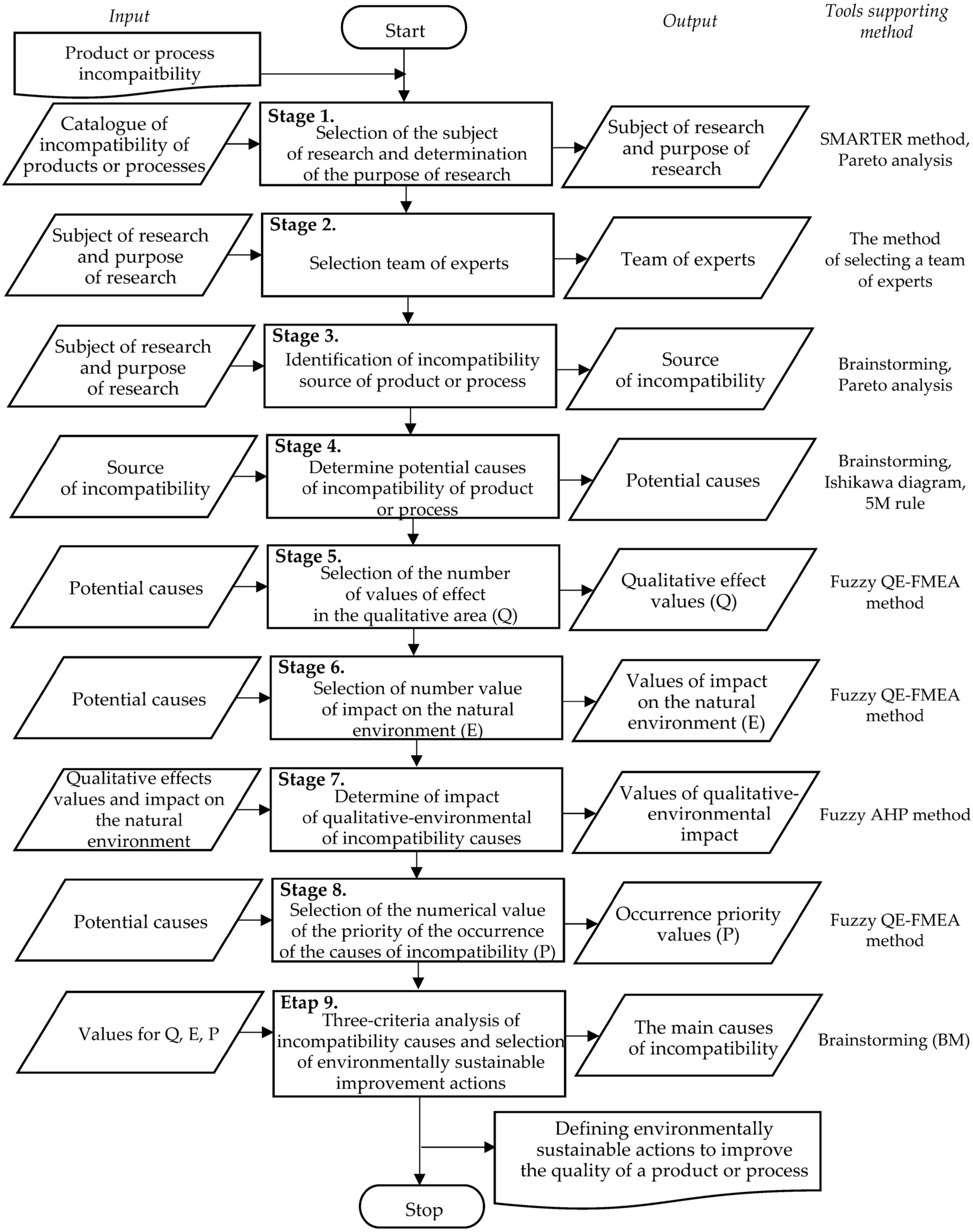

Figure 2. Algorithm of fuzzy qualitatively environmentally sustainable development method (FQE-SD method). Own study.

- Stage 2. Selection the team of experts

The realisation of the proposed FQE-SD method is based on a strong teamwork. Therefore, the key is to select an adequate team of experts who will be responsible for achieving the purpose of the research. In view of this, it is important that members of the team are competent and have knowledge of the theme of the research problem. In the proposed approach, it was assumed that the selection of the team of experts is performed according to the method shown in article [43].

- Stage 3. Identification of incompatibility source of product or process

The source of incompatibility is the place in which incompatibility has occurred. It was assumed that source is determined by a team of experts during brainstorming (BM) [48]. In this order, it is necessary to answer the question "In which place (moment) the incompatibility occurs?". If a large number of incompatibilities are identified, their number can be reduced by using the Pareto–Lorenz analysis [50].

- Stage 4. Determine potential causes of incompatibility of product or process

At this stage, potential causes are identified, i.e., those that probably contributed to the occurrence of nonconformities, but the degree of their impact is still unknown. It is necessary to determine potential causes of incompatibility for the selected subject of research, i.e., for product or process. In this aim, it is necessary to answer the question "What has happened that incompatibility occurred?" In this case, it is necessary to determine potential causes for each place of incompatibility, which were determined at the third stage of the method.

This stage is realised by the team of experts during brainstorming (BM), which usually takes 30 min. After this time, it is necessary to end the work of the team. The effect of this work is a long list of potential causes. Later, from all potential causes, the unreal causes (practically deemed not possible to occur) are removed. Hence, an expert (selected from a team of experts) verifies all causes. The result of this stage is a list of all potential causes of nonconformities of the product or process, depending on the selected subject of the investigation.

- Stage 5. Selection of the number of values of effect in the qualitative area (Q)

It is necessary to select the number of values of the effect of incompatibility occurring in the qualitative area (Q). Characteristics of acceptance of the Q indicator assessment enable the assessment of the potential causes of incompatibility. This data sheet also enables the assessment of deterioration based on the way the product is used or the functioning of the process, or the impact on customer satisfaction, as well as possible repair costs [23,24]. This assessment is necessary to determine the value of the effect in the qualitative area for each potential cause (from the fourth stage of the method). The choice of value is made by the team of experts by multiple votes. These values should be based on characteristics assumed in indicator Q (Table 2), which were created as part of the previous research shown in Ref. [23].

In order to reduce the subjectivity in assigning ratings by experts, and to avoid uncertainty in the assessments, we determined the effect using the triangular Saaty scale. Where $\widetilde{W}_i = (l_{ij}, m_{ij}, u_{ij})$ and $\widetilde{W}_j = (l_{ji}, m_{ji}, u_{ji})$ are two fuzzy numbers. In turn, $\mu_{\widetilde{W}_i}(d)$ is degree of d belonging to $\widetilde{W}_i$ as shown in Figure 3.

Hence, the team of experts, based on the developed Q index characteristics sheet, determines the appropriate value in triangular fuzzy numbers for each potential cause. The handling of the adopted fuzzy estimates is presented in the subsequent stages of the method.

Table 2. Characteristics of acceptance of the Q indicator assessment—the importance of the defect for the customer (quality). Own study based on [54–56].

Importance of the Defect for the Customer (Quality) According to Fuzzy QE-FMEA			Q	Fuzzy Q Triangular	Fuzzy Q Inverse
Very small	Minimal effect; lack of visibility for the customer; no impact on the use of the product	Equally important	1	1, 1, 1	1, 1, 1
		Weak or negligible	2	1, 2, 3	1/3, 1/2, 1
Small	Insignificant effect; slight difficulty in using the product; noticeable deterioration of product quality	Moderate	3	2, 3, 4	1/4, 1/3, 1/2
		Medium moderate	4	3, 4, 5	1/5, 1/4, 1/3
Average	Effect causing limited dissatisfaction and minor difficulties in using the product; the quality of the product does not meet customer expectations or is a source of nuisance; noticeable deficiencies in product quality	Strongly moderate	5	4, 5, 6	1/6, 1/5, 1/4
		Strongly positive moderate	6	5, 6, 7	1/7, 1/6, 1/5
Big	The result is customer dissatisfaction; product repair costs are unknown	Very strong	7	6, 7, 8	1/8, 1/7, 1/6
		Highly important	8	7, 8, 9	1/9, 1/8, 1/7
Very big	The effect is very significant; it threatens the safety of use and violates the law	Extreme	9	8, 9, 10	1/8, 1/9, 1/10
		Very extreme	10	10, 10, 10	1/10, 1/10, 1/10

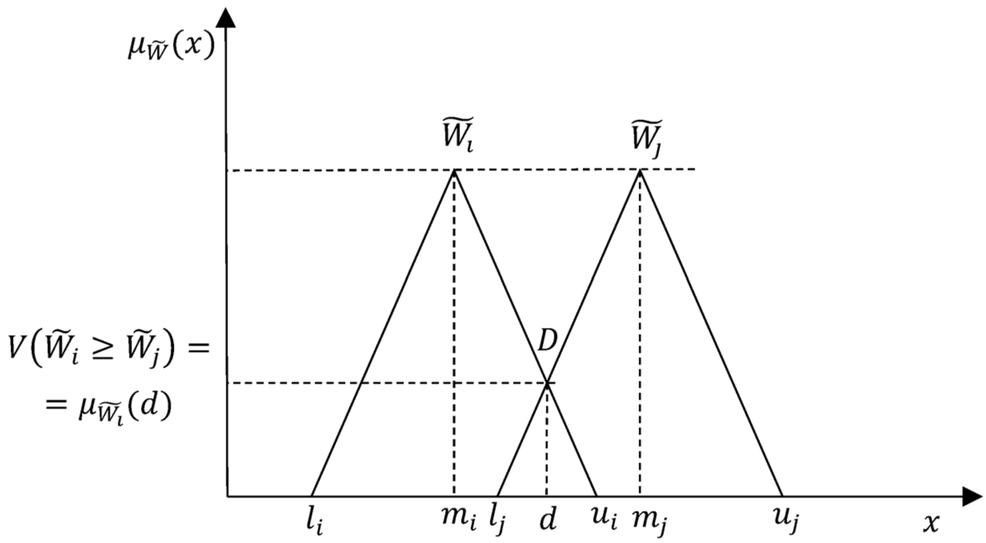

Figure 3. Determination of the coordinates of the intersection point $\widetilde{W}_i$ and $\widetilde{W}_j$. Own study based on [37,38,57].

- Stage 6. Selection of number value of impacts on the natural environment (E)

In order satisfy the sustainable development principles by improving the quality of the product or process, the selection value of impacts on the natural environment (E) was assumed. Indicator (E) refers to the negative impact of causes of incompatibility (product or process) on the natural environment. The numerical value for this indicator is selected for each potential cause (from step 4 of the method). The number value is selected by a team of experts by multiple votes. The selection is carried out based on the characteristic of indicator E (Table 3) developed as part of the modification of the datasheet produced as part of the previous research shown in Ref. [23].

As in the case of qualitative indicators, it is necessary to select assessments of environmental indicators in triangular fuzzy numbers. This resulted from a need to reduce subjectivity during making assessments by experts and avoid uncertainty in assessments, and it is enabled by using the Saaty scale. The handling of the adopted fuzzy estimates is presented in the subsequent stages of the method.

Table 3. Characteristics of adopting the assessment of the E indicator—impacts on the natural environment for the process and product. Own study [23].

Environmental Impacts According to Fuzzy QE-FMEA			E	Fuzzy E Triangular	Fuzzy E Inverse
Negligible	The impact is practically negligible; imperceptible negative impact	Equally important	1	1, 1, 1	1, 1, 1
Not important	The impact is likely to be small and non-hazardous	Weak or negligible	2	1, 2, 3	1/3, 1/2, 1
		Moderate	3	2, 3, 4	1/4, 1/3, 1/2
Important	The impact may be noticeable and cause limited harm or be a source of nuisance	Medium moderate	4	3, 4, 5	1/5, 1/4, 1/3
		Strongly moderate	5	4, 5, 6	1/6, 1/5, 1/4
		Strongly positive moderate	6	5, 6, 7	1/7, 1/6, 1/5
Very important	The impact is noticeable and harmful in large quantities; it reacts to some extent to the environment and affects human health	Very strong	7	6, 7, 8	1/8, 1/7, 1/6
		Highly important	8	7, 8, 9	1/9, 1/8, 1/7
Critical	The impact is destructive and causes significant harm; reacts significantly to the environment; threatens human life and health; violates the law	Extreme	9	8, 9, 10	1/8, 1/9, 1/10
		Very extreme	10	10, 10, 10	1/10, 1/10, 1/10

- Stage 7. Determine the impact of qualitative–environmental incompatibility causes

Based on assessments made for potential causes of incompatibility, the qualitative–environmental analysis is performed. For each cause, the number of simultaneously qualitative and environmental effects should be determined. According to the method shown in the study [23], it was assumed that the qualitative impact (Q) and environmental impact (E) are determined by using triangular fuzzy numbers. Therefore, the popular fuzzy AHP method is used for the combination of qualitative–environmental indicators. The fuzzy AHP method enables decision making with reduced subjectivity and uncertainty in experts' assessments. This method is similar to the AHP method (analytic hierarchy process); however, in this method, the fuzzy Saaty scale is used, as shown in the next part of the study [22].

Initially, a matrix of pairwise comparisons of the qualitative effects of incompatibility with the environmental impact (A_{QE}), is created, as shown in Formula (1) [58]:

$$\begin{cases} A_{QE} = \left[a_{ij}\right] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{21}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{bmatrix}, \text{ where } \tilde{A}_{QE} = \left[\tilde{a}_{ij}\right] \\ \tilde{a}_{ij} = \begin{cases} (1,1,1) & \text{if } 1 = j \\ \left(a_{ijl}, a_{ijm}, a_{iju}\right) & \text{if } j > i \\ \left(\frac{1}{a_{iju}}, \frac{1}{a_{ijm}}, \frac{1}{a_{ijl}}\right) & \text{if } j < i \end{cases} \end{cases} \quad (1)$$

There are always values equal to 1 on the diagonal and their inverse values are also on the diagonal. After developing the fuzzy matrix of pairwise comparisons, it is necessary to create a complex fuzzy matrix, as shown in Formula (2) [52,59]:

$$\begin{cases} \tilde{A}^{E}_{IJ} = \left(l^{E}_{ij}, m^{E}_{ij}, u^{E}_{ij}\right) \\ \text{where } l^{E}_{ij} = \text{Min}\left\{l^{T}_{ij}\right\} \forall T \in E \text{ is the minimum value on the left end,} \\ \text{and } m^{E}_{ij} = \left\{m^{T}_{ij}\right\}^{\frac{1}{n}} \forall T \in E \text{ is the geometric mean of the median of all TFN} \\ u^{E}_{ij} = \text{Max}\left\{u^{T}_{ij}\right\} \forall T \in E \text{ is the minimum value on the right end, where :} \\ \tilde{A}^{E}_{IJ} : \text{the value obtained after multiple comparisons of the opinions of experts} \\ \text{in relation to the ith assessing element and the jth assessing element,} \\ T : \text{the Tth expert.} \end{cases} \tag{2}$$

Later, a relative fuzzy weight for the qualitative–environmental indicators is computed. This is conducted by normalizing the mean value in the row [35,52] (3):

$$\begin{cases} W_i = \dfrac{\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}} \quad \text{where } i, j = 1 \sim n \\ a_{ij} : \text{the Tringular Fuzzy Number located at row i and column j in the pariwise comparison matrix;} \\ W_i : \text{the fuzzy weight of row i, where :} \\ \text{Step 1} : Z_i = \left[\prod_{j=1}^{n} \tilde{a}_{ij}\right]^{\frac{1}{n}}, \forall i, \quad \textit{and} \quad \text{Step 2} : W_i = \dfrac{\left(\prod_{j=1}^{n} \tilde{a}_{ij}\right)^{\frac{1}{n}}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n} \tilde{a}_{ij}\right)^{\frac{1}{n}}} = Z_i(Z_i \oplus \ldots \oplus Z_n)^{-1} \end{cases} \tag{3}$$

This involves calculating the sum of the values for each row in a fuzzy composite matrix, where the sum values of the rows are normalized on the fuzzy numbers. Subsequently, the weight of the qualitative and environmental effect of incompatibility $\left(w_i^{QE}\right)$ is calculated within the so-called centre of area (COA) as represented by Formula (4) [46]:

$$w_i^{QE} = \frac{l + m + u}{3}, \tag{4}$$

As a result, the combined values of the weights of the qualitative–environmental effect of the incompatibility (w_i^{QE}) are obtained. These values are taken into account in the further analysis of product or process nonconformities, as presented in the next steps of the method.

- Stage 8. Selection of the numerical value of the risk of the occurrence of the causes of incompatibility (P)

At this stage, the numerical value for the risk of the occurrence of inconsistencies (P) is selected. This is the probability that such a non-conformity may occur in the product or process. The risk of each potential non-conformity cause identified in step 4 of the method should be assessed. The selection of the value (assessment) of the risk number P is made by a team of experts. Following the authors of [23], the ratings are based on the data sheets shown in Table 4.

In this case, it is possible to choose real number values for the risk number, as in the traditional FMEA method. This is due to the fact that the result of stage 7 (determination of the qualitative and environmental impacts) are the weights of potential causes estimated in real numbers, and further analyses are carried out on real numbers.

Table 4. Characteristics of the evaluation of the risk number P—the probability of a defect. Own elaboration based on [23,55].

Probability of Occurrence According to Fuzzy QE-FMEA		The Frequency of the Defect	P	Fuzzy P Triangular	Fuzzy P Inverse
Unlikely	The occurrence of the defect is unlikely	Less than 1/1,000,000	1	1, 1, 1	1, 1, 1
Very rarely	There are few defects	1/20,000	2	1, 2, 3	1/3, 1/2, 1
Rarely	There are relatively few defects	1/4000	3	2, 3, 4	1/4, 1/3, 1/2
		1/1000	4	3, 4, 5	1/5, 1/4, 1/3
On average	The effect occurs sporadically from time to time	1/400	5	4, 5, 6	1/6, 1/5, 1/4
		1/80	6	5, 6, 7	1/7, 1/6, 1/5
Often	The defect repeats itself cyclically	1/40	7	6, 7, 8	1/8, 1/7, 1/6
		1/20	8	7, 8, 9	1/9, 1/8, 1/7
Very often	This disadvantage is almost unavoidable	1/8	9	8, 9, 10	1/8, 1/9, 1/10
		1/2	10	10, 10, 10	1/10, 1/10, 1/10

- Stage 9. Three-criteria analysis of incompatibility causes and selection of environmentally sustainable improvement actions

Based on the estimated value of qualitative environmental weights of the effects of occurred incompatibility (w_i^{QE}) and selected assessments of risk (P), the analysis is realised. The XY coordinate plot can be used in this analysis, where the X-axis represents the qualitative environmental weightings and the Y-axis represents the occurrence risk ratings. The points on the chart are values for potential causes of the incompatibility of a product or process. Then, it is possible to calculate the distance between potential causes. The purpose is to determine the main distances from the origin of these potential causes. Formula (5) is used for this calculation:

$$d_i = \sqrt{w_i^{QE} \times P_i}, \tag{5}$$

where w—weight of the qualitative–environmental effect of occurred incompatibility; P—risk of occurred potential causes of incompatibility, i = 1, 2, . . . , n.

The greater the distance (d_i), the greater the qualitative–environmental effect and the greater the risk (probability) of the cause. Therefore, improvement actions should be made for causes that are in areas farthest from the origin of the coordinate system. It is possible to assume that the distance will be about 80% according to the Pareto–Lorenz rule, as shown in studies, e.g., Refs. [49,50]. Then, the main causes for the incompatibility of the product or process are identified, i.e., those that generate the incompatibility to the greatest extent. Elimination or minimisation of these causes in the proposed way is conducive to the environmentally sustainable improvement in the quality of products or processes. This is due to the fact that such behaviour is conducive to eliminating the waste of resources or taking adequate actions to reduce the generation of material, financial, or even human losses.

3. Results

The developed FQE-SD method was verified. The test of the method was carried out in nine main stages in accordance with the developed algorithm. The result of each stage is presented in the next part of the article.

- Stage 1. Selection of the subject of research and determination of the purpose of research

As part of the first stage, the subject of research was selected. The choice was made by an expert (entity) who realised the proposed method. It was realised in a production and services company located in Poland, in which non-destructive testing methods were conducted. One of the methods was the magnetic-powder test (MT), which was characterised in study [60]. This control was commissioned by one of the producers of an outer bearing product made from AMS6470 steel, that is, nitrided chromium–molybdenum–aluminium steel. It was observed that welding imperfections were relatively often identified on this product [61]. This incompatibility generated financial losses and a decline in customer satisfaction. Furthermore, the causes of this incompatibility had not previously been analysed in a complex way. Their presence has a significant impact on the resistance and occurrence of local corrosion, as well as on the mechanical properties of the product. Therefore, their elimination would have a significant impact on the overall quality of the product. Hence, it was decided to select this discrepancy as part of the test of the proposed method. An example of a test subject with incompatibility is shown in Figure 4.

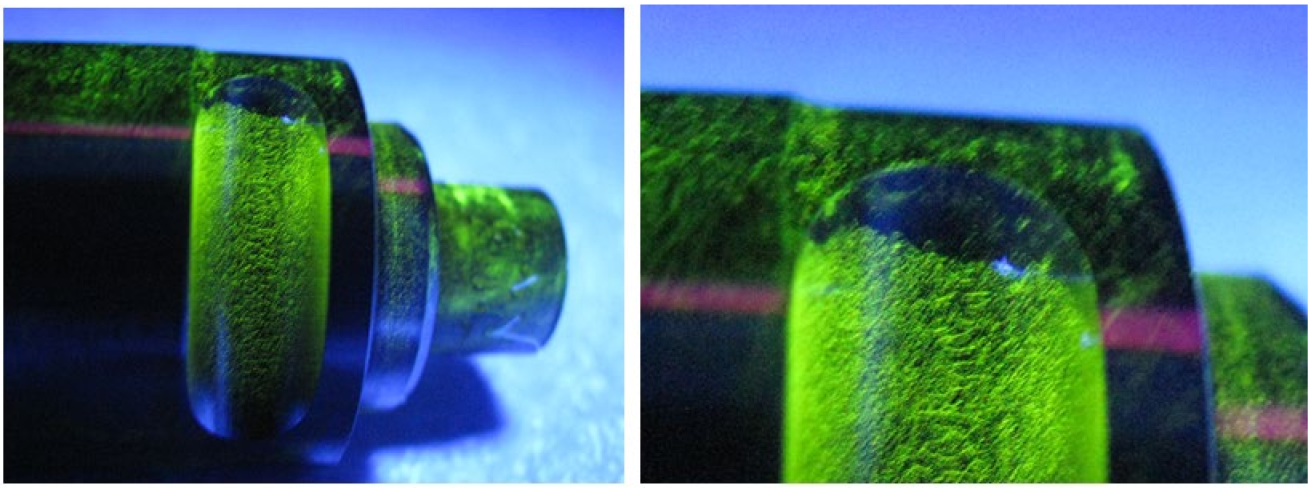

Figure 4. Example of undercutting on an AMS6470 steel outer bearing. Own study.

For the selected research subject, the purpose of the analysis was determined using the SMARTER method [47]. In the proposed approach, the purpose was to determine the rank of sustainable development improvement actions of the outer bearing product made from AMS6470 steel, in order to take appropriate actions to eliminate or reduce undercutting that occurs.

- Stage 2. Selection of the team of experts

Using the method shown in article [43], the team of experts was selected. This selection resulted from the need to realise the later stages of the method with the participation of competent persons who possess knowledge about the problem. Among the selected team were five experts, i.e., the authors of the article, the manager of non-destructive testing, and the manager of production. The same team of experts worked at every stage of the investigation.

- Stage 3. Identification of incompatibility source of product or process

The team of experts analysed the incompatibility in the outer bearing product made from AMS6470 steel to determine its source. In this aim, the answer to the question "When did the undercutting occur on the bearing?" was searched. The brainstorming method was employed by the team of experts and a naked eye analysis was made. The results from the quality control assessment carried out via the magnetic-powder test were then analysed. After observation of the incompatibility, it was concluded that incompatibility occurred during grinding.

- Stage 4. Determine potential causes of incompatibility of product or process

As part of this stage, potential causes of undercutting on the AMS6470 steel outer bearing product were identified, i.e., causes that resulted in the occurrence of this discrepancy to a greater or lesser extent. In order to generate these causes, we explored the question

"What happened that caused the non-compliance?". Potential causes were determined by a team of experts during brainstorming, where these causes were referred to as the source of the undercutting on the outer bearing. As a result, the following potential causes were determined:

1. An elongated and wide arc formed during a small current;
2. An elongated and wide arc formed during high welding speed;
3. Incorrect electrode angle;
4. Extensive weaving movements within the weld formation;
5. Welding current too high;
6. Large liquid weld pool flow;
7. Unclean weld layer;
8. Inappropriate joint ratio (too small width-to-depth ration);
9. Unsuitable material;
10. Bad carbon content in the weld (too much);
11. Impurities inside the weld;
12. Worker rushed the process;
13. No periodic training;
14. Little worker experience;
15. Fatigue;
16. Unsuitable welding tool;
17. Inadequate lighting;
18. No TPM performed (total productive maintenance);
19. Outdated procedures/instructions;
20. Electrode moisture;
21. Noise;
22. Auxiliary tools not calibrated;
23. Poor psychophysical condition of the employee.

The result was a list of 23 potential causes. The team of experts considered all of these reasons as adequate for further analysis, i.e., likely to have an impact on the occurrence of bearing incompatibility.

- Stage 5. Selection of the number of values of effect in the qualitative area (Q)

At this stage, the team of experts selected the value of the number of effects of incompatibility (undercutting) on the outer bearing referring to the qualitative area (Q). The value refers to the importance of the potential causes of the occurrence of incompatibilities or paying attention to the deterioration of analysed bearing during use. A team of experts selected the evaluations. The ratings were matched on the Saaty scale for each potential cause. The developed safety data sheet for the Q indicator was used for this purpose. The results are presented in Table 5.

The most important qualitative effects were inappropriate angle of the electrode setting, too high welding current, elongated and wide arc formed during low current or high current, or welding speed. Assessments of the qualitative effects of the AMS6470 steel bearing melting were analysed in the later stages of the method.

- Stage 6. Selection of number value of impacts on the natural environment (E)

To determine the environmentally sustainable improvement in the bearing quality of the AMS6470 steel product, the number of impact values on the natural environment (E) were determined. The choice was made by the team of experts, where indicator (E) referred to the negative causes of impacts on the natural environment. These assessments were selected by a team of experts using the characteristics of the data sheet for indicator E. The results are shown in Table 5.

The most important potential causes due to impacts on the natural environment were considered to be impurities inside the weld, elongated and wide arc during high welding speed, or inadequate weld proportion. Environmental impact assessments of potential causes of environmental contamination due to AMS6470 bearing melting were analysed at later stages of the study along with quality impact assessments.

Table 5. Assessment of the causes of potential undercutting on an AMS6470 steel bearing.

No.	Potential Causes	Qualitative Effects (Q)		Impacts on the Natural Environment (E)	
		Rating in Real Numbers	Rating in Triangular Fuzzy Numbers	Rating in Real Numbers	Rating in Triangular Fuzzy Numbers
1	Elongated and wide arc formed during a small current	7	6, 7, 8	5	4, 5, 6
2	Elongated and wide arc formed during high welding speed	7	6, 7, 8	6	5, 6, 7
3	Incorrect electrode angle	8	7, 8, 9	3	2, 3, 4
4	Extensive weaving movements as part of the weld formation	6	5, 6, 7	3	2, 3, 4
5	Welding current too high	8	7, 8, 9	5	4, 5, 6
6	High flow of liquid weld pool	5	4, 5, 6	4	3, 4, 5
7	Unclean weld layer	5	4, 5, 6	5	4, 5, 6
8	Inappropriate joint ratio (too small width-to-depth ration)	4	3, 4, 5	6	5, 6, 7
9	Unsuitable material	6	5, 6, 7	4	3, 4, 5
10	Bad carbon content in the weld (too high)	5	4, 5, 6	2	1, 2, 3
11	Impurities inside the weld	4	3, 4, 5	7	6, 7, 8
12	Worker rushed the process	6	5, 6, 7	3	2, 3, 4
13	No periodic training	3	2, 3, 4	2	1, 2, 3
14	Little worker experience	5	4, 5, 6	3	2, 3, 4
15	Fatigue	2	1, 2, 3	2	1, 2, 3
16	Unsuitable welding tool	3	2, 3, 4	3	2, 3, 4
17	Inadequate lighting	4	3, 4, 5	2	1, 2, 3
18	No TPM performed (total productive maintenance)	6	5, 6, 7	3	2, 3, 4
19	Outdated procedures/instructions	5	4, 5, 6	2	1, 2, 3
20	Electrode moisture	6	5, 6, 7	2	1, 2, 3
21	Noise	4	3, 4, 5	4	3, 4, 5
22	No calibration of auxiliary tools	5	4, 5, 6	2	1, 2, 3
23	Poor psychophysical condition of the employee	2	1, 2, 3	3	2, 3, 4

- Stage 7. Determine the impacts of qualitative–environmental incompatibility causes

The qualitative effects and assessments of the potential causes of undercutting in steal bearing were combined to determine the qualitative environmental impacts. The purpose was to determine which qualitative and simultaneously environmental effects can potentially be the result of an incompatibility. To combine qualitative–environmental factors, the fuzzy AHP method was used. The combined qualitative and environmental assessments were created using Formulas (1) and (2) and were expressed in a Saaty scale, as shown Table A1.

Then, as shown in Formula (1), a matrix (A_{QE}) of the comparison of qualitative effects and incompatibilities with impacts on the natural environment was developed. The compared assessments were combined. Fragments of the matrix are shown in Table A2.

Next, using Formula (3), the fuzzy geometric mean value was calculated. The results are shown in Table A3.

Finally, using Formulas (3) and (4), fuzzy qualitative–environmental weights of incompatibility effects were calculated (fuzzy w_i^{QE}), and then the qualitative–environmental weights of incompatibility effects $\left(w_i^{QE}\right)$ were calculated. The results are shown in Table 6.

Table 6. Weights of incompatibility causes of undercutting on an outer bearing made from AMS6470 steel estimated via the FAHP method.

No.	Potential Causes	Fuzzy w_i^{QE}			w_i^{QE}	$w_i^{QE} \times 100$
1	Elongated and wide arc formed during a small current	2.05	1.46	1.31	0.07	6.54
2	Elongated and wide arc formed during high welding speed	2.56	1.59	1.31	0.07	7.42
3	Incorrect electrode angle	1.02	1.34	1.48	0.05	5.15
4	Extensive weaving movements as part of the weld formation	1.02	1.10	1.15	0.04	4.40
5	Welding current too high	2.05	1.59	1.48	0.07	6.92
6	High flow of liquid weld pool	1.53	1.10	0.99	0.05	4.91
7	Unclean weld layer	2.05	1.22	0.99	0.06	5.79
8	Inappropriate joint ratio (too small width-to-depth ration)	1.53	1.22	1.15	0.05	5.28
9	Unsuitable material	1.53	1.22	1.15	0.05	5.28
10	Bad carbon content in the weld (too high)	0.51	0.85	0.99	0.03	3.14
11	Impurities inside the weld	1.53	1.34	1.31	0.06	5.66
12	Worker rushed the process	1.02	1.10	1.15	0.04	4.40
13	No periodic training	0.51	0.61	0.66	0.02	2.39
14	Little worker experience	1.02	0.98	0.99	0.04	4.02
15	Fatigue	0.51	0.49	0.49	0.02	2.01
16	Unsuitable welding tool	1.02	0.73	0.66	0.03	3.27
17	Inadequate lighting	0.51	0.73	0.82	0.03	2.76
18	No TPM performed (total productive maintenance)	1.02	1.10	1.15	0.04	4.40
19	Outdated procedures/instructions	0.51	0.85	0.99	0.03	3.14
20	Electrode moisture	0.51	0.98	1.15	0.04	3.51
21	Noise	1.53	0.98	0.82	0.05	4.53
22	No calibration of auxiliary tools	0.51	0.85	0.99	0.03	3.14
23	Poor psychophysical condition of the employee	0.51	0.61	0.66	0.02	2.39

The qualitative–environmental weights of incompatibility effects (undercutting) were included in the next analysis, as shown in the next stages of the method.

- Stage 8. Selection of the numerical value of the risk of the occurrence of the causes of incompatibility (P)

At this stage, the team of experts selected the values of risk for incompatibility (P) causes of the AMS6470 steel outer bearing. Assessments were selected based on a characteristics table and based on real numbers. The result is shown in Table 7.

The awarded grades were analysed at the next stage of the method, as presented in the following section.

- Stage 9. Three-criteria analysis of incompatibility causes and selection of environmentally sustainable improvement actions

Based on the estimated value of the qualitative–environmental weights of the effects of the incompatibility (w_i^{QE}) and selected assessments of risk (P), an analysis of the future risk of undercutting on the outer bearing made from AMS6470 steel was realised. An XY coordinate chart was used where the X-axis is the qualitative and environmental weights, while the Y-axis is the assessment of the risk of occurrence. The points in the graph are the corresponding values for the relationship of the causes of potential bearing nonconformities in terms of quality, environment, and risk of occurrence. Subsequently, using Formula (5), the estimated distances were marked, which determine the importance (significance) of the causes of noncompliance in terms of quality and environment and, at the same time, the probability of occurrence. The result of this stage is shown in Figure 5.

Table 7. Risk values for incompatibility (P) causes on AMS6470 steel outer bearing.

No.	Potential Causes	Rating in Real Numbers	Rating in Triangular Fuzzy Numbers
1	Elongated and wide arc formed during a small current	8	7, 8, 9
2	Elongated and wide arc formed during high welding speed	8	7, 8, 9
3	Incorrect electrode angle	6	5, 6, 7
4	Extensive weaving movements as part of the weld formation	4	3, 4, 5
5	Welding current too high	4	3, 4, 5
6	High flow of liquid weld pool	8	7, 8, 9
7	Unclean weld layer	4	3, 4, 5
8	Inappropriate joint ratio (too small width-to-depth ration)	6	5, 6, 7
9	Unsuitable material	4	3, 4, 5
10	Bad carbon content in the weld (too high)	6	5, 6, 7
11	Impurities inside the weld	2	1, 2, 3
12	Worker rushed the process	2	1, 2, 3
13	No periodic training	7	6, 7, 8
14	Little worker experience	3	2, 3, 4
15	Fatigue	7	6, 7, 8
16	Unsuitable welding tool	4	3, 4, 5
17	Inadequate lighting	2	1, 2, 3
18	No TPM performed (total productive maintenance)	4	3, 4, 5
19	Outdated procedures/instructions	5	4, 5, 6
20	Electrode moisture	5	4, 5, 6
21	Noise	4	3, 4, 5
22	No calibration of auxiliary tools	2	1, 2, 3
23	Poor psychophysical condition of the employee	2	1, 2, 3

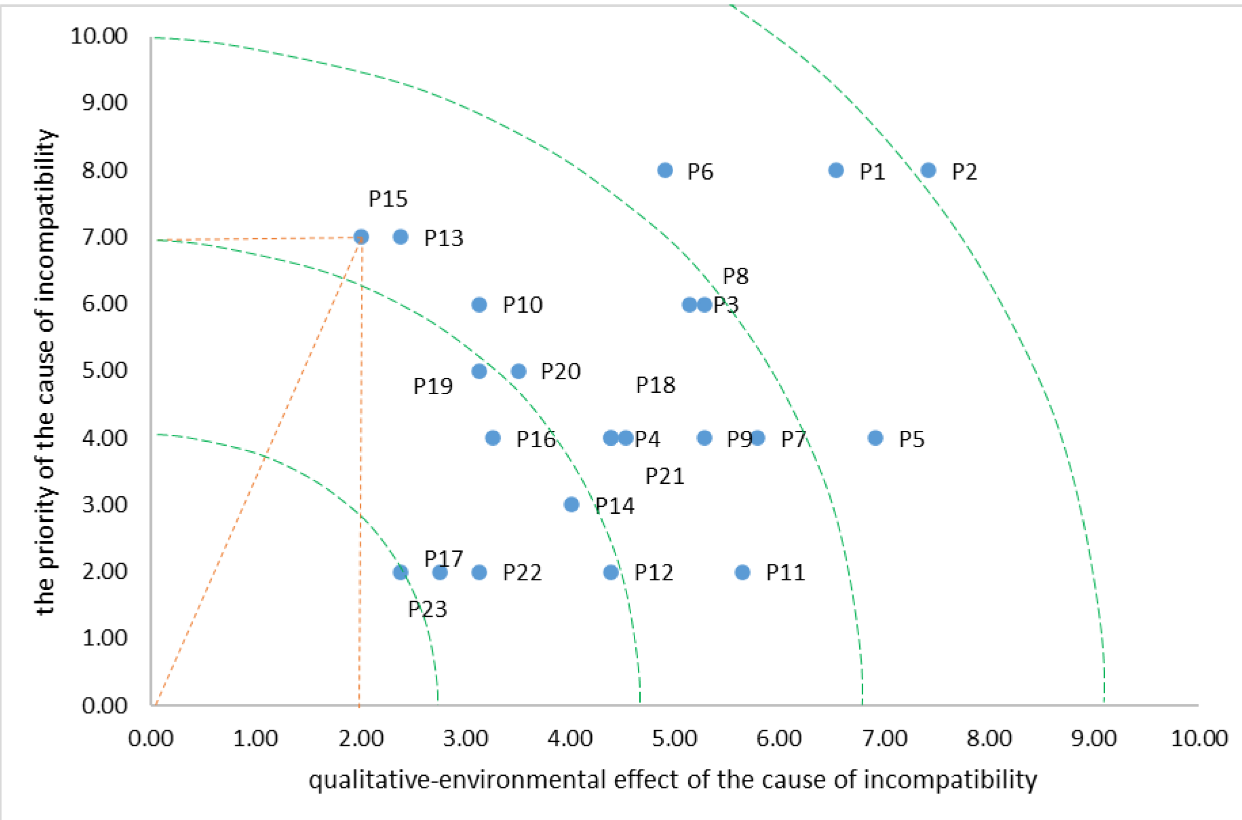

Figure 5. Analysis of causes of incompatibility considering qualitative–environmental effects and the risk of the occurring causes of incompatibility. Own study.

It was concluded that main causes were (P1) elongated and wide arc formed during a small current, (P2) elongated and wide arc formed during high welding speed, welding current too high, and (P5) high weld pool flow. These causes have the biggest negative impacts on the natural environment, and have significant impacts on the quality of the product and high risk of occurring. The improvement actions that can contribute to eliminating or minimising the occurrence of incompatibilities are, for example, using a short arc, i.e., reducing the welding voltage, leading the electrode at the right angle, using a welding technique consisting of the use of weavings supporting the electrodes on the edges of the weld, or reducing the welding current.

4. Discussion

Enterprises strive for effective management of the quality of products or processes. Quality management of product development is one of the essential elements supporting sustainable development [11,12]. To achieve sustainable development goals, it is necessary to meet customers' expectations and simultaneously reduce negative impacts on the natural environment [62–64]. The previous analyses focused mainly on the use of various instruments supporting quality improvement and reducing the negative impacts on the environment, e.g., the QFD method [23], and its modification [22], FMEA, TRIZ [27], FTOPSIS [8], LCA [26], DEMATEL [29], or VIKOR [30]. Nevertheless, the analyses to date have not sufficiently addressed the analysis of the causes of incompatibility of products or the processes that lead to their creation [65]; therefore, these analyses should address quality effects, environmental impacts [66], and the risk of the identified causes occurring. Hence, the purpose of this study was to develop a fuzzy method for the sustainable development of product and process improvement (FQE-SD method). Tests of the method were carried out on the issue of undercutting on an AMS6470 steel outer bearing product. After verifying the FQE-SD method, it was concluded that it can sustainable development principles. This method supports these actions by analysing and rating the causes of incompatibilities in products or processes. These analyses are realized in the fuzzy decision environment and simultaneously refer to the impacts of these causes on quality, environment, and risk of occurrence. After testing this method, it was possible to identify the following main benefits of the FQE-SD method:

- Sequential and consistent analysis of the causes of incompatibility of products or processes;
- Possibility to precisely determine the main causes of incompatibility of products or processes;
- Combining qualitative effects and environmental impacts into one quality–environmental indicator;
- Making decisions about the causes of non-compliance based on the verification of quality and environmental effects and the risk of their occurrence;
- Reducing inconsistencies and uncertainties in expert assessments by using Saaty's fuzzy scale;
- Support for the idea of sustainable development of products and their creation processes.

However, the limitations of the method concern the problem of analysing a very large number of potential causes because there is a need to compare them later in pairs. This determines the time-consuming nature of the method. In addition, a certain limitation is the need to conduct the analysis by a competent and properly selected team of experts.

The presented results confirm the possibility of the practical application of the FQE-SD method. Future research will be based on a combination of three indicators: quality, environment, and risk of occurrence. A procedure for dynamic analysis of potential causes, based on statistical analysis, will be developed as part of future research, the results of which will be presented in a separate article.

5. Conclusions

Improving the quality of products and the processes of their creation are basic activities of companies. However, in the era of climate change, actions should be taken not only to improve quality, but also to protect the natural environment. Hence, the purpose of this research was to develop a fuzzy method for the sustainable development of product and process improvement (FQE-SD method). The method was developed in a hybrid manner so that selected tools and elements of qualitative methods were combined and multi-criteria methods supported decisions. These integrated techniques were as follows: the SMARTER method, brainstorming (BM), a method of selecting the team of experts, the Pareto–Lorenz rule, the fuzzy QE-FMEA method, and the fuzzy AHP method. The FQE-SD method was verified in a case study of an AMS6470 steel outer bearing product, in which incompatibility was identified.

The method was developed and tested in nine main stages. The methodology of FQE-SD relies on an identified source of incompatibilities and then determining the potential causes. These causes were classified in view of qualitative, environmental, and risk indicators. These assessments were expressed in a fuzzy Saaty scale. The selection was conducted according to data sheets for these indicators. The qualitative and environmental assessments were then integrated to determine the qualitative and environmental impacts of the causes of the incompatibility of the product using the FAHP method. Then, a qualitative–environmental indicator analysis of the risk of occurrence was performed. As a result, it was shown that the main causes of outer bearing weld melting were elongated and wide arc formed during low current, elongated and wide arc formed during high welding speed, too high welding current, and large weld pool flow. Improvement actions have been proposed for these root causes. It has been shown that the FQE-SD method can support the process of improving products or processes according to the principles of sustainable development. The methodology was conducted by analysing and validating the causes of incompatibility simultaneously in terms of their impacts on quality, environment, and priority of occurrence in a fuzzy decision-making environment.

The originality of the FQE-SD method is its hybrid methodology, i.e., it combines (integrates) various techniques in a coherent manner. The method supports the implementation of the idea of sustainable development and, at the same time, the pursuit of high quality products or processes. This is conducted by analysing the qualitative and environmental effects of the causes of incompatibility of products or processes, as well as the risks of their occurrence. The method can be used for any products or processes where non-conformities have been identified. In particular, it will be useful for products or processes that have significant impacts on the natural environment.

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Appendix A

Table A1. Combined triangular fuzzy numbers of qualitative effects and impacts on the natural environment.

No.	Potential Causes	Combined TFN from Qualitative and Environment Ratings (QE)		
1	Elongated and wide arc formed during a small current	4	6	8
2	Elongated and wide arc formed during high welding speed	5	6.5	8
3	Incorrect electrode angle	2	5.5	9
4	Extensive weaving movements as part of the weld formation	2	4.5	7
5	Welding current too high	4	6.5	9
6	High flow of liquid weld pool	3	4.5	6
7	Unclean weld layer	4	5	6
8	Inappropriate joint ratio (too small width-to-depth ration)	3	5	7
9	Unsuitable material	3	5	7
10	Bad carbon content in the weld (too high)	1	3.5	6
11	Impurities inside the weld	3	5.5	8
12	Worker rushed the process	2	4.5	7
13	No periodic training	1	2.5	4
14	Little worker experience	2	4	6
15	Fatigue	1	2	3
16	Unsuitable welding tool	2	3	4
17	Inadequate lighting	1	3	5
18	No TPM performed (total productive maintenance)	2	4.5	7
19	Outdated procedures/instructions	1	3.5	6
20	Electrode moisture	1	4	7
21	Noise	3	4	5
22	No calibration of auxiliary tools	1	3.5	6
23	Poor psychophysical condition of the employee	1	2.5	4

Table A2. Fragments of the matrix of comparison in pairs of potential causes.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
P1	1.00; 1.00; 1.00	0.80; 0.92; 1.00	2.00; 1.09; 0.89	2.00; 1.33; 1.14	1.00; 0.92; 0.89	1.33; 1.33; 1.33	1.00; 1.20; 1.33	1.33; 1.20; 1.14	1.33; 1.20; 1.14	4.00; 1.71; 1.33
P2	1.25; 1.08; 1.00	1.00; 1.00; 1.00	2.50; 1.18; 0.89	2.50; 1.44; 1.14	1.25; 1.00; 0.89	1.67; 1.44; 1.33	1.25; 1.30; 1.33	1.67; 1.30; 1.14	1.67; 1.30; 1.14	5.00; 1.86; 1.33
P3	0.50; 0.92; 1.13	0.40; 0.85; 1.13	1.00; 1.00; 1.00	1.00; 1.22; 1.29	0.50; 0.85; 1.00	0.67; 1.22; 1.50	0.50; 1.10; 1.50	0.67; 1.10; 1.29	0.67; 1.10; 1.29	2.00; 1.57; 1.50
P4	0.50; 0.75; 0.88	0.40; 0.69; 0.88	1.00; 0.82; 0.78	1.00; 1.00; 1.00	0.50; 0.69; 0.78	0.67; 1.00; 1.17	0.50; 0.90.1.17	0.67; 0.90; 1.00	0.67; 0.90; 1.00	2.00; 1.29; 1.17
P5	1.00; 1.08; 1.13	0.80; 1.00; 1.13	2.00; 1.18; 1.00	2.00; 1.44; 1.29	1.00; 1.00; 1.00	1.33; 1.44; 1.50	1.00; 1.30; 1.50	1.33; 1.30; 1.29	1.33; 1.30; 1.29	4.00; 1.86; 1.50
P6	0.75; 0.75; 0.75	0.60; 0.69; 0.75	1.50; 0.82; 0.67	1.50; 1.00; 0.86	0.75; 0.69; 0.67	1.00; 1.00; 1.00	0.75; 0.90; 1.00	1.00; 0.90; 0.86	1.00; 0.90; 0.86	3.00; 1.29; 1.00
P7	0.75; 0.83; 0.88	0.60; 0.77; 0.88	1.50; 0.91; 0.78	1.50; 1.11; 1.00	0.75; 0.77; 0.78	1.00; 1.11; 1.17	0.75; 1.00; 1.17	1.00; 1.00; 1.00	1.00; 1.00; 1.00	3.00; 1.43; 1.17
P8	0.75; 0.83; 0.88	0.60; 0.77; 0.88	1.50; 0.91; 0.78	1.50; 1.11; 1.00	0.75; 0.77; 0.78	1.00; 1.11; 1.17	0.75; 1.00; 1.17	1.00; 1.00; 1.00	1.00; 1.00; 1.00	3.00; 1.43; 1.17
P9	0.75; 0.83; 0.88	0.60; 0.77; 0.88	1.50; 0.91; 0.78	1.50; 1.11; 1.00	0.75; 0.77; 0.78	1.00; 1.00; 1.17	0.75; 1.00; 1.17	1.00; 1.00; 1.00	1.00; 1.00; 1.00	3.00; 1.43; 1.17
P10	0.25; 0.58; 0.75	0.20; 0.54; 0.75	0.50; 0.64; 0.67	0.50; 0.78; 0.86	0.25; 0.54; 0.67	0.33; 0.78; 1.00	0.25; 0.70; 1.00	0.33; 0.70; 0.86	0.33; 0.70; 0.86	1.00; 1.00; 1.00

Where: P1—P10—as in Table A1.

Table A3. Fuzzy geometric mean value from assessments of quality and environment (QE) for problems on outer bearing.

No.	Potential Causes	Values of the Geometric Mean (QE)		
1	Elongated and wide arc formed during a small current	2.05	1.46	1.31
2	Elongated and wide arc formed during high welding speed	2.56	1.59	1.31
3	Incorrect electrode angle	1.02	1.34	1.48
4	Extensive weaving movements as part of the weld formation	1.02	1.10	1.15
5	Welding current too high	2.05	1.59	1.48
6	High flow of liquid weld pool	1.53	1.10	0.99
7	Unclean weld layer	2.05	1.22	0.99
8	Inappropriate joint ratio (too small width-to-depth ratio)	1.53	1.22	1.15
9	Unsuitable material	1.53	1.22	1.15
10	Bad carbon content in the weld (too high)	0.51	0.85	0.99
11	Impurities inside the weld	1.53	1.34	1.31
12	Worker rushed the process	1.02	1.10	1.15
13	No periodic training	0.51	0.61	0.66
14	Little worker experience	1.02	0.98	0.99
15	Tiredness	0.51	0.49	0.49
16	Unsuitable welding tool	1.02	0.73	0.66
17	Inadequate lighting	0.51	0.73	0.82
18	No TPM performed (total productive maintenance)	1.02	1.10	1.15
19	Outdated procedures/instructions	0.51	0.85	0.99
20	Electrode moisture	0.51	0.98	1.15
21	Noise	1.53	0.98	0.82
22	No calibration of auxiliary tools	0.51	0.85	0.99
23	Poor psychophysical condition of the employee	0.51	0.61	0.66

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