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A novel extension of Pythagorean fuzzy MULTIMOORA approach for new product development

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A R T I C L E I N F O

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A B S T R A C T

This study explores how to enhance the decision-making processes in the phases of idea generation or alternative selection during the new product development (NPD) process. NPD is acknowledged as the central function of businesses in an increasingly competitive marketplace. In the current era, the highly uncertain and rapidly changing market environment makes the NPD extremely vague and complex. To be able to find a suitable solution to this complexity, the proposed research aims to categorize the decision points in the process of NPD regarding software development and identify the fuzziness elements affecting the process. The goal of a decision-making process is to prioritize several alternatives with respect to some required objectives and to select the best among them. Multi-Criteria Decision-Making (MCDM) may support reaching a consensus judgment with the collective assessment of Decision Makers (DMs). We introduce a novel evaluation approach for this problem. The proposed approach employs a MULTIMOORA (Multi-objective Optimization by Ratio Analysis plus the Full Multiplicative Form) MCDM technique under Pythagorean Fuzzy Sets (PFSs) objective world environment to cope with an ambiguous environment using Group Decision Making (GDM) setting to shape the decisions. The PFSs have demonstrated their advantages in dealing with vagueness and uncertainty over crisp, fuzzy, or intuitionistic fuzzy sets. Therefore, PFSs can represent the DMs' judgments and preferences in a better structure, ensuring enhanced decision-making in a group consensus. A case study on gaming software and app development is presented to validate the functionality of the proposed method. The results are compared and assessed with the help of a sensitivity analysis. This research makes a real contribution to the literature by proposing a novel evaluation method to rate and select NPD (gaming software and apps) to deal with the inexactness and vagueness associated with the criteria and alternatives.

1. Introduction

Today, the rapid development, and change in social, economic, and technological structures redefine new consumer and new consumption trends almost every day. Different companies can launch almost the same product at the same time. The critical point here is to create a distinctive competitive strategy. For this, the right idea and product will be the starting point. Improving the product range and periodically updating products is critical to the success of each organization. The decline in sales and the rapid entry of

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competitors are important criteria for brands to keep themselves up-to-date and on the agenda. This is why the New Product Development (NPD) process is very imperative for any organization. The products need to go through the stages of their life cycle and eventually be replaced [1]. NPD is simple in concept. It is principally the transformation of market demands into a product. It is the creation of tangible products and services from an intangible idea and the formation of new ways of wealth. Continuous improvement, which has become ever more important in an increasingly competitive environment, is constantly compelling companies to produce better so that customers can find better than what they are looking for. Therefore, all production processes covering various organizational units need to be handled and improved to a better level using a systematic approach. Firms must have the ability to compete in the global market to survive. Organizations that transform technological innovations into products by combining them with their savings and gain economic benefits achieve significant advantages in competition. For this reason, the studies carried out on NPD occupy an important place in the agenda of the companies. Being successful in NPD efforts mainly requires a considerable amount of resources and well evaluation of market opportunities. Due to the high risk of failure in implementing NPD, it is substantial to grasp why and how NPD is significant for companies [2]. NPD is the most sensitive spot for companies, it could be considered the lifeblood. Newly developed products can vary from the needle to the airplane, circuit board to smartphone, etc. as in a physical type. They can also be intangible services such as manufacturing processes, novel marketing concepts, or software. If companies desire to move ahead from survival mode to thriving, they have an irreversible road to grow and improve. However, as in all cases of decision-making processes, an NPD process involves an important amount of imprecision-affecting factors to reach the desired performance. Vagueness arises from internal or external sources like commercial, technical, and management issues. Therefore, the key is to use a structured methodology that could reduce the risk of NPD [3]. Verbal terms can be applied to assess the needs and ratings of NPD alternatives to help managers and decision makers (DMs) express their preferences. The fuzzy set theory is a practical tool to accomplish the desired goal.

A crisp set is a collection of objects that share common characteristics, in which the elements' membership degree is stated in a binary term. That is, the elements either belong to the set or not. Decision-making processes can be highly vague and fuzzy, whereas traditional crisp sets may have limitations. The concept of the fuzzy set theory is introduced by Zadeh in 1965 as an extension of the typical set theory, in which a degree of membership is assigned to all elements to permit gradual assessment of membership values with the help of a membership function that produces a value between 0 and 1 [4]. The fuzzy set theory requires only a membership degree. This can also create challenges in decision-making environments. Quantifying the membership and non-membership degrees in the form of a crisp or conventional fuzzy value may not be entirely justifiable. As the defined problem gets further problematic, selecting a distinctive candidate gets harder for DMs [5]. Atanassov proposed an extension to the classical fuzzy set theory, namely the Intuitionistic Fuzzy (IF) set by assigning a degree of hesitancy, non-membership, and membership to each element in the set [6]. Hence, numerous MCDM approaches applied the concept of IF theory to solve decision problems. Furthermore, the IF set theory has also confronted some difficulties in certain areas. Pythagorean Fuzzy Set (PFS) concept is developed to tackle the vagueness and imprecision better compared to orthodox crisp, fuzzy, or IF sets. Yager introduced PFSs theory as an extension of IF sets, defining an element in a set by membership and non-membership degrees, in which their square sum can obtain a maximum value of "1" [7,8]. The concept of PFSs can be successfully applied to numerous MCDM problems in the literature thanks to their strength in representing fuzzy characteristics by capturing the uncertainty and vagueness in expressions of a single DM or a group of DMs. In the case of multiple DMs, most MCDM techniques can also be applied in a group decision making (GDM) setting [9].

To the best of our knowledge, no study so far has applied PFSs values for assessing and rating the NPD alternatives using GDM. This is done by utilizing the MULTIMOORA MCDM method in a GDM PFSs environment to make more rational decisions. The traditional MOORA technique is made up of two distinct approaches: the ratio system and the reference point. The MULTIMOORA technique is a rather innovative extension of MOORA, and the full multiplicative form uses vector normalization [10]. It is commonly applied to construction, economic and managerial problems due to its great flexibility and ease of use. The MULTIMOORA methodology has been chosen for its robustness. The study is novel by proposing an extension of MULTIMOORA methodology, and a PFSs MCDM technique based on the GDM approach, where the alternatives assessments are formed as PFSs values. It provides several systematic contributions by offering a new decision approach by applying the MULTIMOORA MCDM method.

The NPD domain is subject to significant ambiguities. Aside from market-related causes of uncertainty, the innovation degree of new products is a considerable source of uncertainty [1]. In addition, the planning process plays an essential role in uncertainty creation. The Fuzzy set theory allows building strong mathematical models to address vague and uncertain information in real-life circumstances. PFS is a new objective world environment towards uncertainty that is superior to existing models like Crisp, Classic Fuzzy, and Intuitionistic Fuzzy [11]. Since PFS's ability to handle and express uncertain information more fully and PFS has the more lager representation space, uncertainty can better analyze information in more effective and reasonable measures [12]. Hence, the MULTIMOORA method determines ranking results based on three perspectives: the ratio system, reference point, and full multiplicative form. Compared with other methods, MULTIMOORA is effective, simple, and can easily select and relate alternatives [13]. Therefore, The PFS extended MULTIMOORA method overcomes the drawbacks of traditional MCDM methods in the evaluation of uncertain information, variation of importance factors, and priority of NPD.

The central undertaking of the study is to find a fitting NPD (gaming software and apps) evaluation method that can assist DMs in handling their NPD process. The PFSs MCDM methodology is applied to discover the best applicable NPD evaluation approach after gathering a variety of data from DMs. The assortment of characteristics is a fundamental contemplation of the MCDM process. The DMs deeming the linguistic expressions to access membership and nonmembership degrees make logical choices when they employ the MULTIMOORA in this sort of PFSs MCDM approach. All in all, the research paper mainly contributes to the literature as follows.

- It merges MCDM with PFSs setting to consider hesitancy and better reflect DMs' judgments.

- By providing a robust MCDM, the developed approach combines three distinct subordinate ranking processes into one final ranking.
- The setting created under the GDM environment contingent on many DMs generates a value point by taking individual opinions into account under the PFSs extension.
- It delivers true flexibility, greater mobility, better functionality, enhanced performance, and sufficient determination strengths by presenting GDM extension of PFSs setting;
- It offers a rational, simple, and coherent approach of the MULTIMOORA methodology;
- It can effectively be employed in imprecise, vague, and ambiguous environments;
- Its applicability is successfully demonstrated in a real case study;
- It provides a comparative and sensitivity analysis;
- DMs in other NPD projects can effortlessly apply this MCDM approach and adjust it to their decision problems.

The organization of the study is as follows. Section 2 provides a review of the literature on NPD and PFSs. Preliminaries for PFSs and the detailed description of the proposed PFSs MULTIMOORA approach are delivered in Section 3. Section 4 presents a case study. Experimental results involving NPD alternatives are provided in Section 5. Managerial implications, comparison of the results under different objective environments, and sensitivity analysis are offered in Section 6. Section 7 concludes the study with some future study suggestions.

2. Literature review

2.1. New product development

The purpose of this paper is to contribute to the NPD studies, emphasize the importance of the NPD process, and research on decision making by discussing how the decisions related to software and apps are made during an NPD project for new software development.

The following studies summarize some of the existing literature on NPD. Yilmaz et al. developed a fuzzy-based approach for NPD projects by investigating the cross-functional teams and the concepts of utility workers to boost system performance [14]. Weeth et al. respond to the issue of how executives' tendency regarding the escalation of commitment in the NPD decision process affects the thought worlds both in general and under certain project characteristics [15]. Huo et al. contribute by identifying and structuring linguistic terms related to the dislikes and likes of customers by using online reviews to guide NPD in a case study to demonstrate the

Table 1
PFSs studies with MCDM techniques.

Source	Research Area	Applied Technique	GDM	Case Study	Research Objective
[41]	Introduction of New PFSs Operator	Bonferroni mean and Maclaurin symmetric mean	–	–	A PFS Operator Proposal
[42]	Real estate company selection	PFSs Weighted geometric Operator	–	+	A PFS Aggregation Operator Proposal
[43]	Service Quality	AHP and TOPSIS	–	+	Hospital Service Quality Evaluation
[44]	Offshore Facility Platform	DEMATEL	–	+	A PFS Extension is Proposed
[45]	Bridge Superstructure Construction	PROMETHEE	–	+	A PFS Extension is Proposed
[11]	Supplier Selection	AHP and COPRAS	+	+	A PFS Extension is Proposed
[46]	Green Supplier Selection	Data Envelopment Analysis	–	–	A Methodology for Supplier Selection is Introduced
[47]	Mining Hazards and Risks	VIKOR	–	+	A Ris Assessment Methodology Proposal
[48]	Banking Website	VIKOR and TODIM	–	+	Website Quality Evalution
[49]	Occupational safety and health risk	VIKOR	–	+	Assessment Methodology for a natural gas pipeline
[50]	Well-being Index	AHP	–	+	A Reginal Development Assessment
[51]	Renewable Energy	VIKOR	+	+	A PFS Extension is Proposed
[52]	Supplier Selection	CODAS	–	–	A PFS Extension is Proposed
[53]	Project Investment	VIKOR	–	–	A PFS Distance Measure Operator Proposal
[54]	Solar Energy Investment	Present Worth Analysis	+	–	An Application of PFS in Energy Sector
[55]	Risk Assessment	AHP and Inference System	–	+	An Application of PFS in Risk Assessment
[56]	Risk Assessment	Critical Effect Analysis	–	–	An Application of PFS in an Illustrative Study
[57]	Internet Companies	Distance-Based	+	–	A PFS Operator Proposal
[58]	Smart phones	Ranking Method	–	–	An Application of PFS in an Illustrative Study
[59]	Medical Diagnosis	Correlation Coefficient	–	–	A PFS Operator Proposal and its application in an Illustrative Study
[60]	Domestic Airlines	Score Function	–	+	A PFS Operator Proposal
[61]	Stock Market	Choquet Integral based MABAC	+	–	A PFS Extension is Proposed
[62]	Bank Investment	TODIM	–	+	A PFS Extension is Proposed
[63]	Internet Stocks	Superiority and inferiority Ranking	+	–	A PFS Extension is Proposed
[64]	Domestic Airlines	TOPSIS	–	–	A PFS Extension is Proposed

developed method [16]. Oliveira et al. explore the compliance of lean and green practices for NPD, to enhance efficiency from a lean perspective and produce eco-friendly items from a green perspective [17]. Dogu and Albayrak propose an IF cognitive map approach to assess the criteria influencing the marketing strategy in the NPD process and they present a case study [18]. Ying et al. suggest a hybrid MCDM methodology based on cumulative prospect theory to choose among the NPD alternatives [19]. Yan and Azadegan deliver inter-organizational NPD strategies using a theoretical and empirical categorization with two dimensions of external source type and engagement form [20]. Büyükozkan and Guleryuz propose a novel IF GDM approach for NPD partner selection and evaluate potential alternatives in a case study from Turkey [21]. Karniel and Reich offer a modeling approach to support the management of NPD processes and illustrate its effectiveness with an example based on two products [22]. Büyükozkan and Arsenyan present a literature review on collaborative product development aiming to investigate the limitations of the existing studies and provide suggestions for future research [23]. Lu et al. propose a fuzzy GDM approach to evaluate the garment NPD process in a real case study [24]. Lee and Lin use QFD (Quality Function Deployment) technique to solve the NPD process for a case study involving a thin film transistor liquid crystal display [25]. Chin et al. offer a multi-attribute decision making analysis to assess the NPD process in the early product design stage with an industrial case study of electrical appliances [26]. Kahraman et al. aim to improve the quality of decision-making in NPD by proposing a novel two-phase MCDM approach [27]. The proposed study differentiates itself from the extant literature with its novel objective world environment and its area of application. This study is an innovative research and highlights the importance of increasing the decision-making efficiency related to applicable gaming software and app selection during a novel NPD Project. The next section goes on with a depiction of a key pillar for the proposed study: PFSs studies in various MCDM areas.

2.2. PFSs studies

The initial outline of PFSs is presented by Atanassov [28] as a second-type IF set. It is the novel development of IF sets and rather fitting to represent the imprecision and ambiguity features. Parallel to the IF sets, PFSs [7] also allow expressing both the membership degree and non-membership degree of an element, but unlike IF, the square sum of the element's membership degree and non-membership degree should be less than or equal to '1'. This integral of PFSs delivers a more robust representation of obscurity than IF sets do. There are many recent studies focusing on different applications of PFSs. For example, Yan et al. [29] offer an enhancement of PFSs correlation measures by discussing a classification and pattern recognition case. Ejegwa et al. [30] apply PFSs based distance operators in pattern classification and disease diagnosis. Ejegwa et al. [31] deliver a three way PFSs correlation coefficient by discussing the recognition of patterns and diagnostic medicine. Ejegwa et al. [32] propose a PFS correlation coefficient measure by discussing a career placement and pattern recognition case. The following studies support the superiority of PFSs and provide practicality and effectiveness of PFSs. The review in Table 1 gives a synopsis of the applied techniques for the related studies. The thorough review of all present PFSs studies so far reveals that the provided approach is never been applied before to this extent. Interval-valued PFSs MULTIMOORA approaches have been presented before [33,34]. There is also a recent MOORA study [35] applying interval-valued PFSs, without a full multiplicative form. Single-valued PFSs MULTIMOORA approaches have also been presented in some studies [36–39]. Akram et al. [40] also apply PFSs-based MCDM MULTIMOORA methodology in their paper. They utilize linguistic information expressed by means of 2-tuples. 2-tuples are composed of a linguistic term and a numeric value assessed in $(-0.5, 0.5)$. However, there has been no study considering the GDM effect in a real case study by combining the three distinct subordinate ranking processes into one final ranking with a 9-point linguistic scale in MULTIMOORA evaluations. Thus, the proposed extension delivers true flexibility, greater mobility, better functionality, enhanced performance, and sufficient determination strengths by presenting the GDM extension of PFSs setting of MULTIMOORA MCDM.

In this paper, PFSs are applied as an objective world environment for the MULTIMOORA approach in NPD evaluation. The existing MULTIMOORA methods under a single-valued PFS environment use different distance measures and different operators in calculating the ratio, reference point, and full multiplicative form. The proposed single-valued PFSs MULTIMOORA method includes characteristics and features, which are easy to use, have a simple process, and have the same number of steps regardless of the number of attributes. Also, the proposed method allows a larger preference domain for DMs to assign membership grades compared to other MULTIMOORA extensions. Thus, there are distinct differences between our proposed methodology and theirs. Therefore, the presented manuscript has its distinctions and advantages. We have carefully reviewed all related studies in detail. To the best of the authors' knowledge, this is the first of its kind to use the PFSs in the MULTIMOORA approach and is utilized in an NPD decision under a GDM environment. Papers on PFSs generally offer aggregation operators for PFSs in an illustrative numerical example. To the best of our knowledge, MULTIMOORA has not yet been integrated with PFSs to the extent this paper presents.

3. Proposed methodology

The presented paper intends to characterize the most desirable alternative among the set of NPD options considering the opinions of a group of DMs. Since software and app evaluations are characterized by imprecision, PF MULTIMOORA is carried out to rank NPD candidates in this study. The succeeding sub-section provides a short outline of PFSs theory.

3.1. Preliminaries for PFS theory and arithmetic operations

The PFSs, originally developed by Yager, establish a distinguishing tool to cope with data uncertainty by considering the pairs of membership degrees and non-membership degrees [7,65].

Let X be a non-empty fixed universe;

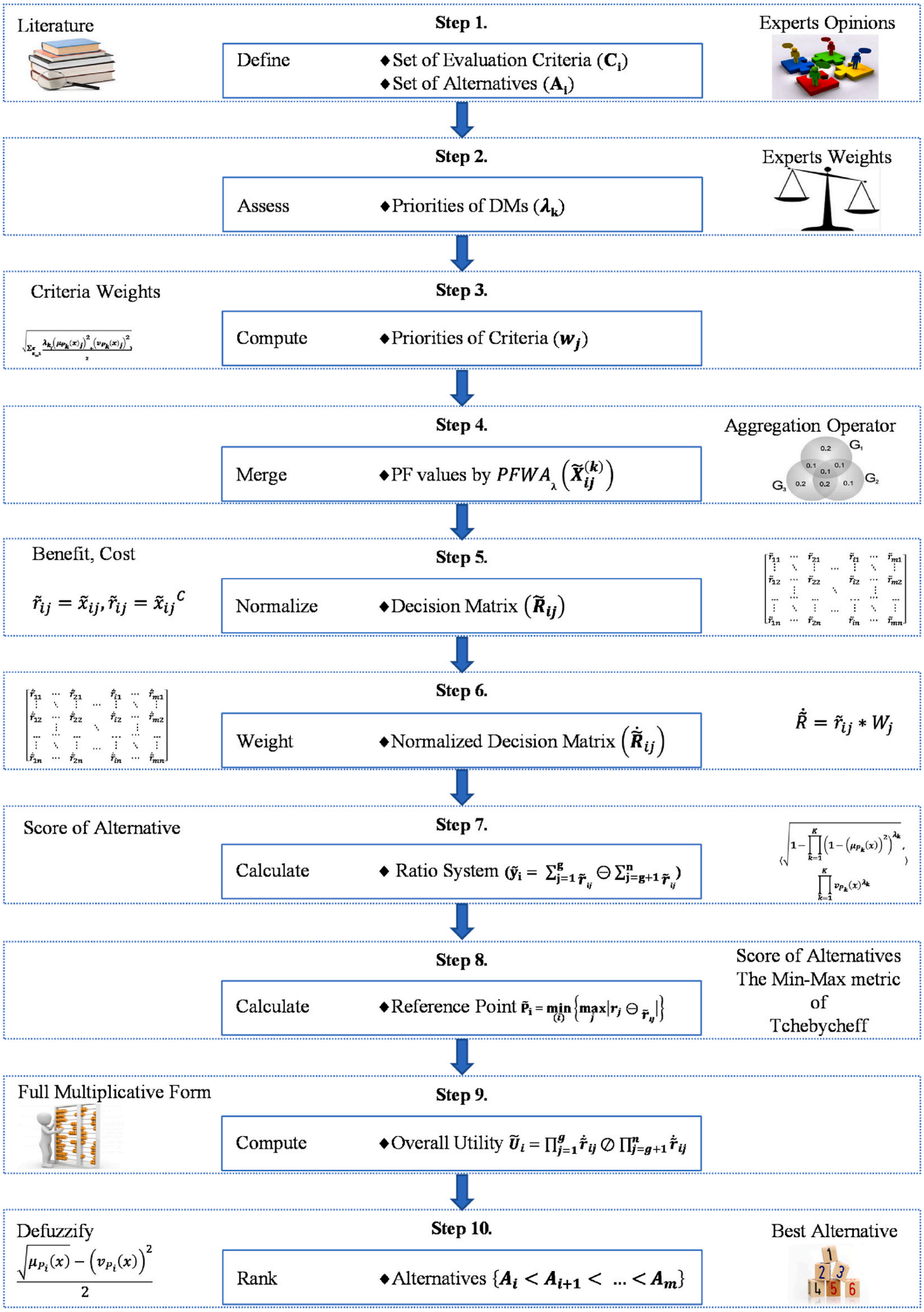

Fig. 1. The graphical representation of the proposed PF MULTIMOORA methodology.

Then P, PFS, in X is denoted as:

$$P = \{\langle x, \mu_P(x), v_P(x)\rangle\}, \tag{1}$$

PFSs are characterized by a membership degree $\mu_P : X \rightarrow [0,1]$ and a non-membership degree $v_P : X \rightarrow [0,1]$ to the set P, correspondingly. The values of these degrees are subjected to the following condition:

$$0 \leq (\mu_P(x))^2 + (v_P(x))^2 \leq 1, \pi_P(x) = \sqrt{1 - (\mu_P(x))^2 + (v_P(x))^2} \forall x \in X, \tag{2}$$

The hesitant degree of element x belonging to the PFS P is defined as $\pi_P(x)$, where $0 \leq \pi_P(x) \leq 1$ and $x \in X$.

In conventional terms, the**union** of two PFSs contains all the elements contained in either set (or both sets); The **intersection** of two sets contains only the elements that are in both sets; The **complement** of a PFSs contains everything that is *not* in the set *P*. In this study, the union, intersection, complement, summation, subtraction, product, division, scalar multiplication and power, etc., of PFSs operators are defined only in terms of membership and non-membership degrees. Let $p_1 = (\mu_{P_1}(x), v_{P_1}(x))$ and $p_2 = (\mu_{P_2}(x), v_{P_2}(x))$ be two PFS numbers and $\lambda > 0$. Basic PFSs functions are provided as follows [63,64]:

$$p_1 \bigoplus p_2 = \left(\sqrt{(\mu_{P_1}(x))^2 + (\mu_{P_2}(x))^2 - (\mu_{P_1}(x))^2.(\mu_{P_2}(x))^2}, v_{P_1}(x).v_{P_2}(x)\right), \tag{3}$$

$$p_1 \bigotimes p_2 = \left(\mu_{P_1}(x).\mu_{P_2}(x), \sqrt{(v_{P_1}(x))^2 + (v_{P_2}(x))^2 - (v_{P_1}(x))^2.(v_{P_2}(x))^2}\right), \tag{4}$$

$$p_1 \ominus p_2 = \left(\sqrt{\frac{(\mu_{P_1}(x))^2 - (\mu_{P_2}(x))^2}{1 - (\mu_{P_2}(x))^2}}, \frac{v_{P_1}(x)}{v_{P_2}(x)}\right), if\ \mu_{P_1}(x) \geq \mu_{P_2}(x), v_{P_1}(x) \leq min\left\{v_{P_2}(x), \frac{v_{P_2}(x).\pi_{P_1}(x)}{\pi_{P_2}(x)}\right\}, \tag{5}$$

$$p_1 \oslash p_2 = \left(\frac{\mu_{P_1}(x)}{\mu_{P_2}(x)}, \sqrt{\frac{(v_{P_1}(x))^2 - (v_{P_2}(x))^2}{1 - (v_{P_2}(x))^2}}\right), if\ \mu_{P_1}(x) \leq \min\left\{\mu_{P_2}(x), \frac{\mu_{P_2}(x).\pi_{P_1}(x)}{\pi_{P_2}(x)}\right\}, v_{P_1}(x) \geq v_{P_2}(x), \tag{6}$$

$$\lambda p_1 = \left(\sqrt{1 - \left(1 - (\mu_{P_1}(x))^2\right)^\lambda}, (v_{P_1}(x))^\lambda\right), \tag{7}$$

$$p_1{}^\lambda = (\mu_{P_1}(x))^\lambda, \sqrt{1 - \left(1 - (v_{P_1}(x))^2\right)^\lambda}, \tag{8}$$

$$p_1{}^C = (v_{P_1}(x), \mu_{P_1}(x)), \tag{9}$$

3.2. Novel pythagorean MULTIMOORA methodology

The steps of the proposed PF MULTIMOORA approach are described above and pictured in Fig. 1.

Step 1: State available alternatives and decision criteria.

The first step in decision-making is to define the decision problem. When a decision is met, it is clear that the objective (goal) is to be achieved. Thus, according to the overall goal and specific objective, the decision **criteria** and the available **alternatives** are stated for the defined problem in this step.

A set of alternatives A_i $(i = 1, 2, \ldots, m)$ is evaluated based on the set of decision criteria C_j.

$(j = 1, 2, \ldots, n)$. Let w_j $(\sum_{j=1}^n w_j = 1, w_j \geq 0)$ be the set of weights that define the priorities of criteria.

Step 2: Decide on the DMs' weights.

A set of DMs, D_k $(k = 1, 2, \ldots, K)$ is identified. The decision maker D_k is assigned an individual weight λ_k $(\sum_{k=1}^K \lambda_k = 1, \lambda_k \geq 0)$, which represents the importance degree of the DM's opinion. DMs in the set are not duplicates and consist of K different DMs. In dissimilar decision-making groups, the relative significance of each DM may vary. Some DMs may be less or more important than other DMs due to the difference in their responsibilities, knowledge, and experience. DMs' preferences are fused by the PFWA aggregation operator [7,8]. This nine-point scale is provided in Table 2. The importance of DMs is represented in verbal terms. To determine the weights of DMs, verbal variables are expressed in PFSs values.

Table 2
Linguistic variables for assessment.

Preference		$[\mu_P(x), v_P(x)]$	Preference		$[\mu_P(x), v_P(x)]$
Extremely Unimportant	EU	[0.05, 0.95]	Somewhat Important	SI	[0.65, 0.35]
Very Unimportant	VU	[0.15, 0.85]	Important	I	[0.75, 0.25]
Unimportant	U	[0.25, 0.75]	Very Important	VI	[0.85, 0.15]
Somewhat Unimportant	SU	[0.35, 0.65]	Extremely Important	EI	[0.95, 0.05]
Medium Importance	MI	[0.50, 0.50]			

Let $D_k = (\mu_{P_k}(x), v_{P_k}(x))$ be a PFS value to evaluate the kth DM.

To determine the weight of DMs, each DM has evaluated the other DMs.

- Get the opinions of the DMs about each other in linguistic variables.
- Transform verbal judgments of DMs into PFSs values.
- Combine distinct evaluations by PFWA operator in Eq. (10).
- The weight for the kth DM is estimated by Eq. (11).

$$PFWA(P_1, P_2, \ldots, P_K)_{D_k} = P_1^{\lambda'} \otimes P_2^{\lambda'}, \ldots, \otimes P_K^{\lambda'} = \left\langle \begin{array}{c} \sqrt{1 - \prod_{k=1}^{K} \left(1 - \left(\mu_{P_k}(x)\right)^2\right)^{\lambda'}}, \\ \prod_{k=1}^{K} v_{P_k}(x)^{\lambda'} \end{array} \right\rangle, \lambda' = \frac{1}{K-1} \tag{10}$$

$$\lambda_k = \frac{\frac{\sqrt{\mu_{P_j}(x) - \left(v_{P_j}(x)\right)^2}}{2}}{\sum_{k=1}^{K} \frac{\sqrt{\mu_{P_j}(x) - \left(v_{P_j}(x)\right)^2}}{2}}, \text{ where } \sum_{k=1}^{K} \lambda_k = 1 \tag{11}$$

Step 3: Calculate the level of influence for the criteria weights.

In decision-making problems, the criteria weights are not equal. The degree of importance for each criterion is at a different level for each DM. Therefore, it is necessary to combine the PFSs values given to the criteria by each DM.

- Acquire the ratings of the DMs on all criteria.
- Transform verbal judgments of DMs into PFSs values.
- The weight for the jth criterion is assessed by Eq. (12).

$$w_j = \frac{\sqrt{\sum_{k=1}^{K} \frac{\lambda_k \left(\left(\mu_{P_k}(x)_j \right)^2 + \left(v_{P_k}(x)_j \right)^2 \right)}{2}}}{\sum_{j=1}^{n} \sqrt{\sum_{k=1}^{K} \frac{\lambda_k \left(\left(\mu_{P_k}(x)_j \right)^2 + \left(v_{P_k}(x)_j \right)^2 \right)}{2}}} \tag{12}$$

Step 4: Aggregate distinct evaluations of alternatives into group opinion.

People often rely on personal beliefs and values in their assessment. Evaluations based on such individual values (such as classic cars are better than new ones, etc.) would be detrimental to the solution of problems involving more than one person, even if they apply to individuals in some cases. Therefore, there should be a fusing method to combine individual DM evaluations into group opinions. The following procedure is applied to obtain a GDM matrix of alternatives. In the GDM process, the thoughts of all DMs need to be aggregated as group opinions without any loss of information to obtain a unified decision matrix.

- Collect the expressions of the DMs on all alternatives.
- Transform verbal judgments of DMs into PFSs values.

Let $X_{(k)} = (X_{(k)_{ij}})_{mxn}$ be a PFSs decision matrix of the kth DM.

- Form an aggregated PFS preference matrix $(\widetilde{X})$ by Eq. (13).

$$PFWA(P_1, P_2, \ldots, P_K)_{A_i} = P_1^{\lambda_1} \otimes P_2^{\lambda_2}, \ldots, \otimes P_Z^{\lambda_K} = \left\langle \begin{array}{c} \sqrt{1 - \prod_{k=1}^{K} \left(1 - \left(\mu_{P_k}(x)\right)^2\right)^{\lambda_k}}, \\ \prod_{k=1}^{K} v_{P_k}(x)^{\lambda_k} \end{array} \right\rangle \tag{13}$$

$$\widetilde{X} = \begin{bmatrix} \widetilde{x}_{11} & \cdots & \widetilde{x}_{21} & & \widetilde{x}_{i1} & \cdots & \widetilde{x}_{m1} \\ \vdots & \ddots & \vdots & \cdots & \vdots & \ddots & \vdots \\ \widetilde{x}_{12} & \cdots & \widetilde{x}_{22} & & \widetilde{x}_{i2} & \cdots & \widetilde{x}_{m2} \\ & \vdots & & \ddots & & \vdots & \\ \ldots & \cdots & \ldots & & \ldots & \cdots & \ldots \\ \vdots & \ddots & \vdots & \cdots & \vdots & \ddots & \vdots \\ \widetilde{x}_{1n} & \cdots & \widetilde{x}_{2n} & & \widetilde{x}_{in} & \cdots & \widetilde{x}_{mn} \end{bmatrix} \tag{14}$$

where, $\widetilde{x}_{ij} = (\mu_P(x), \nu_P(x))$ represents PFS values denoting the merged i th alternative for the j th criterion.

Step 5: Institute the normalized decision-matrix.

The normalized decision-matrix $\widetilde{R} = [\widetilde{r}_{ij}]_{mxn}$ with $\widetilde{r}_{ij} = (\mu_P(r), \nu_P(r))$ is estimated by Eq. (15) and Eq. (16).

$$\widetilde{R} = \begin{bmatrix} \widetilde{r}_{11} & \cdots & \widetilde{r}_{21} & & \widetilde{r}_{i1} & \cdots & \widetilde{r}_{m1} \\ \vdots & \ddots & \vdots & \cdots & \vdots & \ddots & \vdots \\ \widetilde{r}_{12} & \cdots & \widetilde{r}_{22} & & \widetilde{r}_{i2} & \cdots & \widetilde{r}_{m2} \\ & \vdots & & \ddots & & \vdots & \\ \ldots & \cdots & \ldots & & \ldots & \cdots & \ldots \\ \vdots & \ddots & \vdots & \cdots & \vdots & \ddots & \vdots \\ \widetilde{r}_{1n} & \cdots & \widetilde{r}_{2n} & & \widetilde{r}_{in} & \cdots & \widetilde{r}_{mn} \end{bmatrix}$$

$$\widetilde{r}_{ij} = \widetilde{x}_{ij}, (\mu_P(r), \nu_P(r)) = (\mu_P(x), \nu_P(x)), \tag{15}$$

For benefit criteria

$$\widetilde{r}_{ij} = \widetilde{x}_{ij}{}^{C}, (\mu_P(r), \nu_P(r)) = (\nu_P(x), \mu_P(x)), \tag{16}$$

For cost criteria.

Step 6: Launch the normalized weighted matrix.

The normalized and weighted decision matrix $\dot{\widetilde{R}} = [\dot{\widetilde{r}}_{ij}]_{mxn}$ is formed by Eq. (17).

$$\dot{\widetilde{R}} = \begin{bmatrix} \dot{\widetilde{r}}_{11} & \cdots & \dot{\widetilde{r}}_{21} & & \dot{\widetilde{r}}_{i1} & \cdots & \dot{\widetilde{r}}_{m1} \\ \vdots & \ddots & \vdots & \cdots & \vdots & \ddots & \vdots \\ \dot{\widetilde{r}}_{12} & \cdots & \dot{\widetilde{r}}_{22} & & \dot{\widetilde{r}}_{i2} & \cdots & \dot{\widetilde{r}}_{m2} \\ & \vdots & & \ddots & & \vdots & \\ \ldots & \cdots & \ldots & & \ldots & \cdots & \ldots \\ \vdots & \ddots & \vdots & \cdots & \vdots & \ddots & \vdots \\ \dot{\widetilde{r}}_{1n} & \cdots & \dot{\widetilde{r}}_{2n} & & \dot{\widetilde{r}}_{in} & \cdots & \dot{\widetilde{r}}_{mn} \end{bmatrix}$$

$$\dot{\widetilde{R}} = \widetilde{r}_{ij} * W_j \tag{17}$$

Step 7: Estimate the Score of Alternatives on the Ratio System.

The score of alternatives on the ratio system is estimated by Eq. (18).

$$\widetilde{y}_i = \sum_{j=1}^{g} \dot{\widetilde{r}}_{ij} \ominus \sum_{j=g+1}^{n} \dot{\widetilde{r}}_{ij} \tag{18}$$

Where, the benefit criteria are organized as $j = 1, 2, \ldots, g$ and the cost criteria are organized as $j = g + 1, g + 2, \ldots, n$.

Step 8: Estimate the Score of Alternatives on the Reference Point.

The Min-Max metric of Tchebycheff is calculated by Eq. (19).

$$\widetilde{P}_i = \min_{(i)} \left\{ \max_{j} \left| r_j \ominus \dot{\widetilde{r}}_{ij} \right| \right\} \tag{19}$$

Where, $\widetilde{P}_i$ is a PFSs value and r_j is the top criteria value on all alternatives.

Step 9: Estimate the Overall utility function for the Full Multiplicative Form.

The overall utility function for all alternatives is estimated by Eq. (20) by utilizing the PFSs division in Eq. (6).

$$\widetilde{U}_i = \prod_{j=1}^{g} \dot{\widetilde{r}}_{ij} \oslash \prod_{j=g+1}^{n} \dot{\widetilde{r}}_{ij} \tag{20}$$

Where, the benefit criteria are organized as $j = 1, 2, \ldots, g$ and the cost criteria are organized as $j = g + 1, g + 2, \ldots, n$.

Step 10: Rank alternatives.

- Defuzzify [66] the PFSs value of Ratio System, Reference Point Approach, and Full Multiplicative Form. The defuzzification is done by Eq. (21)
- Apply the dominance theory [67] to finalize three rankings into one single rank.

$$\frac{\sqrt{\mu_{P_i}(x)} - (\nu_{P_i}(x))^2}{2} \tag{21}$$

4. Case study

4.1. Case background

The proposed method is implemented in a case study for a software company operating in Turkey. The designation of the software company is unrevealed due to privacy and confidentiality reasons and will be addressed as ABC henceforward. The ABC software company has been established recently by high school friends of 20 years, founded in 2012. It has been mainly prototyping new game ideas and developing fully in-house gaming software and apps for computers and smartphones. Developing software to entertain people is a difficult task and one of the most difficult areas of the software industry. Some of the key challenges are performance concerns and variability in the hardware market. ABC's first gaming software had launched in Turkey and Canada in 2014. Since then, it gradually releases an increasing number of new software and apps to the global market. Global competition is a key issue for ABC, hence it is considered in the NPD process and company strategy. The selection of the most appropriate gaming software and apps is an important decision for ABC. Our study adopts an explorative and qualitative approach, supported by a team of experts specialized in software development to gain in-depth insights into the initialization of a new product and how real-world experts navigate the new software development ecosystem. GDM is a type of participatory process in which multiple DMs act cooperatively to assess and consider alternatives and criteria, analyze situations or problems, and chose a solution or solutions among multiple alternatives. The number of DMs involved in GDM may vary greatly but often ranges from two to nine [68]. The quality of a group decision often depends on the qualitative features of individuals participating in the decision-making process. Some studies suggest more DMs for improved decision processes. However, most of the studies deem three DMs as good enough to make a good decision [11,68,69]. In our case study, we thus selected three DMs with diverse strengths, specific knowledge, and expertise in the area. Making use of real practitioners' viewpoints is a widespread approach in the area of NPD [70]. Practitioners in a particular field of concern may have a better knowledge of the underlying structures of a specific system. They are also likely to have more reasonable and well-grounded judgments of the state of affairs in that particular problem area. Three DMs, an academic, an engineer (cofounder of ABC), and a top-level manager (research and development manager of ABC), are selected to evaluate 5 NPD alternatives, a new software and app development in this case study. Software and app development is an exceptional setting for NPD, as there is an evident dissimilarity between conventional production processes and software development. The evaluation criteria, which is used to assess and rank the alternative software and apps, are collected from the extant review of literature, as well as from ABC executives.

4.2. Criteria structuring

The findings from the literature and the suggestions of the DMs have led to the selection of eight suitable criteria. The DMs stated the requisite benefit and cost factors in the criteria determination to evaluate NPD alternatives in a feasible manner. Therefore, the authors have deemed eight criteria as adequate for the evaluation process of the study. Criteria 1 through 4 and 5 through 8 are regarded as benefit criteria and cost criteria, respectively. In the subsequent section, ABC's selection process is demonstrated systematically. ABC wishes to select the best developer that suits its prerequisites and expectations. In this case study, five candidate software and apps were assessed, which ABC has identified to work together. These candidates are referred to as A_1, A_2, A_3, A_4 *and* A_5 from now on.

Brief descriptions of candidate gaming software and apps are as follows.

- A_1: A casual puzzle game that will tickle the brain with its brand-new wind mechanism.
- A_2: A soccer game of headers running on a virtual reality head-mounted display with positional tracking
- A_3: A fast-paced tactical game of futuristic gunship with an innovative hybrid shooter and endless runner
- A_4: A war simulation game that deals with historical military operations of various types
- A_5: A strategy of tower defense where the goal is to defend a player's territories

NPD selection criteria are adapted mostly from the studies of [27,70] as follows.

- C_1: Profitability in NPD or market share for new products under the current competitive environment
- C_2: Efficiency in NPD reduces the time and costs to reach in markets
- C_3: Business Impact describes the general motivation and the nature of the business in the NPD process
- C_4: Strategic Value creates a value stream
- C_5: Financial Risk in NPD makes reactions to the price alterations, levels, and strategies
- C_6: Technical Risk in NPD needed for more innovative and better-targeted products
- C_7: Managerial Risk is the competitive response to NPD strategies
- C_8: Personnel Risk is the impact of NPD on market share or profits

5. Results

The result section provides the execution of the developed approach.

Step 1: The core objective is set to evaluate gaming software and apps using eight decision **criteria** to assess five **alternatives** at hand.

Step 2: The significance of each DM is stated in the form of linguistic statements with the help of the nine-point scale in Table 2. DMs' judgments are combined by the PFWA aggregation operator by Eq. (10). The weights of each DM are processed by Eq. (11).

The status values of DMs are stated as:

D_1's judgment on 'D_2', and 'D_3' is 'VI', 'I', respectively. D_2's judgment on 'D_1', and 'D_3' is 'EI', 'VI', respectively. D_3's judgment on 'D_1', and 'D_2' is 'EI', 'VI', respectively.

An example calculation for D_1 is presented below:

$$\lambda_1 = \frac{\frac{\sqrt{0.95 - (0.05)^2}}{2}}{\left(\frac{\sqrt{0.95 - (0.05)^2}}{2}\right) + \left(\frac{\sqrt{0.85 - (0.15)^2}}{2}\right) + \left(\frac{\sqrt{0.81 - (0.19)^2}}{2}\right)} = 0.356, \lambda_2 = 0.329, \lambda_3 = 0.315.$$

Step 3: The level of impact of the criteria weights is processed by Eq. (12). The assessment of the DMs on all criteria and respective criterion weights and their rank are presented in Table 3.

Step 4: The ratings of each DM on alternatives are presented in Table 4. The individual alternative evaluations are fused into GDM by the PFWA aggregation operator in Eq. (13). The aggregated PFSs preference relation matrix $(\widetilde{X})$ is established. A sample matrix $(\widetilde{X})$ for Alternative 1 for each DM and respective GDM is presented in Table 5.

Step 5: The normalization of the decision-matrix for benefit and cost criteria is established $\widetilde{R} = [\widetilde{r}_{ij}]_{mxn}$ by Eq. (15) and Eq. (16). Table 6 presents a sample of the first alternative.

Step 6: The normalized matrix is weighted $\dot{\widetilde{R}} = [\dot{\widetilde{r}}_{ij}]_{mxn}$ by Eq. (17). Table 6 presents a sample of the first alternative.

Step 7: The Score of Alternatives for the Ratio System is computed by Eq. (18). Table 7 presents the benefit and cost sums of alternatives and their respective score.

Where the benefit criteria are organized as $j = 1, 2, \ldots, g$ and the cost criteria are organized as $j = g + 1, g + 2, \ldots, n$.

Step 8: The Min-Max metric of Tchebycheff calculation for the Reference Point Approach is made by Eq. (19). The best criteria values and calculated subtraction for the first alternative are presented in Table 8. Table 9 presents the PFSs values of the Reference Point Approach for each alternative.

Step 9: The overall utility function for all alternatives is estimated by Eq. (16), and the PFSs operator in Eq. (6) is used for division. Table 10 presents the results.

Where the benefit criteria are organized as $j = 1, 2, \ldots, g$ and the cost criteria are organized as $j = g + 1, g + 2, \ldots, n$.

Step 10: The defuzzification is practiced by Eq. (21) to rank alternatives. The dominance theory is applied to finalize '3' rankings into '1' single rank. The outcomes are presented in Table 11.

6. Managerial implications and discussions

Decision-making is the choice of alternatives. In other words, the decision-making of a DM is the process of choosing terms of various alternatives to perform the task assigned to it. The DM has to make many decisions, both in business and in his private life, and he/she makes his/her decision without much difficulty in the vast majority of them (e.g. what time to get up, what clothes to wear, and what food to eat, etc.). This is true, in cases where the decision does not concern others. However, it is a problem to be able to make a correct decision in cases where the decision is of interest to others and so the wrong decision can have some heavy consequences. Also, the alternatives and selection criteria to be considered are the other critical factors. In short, making the right decision and ensuring the effective implementation of the decision can be considered as the most important executive function task for the whole DMs [71]. Decision-making aims to identify the top candidate among the set of available ones. Since the early 1970s, MCDM techniques are being developed by considering the impact of several criteria simultaneously. MCDM methods are divided into Multi-Objective approaches and Multi-Attribute approaches. The fundamental difference among these is based on the determination of the alternatives. In

Table 3
The judgments and respective weights of each criterion.

	D_1	D_2	D_3	w_j	Rank
C_1	VU	EI	SI	0.135	1
C_2	I	I	SU	0.122	5
C_3	U	U	VU	0.128	3
C_4	SI	SU	U	0.119	8
C_5	U	SI	EI	0.131	2
C_6	U	SI	SU	0.119	7
C_7	SI	I	U	0.122	6
C_8	VU	MI	U	0.125	4

Table 4
The judgments of the DMs on Alternatives.

	A_1			A_2			A_3			A_4			A_5		
	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
C_1	U	I	VU	VU	MI	U	MI	I	U	VU	MI	U	EU	MI	VU
C_2	MI	U	MI	U	SI	MI	U	MI	MI	VU	U	MI	U	U	MI
C_3	VU	U	VU	SI	VU	U	VI	VU	U	MI	U	VU	MI	U	SI
C_4	MI	U	VU	MI	I	EU	U	I	SI	MI	VI	U	VU	MI	U
C_5	VI	I	VU	MI	U	VU	VU	VU	VU	MI	MI	U	MI	VI	SI
C_6	U	VI	MI	U	SI	U	U	SU	SI	SI	U	MI	U	SI	VU
C_7	MI	I	VU	I	MI	U	SI	I	VU	VU	SI	MI	SI	VU	I
C_8	I	VU	VU	MI	I	U	SU	U	SU	SI	U	VI	U	EU	VI

Table 5
The preference relation matrix of A_1 for each DM and respective GDM matrix.

		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
D_1	$[\mu_P(x), \nu_P(x)]$	[0.250, 0.750]	[0.500, 0.500]	[0.150, 0.850]	[0.500, 0.500]	[0.850, 0.150]	[0.250, 0.750]	[0.500, 0.500]	[0.750, 0.250]
D_2	$[\mu_P(x), \nu_P(x)]$	[0.750, 0.250]	[0.250, 0.750]	[0.250, 0.750]	[0.250, 0.750]	[0.750, 0.250]	[0.850, 0.150]	[0.750, 0.250]	[0.150, 0.850]
D_3	$[\mu_P(x), \nu_P(x)]$	[0.150, 0.850]	[0.500, 0.500]	[0.150, 0.850]	[0.150, 0.850]	[0.150, 0.850]	[0.500, 0.500]	[0.150, 0.850]	[0.150, 0.850]
PFWA	$[\mu_P(x), \nu_P(x)]$	[0.511, 0.543]	[0.439, 0.571]	[0.189, 0.816]	[0.350, 0.675]	[0.722, 0.307]	[0.644, 0.389]	[0.563, 0.470]	[0.515, 0.550]

Table 6
The normalized and weighted decision-matrix of A_1.

	$[\widetilde{r}_{ij}]_{mxn}$		$[\dot{\widetilde{r}}_{ij}]_{mxn}$	
	$[\mu_P(x),$	$\nu_P(x)]$	$[\mu_P(x),$	$\nu_P(x)]$
C_1	[0.511,	0.543]	[0.200,	0.921]
C_2	[0.439,	0.571]	[0.160,	0.934]
C_3	[0.189,	0.816]	[0.068,	0.974]
C_4	[0.350,	0.675]	[0.124,	0.954]
C_5	[0.307,	0.722]	[0.113,	0.958]
C_6	[0.389,	0.644]	[0.139,	0.949]
C_7	[0.470,	0.563]	[0.173,	0.933]
C_8	[0.550,	0.515]	[0.209,	0.921]

Table 7
The score of alternatives for the ratio system.

	$\sum_{j=1}^{g} \dot{\widetilde{r}}_{ij}$	$\sum_{j=g+1}^{n} \dot{\widetilde{r}}_{ij}$	$\widetilde{y}_i$
	$[\mu_P(x), \nu_P(x)]$	$[\mu_P(x), \nu_P(x)]$	$[\mu_P(x), \nu_P(x)]$
A_1	[0.289, 0.800]	[0.320, 0.781]	[0.143, 0.98]
A_2	[0.344, 0.753]	[0.411, 0.691]	[0.239, 0.92]
A_3	[0.422, 0.681]	[0.519, 0.582]	[0.333, 0.85]
A_4	[0.327, 0.771]	[0.365, 0.726]	[0.172, 0.94]
A_5	[0.282, 0.801]	[0.343, 0.763]	[0.203, 0.95]

Multi-Objective models, the alternatives are not predefined. Instead, objectives are pre-defined and optimized subject to a fixed set of constraints. In Multi-Attribute models, the set of alternatives is pre-determined, and they are evaluated against a set of criteria. The diversity in needs and technical preferences has led to the emergence of numerous types of different MCDM methodologies [72], such as AHP (Analytic Hierarchy Process) [73], COPRAS (Complex Proportional Assessment) [74], MOORA (Multi-Objective Optimization on the basis of Ratio Analysis) [75], MULTIMOORA (Multi-Objective Optimization on the basis of Ratio Analysis plus the Full Multiplicative Form) [13], and VIKOR (VlseKriterijuska Optimizacija. I Komoromisno Resenje) [76], among others. Several types of MCDM approaches have been also developed but most of them are applied with crisp or fuzzy numbers, which can be insufficient in certain environments.

In 2010, Brauers and Zavadskas, researchers from Vilnius Gediminas Technical University, developed a multi-criteria decision-making method. This new method is called MULTIMOORA and it is a newly introduced MCDM method used to determine the best

Table 8
The best criteria values and calculated subtraction for A_1.

	r_j	$\lvert r_j \ominus \dot{\tilde{r}}_{ij} \rvert$
	$[\mu_P(x), \nu_P(x)]$	$[\mu_P(x), \nu_P(x)]$
C_1	[0.227, 0.899]	[0.111, 0.976]
C_2	[0.188, 0.922]	[0.099, 0.987]
C_3	[0.245, 0.900]	[0.236, 0.924]
C_4	[0.251, 0.892]	[0.219, 0.935]
C_5	[0.393, 0.780]	[0.379, 0.814]
C_6	[0.231, 0.906]	[0.186, 0.955]
C_7	[0.201, 0.918]	[0.104, 0.984]
C_8	[0.274, 0.868]	[0.180, 0.943]

Table 9
The reference point approach.

$\tilde{P}_i$	A_1	A_2	A_3	A_4	A_5
$[\mu_P(x), \nu_P(x)]$	[0.379, 0.810]	[0.290, 0.890]	[0.135, 0.970]	[0.332, 0.870]	[0.379, 0.820]

Table 10
The overall utility function.

	$\prod_{j=1}^{g} \dot{\tilde{r}}_{ij}$	$\prod_{j=g+1}^{n} \dot{\tilde{r}}_{ij}$	$\tilde{U}_i$
	$[\mu_P(x), \nu_P(x)]$	$[\mu_P(x), \nu_P(x)]$	$[\mu_P(x), \nu_P(x)]$
A_1	[0.00027, 0.99996]	[0.00057, 0.99992]	[0.477, 0.275]
A_2	[0.00084, 0.99986]	[0.00166, 0.99966]	[0.509, 0.764]
A_3	[0.00206, 0.99956]	[0.00341, 0.99909]	[0.603, 0.721]
A_4	[0.00050, 0.99992]	[0.00104, 0.99980]	[0.481, 0.774]
A_5	[0.00035, 0.99995]	[0.00072, 0.99989]	[0.485, 0.732]

Table 11
The defuzzified values and respective rankings.

	y_i	Rank	P_i	Rank	U_i	Rank	Overall
A_1	−0.286	5	−0.023	5	0.307	1	5
A_2	−0.177	2	−0.131	2	0.065	4	2
A_3	−0.076	1	−0.290	1	0.128	2	1
A_4	−0.236	4	−0.088	3	0.046	5	4
A_5	−0.228	3	−0.025	4	0.080	3	3

alternative among the possible available options. The primary purpose of the method is to determine the rankings of the alternatives involving three components, the ratio system, the reference point, and the full multiplicative form. Since the MULTIMOORA method does not require much initial information compared to other MCDM methods, it can also be used in determining the criteria weights and choosing the most suitable alternative. Also, the MULTIMOORA method helps to find a solution to optimization problems. All MCDM methods, as well as MULTIMOORA, have many advantages and disadvantages. Such as being able to evaluate quantitative and qualitative criteria together by providing a common ground for a decision making process in the existence of more than one contradictory criterion. At the same time, it can evaluate large sets of data, analyze complex and difficult-to-perceive issues, and facilitate a better understanding of the given situation. Of course, there are also some disadvantages. During the decision-making process, for instance, while an alternative among different alternatives is superior to other options for a criterion, it may be the opposite for another criterion. Therefore, comparing one alternative to another during the decision-making process might create some confusion.

There are several PFSs-based MCDM MULTIMOORA methodologies, but our analysis is based on Group Decision Making. There has been no study considering the GDM effect in a real case study by combining the three distinct subordinate ranking processes into one final ranking. Therefore, to create a consensus of multiple decision makers, among different aggregation operators, the Pythagorean fuzzy weighted averaging aggregation operator is utilized in this study. PFWA aggregation operator is already applied to many PFSs MCDM studies but has never been utilized for any MULTIMOORA approaches before. Therefore, our study is to first to offer a reliable application of PFSs MULTIMOORA to a real-world problem. The score function and defuzzification operator are also utilized to make the developed MCDM framework more reliable and consistent since there are many applications of them in the extant literature.

For example, Huang et al. [38] have also applied the MULTIMOORA methodology under the PFSs setting. However, they have not included the concept of GDM in their analysis and used only an illustrative example to demonstrate the tenacity of their methodology. Similarly, Li et al. [39] also utilize PFSs MULTIMOORA for an illustrative example. They apply Pythagorean fuzzy ordered weighted averaging to combine large group data, but they lack the necessary precision provided by the PFWA operator to aggregate group opinions. Akram et al. [40] developed PFSs-based MCDM MULTIMOORA approach under GDM environment but the details of MULTIMOORA application under PFS is also quite dissimilar. To say the least, this manuscript uses 9-point linguistic scale in MULTIMOORA evaluations, they apply 2-tuples. They use generalized 2-tuple aggregation operators while we apply Pythagorean fuzzy weighted averaging aggregation operator to create a consensus of multiple decision makers, among different aggregation operators. Our study is to first to offer a reliable application of PFSs-based MCDM MULTIMOORA methodology to a real world problem. Li et al. [33] offer a MULTIMOORA MCDM methodology but under interval valued PFSs environment. The operations in interval valued PFSs and single valued PFSs are entirely different from each other, thus unsurpassed with each other. This list can extend further if the details are probed farther. Consequently, the given manuscript has its own superiorities and distinctions. The authors have cautiously searched all relevant papers and take certain benefits of them by using proper citations of stated research.

The organizations' effectiveness in today's aggressive business setting relies mostly upon their capacity to launch new products. Organizations must develop new products more often than before because the market demands them. Otherwise, they are in danger of going out of business. The turnover of digital age organizations is largely due to newly developed products. For example; Fifty percent of the turnover of the companies operating in the field of Information Technology in the last year consists of products/services developed in the last three years [11]. Now, companies attach great importance to the NPD process along with production processes and allocate important resources to this field. The effectiveness and success of the NPD process are vital to the organizations, but the NPD is a time-consuming and costly process and the development strategy is a complex problem involving multiple criteria to be considered simultaneously. That is why in this paper, we propose an MCDM approach, which integrates the MULTIMOORA to measure the performance of NPD alternatives under the PFSs environment. The PFSs have shown some convincing advantages in dealing with the fuzziness and hesitation over crisp, fuzzy, or intuitionistic fuzzy sets to depict DMs' preferences in a more representative structure. The developed evaluation model is illustrated through a real-case study. The comprehensive steps involved in NPD for new software and apps such as the market requirement evaluation, defining the type of app to be built, the budget constraints, and eventually the execution of the NPD process, can be discouraging sometimes. Nevertheless, all these steps are equally important, and ignoring any of them can weaken others and eventually cost time and money. The decision criteria for NPD assessment are identified with an extensive literature review and a group of DMs. These criteria should be considered in selecting the most suitable alternative. In light of the identified criteria, all NPD alternatives are ranked with the proposed approach. Looking at the overall literature on software and app development, and the revealed lack of research on them, the proposed study will provide a real contribution to NPD literature, in addition to the development of MCDM studies. This is state-of-art pioneer research that uses PFSs-based MCDM under a GDM setting.

Alternative A_3, which is a fast-paced tactical game of futuristic gunship with an innovative hybrid shooter and an endless runner is selected as the best candidate. We have also consulted our findings with the company owners and managers and we were happy to see that our findings pleased them and they have decided to work on A_3 gaming software for personal computers and apps for smartphones.

6.1. Comparative analysis

The presented research is assessed with several distinct objective world setting to further demonstrate the rationality of the proposed approach. The outcome of the estimated ranks is presented in Fig. 2. To compare the proposed method under the PFSs setting, classical fuzzy sets and IF sets are equated. It is easy to spot from Fig. 2, the variance among PFSs, IF, and Fuzzy set application of the proposed method is subtantial. For instance, the third alternative has the best ranking for the proposed PFSs setting. However, it has the fourth ranking for the fuzzy and second-ranking place for the IF setting. The weaknesses of classical fuzzy-based evaluations are revealed by this comparison in choosing the best alternative. On the other hand, the developed solution methodology is able to tackle the challenges associated with the classical fuzzy settings. Another comparative analysis is also carried out and the developed approach

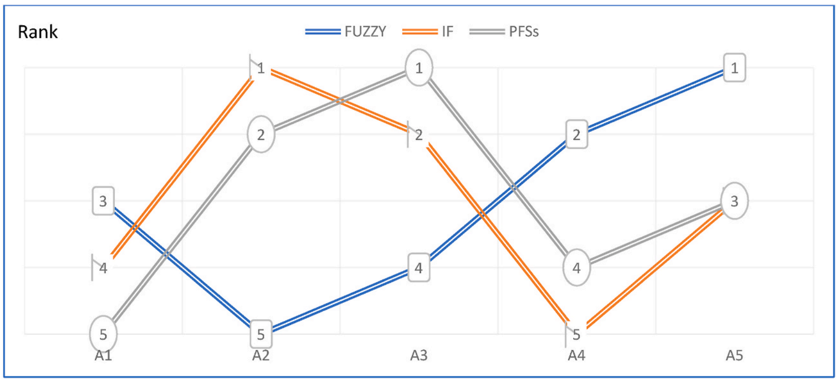

Fig. 2. The outcome of ranks under various settings.

Table 12
Comparative analysis of the proposed method with existing techniques by Spearman's rank correlation (2-tailed).

	MULTIMOORA	TOPSIS	VIKOR	EDAS	COPRAS	TODIM
MULTIMOORA $A_3 > A_2 > A_5 > A_4 > A_1$	–	0.8728	0.0373	0.1040	0.3910	0.5046
TOPSIS $A_1 > A_3 > A_5 > A_2 > A_4$		–	0.6238	0.5046	0.8728	0.1040
VIKOR $A_3 > A_2 > A_4 > A_5 > A_1$			–	0.391	0.2847	0.6238
EDAS $A_3 > A_5 > A_2 > A_1 > A_4$				–	0.7470	0.2847
COPRAS $A_2 > A_3 > A_1 > A_4 > A_5$					–	0.2847
TODIM $A_3 > A_1 > A_2 > A_5 > A_4$						–

is applied under the IF setting. The differences in the ranking are getting diminished under this comparison. The consistency can be observed as the result of the developed solution approach. There exist some variations but compared techniques have a different operational mechanism in the determination of the best candidate. Thus, the proposed PFSs based MULTIMOORA technique can obtain more rational priority rankings.

Table 12 presents the Spearman's rank correlations among MULTIMOORA, TOPSIS, VIKOR, EDAS, COPRAS, and TODIM signifying the strongest association between the ranks of MULTIMOORA with VIKOR. The association between the two sets of ranks is stronger if Spearman's rank correlation has a higher positive value. If there are stronger correlations for the ranking of alternatives between two MCDM methodologies, it indicates that they have similar ranks according to Spearman's rank correlation concept [69]. If the correlation value is negative, then the ranks are rather reverse in nature. By normal standards, the association between MULTIMOORA and TOPSIS ranks would not be considered statistically significant indicating a correlation of -0.1; the association between MULTIMOORA and VIKOR rankings would be considered statistically significant indicating a correlation of 0.9; the association between MULTIMOORA and EDAS rankings would not be considered statistically significant indicating a correlation of 0.8; the association between MULTIMOORA and CODAS rankings would not be considered statistically significant indicating correlation of 0.5; the association between MULTIMOORA and TODIM rankings would not be considered statistically significant indicating correlation of 0.4.

The association can be enlightened further for MULTIMOORA and VIKOR methods since the correlation has the utmost value between them. The rankings of the two MCDM approaches (see Table 12), MULTIMOORA and VIKOR, reveal that three alternatives have the same ranking among the five alternatives. The worst negative correlation (-0.1) is detected between approaches of "MULTIMOORA and TOPSIS" and "TOPSIS and COPRAS". This is obvious for the rankings of MULTIMOORA and TOPSIS. For instance, alternative A_1, MULTIMOORA and TOPSIS rankings are in reverse (5th and 1st rankings, respectively). Likewise for alternative A_2, 4th (for TOPSIS) and 1st (for COPRAS) ranking order is appeared. A similar logic is valid for other alternatives as well. The presented outcome evidently displays that the MULTIMOORA ranking can be identified as the most appropriate ranking via Spearman's rank correlation application. However, the comparison is merely restricted to determining the degree of association between alternative sets. Hence, to make an effective comparison of the rankings and to identify the best suitable MCDM approach for the presented study, the subsequent section of sensitivity analysis is also applied to the proposed methodology in addition to performing a comparison between MULTIMOORA and the other five MCDM techniques.

6.2. Sensitivity analysis

The robustness of the presented solutions and the benchmarking of the PFSs MULTIMOORA approach is validated through sensitivity analysis to observe the instances of the alternatives under different criteria weights. In the analysis, the criteria weights are modified to observe the ranking variations. The results of the analysis are displayed in Table 13 and depicted in Fig. 3. Sensitivity analysis has been employed by various studies to validate their respective findings [77]. Eight states overall are studied. The objective of sensitivity analysis is to examine for alterations in the proposed solution under the conditions of increased or decreased criteria weights. The highest possible weight is given to each criterion in turn whereas keeping the others equal. The sensitivity analysis illustrates to us the ranking of all alternatives is affected by DMs' judgments about the criteria. For each state, the overall ranking is calculated. This analysis suggests that the ranking of alternatives is quite robust against the changes in criteria weights. The changes depicted in Fig. 3 indicate that the Rank values do change as criteria weights are varied, as expected. However, these variations do not lead to significant changes in the rankings in general. Even when the ranks alter in the states of 7 and 8, the difference in rank values is so low that the proposed framework generates similar solutions, instead of completely flipping the ranking. Moreover, A_3, the best alternative, continues not to have the lowest rank value for all of the scenarios. This analysis underlines that the framework's functionality is not overshadowed by the criteria or their priorities. It also demonstrates that its proposed 1st ranked alternative is not sensitive to criteria weights, strengthening the framework's usability. The case study shows that the proposed framework is feasible for identifying the best NPD candidate from other available NPD candidates in terms of ranking performance. It is clear that the importance of criteria C_1 and C_5 are dominant in the selection process.

7. Conclusion

NPD strategies are attracting attention among scholars and professionals day by day. The NPD process is seen as a prominent undertaking for businesses having the desire to stay alive in the competitive market environment. However, a new product launch comes with a price of huge risks and uncertainties associated with it. A well-defined NPD strategy can balance these threats and

Table 13
Sensitivity analysis.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
w_j	0.135	0.122	0.128	0.119	0.131	0.119	0.122	0.125
State 1	0.510	0.070	0.070	0.070	0.070	0.070	0.070	0.070
State 2	0.070	0.510	0.070	0.070	0.070	0.070	0.070	0.070
State 3	0.070	0.070	0.510	0.070	0.070	0.070	0.070	0.070
State 4	0.070	0.070	0.070	0.510	0.070	0.070	0.070	0.070
State 5	0.070	0.070	0.070	0.070	0.510	0.070	0.070	0.070
State 6	0.070	0.070	0.070	0.070	0.070	0.510	0.070	0.070
State 7	0.070	0.070	0.070	0.070	0.070	0.070	0.510	0.070
State 8	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.510

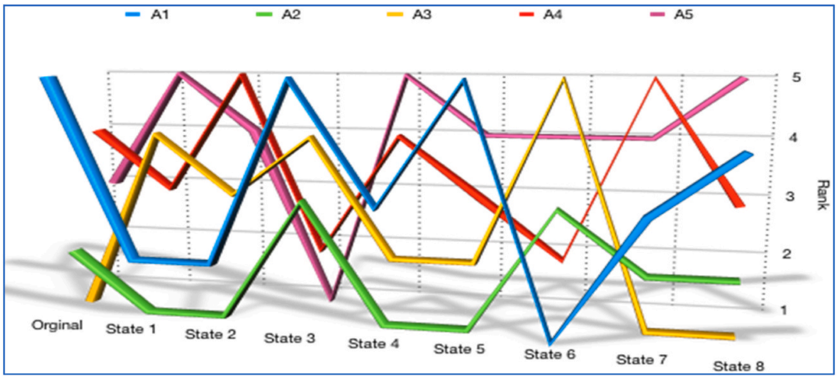

Fig. 3. Sensitivity analysis.

hesitations. In this manner, companies can adapt to the NPD processes more effectively. This research provides a logical NPD method to select the more reasonable candidate among the offered new products. The case of the NPD selection process is explored in this paper, and the proposed method is used to determine the most suitable NPD alternative. Its practicality and validity are illustrated with a case study. The following bullets summarize the contribution of this study.

- To our best knowledge, the PFSs MULTIMOORA method is developed for the first time to this extent. This research aimed to apply an MCDM approach that integrates MULTIMOORA and PFSs to assess a set of available NPD candidates on the ground of determining the best one.
- The proposed method provides greater flexibility and adequate determination of the DM judgments through a GDM setting using real industrial experts' evaluations of the problem.
- Linguistic terms in the evaluation process represent PFSs numbers for each alternative. This study provides a greater membership grade and handles the imprecision and ambiguity that is inherently present in human judgments by applying PFSs.
- A demonstrative application of the proposed method illustrates its applicability by evaluating five candidate software and apps.

This integrated approach is capable of handling comparable uncertain situations in MCDM problems. Despite the certain advantages offered by the presented study, our article has the following main constraints. Initially, the number of DMs is selected as three experts identified according to their understanding of the subject. This limitation can be clarified by involving more DMs in the decision process and weighting the experts based on their experience. Additionally, PFWA aggregation is considered as a single operator, and sole defuzzification is made for the PFSs values, other operators and aggregation techniques providing similar pertinent results may be considered during the algorithmich process of the given methodology. As a follow-up study, there exist a few paths to consider. The developed approach makes use of the PFSs MULTIMOORA approach. An encouraging research area is making a comparison with the existing MCDM approaches under type-2 or event classical fuzzy logic setting. Another promising area would be integrating a separate approach to note the variation of criteria weights. Incorporating additional MCDM techniques may comfort exploring efficiency and provide new scientific perspectives.

Author contribution statement

Fethullah Göçer: Conceived and designed the experiments, Performed the experiments; Analyzed and interpreted the data; Methodology; Writing - original draft.

Gülçin Büyüközkan: Conceptualization; Methodology; Resources; Investigation; Writing - review & editing; Project administration; Funding acquisition.

Data availability

Inquiries about data availability should be directed to the author.

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Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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