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A New QFD-CE Method for Considering the Concept of Sustainable Development and Circular Economy

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Abstract: The idea of sustainable development (SD) forces companies to combine the quality development of products with the simultaneous care of the natural environment. These actions should start with the product design process. The aim of the study was to create a modified method of Quality Function Development (QFD-CE), which will support the design of new products or improve the existing products on the market. In the proposed method (QFD-CE), the method integrates techniques such as: SMARTER method, brainstorming (BM), the method of selecting a team of experts, kinship diagram, fixed sum scale, and Likert scale. A novelty compared to the traditional QFD methodology is that design goals are set not only based on customer expectations, but also considering the impact on the natural environment. The originality of this proposition comes to the practical inclusion of including sustainability development criteria. The proposed method can be used in companies that design new products and are focused on caring for the natural environment. The QFD-CE method test method was performed for photovoltaic panels (PV). As part of the proposed QFD-CE method, the sequence of design activities was determined so that they meet customer expectations and can be simultaneously implemented according to the idea of SD. This method can be used for any product, mainly those that have a significant impact on the natural environment.

Keywords: QFD; quality function deployment; circular economy; customers' expectations; sustainable development; product improvement; production engineering; making decisions; mechanical engineering

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1. Introduction

Changes in the effectiveness of renewable energy resources (RES) and low-carbon technology are causing the global electricity supply to also change [1]. According to data from October 2022 [2], 90% of 139 countries established neutrality goals for carbon emissions by 2050. The reaction to these changes is important in view of responsibility for the environment, mainly in the areas of the philosophical function of the modern economy and taking care of the climate in case of anthropogenic climate changes [3]. In this area, the Intergovernmental Panel on Climate Change (IPCC) showed that to achieve a temperature reduction of 1.5 C around the world, it is necessary to achieve a net anthropogenic emission total of CO_2 of zero by 2050 [4]. To help with this, so-called green energy is being used [4–6]. Its use should have long-lasting benefits for the environment, for example, in reducing emissions related to electricity production, where, as stated by the International Energy Agency (IEA), more than 40% of all emissions are caused by electricity generation [7,8]. It is important to mention that around the world, fossil fuels emit approximately 34 billion tonnes of CO_2 annually, which causes threats to the environment and society [7]. Hence, it is necessary to manage social capital, but also, the economy and nature, which are pillars of sustainable development, i.e., society, economy, and environment improves economy [8].

Sustainable development supports the achievement of biodiversity, improvements of the circular economy, the saving of energy, the reduction of the carbon footprint, and the promotion of the effective management of resources and the improvement of the health and well-being of society [9].

As part of the realisation of the concept that the United Nations (UN) refers to, it is important to also include the relatively new area of this concept, which is a circular economy (CE) [10]. It refers to economic conditions targeted at the environment and sustainable development. The principles characterizing the circular economy consist of maintaining the value of products and materials for as long as possible and reducing waste and the consumption of resources [11]. The CE strives to close the loop in the use of raw materials and turn linear systems into circular ones [12]. It refers to those principles of CE that depend on maintaining the value of products and materials for as long as possible, and also reducing waste and the consumption of resources, and these resources should remain reusable after the end of the product's life [13,14]. The creation of a circular economy can support the reduction and limited use of sources, which could be a pillar for enterprises in the case of the creation of a product's value during its design. At the same time, designing products according to the principles of a circular economy provides financial savings, which have been shown by the authors of other studies, for example [15–18]. In the general approach, financial savings are caused by waste reuse, which occurs as part of extending the life of the product and resource recovery [11,19–22]. Currently, innovative actions do not only refer to enterprises, but also, are so-called "joint achievements" of companies and customers to achieve added value. It is confirmed by Wurster and others [11] that ecosystems of the circular economy, to be sustainable and innovative, should be destinations for customers. This is not only in line with the idea of a circular economy (within sustainable development), but also with the idea of continually improving products, where a key is to obtain and include the Voice of Customers (VoC) [23] during the design or improvement of products. The mentioned VoC allows the development of new products together with the customer, i.e., involving them in the product development process [20,21]. Hence, it is essential to take these expectations into account also in activities focused on the circularity and sustainable development of products. These expectations should be included in the early stage to include specific requirements, but also market conditions [22]. This can help to reduce failures. However, it is still difficult because it is common that companies focus on meeting customer satisfaction, that is, improving the quality criteria of products, while ignoring the environmental criteria [24]. In addition, the number of products on the market is very large, which is why companies strive to improve existing products and do not produce new ones. The difficult issue is also the fact that customer needs are becoming more and more demanding. The specific preferences of customers and their role in the creation of products according to sustainable development or the circular economy have not been sufficiently investigated, as confirmed by the authors of the studies [11]. Photovoltaic (PV) panels are one of those products that are developing dynamically, but have not been sufficiently tested in terms of meeting customer expectations and, at the same time, adapting to the circular economy [25–27].

Following the authors of [28–32], it was considered that extending the life of photovoltaic through repair and reuse, but also the recovery of materials through recycling, can contribute to minimizing the negative impact of products on the natural environment. As shown by the authors of [33], the photovoltaic power total in 2019 was equal to 114 GW, with a demand during that year of about 17.5%. Additionally, the population is expected to demand 700 GW by 2025 and about 4500 GW by 2050. Furthermore, as shown by the authors of [31], in 2016, the amount of photovoltaic waste reached 250,000 tonnes in the world. The authors of [30], who showed that grid-connected photovoltaic power has increased about 11 times in just five years, also confirmed the results. This development generates significant amounts of photovoltaic waste, which will only increase in the coming years. Hence, photovoltaics are a challenge for the waste management system. It results from the reduced impact of the life cycle on the environment by minimizing the consumption of

energy, costs, and greenhouse gas emissions caused by transport, the refining of materials, or the production and distribution of new photovoltaic energy (PV). Additionally, the use of the circular economy for photovoltaic energy is only in the initial phase. Therefore, a major barrier to its use, for example, is the lack of a standardized, recognized process for testing photovoltaic PV modules as part of their safe and effective reuse. At the same time, there are no mastered systems that would improve their optimal recovery. In this area, the literature review in this study was carried out. The main conclusion is that adjusting products (e.g., in the energy area and UN) to meet customer expectations according to sustainable development rules (including the circular economy) has been insufficiently researched. According to [32], techniques that support the implementation of sustainable development and the CE in the area of production for the generation of RES of energy (mainly for the mentioned PV) are necessary from a long-term perspective. According to the literature review, the most popular technique is Quality Function Deployment (QFD), which is the so-called implementation of the quality function or House of Quality (HoQ) [33]. The QFD method is the process of planning with a qualitative approach to the design, development, and implementation of new products, which is guided by the needs and values of the customers. QFD is a structured approach to define customer needs or requirements and convert them into concrete product production plans to meet these expectations [34].

Hence, the purpose of the research was to develop a new House of Quality method to design and improve products considering customers' expectations, ideas of sustainable development, and the circular economy. As part of the research, the following hypothesis was adopted:

Hypothesis 1. *It is possible to create of QFD-CE method that will allow for the design of new products or improve products existing on the market. Designing in this original way will include, simultaneously, aspirations for high-quality products and a minimalized impact on the natural environment.*

The proposed method was called QFD-CE, where the abbreviation "QFD" comes from the traditional name of the QFD method [35,36], whereas the abbreviation "CE" means, simultaneously, "customer" expectations" [5,6] and "circular economy" [37,38], which are combined as part of this method. Hence, the originality of the proposed method relies on:

- The extension of the traditional quality house methodology to the area of sustainable development, including the circular economy (CE), which will be confronted with the expectations of customers (CE);
- Adding new blocks in the house of quality intended for the expectations in terms of the environment in relation to the newly designed product;
- Inclusion in one block (at one level) of weights not only for quality criteria (customers' criteria), but also weights for environmental criteria (sustainable development and circularity), where these weights will be correlated with the weights of technical criteria;
- Implementation of other techniques supporting it in this method, mainly decision-making support;
- Determining purposes to design purposes according to customers' expectations towards the products' quality and its impact on the natural environment;
- Possible use of QFD-CE for any product, hence, this method can be useful for enterprises that want to design and improve products according to the idea of sustainable and continuous development.

The scientific aspect of the article is the creation of a new, original method that also takes into account environmental aspects (sustainable development) in designing high-quality products. The developed method QFD-CE was tested. The test was carried out for photovoltaic panels, which are the most popular ones in the field of renewable energy sources. In the next part of the study, the model of QFD-CE method is shown. Then, the QFD-CE method is described and tested.

2. Literature Review

The literature review was conducted using studies in the area of design and improvement of different products in the context of sustainable development, where the analysis focused on using the QFD method in this way and, simultaneously, the circular economy, and also producing green energy or policies on energy efficiency [39]. The review focused on using the most popular method, which is QFD, and its use for these types of products. During the review, it was verified whether the requirements of customers, the idea of sustainable development, and circularity were also taken into account for the RES. For example, the authors of [40] analyzed the savings of the analysis of the hydraulic cylinder piston seal. The QFD method was used to determine the customer requirements and align them with the technical requirements. The purpose was to design this seal, and possibly, to reduce the environmental pollution and energy consumption from oil spills. The authors of [41] used the QFD method to design the most advantageous RES energy production system that can be used in various areas and for different types of use. Ultimately, wind turbines were chosen. Another example is [42], in which the Axiomatic Design model, the model, the QFD method, and the TRIZ method (Inventive Problem Solving Theory) were used in a combined combination. The idea was to design products as part of Green Design, so that energy will be saved. The next example is [43], which is a study that analyzed energy saving and improved the way that wells are pumped. Similarly, as mentioned previously, the QFD method and the TRIZ method were used in a combined way. Another example is shown in [44], where by using integrated techniques, which were QFD and TRIZ, the production design reduced the time, consumption of material, energy, and waste. A similar combination of methods was proposed in [45]. Additionally, the authors of [46] analyzed the innovation strategy in the field of green supply chain management. For this purpose, the QFD method was designed, which was supported, for example, by the DEMATEL method. It has been shown that it is important for companies to properly manage their energy in the context of a green supply chain. The next example is an article [47] that used the fuzzy quality function (FQFD) to improve energy effectiveness in enterprises, for example, the generation, transmission, and distribution of electricity. The fuzzy range of values in the QFD method was also used by the authors of [48], where an analysis of the development of photovoltaic technology was carried out. In [49], a two-slice Pythagorean analysis using FQFD was proposed. This involved an analysis of the costs and duration of innovation for energy from renewable energy sources. The analysis of renewable energy sources (RES) was carried out by the authors of [30,47,50]. The analysis of renewable energy sources (RES) was carried out by the authors of these papers. It consisted of the selection of an appropriate RES, where this selection was supported by the AHP (analytical hierarchy process) method and the QFD method. A similar example is presented in [51], in which four solar power plants were selected for energy production in Chile. The QFD method was used for this. Additionally, the literature review was carried out in the context of using the QFD method and, simultaneously, the circular economy. The authors of [52] proposed the methodology PPS (Product Services System) to analyze different criteria of products to achieve better environmental effectiveness. In this approach, techniques such as the QFD method, SLCM method (Screening Life Cycle Modeling), and FAHP (Fuzzy Analytic Hierarchy Process) method were used. The SLCM method assesses the possible results and determines the impact on the natural environment and the current solution of the producer. In turn, the authors of [53] used the aforementioned PPS method to design environmental products and services. With this aim, the navigator of the system (LFD—Lifecycle-Oriented Function Deployment) was used. The LFD system is based on LCA (Life Cycle Assessments) and also the QFD method. In this method, the customers' expectations about product attributes were obtained. Then, based on these expectations, the design decisions aimed at reducing the impact on the natural environment were realized.

Based on a review of the literature on the subject, it was shown that the QFD method is used in complex ways to design products responding to the collected customer expectations, for example as shown in the studies [40,41]. This method was used to analyze problems related to energy, including renewable energy sources (e.g., for popular photovoltaic panels). The QFD method was combined with other techniques, mainly the TRIZ method [42], fuzzy numbers, or decision support methods [50,51]. It has been shown that there have been very few papers in which an attempt was made to use the QFD method to analyze the circular economy criteria, e.g., [52,53]. However, the QFD method has not been modified so far in order to take into account the expectations of customers and circularity in terms of sustainable product development. It refers to the lack of the QFD method to ensure simultaneous consideration of customer expectations (product quality criteria) and the impact of the product on the natural environment in the context of sustainable development (including circularity). This was considered to be a research gap that needed to be filled. For this purpose, the QFD-CE method was developed, which is presented in the next part of the article. It was considered to be crucial to developing this method, which was created in accordance with the concept of the QFD method and the closed circuit. This is because the Quality Function (QFD) is one of the most popular methods for designing new products or improving existing products on the market [46,49,54]. It is an important method because in a competitive economy, it is important to design and improve products so that they are satisfactory for customers. In turn, the continuous improvement of production contributes to the increase in the waste of raw materials. In order to offset this negative impact on the natural environment, the implementation of a circular economy system is becoming more and more popular in practice [29,55]. Therefore, the circular economy is important because it is one of the basic ways to reduce the negative impact on the natural environment. The model of the QFD-CE method is shown in the next part of the study.

3. Model of QFD-CE Method

3.1. General Concept

The general concept refers to improving the QFD method (Quality Function Deployment) [35], also called a quality function or House of Quality (HoQ). Improving this method refers to an expansion of this method to allow us to determine the rules of designing new products or rules to improve the products already present on the market. The mentioned rules will be determined by simultaneous analyses to meet the expectations of customers and the ideas of sustainable development (including the circular economy) [56]. The concept of the method relies on the developed quality house matrix to designate correlations between the technical criteria (measurable) of the product and the product criteria determined by customers, which, simultaneously, will refer to environmental aspects of the product (i.e., sustainable development and circular economy). These dependencies will also consider the importance of these criteria for customers, as shown in Figure 1.

Additionality, the proposed QFD-CE method was extended to other techniques, i.e., the SMARTER method (S—specific; M—measurable; A—achievable; R—relevant realistic, or reward; T—'based on timeline' or timebound; E—exciting or evaluated; R—recorded or reward) [57], the brainstorming method (BM) [58], the method of selecting a team of experts [21], the kinship diagram [59], the fixed sum scale [60], and Likert scale [61]. A detailed description of the proposed QFD-CE method is presented later in the article.

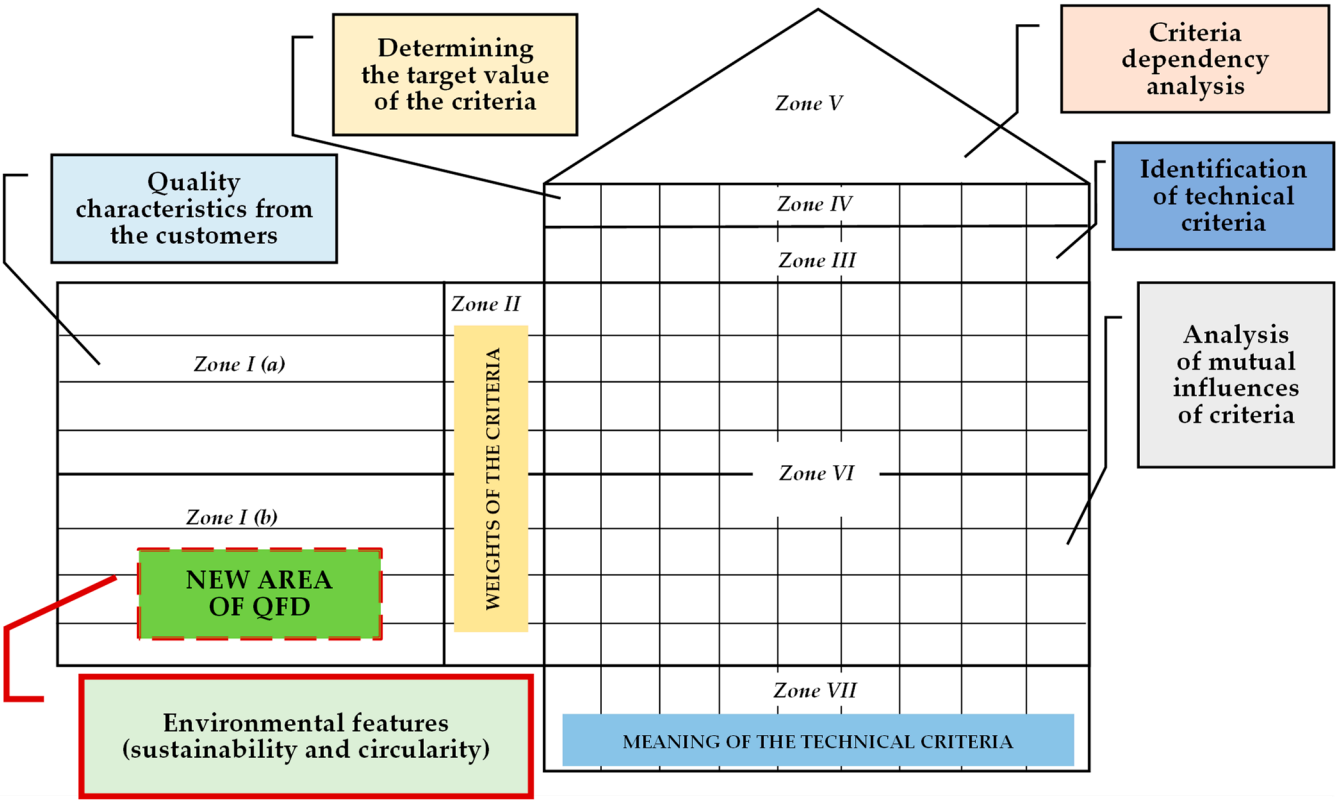


Figure 1. New House of Quality according to the developed QFD-CE method in our own study.

3.2. Assumptions

The assumptions for the QFD-CE method were adopted on the basis of the traditional QFD method, a review of the literature on the subject, and according to the principles of selected techniques supporting the proposed method. To better understand the proposed method, it is useful to devise a way to name the criteria, as shown in Table 1.

Table 1. Approach to combine criteria in the proposed method in out own study.

Name of Criteria	Type of Criteria
Customers' criteria	Criteria determined by customers
Environmental criteria	Circular economy criteria and sustainable development criteria
Qualitative criteria	Criteria determined by customers + environmental criteria
Technical criteria	Measurable criteria which are selected based on catalogue of product

The total number of criteria (customer and environmental) should not exceed 25, while similarly, the number of qualitative and technical criteria should be in the range from 14 to 25 [5,22]. The assumptions of the QFD-CE method were as follows:

- The number of product for the research is unlimited [21,62];
- Qualitative criteria are criteria determined by the customers, so-called subjective criteria [4], and in these criteria, it is necessary to include environmental criteria, which are the circular economy criteria and sustainable development criteria [63,64];
- Refs. [63–65] proposes a systematic the total number of qualitative criteria should be equal from 14 to 25 [5,22];
- Technical criteria are measurable criteria, which are selected based on a catalogue of products, and the number of technical criteria should be equal to between 14 and 25 [5,22];
- Dependencies between technical criteria are determined for qualitative criteria (i.e., customer's criteria, sustainable development, and circular economy criteria);

- The weight of the qualitative criteria (i.e., customers' criteria, sustainability criteria, and CE criteria) is determined by customers according to a fixed sum scale, and then converted by experts into a Likert scale [60,61].

The weights of the criteria are determined by the customers. It is assumed that these criteria in the input have the same weight (the customers' criteria, which refer to the quality of the product, are not more important than the environmental criteria, which refer to the impact product on the natural environment, and vice versa). This means that customer criteria (which relate to product quality) are just as important as the environmental criteria relating to the environmental impact. The final weights of the quality and environmental criteria are determined on the basis of information obtained from customers. On the basis of these weights, but also the correlation of these criteria, the weights of the technical criteria are determined.

The adopted assumptions were the basis for the development of the proposed method, the description of which is presented in the next part of the study.

3.3. Description of QFD-CE Method

The QFD method was modified. This modification relied on its improvement to allow the design and improvement of products according to the customers' expectations and including the idea of sustainable development and the circular economy (CE). This method was developed according to the traditional QFD methodology in nine main stages, as shown in the model of the method (Figure 2). The characteristic way of improving the QFD method is shown in a form of descriptions of the stages of the QFD-CE method, as shown in the next part of the study.

3.3.1. Stage 1: Selection of the Subject of Research and Definition of the Purpose

The products available for research are unlimited, for example, the products in the design phase or the products available on market [21,62]. The choice of the subject of research is made by the entity (expert, e.g., designer or enterprise manager). The choice may depend on the requirements (customer applications) or market observations or the phase of the product's life, e.g., maturity [22]. At the same time, it is good to draw attention to the impact of the product on the natural environment or the need to design or modify the product according to the principles of sustainable development and circularity [66,67]. In the case of modifying (improving) a product, it is recommended that it be popular and widely available to meet the customers' expectations for this product as precisely as possible.

Based on a selected topic of research, it is possible to determine the purpose of the research. The purpose of the research is determined by the entity (expert). In the proposed approach, the purpose is to determine the importance of design assumptions or improvements of the product considering the customers' expectations and sustainable development criteria (including circular economy criteria). To precisely determine the purpose, the SMARTER method should be used [57].

3.3.2. Stage 2: Selection of a Team of Experts

As part of the proposed QFD-CE method, it is necessary to select a team of experts. The team of experts is responsible for completing the selected stages of this method and achieving the purpose of the investigation. Hence, the team of experts should have knowledge and experience in designing and improving products and, simultaneously, should have basic knowledge about sustainable development and the circular economy. The method for selecting a team of experts is presented in [21]. In this method, the kind of criteria used for recruit experts, were, i.e., the factor of the degree of knowledge of the problem of the experts and the factor of arguments, based on which, the competence factor is calculated.

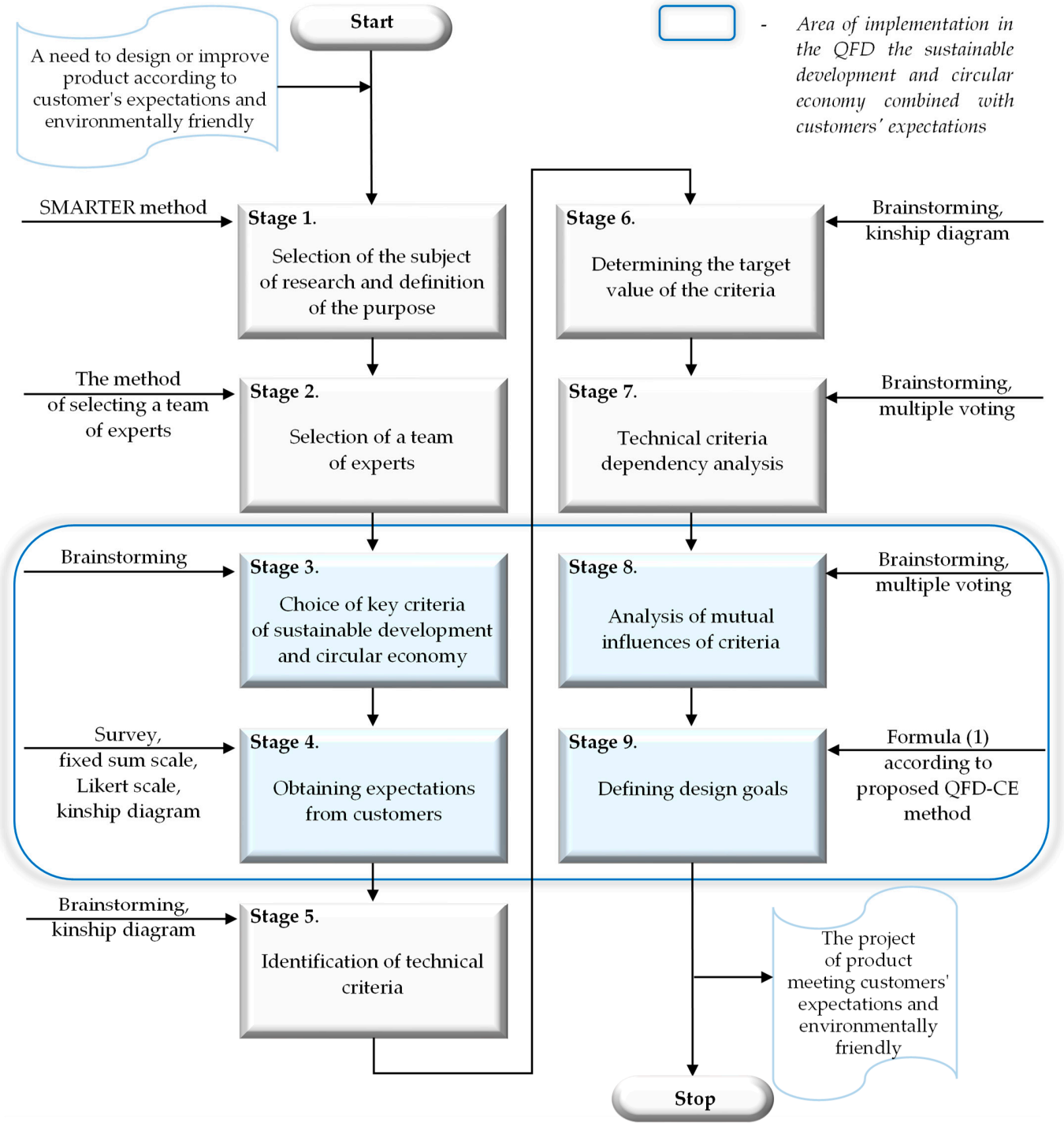


Figure 2. Model of QFD-CE method in our own study.

3.3.3. Stage 3: Choice of Key Criteria of Sustainable Development and Circular Economy

As part of the extension of the traditional QFD method, it was proposed to analyze possibilities of designing or improving products, not only according to the customers' requirements, but also according to the sustainable development criteria and circular economy criteria. The sustainable development criteria and circular economy criteria were accepted to be called 'environmental criteria'. These criteria are selected by a team of experts during brainstorming (BM) [58] based on basic criteria presented in the subject of the literature, so the economic, environmental, and social criteria, i.e., [68–74]:

- Basic sustainable development criteria;
- Criteria for sustainable economic development, e.g., cost of energy production, cost of recycling activities, production cost, and lower energy consumption for raw materials, for example, use of waste (%), less use of materials (%), and machine set-up time for new products;
- Environmentally sustainable criteria, e.g., non-processing energy, emissions of CO_2, energy consumption, number of machine settings to minimize waste, wastewater, greenhouse gases, less use of natural resources, non-toxic materials, modularity, and potential for reuse or recycling;
- Socially sustainable criteria, e.g., low labor utilization threshold, high employee learning rate, and low forgetting rate;
- Basic circular economy criteria, i.e., reduce, reuse, and recycle, which are characterized in the literature, e.g., [75], but also in the next Section of the article (Section 4).

The final selection of sustainability and circularity criteria depends on the nature of the subject of research and the production capacity of the company. Therefore, the selection is made by a team of experts. Following the authors of [22,76], it was assumed that the total number of customer criteria and sustainability criteria (including circularity) should be from 14 to 25 criteria. The environmental criteria are recorded in zone I (b) in the QFD-CE framework.

3.3.4. Stage 4: Obtaining Expectations from Customers

As part of the QFD-CE method, it is necessary to obtain expectations from customers. As part of the initial research, it was assumed that it will be enough to obtain expectations from at least 10 customers [77,78]. According to the authors of [60,79], it was assumed that the minimum sample size should be equal to 100 customers. Although estimating a needed sample size will be useful to use the method shown in the study, i.e., [22].

It is carried out through survey research (questionnaire). The purpose of the survey is to determine what product criteria are important for customers, and then what is the importance (weight) of these criteria. As part of the proposed method, qualitative (customer) criteria, sustainable development criteria, and circular economy criteria are included, the so-called "environmental criteria". The environmental criteria included in the survey are criteria that were selected by a team of experts in the fourth stage of the method. However, qualitative criteria are determined by the customers. However, it is possible to propose a few examples of criteria for products (main or basic criteria). Despite that, customers should independently determine criteria that are important to them. It should be remembered that the client's criteria will be vague, subjective, and expressed in a general way [47]. In addition, the customers' criteria can be different. Following the authors of [33,36], as part of systematizing these criteria, it is proposed to develop a kinship diagram, which is a tool for the so-called new quality management tools. This diagram is effective in prioritizing customer attributes. The effective development of a kinship diagram is possible as part of teamwork and, for example, during brainstorming (BM). It is necessary to group all the qualitative criteria according to their similarity. Most often, several coherent groups of criteria are created, that is, from two to four groups [36] The customer-specified criteria are recorded in zone I (a) of the QFD-CE framework.

Then, customers determine the importance of the product criteria. Weights are determined simultaneously for qualitative and environmental (sustainability development circular economy) criteria. The importance of criteria is determined according to a fixed sum scale, that is, by dividing 100 points between the individual criteria [33,60]. The higher the value is, the more important the criterion is. The values are saved by the customer in the survey. These values should then be converted into criteria weights. The weight can be determined according to the Likert scale, that is, a number between one and five [36,61]. To assign weights to the criteria according to the values obtained by the customers, it is proposed to sum up all the values of individual customers for a given criterion. Then, these criteria should be divided into five groups, where the division will result from the obtained

sum of the weight values. The largest value pools are weighted at five (most important criteria), while the smallest value pools are weighted at one (least important criteria). The weights of the quality and environmental criteria are recorded in the second zone of the QFD-CE framework.

3.3.5. Stage 5: Identification of Technical Criteria

In this stage, it is necessary to determine the technical criteria of the product, so the design criteria. These criteria should be measurable [26]. In order to determine these criteria, it should be based on a catalogue of products. Then, according to the kinship diagram, it can be possible to divide them (similar to the fourth stage of the method for qualitative criteria). The technical criteria should be taken into account in the III zone of the QFD-CE framework.

3.3.6. Stage 6: Determining the Target Value of the Criteria

The next stage is creating a so-called "roof" for the house in the QFD-CE method. It is achieved for each technical attribute of the product. It consists of determining if the value of the technical product criteria should be: maximized (↑), minimized (↓), or should it be optimized (○), that is, have a given value [36,80]. This should be recorded in zone IV of the QFD-CE framework.

3.3.7. Stage 7: Technical Criteria Dependency Analysis

Between technical criteria of a product is the dependence, the so-called mutual influences. According to the traditional approach in the QFD method, it is assumed that the impact can be: positive (+), negative (−), or nominal (•). A positive impact is when the improvement of one of the criteria has a positive impact on the other criterion, i.e., it also allows for its improvement. A negative impact is one where an improvement in one of the criteria negatively affects the other criterion. On the other hand, the nominal impact occurs when there is an optimal combination of two parameters [33,80]. Dependencies are saved in zone V of the QFD-CE framework.

3.3.8. Stage 8: Analysis of Mutual Influences of Criteria

The main stage in creating of the proposed QFD-CE method is determining the mutual influences of criteria belonging to three groups, i.e., customer criteria (qualitative), environmental criteria (sustainable development and circular criteria), and technical criteria. Mutual influences between these criteria are determined by team of experts using: weak (Δ—rating 1), average (O—rating 3), strong (■—rating 9), or no dependence labels (no marking—rating 0) [36,81]. Mutual influences are recorded in zone VI of the QFD-CE framework.

3.3.9. Stage 9: Defining Design Goals

In this stage, the product design goals should be defined, i.e., the sequence of actions to be taken to achieve the product quality expected by customers, which will also be environmentally friendly. It is based on determining the importance of the technical product criteria [36,54,82]. It is realized according to previous analyses realized for technical criteria, and dependencies, and mutual influence with customer and environmental criteria. Furthermore, in this stage, the weight of the criteria (from Step 4 of the method) is taken into account, as shown in Formula (1) [33]:

$$T_j = \sum_{j=1}^{1} W_j \quad (1)$$

where i—technical criteria; j—customer and environmental criteria; W_j—weight of customer's criterion or environmental criterion, i, j = 1, 2, 3, . . . , n.

The higher the value of the technical criterion is, the more important the criterion is for the customer, and at the same time, it has a more positive impact on the natural environment.

Therefore, the highest value (T_j) is the first goal, while the lowest value (T_j) is the last design goal. The result of this stage is recorded in zone VII of the QFD-CE framework.

4. Results

A test of the improvement of the QFD-CE method was carried out for products belonging to renewable energy sources (RES). These were photovoltaic panels (PV). The choice of photovoltaics resulted from its popularity for producing hot water. Furthermore, photovoltaic panels are considered to be one of the key devices for producing green energy [25,26]. The method test was carried out according to the nine main steps in the method model.

4.1. Stage 1: Selection of the Subject of Research and Definition of the Purpose

A test of the proposed method was carried out for PV, one of the key producers of UE. The choice of these types of products resulted from their popularity and universality in recent years. In addition, the increased production of these products caused a large number of recalled photovoltaic equipment, e.g., modules, to lead to supply chain and environmental problems. An example is the need to use, e.g., solar-grade polysilicon (c-Si), photovoltaic cells, and modules. The production of photovoltaic energy requires the import of elements of these products, which also result in a negative impact on the natural environment. At the same time, the growth of PV production has resulted in the growth in the number of these products, and also the need for the extraction of raw materials, i.e., silicon, indium, silver, tellurium, and copper. For this reason, it is justified to choose this subject of research in terms of RES products. According to the authors of [28], efforts have been made in the American industry to develop solutions that support photovoltaic production in the context of sustainable development and the possibility of identifying the barriers to using these products in the context of circular economy application.

According to the selected research topic, the purpose of the research was determined. For that, the SMARTER method [57] was used. In the proposed approach, the purpose was to determine the dependence of designing or improving photovoltaic panels considering the customers' expectations and sustainable development criteria (including the circular economy criteria).

4.2. Stage 2: Selection of a Team of Experts

In this stage, a team of experts was selected. The method shown in [21] was used for that. The experts in the team were among the authors of this study. The team of experts was responsible for the implementation of the remaining stages of the QFD-CE method, where this implementation was carried out according to the method model.

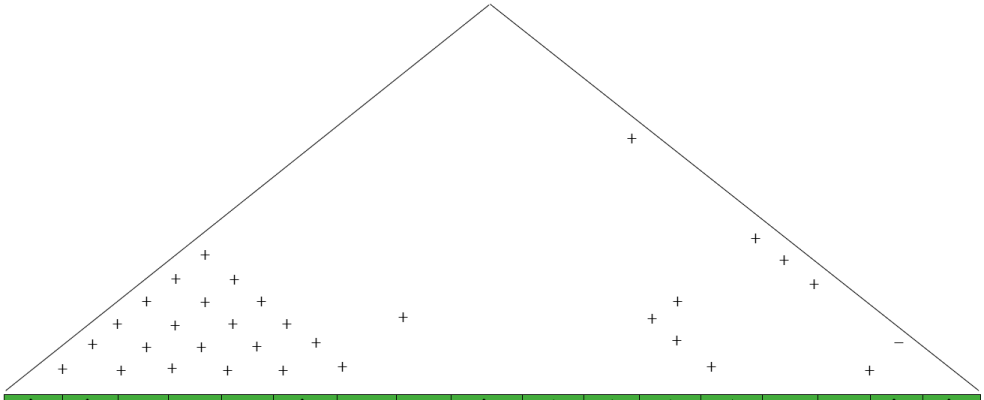
4.3. Stage 3: Choice of Key Criteria of Sustainable Development and Circular Economy

As part of the extension of the traditional QFD method, it was proposed to include sustainable development criteria and circular economy criteria. According to these assumptions, these criteria were called "environmental criteria". The environmental criteria were selected by a team of experts during brainstorming (BM) [58] and based on the literature review of studies, e.g., [68–74]. These criteria were as follows:

- Sustainable development criteria;
- Criteria for sustainable economic development, i.e., the possibility of using waste (%) and less material consumption (%);
- Environmentally sustainable criteria, i.e., energy consumption and number of machine settings to minimize, e.g., waste, sewage, greenhouse gases, less use of natural resources, and non-toxic materials;
- Socially sustainable criteria, i.e., effective and productive use of labor;
- Basic circular economy criteria [75];

- Reduce—reducing the amount of materials, resources, or waste generated as a result of increased production and consumption efficiency, while minimizing the amount of such waste and the negative impact on the natural environment;
- Reuse—reuse materials, products, or components that have not been wasted for the same purpose, where their use requires less resource and energy consumption than it does in the case of the need to produce them in a new state;
- Recycling—any recovery operation that ensures the reprocessing of waste into products, materials, or components, so that they can be used for the same or a different purpose; refers to the process by which used or waste materials are treated so that they can be reused.

These criteria were considered to be suitable for photovoltaic panels. As a result, several sustainability and circularity criteria were selected. These criteria were included in zone I (b) of the QFD-CE framework (Figure 3).



		↑	↑	◦	◦	◦	↑	◦	◦	↑	↓	↓	↓	↓	◦	◦	↑	↑
		Rated power (Wp)	Short-circuit current (A)	Max. current (A)	Idle voltage (V)	Max. tension (V)	Efficiency (%)	Max. tension (VDC)	Black color	Warranty period (years)	Length (mm)	Width (mm)	Thickness (mm)	Weight (kg)	Frame	Type of cells	Number of cells	Kinematics
Light weight	1										0	0	0	■	Δ		0	Δ
Low thickness	1												■	0	Δ	Δ		
Availability of various shapes	1																	Δ
Easy assembly	1										Δ	Δ	Δ	■	Δ			■
High corrosion resistance	2						Δ								0			
High heat/fire resistance	2						Δ											
Long warranty period	3									■								
Validity of technical criteria considering qualitative criteria		0	0	0	0	0	4	0	0	27	4	4	13	21	3	1	3	11
Ranking of technical criteria considering qualitative criteria		11	11	11	11	11	5	11	11	1	5	5	3	2	8	10	8	4
Possibility of using waste (%)	2														Δ	■	0	0
Less material consumption (%)	2								Δ					Δ			0	■
Reduction of waste	3									Δ					Δ	■	0	Δ
Reduction of wastewater	2									Δ								
Reducing greenhouse gases	5	Δ	Δ	Δ	Δ	Δ	Δ	Δ		Δ								
Less use of natural resources	5								0	■						0		0
Non-toxic materials	5								0	Δ					Δ	■		0
Effective and productive use of labor	3						0			■								
Limitation	4						0			Δ	Δ	Δ	Δ	Δ		■	0	0
Recycling	4							0	0	Δ	Δ	Δ	Δ	Δ		■	0	■
Reuse	4									Δ	Δ	Δ	Δ	Δ	■	■	0	0
Validity of technical criteria considering qualitative and environmental criteria		5	5	5	5	5	30	17	44	126	16	16	25	35	49	214	60	128
Ranking of technical criteria considering qualitative and environmental criteria		12	12	12	12	12	8	10	6	3	11	11	9	7	5	1	4	2

Figure 3. Quality environmentally modified House of Quality (QFD-CE) developed for the example of photovoltaic panels in our own study.

4.4. Stage 4: Obtaining Expectations from Customers

In the proposed QFD-CE method, it was necessary to obtain customers' expectations about photovoltaic panels. Based on the method test and following the authors [63,77,78], a minimum sample size was obtained that was equal to 10 customers. The expectations were obtained by survey research. The purpose of the research was to determine which criteria of the product were important to the customers, and then what importance these criteria had. The qualitative (customers') criteria were determined by individual customers. To systematize the criteria obtained, a team of experts developed a kinship diagram during a brainstorming session [33,36]. Its result is presented as a list of criteria grouped into three categories:

- Efficiency of the photovoltaic panel;
- High power;
- High-level performance;
- Minimal energy loss;
- Appearance of the photovoltaic panel;
- Color;
- Small dimensions;
- Small dimensions;
- Small thickness;
- Availability of different shapes;
- Functionality of the photovoltaic panel;
- Easy assembly;
- High corrosion resistance;
- High heat/fire resistance;
- Long warranty period.

These customers' criteria are noted in zone I (a) in the QFD-CE framework.

Then, the customers determined the importance of the PV criteria. The survey was used again for that. The weight was determined for grouped qualitative and environmental criteria (sustainable development criteria and circular economy criteria). The importance of the criteria was determined according to the scale of a fixed sum, i.e., by dividing 100 points between the individual criteria [33,60]. The higher the value is, the more important the criterion is. Customer weights were processed according to criteria weights on the Likert scale [36,61]. To determine the weight of the criteria according to the values obtained from the customers, all the values from each customer for the criterion were summed. Then, the team of experts divided these criteria into five groups, as assumed in the fourth stage of the general model of the method. The result is presented in Table 2.

Table 2. The importance of PV criteria according to customers in our own study.

No.	Type/Group of Criterion	Criteria of Photovoltaic Panels (Qualitative and Environmental)	Sum of Values from Customers	Criteria Weight
1	Efficiency of the photovoltaic panel	High power	82	5
2		High-level performance	78	
3	Environmentally sustainable criteria	Non-toxic materials	78	
4		Reducing greenhouse gases	76	
5		Less use of natural resources	72	
6	Basic circular economy criteria	Limitation	62	4
7		Reuse	62	
8		Recycling	58	

Table 2. *Cont.*

No.	Type/Group of Criterion	Criteria of Photovoltaic Panels (Qualitative and Environmental)	Sum of Values from Customers	Criteria Weight
9	Socially sustainable criteria	Effective and productive use of labor	52	3
10	Environmentally sustainable criteria	Reduction of waste	50	
11	Functionality of the photovoltaic panel	Long warranty period	42	
12	Efficiency of the photovoltaic panel	Minimal energy loss	40	
13	Environmentally sustainable criteria	Reduction of wastewater	36	2
14	Sustainable economic development	Possibility of using waste (%)	32	
15	Functionality of the photovoltaic panel	High corrosion resistance	30	
16		High heat/fire resistance	30	
17	Sustainable economic development	Less material consumption (%)	30	
18	Appearance of the photovoltaic panel	Light weight	24	1
19		Color	22	
20		Availability of various shapes	12	
21	Functionality of the photovoltaic panel	Easy assembly	12	
22	Appearance of the photovoltaic panel	Small dimensions	10	
23		Low thickness	10	

It was observed that criteria referring to the effectiveness of PV and criteria including sustainable development in the group of environmental criteria (impact on the natural environment) are the most important for customers. These criteria were rated five on the Likert scale. These were: high power, high efficiency, non-toxic materials, reduction of greenhouse gases, and reduced use of natural resources. The weights of the criteria were recorded in zone II of QFD-CE framework (Figure 3).

4.5. Stage 5: Identification of Technical Criteria

In this stage, the team of experts determined the technical criteria of photovoltaic, so the design criteria. These criteria were generated during brainstorming (BM), where additional focus was given to the catalogue of PV. After determining these criteria, they were grouped according to the rules of the kinship diagram, which are:

- Electrical criteria;
- Rated power (Wp);
- Short-circuit current (A);
- Maximum current (A);
- No-load voltage (V);
- Maximum voltage (V);
- Efficiency (%);
- Application criteria;
- Maximum system voltage (VDC);
- Color;
- Warranty period (years);
- Mechanical criteria;
- Length (mm);
- Width (mm);
- Thickness (mm);
- Weight (kg);
- Design criteria;
- Frame;
- Type of cells;
- Number of cells;
- Kinematics.

The characteristics (description) of all the criteria are presented in the literature on the subject, i.e., [6]. All the technical criteria are recorded in zone III of the QFD-CE framework (Figure 3).

4.6. Stage 6: Determining the Target Value of the Criteria

Then, the team of experts developed the so-called "roof" of the QFD-CE framework. For each technical criterion of PV, they determined if the value of the criterion should be: maximized (↑), minimized (↓), or optimized (○) [36,80]. This was recorded in zone IV of the QFD-CE framework (Figure 3).

4.7. Stage 7: Technical Criteria Dependency Analysis

According to the assumptions of the QFD-CE method, the team of experts determined the mutual dependency impact between the technical criteria of PV. As assumed, this impact could be: positive (+), negative (−), or nominal (•) [33,80]. The results of this stage are shown in the IV zone of QFD-CE framework (Figure 3).

4.8. Stage 8: Analysis of Mutual Influences of Criteria

In this stage, the team of experts identified the mutual influences of the PV criteria belonging to three groups, i.e., customer criteria (qualitative), environmental criteria (sustainability and circularity), and technical criteria. Markings were used for this, i.e., weak (Δ—rating 1), average (O—rating 3), strong (■—rating 9), and no dependence (no marking—rating 0) [36,81]. The result of this stage is presented in zone VI of the QFD-CE framework (Figure 3).

4.9. Stage 9: Defining Design Goals

In the final stage, the design goals of the photovoltaic panels were defined. It consisted of determining the sequence of actions to be taken in order to achieve the PV quality expected by customers, which at the same time would be environmentally friendly. Formula (1) was used for this. The result of this stage is presented in zone VII of the QFD-CE framework.

The quality environmental framework for photovoltaic developed according to the proposed QFD-CE method is shown in Figure 3.

The relationships between the criteria were established by a teamwork of experts. The signs and fields in the quality framework shown in Figure 3 are interpreted in the same way as they are in the case of the traditional QFD method. Symbols are also discussed in the description of the QFD-CE methodology. The most important technical criteria resulting from the conducted method are based on quality and environmental criteria and their weights, and these are the criteria with the highest number of points obtained. Their rankings from the most important to the least important are presented in the last row in Figure 3. In the process of constructing a new product, the best criteria in this ranking should be taken into account in the first place in relation to the other technical criteria. The method of obtaining the ranking is important because it takes into account not only the qualitative, but also the environmental, criteria. Based on the analysis, it was concluded that the most important criteria for PV were: (1) type of links, then (2) kinematics, (3) warranty period, (4) number of links, (5) frame, (7) weight, (8) efficiency, etc. These criteria in this order show what order the design actions should be taken (perfecting PV). The design actions are designated as part of the proposed concept of the QFD-CE method, so that they can meet customers' expectations and can be simultaneously made according to the idea of sustainable development and circular economy (CE).

5. Discussion

In the period of dynamic climate change, it is necessary to manage social, but also economic and natural, capital [83]. They are the pillars of sustainable development, i.e., society, economy, and environment [84,85]. However, achieving sustainable development is

problematic in the area of the economy [86–88]. Simultaneously, it can be observed that the phenomenon of consumerism is related to the quality of products [89]. Hence, production should allow the best possible circular economy of these products [90–92]. Although, customers' expectations of product quality can interfere with the functioning of the natural environment, so they could have a negative impact on the natural environment [93,94]. It was shown that a hitherto popular tool to improve the quality of the products was the QFD method [95]. The QFD method has been integrated with various methods, e.g., DEMATEL, TRIZ, AHP, or FAHP, as shown in [40,49,96]. The combinations of these methods allowed for better results in specific decision-making situations. Therefore, it was considered that introducing new methods or integrating methods improves the QFD method for specific solutions. However, the QFD method has not been sufficiently improved in terms of considering circularity, which is important because the consideration of the environmental criteria may force the design of products from a different angle [10,29–31]. It was not found that a complex method will support improving the products both in terms of the customers' requirements and the impact on the natural environment. Therefore, the purpose of the research was to develop a new House of Quality to design and improve products considering the customers' expectations, ideas of sustainable development, and the circular economy. The method was tested for photovoltaic panels, which are problematic to adjust in view of sustainable development and the circular economy at the same time.

It was shown that taking into account only qualitative criteria in a traditional way may give a different ranking of the importance of the technical criteria. This may result in adopting other assumptions for product design. In the presented example, the most important technical criterion, taking into account only the quality criteria, was the criterion (guarantee), which when environmental criteria were also taken into account, was ranked only third. Comparing the ranking based on quality criteria with the one based on quality and environmental criteria, one can observe significant differences that translate into design decisions in the created product. As a result, it was shown that the proposed method, QFD-CE, can support the design of new products or improve products already available on the market. In this case, it is realized by simultaneously meeting the customers' expectations and possibilities for their fulfilment according to sustainable development ideas of products and the circular economy. Additionally, it was shown that it is possible to modify the QFD method to simultaneously include customers' expectations (qualitative) and environmental (sustainable development and circular economy) as part of designing new products or improving products already present on the market.

The main advantages of the proposed method:

- Simultaneously including qualitative criteria (customers' criteria) and environmental criteria (sustainable development and the circular economy);
- Analysis of product design requirements in view of the importance of product criteria, which are determined simultaneously for customer criteria and environmental criteria;
- Adjusting products to the so-called "Voice of Customers" (VoC);
- Possibility of improving actions of products with taking care of the natural environment;
- Effectiveness at determining design purposes (or modifying) of products, which will be in accordance with customers' expectations and simultaneously support making design actions or improving according to the sustainable development idea;
- Low-cost method that supports companies in the development of products in terms of quality and environment.

It is possible to highlight the shortcomings of the proposed QFD-CE method, i.e., there is a need to obtain expectations from more customers, it is problematic in searching for dependence and correlations between a large number of criteria, and there is a need to support a team of experts in the analysis of customers' (qualitative) criteria, environmental criteria (sustainable development criteria and circular economy), and technical criteria. The concept of sustainable development requires contemporary generations to develop in such a way that the next generations also have the opportunity to develop, while achieving their civilization goals. It is possible by using this new QFD-CE method because by taking into

account the quality criteria, it is possible to design products of better quality, and taking into account the environmental criteria at the same time minimizes the negative impact on the environment, giving future generations a chance for development. Hence, the proposed QFD-CE method realized according to the assumed methodology and assumptions can be effective in designing and improving products to achieve customer satisfaction, while complying with the principles of sustainable development and circularity.

6. Conclusions

Improving products according to customer' expectations and simultaneously taking care of the natural environment are key to the sustainable development of products. The purpose of the research was to develop a new House of Quality to design and improve products considering customers' expectations, ideas of sustainable development, and the circular economy. As a result, the QFD-CE method was developed, which occurred based on the QFD method (Quality Function Deployment). In this method, we also implemented other techniques to support its realisation, i.e., SMARTER method, brainstorming (BM), method of selecting a team of experts, kinship diagram, fixed sum scale, and Likert scale. The basis of the method relies on building the so-called house of quality to determine correlations between the technical (measurable) criteria of the product and the criteria of the product determined by customers, and at the same time, the environmental aspects (i.e., sustainable development criteria and circular economy criteria). A novelty compared to the traditional QFD methodology is that design goals are set not only on the basis of customer expectations, but also considering the impact on the natural environment. The originality of this proposition is the practical inclusion of sustainable development criteria.

The QFD-CE method can be used by companies whose design activities focus on caring for the natural environment and it is possible to use it in a closed circuit that will meet customer expectations. Thanks to the use of this method, it will be possible to design environmentally friendly products, thanks to which it will be beneficial to society in terms of sustainable development.

Future works will aim to adjust this method to reduce the uncertainty of customers during expressing their expectations. This method will be excited about the fuzzy decision environment. It will be realized by triangular fuzzy numbers, which will be used to determine the weights of product criteria. Additionally, future research will be conducted towards testing the method on different products. The resulting conclusions should become the basis for specifying the assumptions and universalization of the QFD-CE method (creating a more universal method).

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