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Prioritizing the Factors for Customer-Oriented New Product Design in Industry 4.0

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Abstract

Customer-oriented new product design is one of the most important processes in the production environment to improve product quality and reliability and maximize their productivity. It is also necessary to consider customer expectations in this process for an effective design. In this paper, we present a methodology which is called Pythagorean Fuzzy Analytic Hierarchy Process (PF-AHP) for prioritizing criteria which should be considered for an efficient customer-oriented new product design in Industry 4.0 transition primarily. We use Pythagorean Fuzzy Sets (PFSs) to allow experts to make more flexible evaluations and handle the uncertain and vague information in a wider way. We determine five main and eighteen sub-criteria that affect the new product design process and after applying PF-AHP, we find that the most important main-criterion determined as "Production" and sub-criterion determined as "Return on Investment".

Keywords: Industry 4.0, Multi-Criteria Decision Making, Product Design, PFSs

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1. INTRODUCTION

In today's competitive environment, it is a priority to meet customer demands when designing a new product. New business principles should be taken into account when considering customer requirements and companies need to design product development, purchasing, marketing, production, sales and customer service processes in line with new trends. Product lifecycle management is conducting the process from the moment a company creates the first idea for its products to the end of production. It aims to accelerate product development time, encourage innovation, reduce costs, shorten communication gaps, improve quality, and visualize product information between collaborating parts [1], [2]. This cycle begins with the development of a new product step and the success of a product life cycle comes from the success product design process. Therefore, the issue of new product design is of great importance for businesses. The new product development process' objective is to translate an opinion into a tangible physical asset. This process is structured around well-defined stages and each stage consists of lots of decision-making problems.

However, in today's developing technological conditions, the product life cycle should be realized by considering different dimensions of new product design. The latest technological developments that the industry is experiencing and expected to live in can be described as Industry 4.0. Industry 4.0 is an understanding that involves the processes of businesses and creates a global network. This approach is an innovative approach that requires the participation of internal customers, external customers and suppliers, enabling technological systems to work together and exchange information [3]. Transition to Industry 4.0 is supported by the digitalization of all areas for product generation and lifecycle management in almost all industrial sectors. To continue the competition, companies in most industrial sectors will need to digitalize their processes to gain great efficiency especially in the production environment [2]. Within the framework of the new conditions in which Industry 4.0 drives businesses, the criteria to be considered for designing a new product that meets these conditions should be revealed and the most important criteria should be determined in order to design a successful new product.

In a new product development problem, decision-makers must take into account the customers' expectations, the company's strategies, technological opportunities, and the company's capabilities. Decision-makers should be aware that any new product development process cannot be successful without taking these criteria into account [4]. Decision-making theory is one of the most fundamental issues used to find feasible solutions in decision-making situations where many factors should be taken into account. Considering the uncertainty and multi-factor inherent in new product development, applying multi-criteria decision making (MCDM) theory in the process will be useful [5].

Fuzzy logic has emerged that the mathematical methods of classical system theory are insufficient in many systems in the real world, especially in partially complex systems involving people hence uncertainty [6]. Fuzzy logic is useful for modeling uncertainty in linguistic expressions. To better address uncertainty in fuzzy sets, extended versions have been introduced on regular fuzzy sets. Among them, the PFSs are an extension of the intuitionistic fuzzy sets and give decision-makers independence in expressing their opinions in an uncertain environment [7]. PFSs are unsurpassed to other extensions, allowing membership functions to be defined more flexibly [8]. Especially in MCDM problems, membership functions need to be defined better and flexibly. PFSs facilitate representation on a broader membership and non-standard membership degrees, allowing experts to consider uncertainty more effectively than other extensions [8]–[10]. PF- AHP also appears as an approach that has been successfully applied in the literature and has proven its usability with many studies conducted in multi-criteria environment. AHP has frequently used MCDM method because of the ability to deal with decision-making problems that are difficult or impossible to configure with traditional methods and to be able to model the problem in a hierarchical manner [11]. Besides, the ability to handle many qualitative and quantitative criteria and factors with the system approach at the same time and ease of use can be seen among the reasons for frequent reference to AHP in the literature [12]. Based on all these, we applied AHP, which is the most commonly used MCDM approach in decision making studies, in the environment of PFSs, while prioritizing the factors that should be addressed in customer-oriented new product design in Industry 4.0 for the first time unlike the other studies in the literature. At this point, our study fills the gap and contributes to the literature in terms of the combination of the proposed method and subject. In this paper, we aim to propose a methodology to prioritize the criteria which are important for the customer-oriented new product design in Industry 4.0 transition processes. In section 2, we reviewed the relevant literature to reveal the MCDM applications in new product development processes and newly released PF-AHP applications. Section 3, we presented the details of the proposed fuzzy methodology. Section 4 was included the case study for the development of the new product in Industry 4.0 transition process. In the last section, the results and discussion were given.

2. LITERATURE REVIEW

There are lots of papers in the literature about product design and design considerations. One of the most frequently approaches used in product design studies is MCDM method. In the following sub-sections, studies on product design in Industry 4.0, studies using MCDM in product design and recent studies on the proposed fuzzy extension with applied MCDM method are reviewed and summarized.

2.1. Product design in Industry 4.0

The subject of product design in Industry 4.0 applications has been addressed in some studies. Some of them can be summarized as follows. Mourtzis et.al. [13] presented an approach to apply advanced visualization methods using Augmented Reality in product design that will be used from engineering students for visualizing product design and improving it. Wagner et.al. [14] tried to determine a consistent structure for the holistic use of digital twins in the whole process of product development. Zakoldaev et.al. [15] considered the duties of organization project activities in a digital factory and they described the components of a digital enterprise at the physical level of technological equipment and the cyber level of cloud services. Shinohara et.al. [16] aimed to propose a set of critical success factors for digital manufacturing implementation. They collected critical success factors based on academic literature review and consulting reports. They handled a conceptual framework to assist organizations in developing a strategy for digital manufacturing implementation, and map for that purpose all the required resources and capabilities. Ang et.al. [17] highlighted smart design and with smart operation as a way forward in an Industry 4.0, ranging from design to smarter ships and smart operation for energy efficiency. Albers et.al. [18] focused on identifying Industry 4.0 potentials on the product taking into account its interdependencies on the system of production. They developed an approach for assessing the impact and risk of changes on the process side or product side. Ahmed et al. [19] [20] presented a system called smart virtual product development, which can increase the product development process for industrially manufactured products and assist in decision making by using clear information about official decision events and explained how product production can be improved by using the smart virtual product development system in Industry 4.0. Bilal Ahmed et al. [20] proposed the concept of the smart virtual product development system that improves the decision making process at different phases and activities such as product design, production and inspection planning and the system they offered has a key role in Industry 4.0. Lin [21] aimed to define a product design approach based on user experience from a human-oriented viewpoint. The smart manufacturing approach proposed to strengthen

Industry 4.0 in the circular economy of the glass recycling industry investigates product decision making information systems and data-driven innovation.

2.2. MCDM studies in product design

The outstanding papers using MCDM in product design are as follows. Asmae et al. [22] presented a MCDM study based on fuzzy ontology when choosing between alternatives in the final assessment of the product design concept. Favi [23] adopted a mathematical model approach based on MCDM theory in order to determine the optimum and feasible design options in the conceptual design stage. Fatchurrohman et al. [24] used a combined decision-making approach in conceptual design selection named CoNQA which includes Concurrent Network, Quality Function Deployment and AHP. Kumar and Tandon [25] used axiomatic design taking customer requirements and design parameters into consideration in customer-driven product design and many design alternatives had developed with the help of AHP in their study. Favi [26] et al. applied MCDM to determine the applicable design options and determine the best design option for the tool holder carousel of a machine tool. Joshi and Gupta [27] used an ARTODTO system model to achieve financial, environmental and physical objectives in assessing the impact of product design in rescue operations. Zeng et al. [28] presented a fuzzy decision model for evaluating fashion-oriented industrial products for new product design that meets some selective market requirements. Song et al. [29] proposed a fuzzy AHP method to analyze and sort design parameters in the design of upper extremity rehabilitation devices. Xingli and Huchang [30] applied an improved Quality Function Deployment model for the innovative product design problem. Wang [31] proposed an AHP and DEMATEL (The Decision Making Trial and Evaluation Laboratory) under fuzzy environment approach in marketing-oriented product development realizing the practice of quality function deployment. Buchert et al. [32] integrated Life Cycle Sustainability Assessment with discrete decision trees for sustainable product design. The benefits and barriers of the developed approach are evaluated on a bicycle framework. Lian et al. [33] adopted a MCDM approach based on layered ordinal relationship analysis in choosing the optimum scheme for product design. Liu [34] applied fuzzy Quality Function Deployment with a fuzzy MCDM approach in product design development and selection process. İç and Yıldırım [35] revealed the factors affecting the quality characteristics of a washing machine and determined the levels for each factor and an experimental design model was used in which levels of the factors optimize quality characteristics. In the analysis, Taguchi method and Gray Relational Analysis, TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) and VIKOR methods were used together. Guini et al. [36] proposed a multi-criteria decision support approach to select the finest design concept with the best industrial performance measures in a manufacturing company using ROC (Rank Order Centroid) and PROMETHEE (The Preference Ranking Organization Method for Enrichment Evaluation) methods. Khan et al. [37] analyzed various product design alternatives from a risk perspective for environmentally cognizant product risk modeling and assessment. Wang and Chen [38] applied a fuzzy MCDM based Quality Function Deployment approach which integrates fuzzy Delphi, fuzzy DEMATEL with linear integer programming for cooperative product design and optimal selection of module mix.

2.3. Pythagorean Fuzzy Analytic Hierarchy Process (PF-AHP)

The following studies can be given as an example of recent studies conducted using PF-AHP. Büyüközkan and Göçer [39] proposed an approach which integrated PFSs, AHP and complex proportional assessment under to evaluate alternative digital supply chain partners and they conducted a case study in Turkey to validate their proposed approach. Yıldız et al. [40] applied PF-AHP and PF-TOPSIS methods to assess 25 different districts in Istanbul for ATM location selection for a public bank serving in Turkey. Kaya et al. [41] used the MCDM approach with PFSs to take into account a variety of contradictory factors, from qualitative to quantitative, in the site selection of the WEEE recycling facility. For this purpose, they applied to PF-AHP and PF-TOPSIS methods to find the best location alternative. Otay and Jaller [42] proposed AHP method in a Pythagorean Fuzzy environment to better model uncertainties in wind farm location selection. Karasan et al. [43] used PF-AHP method to analyze risks in the autonomous drive system. Gül [44] applied an integrated methodology consisting of PF-AHP and PF-VIKOR for risk assessment in the field of occupational health and safety. Yücesan and Kahraman [45] tried to perform a risk assessment for hydroelectric power plants using PF-AHP method. Experts identified twenty hazards and their results that could occur in the operation of the hydroelectric power plant. As a result of the study, for the three most important hazards, preventive actions had been taken and the expected result was to contribute to the safety of hydropower plants and the prevention of financial losses.

New developments for digitalization are presented and the benefits of these systems are emphasized in the presented studies related to Industry 4.0 and the new product design above. However, in our paper, we aim to present a methodology based on PF-AHP which helps decision-makers to determine and prioritize the criteria that are important and should be considered for customer-oriented new product development in Industry 4.0 era primarily. This paper is the first to implement the MCDM approach under the Pythagorean fuzzy environment for considering product design factors. With this study, it has been shown that extended fuzzy sets can be successfully applied in product design studies and the feasibility of the method in product design decision environments where uncertainty and vagueness is present.

3. Proposed Methodology

This section of the paper includes the suggested methodology and steps of the adopted application are given in the following subsections.

3.1. Pythagorean fuzzy sets

PFSs were proposed by Yager [46] derived from intuitionistic fuzzy sets which were originally proposed by Atanassov [47].

Unlike the intuitionistic fuzzy sets, the sum of membership and non-membership degrees can exceed 1, but the sum of their squares cannot in PFSs [9], [10]as defined in Definition 1.

Definition 1: Let X be a fixed set. A PFS is shown as $\tilde{P}$ [9], [10]:

$$\tilde{P} \cong \{x, \mu_{\tilde{p}}(x), \upsilon_{\tilde{p}}(x); x \in X\}$$

where the function $\mu_{\tilde{p}}(x): X \mapsto [0,1]$ describes the degree of membership and $v_{\tilde{p}}(x): X \mapsto [0,1]$ defines the degree of non-membership of the element $x \in X$ to P respectively and for every $x \in X$, it holds:

$$0 \leq \mu_{\tilde{p}}(x)^2 + v_{\tilde{p}}(x)^2 \leq 1 \qquad (1)$$

The indeterminacy ratio is obtained as in the following:

$$\mu_{\tilde{p}}(x) = \sqrt{1 - \mu_{\tilde{p}}(x)^2 - v_{\tilde{p}}(x)^2} \qquad (2)$$

A number of basic operations for PF numbers are given as in Definition 2.

Definition 2: $\beta_1 = P\left(\mu_{\beta_1}, v_{\beta_1}\right)$ and $\beta_2 = P\left(\mu_{\beta_2}, v_{\beta_2}\right)$ are two PF numbers and $\lambda > 0$. Operations on these two PF numbers are shown in the following such as [48]–[50]:

$$\beta_1 \oplus \beta_2 = P\left(\sqrt{\mu_{\beta_1}^2 + \mu_{\beta_2}^2 - \mu_{\beta_1}^2\mu_{\beta_2}^2}\ , v\beta_1 v\beta_2\right) \qquad (3)$$

$$\beta_1 \otimes \beta_2 = P\left(\mu\beta_1\mu\beta_2, \sqrt{v_{\beta_1}^2 + v_{\beta_2}^2 - v_{\beta_1}^2 v_{\beta_2}^2}\right) \qquad (4)$$

$$\lambda\beta_1 = P\left(\sqrt{1-\left(1-\mu_{\beta_1}^2\right)^\lambda}\ ,(v\beta_1)^\lambda\right), \lambda > 0$$
(5)

$$\beta_1^\lambda = P\left((\mu\beta_1)^\lambda, \sqrt{1-\left(1-v_{\beta_1}^2\right)^\lambda}\right), \lambda > 0 \quad (6)$$

$$\beta_1 \ominus \beta_2 = P\left(\sqrt{\frac{\mu_{\beta_1}^2-\mu_{\beta_2}^2}{1-\mu_{\beta_2}^2}}, \frac{v_{\beta_1}}{v_{\beta_2}}\right), if\ \mu_{\beta_1} \geq \mu_{\beta_2}, v_{\beta_1} \leq min\left\{v_{\beta_2}, \frac{v_{\beta_2}.\pi_{\beta_1}}{\pi_{\beta_2}}\right\} \quad (7)$$

$$\frac{\beta_1}{\beta_2} = P\left(\frac{\mu_{\beta_1}}{\mu_{\beta_2}}\sqrt{\frac{v_{\beta_1}^2-v_{\beta_2}^2}{1-v_{\beta_2}^2}}\right), if\ \mu_{\beta_1} \leq min\left\{\mu_{\beta_2}, \frac{\mu_{\beta_2}.\pi_{\beta_1}}{\pi_{\beta_2}}\right\}, v_{\beta_1} \geq v_{\beta_2} \quad (8)$$

π_{β_1} and π_{β_2} denote the degree of indeterminacy.

3.2. Pythagorean Fuzzy Analytic Hierarchy Process (PF-AHP)

This section of the paper includes the proposed fuzzy methodology. The stages of the PF-AHP method are shown in the following steps [43], [50], [51]:

Step 1. Compromised pairwise comparison matrix $R = (r_{jt})_{mxn}$ is constructed according to experts' evaluations. The linguistic scale that is used for decision matrices is presented in Table 1 adopted from [9].

Table 1. Scale for the interval-valued PF-AHP evaluations [9]

Linguistic Term	**IVP Fuzzy Sets**
Strictly Low Significance - SLS	[0,0.15][0.8,0.95]
Very Low Significance - VLS	[0.1,0.25][0.7,0.85]
Low Significance - LS	[0.2,0.35][0.6,0.75]
Below Same Significance - BSS	[0.3,0.45][0.5,0.65]
Strictly Same Significance - SSS	[0.4,0.55][0.4,0.55]
Above Same Significance - ASS	[0.5,0.65][0.3,0.45]
High Significance -HS	[0.6,0.75][0.2,0.35]
Very High Significance -VHS	[0.7,0.85][0.1,0.25]
Strictly High Significance -SHS	[0.8,0.95][0,0.15]

Step 2. The differences matrix $D = (d_{ij})_{mxm}$ is found between lower and upper points of the membership and non-membership functions using Eqs. (9) and (10):

$$d_{ij_L} = \mu_{ij_L}^2 - \upsilon_{ij_U}^2 \quad (9)$$

$$d_{ij_U} = \mu_{ij_U}^2 - \upsilon_{ij_L}^2 \quad (10)$$

Step 3. The interval multiplicative matrix $S = (s_{ij})_{mxm}$ is calculated via Eqs. (11) and (12):

$$S_{ijL} = \sqrt{1000^{d_{ijL}}} \quad (11)$$

$$S_{ijU} = \sqrt{1000^{d_{ijU}}} \quad (12)$$

After simulations, 1000 is found as the best value of the base, which makes all the relationships between the elements of the matrix clearer without sacrificing consistent relationship.

Step 4. The indeterminacy value $H = (h_{ij})_{mxm}$ of the r_{jt} is calculated using Eq. (13):

$$h_{ij} = 1 - \left(\mu_{ij_U}^2 - \mu_{ij_L}^2\right) - \left(\upsilon_{ij_U}^2 - \upsilon_{ij_L}^2\right) \quad (13)$$

Step 5. The indeterminacy degrees are multiplied with $S = (s_{ij})_{mxm}$ matrix to calculate the matrix of unnormalized weights $T = (\tau_{ij})_{mxm}$ via Eq. (14):

$$\tau_{ij} = \left(\frac{s_{ij_L} + s_{ij_U}}{2}\right) h_{ij} \quad (14)$$

Step 6. The priority weights w_i are obtained via Eq. (15).

$$w_i = \frac{\sum_{j=1}^{m} w_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{m} w_{ij}} \quad (15)$$

4. Case study

In this paper, we tried to prioritize the criteria to be considered in customer-oriented new product design for Industry 4.0 transition processes. For this purpose, the factors that are effective in designing customer-oriented products were determined by conducting literature research and interviewing with experts. As a result of the literature research and interviews, it was observed that the criteria will be collected in five groups as shown in Table 2. Thus, the decision problem had been composed of five main criteria and eighteen sub-criteria. Figure 1 shows the hierarchy of considered decision problem.

Table 2. Main and sub-criteria and references

Main Criteria	Sub-criteria	Reference
C1: Economical	C11: Return on Investment	Gupta et.al. (2015) [52]
	C12: Product Innovation	Gupta et.al. (2015) [52]
	C13: Profitability	Gupta et.al. (2015) [52]
C2: Environmental	C21: Low waste	Choi et.al. (2007) [53]
	C22: Carbon footprint	Gupta et.al. (2015) [52]
	C23: Clean development mechanism	Gupta et.al. (2015) [52]
C3: Production	C31: Energy consumption	Chandrakumar et.al. (2017) [54]
	C32: Fewer consumable	Choi et.al. (2007) [53]
	C33: Production technique	Choi et.al. (2007) [53]
	C34: Maintenance	Chandrakumar et.al. (2017) [54]
C4: Social	C41: Housing and service infrastructure	Gupta et.al. (2015) [52]
	C42: Health and education	Gupta et.al. (2015) [52]
	C43: Job opportunity	Gupta et.al. (2015) [52]
	C44: Social capital	Gupta et.al. (2015) [52]
	C45: Legislation and enforcement	Gupta et.al. (2015) [52]
C5: Competitiveness	C51: Customer demand	Choi et.al. (2007) [53]
	C52: Supplier relation	Choi et.al. (2007) [53]
	C53: Competitor trend	Choi et.al. (2007) [53]

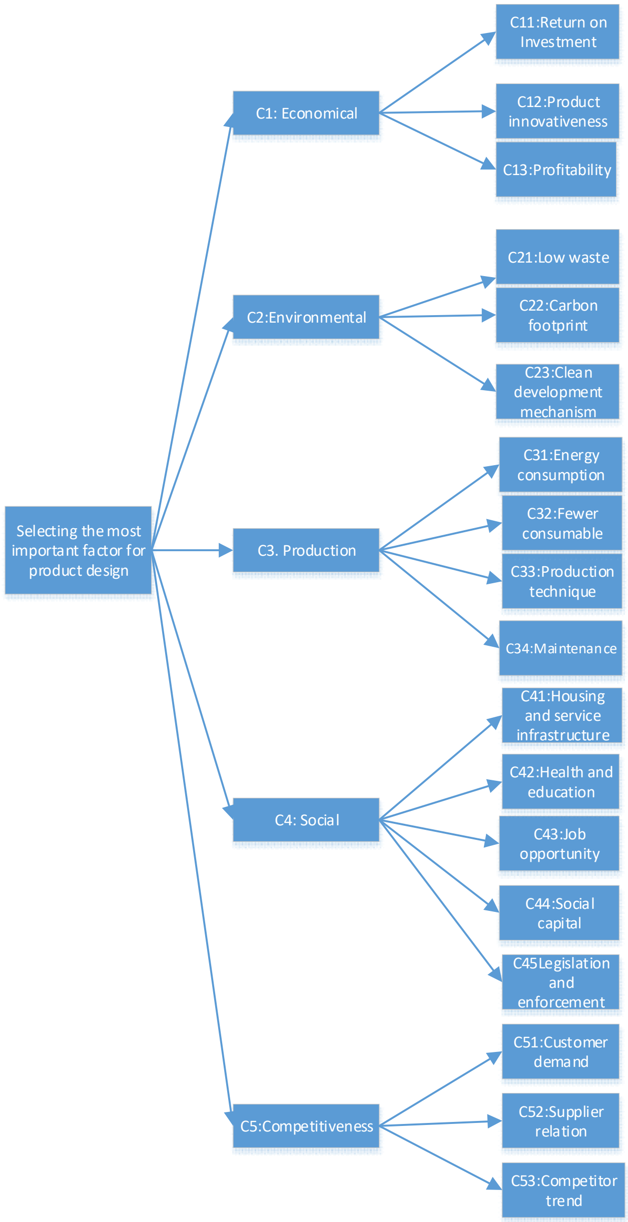

Figure 1. Hierarchy of criteria and sub-criteria for product design

Besides, the definitions of criteria are below:

- C1: Economical
  - * *C11: Return on Investment:* performance measure to evaluate the efficiency of new product design industry 4.0 investments.
  - * *C12: Product Innovation:* the creation or development amount of new products in industry 4.0

  * *C13: Profitability:* the ability of a business to produce profit as a result of new product design in industry 4.0
- C2: Environmental
  * *C21: Low waste:* the achievement level of a low waste objective by the production of new product design in industry 4.0.
  * *C22: Carbon footprint:* the achievement level the low carbon footprint production objective by the production of new product design in industry 4.0.
  * *C23: Clean development mechanism:* to design the new product with clean development mechanism
- C3: Production
  * *C31: Energy consumption:* to design the new product with a low energy consumption feature.
  * *C32: Fewer consumable:* the low need for consumable products for the new product design in industry 4.0.
  * *C33: Production technique:* appropriate production technique for the new product design in industry 4.0.
  * *C34: Maintenance:* the easiness of determination of maintenance needs and strategies for the new product design in industry 4.0.
- C4: Social
  * *C41: Housing and service infrastructure:* easy access to housing and service infrastructure for the new product design in industry 4.0.
  * *C42: Health and education:* the effect of new product design in industry 4.0 to health and education of employees.
  * *C43: Job opportunity:* the emergence of new employment opportunities with new product design in industry 4.0.
  * *C44: Social capital:* the effect of the social relationships and structure to new product design.
  * *C45: Legislation and enforcement:* the content of legislation and enforcement on new product design.
- C5: Competitiveness
  * *C51: Customer demand:* better analysis of the level of customer requirements for new products will provide a competitive advantage.
  * *C52: Supplier relation: a* better relationship with suppliers will help to handle competitive advantage.
  * *C53: Competitor trend:* the trends in the same business area will help to determine the right product features and handle competitive advantage.

After assigning the sub-criteria to the criterion groups, the scoring of the criteria was obtained. This scoring was done with the focus group work of the experts. 5 experts from university and industry are evaluated the criteria and sub-criteria. After this step, pairwise comparison matrices were formed based on these scores. The consistency of these matrices was checked and inconsistent evaluations were asked to be revised. After all matrices were made consistent, the most important factor in this decision-making process was found. Figure 2 shows the flow chart of the proposed methodology as follows.

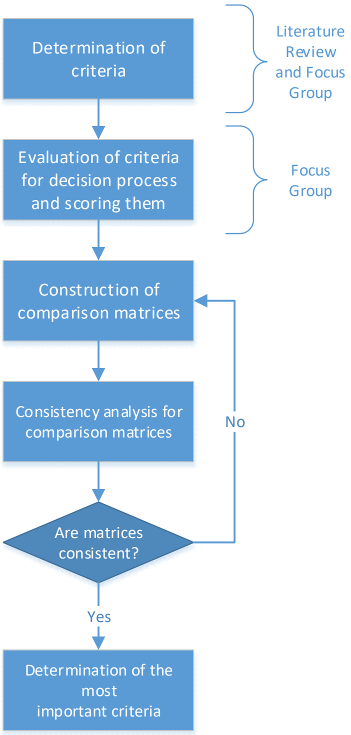

Figure 2. Flowchart of the proposed methodology

Firstly, pairwise comparisons of the main criteria were discussed and the linguistic evaluations were converted to interval-valued fuzzy numbers using the scale in Table 1. Table 3 contains the linguistic evaluations of the pairwise comparisons of the main criteria for the goal.

Table 3. Pairwise comparison of main criteria for goal

Goal	C1	C2	C3	C4	C5
C1	SSS	ASS	SSS	LS	HS
C2	BSS	SSS	BSS	BSS	SSS
C3	SSS	ASS	SSS	SSS	VHS
C4	HS	ASS	SSS	SSS	VHS
C5	LS	SSS	VLS	VLS	SSS

In the same way, pairwise comparisons of sub-criteria were obtained and matrices were formed. The pairwise comparison matrix for the social sub-criterion is shown in Table 4 below as an example.

Table 4. Pairwise comparison of sub-criteria for social criteria

C4 (Social)	C41	C42	C43	C44	C45
C41	SSS	HS	LS	LS	ASS
C42	LS	SSS	VLS	BSS	SSS
C43	HS	VHS	SSS	SSS	VHS
C44	HS	ASS	SSS	SSS	HS
C45	BSS	SSS	VLS	LS	SSS

After the pairwise comparisons were obtained for all matrices, the consistency ratios were calculated. Experts were asked to rearrange inconsistent assessments for ensuring that all matrices were consistent. Meanwhile, Table 5 was used to convert linguistic terms into crisp numbers to find consistency ratios, and then Saaty's consistency calculations were applied [55].

Table 5. Scale for the consistency ratio

Linguistic Term	Corresponded Crisp Number
Strictly Low Significance – SLS	0.11
Very Low Significance – VLS	0.14
Low Significance – LS	0.2
Below Same Significance – BSS	0.33
Strictly Same Significance – SSS	1
Above Same Significance – ASS	3
High Significance – HS	5
Very High Significance – VHS	7
Strictly High Significance – SHS	9

The consistency ratios for each matrix were calculated as in Table 6.

Table 6. Consistency degrees for pairwise comparison matrices

Based on	Consistency Ratio -CR
Goal	0,08107
Economical	0,03337
Environmental	0,03337
Production	0,05716
Social	0,09120
Competitiveness	0,02518

As shown in Table 5, the consistency ratio of all evaluations is less than 0.1. Therefore, the matrices are consistent and can be proceeded to the calculation of priority values. First, the main criteria weights were calculated. Then these weights were aggregated with the sub-criteria weights and the most important criteria can be determined.

The application of the adopted method started with the converting of the linguistic evaluations which are pairwise comparisons made for the goal by experts in Table 2 into the interval-valued PFSs in Table 1. Then, the differences matrix is calculated using Eq. (9) and (10) as in Table 7 for the main criteria:

Table 7. Differences matrix for goal

C1		C2		C3		C4		C5	
d_{ijL}	d_{ikU}	d_{ijL}	d_{ikU}	d_{ijL}	d_{ikU}	d_{ijL}	d_{ikU}	d_{ijL}	d_{ikU}
-0,14	0,14	0,05	0,33	-0,14	0,14	-0,52	-0,24	0,24	0,52
-0,33	-0,05	-0,14	0,14	-0,33	-0,05	-0,33	-0,05	-0,14	0,14
-0,14	0,14	0,05	0,33	-0,14	0,14	-0,14	0,14	0,43	0,71
0,24	0,52	0,05	0,33	-0,14	0,14	-0,14	0,14	0,43	0,71
-0,52	-0,24	-0,14	0,14	-0,71	-0,43	-0,71	-0,43	-0,14	0,14

After the differences matrix is calculated, interval multiplicative matrix S is calculated via Eqs. (11) and (12) as in Table 8:

Table 8. Multiplicative matrix for goal

C1		C2		C3		C4		C5	
S_{ijL}	S_{ijU}	S_{ijL}	S_{ijU}	S_{ijL}	S_{ijU}	S_{ijL}	S_{ijU}	S_{ijL}	S_{ijU}
0,6	1,6	1,2	3,2	0,6	1,6	0,2	0,4	2,3	6,1
0,3	0,8	0,6	1,6	0,3	0,8	0,3	0,8	0,6	1,6
0,6	1,6	1,2	3,2	0,6	1,6	0,6	1,6	4,4	11,7
2,3	6,1	1,2	3,2	0,6	1,6	0,6	1,6	4,4	11,7
0,2	0,4	0,6	1,6	0,1	0,2	0,1	0,2	0,6	1,6

The indeterminacy value H of the r_{jt} is calculated using Eq. (13) and the indeterminacy degrees are multiplied with $S = (s_{ij})_{mxm}$ matrix to calculate the matrix of unnormalized weights $T = (\tau_{ij})_{mxm}$ via Eq. (14) as in Table 9:

Table 9. Unnormalized weights matrix for goal

	C1	C2	C3	C4	C5
C1	0,80	1,55	0,80	0,22	2,98
C2	0,42	0,80	0,42	0,42	0,80
C3	0,80	1,55	0,80	0,80	5,75
C4	2,98	1,55	0,80	0,80	5,75
C5	0,22	0,80	0,11	0,11	0,80

Finally, the weights of the main criteria is obtained as in Table 10 with normalizing the calculations in Table 9.

Table 10. Main criteria weights

Main Criteria	Weight
Economical	0,29
Environmental	0,20
Production	0,36
Social	0,06
Competitiveness	0,09

As can be seen from Table 10, the most important main criterion in customer-oriented product design for Industry 4.0 transition was found as "production". This criterion is followed by the "economical" and "environmental" criteria. The least important criterion in this process is the "social" criterion. After this step, the sub-criterion weights were calculated with the same steps and aggregated with the main criteria weights, and the priority value of each sub-criterion was calculated. Table 11 shows the criteria weights which aggregated with main criteria weights.

Table 11. Priority values of criteria for customer-oriented new product design

Criteria	***Sub-criteria***	***Global Weights***
Environmental	Low waste	0,031
	Carbon foot print	0,06
	Clean development mechanism	0,115
Competitiveness	Customer demand	0,061
	Supplier relation	0,019
	Competitor trend	0,005
	Return on Investment	0,163

Economical	Product innovativeness	0,044
	Profitability	0,084
Production	Energy consumption	0,111
	Production technique	0,053
	Fewer consumable	0,091
	Maintenance	0,101
Social	Housing and service infrastructure	0,01
	Health and education	0,004
	Job opportunity	0,028
	Social capital	0,016
	Legislation and enforcement	0,004

When Table 11 is examined, it is seen that the most important factor in customer-oriented new product design is "Return on Investment". This factor is followed by the "Clean development mechanism" factor under the environmental main criteria. Another factor which has a very close importance degree to this criterion is "Energy consumption". The criteria that should be given the least attention are the factors under the social main criterion. According to these results, it is confirmed that more emphasis should be given to environmental and economical factors-oriented criteria in customer-oriented new product design in Industry 4.0.

5. Comparative Analysis

In this section, a comparative analysis has been carried out to check the validity of our proposed approach. To this end, Buckley's fuzzy AHP method with triangular fuzzy numbers is utilized. The Buckley model is one of the most common approaches in studies applying to fuzzy AHP in many different areas [56]–[63]. The steps of the Buckley's fuzzy AHP method can be explained as follows [64], [65]:

Step 1: Pairwise comparison matrices are constructed. Each element ($\tilde{c}_{ij}$) of the pairwise comparison matrix (C) is a linguistic term and it is presenting the importance between two criteria. The pairwise comparison matrix is given below:

$$\tilde{C}_k = \begin{bmatrix} \tilde{1} & \tilde{C}_{12} & \dots & \tilde{C}_{1n} \\ \tilde{C}_{21} & \tilde{1} & \dots & \tilde{C}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{C}_{n1} & \tilde{C}_{n2} & \dots & \tilde{1} \end{bmatrix} \quad k= 1,2,\dots,K \qquad (16)$$

$\tilde{C}_k$ is a pairwise comparison matrix belonging to k_{th} expert. Table 12 presents the linguistic terms used for the evaluation procedure. The geometric mean is used to aggregate expert opinions.

Table 12. Linguistic Scale [64]

Linguistic Expression	Fuzzy Number
Equally important (Eq)	(1,1,3)
Weakly important (Wk)	(1,3,5)
Essentially important (Es)	(3,5,7)
Very strongly important (Vs)	(5,7,9)
Absolutely important (Ab)	(7,9,9)

Step 2: Weights are calculated. Firstly, the fuzzy weight matrix is calculated by Buckley's method.

$$\tilde{r}_i = \left[\tilde{C}_{i1} \otimes \tilde{C}_{i2} \otimes \dots \otimes \tilde{C}_{in} \right]^{1/n} \qquad (17)$$

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 + \tilde{r}_2 + \dots + \tilde{r}_n)^{-1} \qquad (18)$$

where $\tilde{r}_i$ is the geometric mean of fuzzy comparison value and $\tilde{w}_i$ indicated by triangular fuzzy numbers, $\tilde{w}_i$ (L_i,M_i,U_i) is fuzzy weight of ith criterion.

Step 3: Fuzzy relative weights are defuzzified. In defuzzification process, fuzzy numbers are converted into crisp values. For defuzzification, Liou and Wang's [66] total integral value method with an index of optimism ω∈[0,1] is used. Let $\tilde{A}$ be a fuzzy number with left membership function $f^L_{\tilde{A}}$ and right membership function $f^R_{\tilde{A}}$. Then the total integral value is defined as follows:

$$E_\omega(\tilde{A}) = \omega E_R(\tilde{A}) + (1-\omega) E_L(\tilde{A}) \quad (19)$$

where

$$E_R(\tilde{A}) = \int_\alpha^\beta x f^R_{\tilde{A}}(x) dx \quad (20)$$

and

$$E_L(\tilde{A}) = \int_\gamma^\delta x f^L_{\tilde{A}}(x) dx \quad (21)$$

where $-\infty \le \alpha \le \beta \le \gamma \le \delta \le \infty$. For a triangular fuzzy number $\tilde{A} = (a,b,c)$, the total integral value is obtained by:

$$E_\omega(\tilde{A}) = \frac{1}{2}[\omega(a+b) + (1-\omega)(b+c)] \quad (22)$$

Based on the above steps, Buckley's fuzzy AHP method was applied to the problem discussed in this study. Experts were asked to reconstruct pairwise comparison matrices according to the linguistic scale in Table 12. Table 13 presents reconsidered evaluations for goal as an example:

Table 13. Evaluations for the goal by experts

	C1	C2	C3	C4	C5
C1	1	1/Ab	Ab	Eq	Wk
C2	Ab	1	1/Ab	1/Ab	1/Vs
C3	1/Ab	Ab	1	Wk	Vs
C4	Eq	Ab	1/Wk	1	Ab
C5	1/Wk	Vs	1/Vs	1/Ab	1

After all evaluations were obtained and pairwise comparison matrices were constructed, calculations for finding criteria weights were performed by applying Buckley's fuzzy AHP method. All the factors weights are calculated as in Table 14:

Table 14. Criteria Weights for Buckley's fuzzy AHP

Main Criteria	Sub-criteria	Global Weights
Environmental (0,22)	Low waste	0,035
	Carbon foot print	0,067
	Clean development mechanism	0,118
Competitiveness (0,07)	Customer demand	0,057
	Supplier relation	0,012
	Competitor trend	0,004
Economical (0,3)	Return on Investment	0,163
	Product innovativeness	0,048
	Profitability	0,088
Production (0,31)	Energy consumption	0,099
	Production technique	0,083
	Fewer consumable	0,071
	Maintenance	0,062
Social (0,09)	Housing and service infrastructure	0,030
	Health and education	0,019
	Job opportunity	0,013
	Social capital	0,027
	Legislation and enforcement	0,004

To understand the difference in rankings between adopted methodology and Buckley's fuzzy AHP results, we presented a bar chart as in Figure 3.

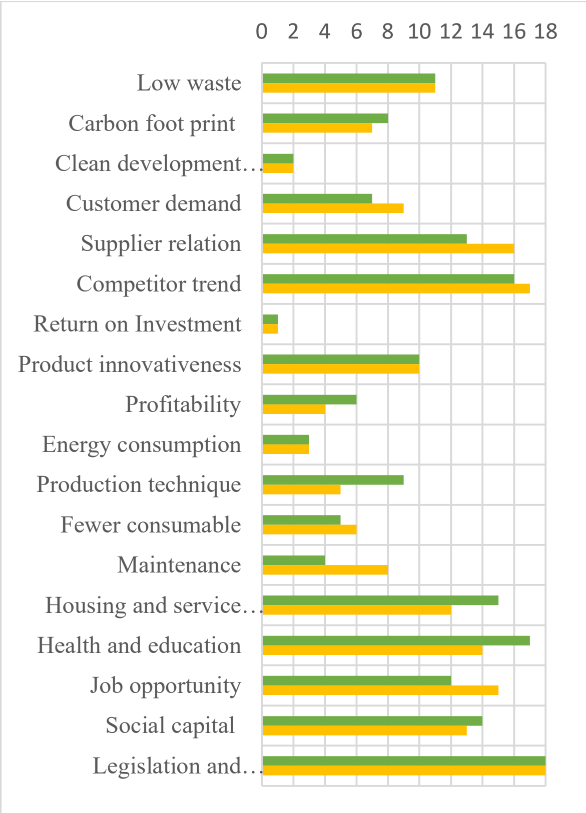

Figure 3. Ranks of criteria for PF-AHP (green line) and Buckley's fuzzy AHP (yellow line)

As can be seen from Figure 3, the criterion that should be taken in the first place in the new product design is the "Return on Investment" criterion, which is also placed on the top in the method we adopt. Likewise, the criteria placed in the second and third were in the same rankings in the comparative application. "Legislation and enforcement" and "Competitor trend" criteria, which were found in the last ranks, were found at the end of the list. In the meantime, the criteria in the ranks in intermediate levels appeared in changing rows. This comparative analysis has shown us that our results are valid; however, it has also shown that changes can be observed in the results because greater flexibility is given to decision-makers using PFs when compared to regular fuzzy sets.

6. Results and Conclusions

Making a new product design decision for a business, determining the design specifications and performing the design according to these specifications is critical for the survival of the company. It is also essential to design new products taking into account customer expectations in product development for all types of production businesses. Unless customer expectations are included in the design process, it is likely to be confused with design deficiencies. Therefore, after the need for new product design is occurred, companies need to determine the product design criteria. Within the framework of new conditions directed by Industry 4.0, the criteria that should be taken into consideration when designing a new product that meets customer expectations should be revealed and the most important criteria should be determined to design a new product successfully. For this reason, in this study, it is aimed to determine the importance ranking of the criteria to be considered for new product design in customer-oriented new product design for Industry 4.0 transition processes.

To achieve this goal, firstly, the factors that are effective in designing customer-oriented new products were determined by conducting literature research and interviewing with experts. In order to model the uncertainty in the process and to obtain the linguistic evaluations of decision-makers, a MCDM methodology was used within the fuzzy logic environment called PF-AHP. As a result of the paper, the most important main criterion in customer-oriented product design was found as "production". This criterion is followed by the "economical" and "environmental" criteria. The least important criterion in this process is the "social" criterion.

In addition, the main criteria were detailed by dividing into sub-criteria and it is observed that the most important factor in customer-oriented new product design is "Return on investment". This factor is followed by the "Clean development mechanism" factor under the environmental main criteria. The criteria that should be given the least attention are found as the factors under the social main criterion. According to these results, it is confirmed that more importance should be given to environmental and economical factors-oriented criteria in customer-oriented new product design in Industry 4.0. This study is expected to guide companies to plan their actions according to these criteria by first determining the criteria that they should focus on.

In future studies, existing results can be compared by using different MCDM methods or by applying different fuzzy logic extensions. In addition, a prioritization study can be carried out among the products planned to be produced in the transition to Industry 4.0 using the proposed method.

Research and Publication Ethics

This paper has been prepared within the scope of international research and publication ethics.

Ethics Committee Approval

This paper does not require any ethics committee permission or special permission.

Conflict of Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this paper.

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