International Journal on Advanced Science Engineering Information Technology

Vol.12 (2022) No. 3
ISSN: 2088-5334

Decision Method Focused on the Fuzzy Front-End Phase: A Study Applied to the Development of an Electronic Starting Block for Running Athletes

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***Abstract*— In this work, we present a model to support multi-criteria decision-making in the selection of components for the initial proposals of a product or portfolio of products during the Fuzzy Front-End (FFE) phase of the Product Development Process (PD) to reduce risk and uncertainty and increase agility. The model is made of eight stages in which triangular-based fuzzy is employed to weigh customer requirements, and a direct numerical scale is used to weigh technical requirements. The main differences of this model are the identification and weighting of requirements based on different customer profiles and the identification of global customer requirements that have a direct or indirect relationship with all or most technical requirements. We applied the model in the development of an electronic starting block for running athletes with sensors that collected data to assist in training and performance improvement and were able to reduce the number of combinations of components in the FFE stage, and consequently, the development time, with the prioritization of roughly 30% of the components (10 parts of a total of 33). We highlight that there is still a need for further studies investigating the relationship of customer profiles and the impact on PDP and other ways to analyze how customer requirements impact technical requirements.**

***Keywords*— Product development; fuzzy-front end; customer requirements; decision method; electronic starting block.**

Manuscript received 18 Aug. 2021; revised 24 Sep. 2021; accepted 13 Dec. 2021. Date of publication 30 Jun. 2022.

I. INTRODUCTION

Product Development Process (PDP) is a set of activities that includes ideation, information gathering regarding the product idea, conceptual portfolio construction, prototyping, manufacturing design, testing, and market launch [1], [2], [3], [4]. The initial phases of PDP consist of actions of search, research, and definition of goals and objectives conditioned to innovation [5]. Oh, Yang, and Lee [6] call these actions the Fuzzy Front End (FFE) phase, which starts with the proposal of new products and alignment with internal strategies and value maximization for the organization and ends with the selection of the product portfolio that could be conceptually worked. The term FFE was popularized by Smith and Reinertsen [7], and receives the denomination "Fuzzy" as the activities developed in this phase present a high degree of uncertainty. Compared with the activities of later stages of PDP (clear, specific, systemic, and deterministic the FFE is ambiguous, not standardized, and probabilistic [8].

Park, Han, and Childs [9] revealed a broad review of specific studies on FFE that define the attributes and the structure of the performance related to the tasks, activities, and tools employed. The authors state six main FFE activities: opportunity identification, idea generation, requirements list, project mission definition, conceptual design, and prototyping tasks. However, conceptual design and prototyping tasks have been addressed separately from the other FFE activities.

Therefore, the definition of the product requirements is one of the initial activities of PDP and impacts the following ones.

The decisions related to the requirements at the start of the development are complex as several variables that represent these requirements only show noticeable results in the manufacturing stage and when the product is finally made. Bathia *et al.* [10] suggest using an agile methodology for product development and state that this can make development activities more efficient during the FFE phase. Thus, methodologies that aim to identify and relate requirements in the early stages of PDP are essential.

According to Albers *et al.* [11], decisions undertaken in the early PDP stages present great uncertainty and influence the commercial success of products when launched in the market. The authors proposed a methodology to support the validation of the activities in the early stages of PDP. They emphasize four stages of main actions: definition of relevant attributes for product composition, prioritization and selection of attributes, realization, and detailing.

The attributes that compose a product are defined as follows:

- The expectation of the customers and the organization responsible for the product's development and expectations concerning its physical and functional characteristics [12].
- Technical resources are required to obtain the desired physical and functional characteristics.

The expectations are represented as Customer Requirements (*Rc*) and the technical resources as Product Requirements (*Rp*). Cooper [13] states that 73% of flawed projects in Product Development (PD) are due to insufficient market research, which clearly relates to *Rc*. Cooper also emphasized that the vast majority of problems in PD are due to weaknesses in the FFE phase and that only 18% of the companies successfully take actions directed to the Voice of Customer (VOC) survey. The survey of customers' needs is indispensable for product improvement and innovation [14]. Yamamura *et al.* [8] reinforce the need to create value for the customer in the FFE phase.

There are considerable differences in developing simple and complex products [15], [16], [17]. Product complexity, according to Bolaños and Barbalho [18], is linked to the following indicators: quantity of components involved, the complexity of the interconnections between product subsystems, number of components that need to be designed by the organization developing the new product, areas of knowledge required to develop the product's primary functionalities and the variability (no repetition) of product components. The higher the complexity of a product, the more critical the relationship between the customers' requirements and the product; consequently, the risk in PDP increases.

Thus, optimization and agility in the PDP are directly linked to efficient decision-making activities, especially in the FFE phase. According to Cooper [13], the focus on the customer and the early and accurate definition of the product are among the motivating factors for success in PDP, thereby avoiding an increase in scope and unstable specifications and consequently contributing to higher success rates. Cooper mentioned the need for good practices that accelerate the development processes without compromising quality. Using methods to support decision-making in PDP is common in these cases. Multicriteria decision-making seeks to unite conflicting ideas and concepts of a particular theme. The main purpose is to find and collect knowledge of a specific group and their interrelations and establish ideas of cause and effect [18].

Yang *et al.* [19] highlight the methods of summation, weighted multiplication, Analytic Hierarchy Process, ELECTRE, and TOPSIS, as well as proposed mathematical variations that can be observed in each one of them. The authors propose a decision support method aimed at situations of uncertainty in which probability distribution is employed when information that impacts decision-making is missing. Mousavi *et al.* [20] offer the R-VIKOR method for risk analysis involved in the PDP.

Many multi-criteria methods have been developed and employed in decision-making at early PDP phases. Oh, Yang, and Lee [6] and Relich and Pawlewski [21] examples of studies that proposed models to support decision-making for portfolio selection during the FFE and highlight the uncertainty that predominates in this phase. Ying et al. [22] suggested a model for selecting alternative concepts in which the behaviors at decision-making are considered. Other studies on the application of multi-criteria decision-making in FFE [23], [24], [25].

Khastehdel and Mansour [26] related the modularity to the complexity of portfolio composition and proposed a model in which the optimal level of modularity is identified for the intended project, and the uncertainty of the generated idea is also considered. The modularity in FFE is also addressed in the study of Sankowski *et al.* [27]. The model, however, does not consider the direct impact of customer expectations.

Regarding decision support methods for requirements of customers and product, as well as the relationship between both, it is necessary to apply Quality Function Deployment (QFD) and its variations. QFD focuses on quality assurance during PDP [28], [29]. Fetanat and Tayebi [30] list several studies on QFD among the following categories: multi-attribute decision methods, linear and nonlinear programming, metaheuristic methods, and hybrid models.

This article presents a new method in which the problem considered refers to the decision at the FFE phase. Unlike the studies aforementioned, our proposal does not only seek to select the requirements of customers and products, or even choose the product portfolio, as the model of Li *et al.* [31], but rather focuses on the activity prior to the portfolio decision. It is important to select the appropriate parts and components for the initial structure of product options that compose the portfolio, which will then follow for conceptual and detailed development analyses.

The relationship between customer requirements and the product is considered critical when weighing the choice of the best possible combination of parts and components. Another particularity of the proposed method is the identification of different customer profiles and assigning weightings to different requirements based on them, an aspect that impacts the decision-making. To illustrate its applicability, we used the method to develop an electronic starting block for running athletes.

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The remainder of the article is structured as follows: in the next subsection, theoretical aspects of PD and the requirements involved are presented; in Section II, the proposed method is described; in Section III, we report the development of an electronic starting block for running athletes with the proposed method; and in section IV, the conclusions and the suggestions for future studies are presented.

A. Product Development and the Requirements Involved

Cheng and Filho [28] categorized the product development projects in research and advanced developments, breakthrough projects in which there are significant changes in products and processes, next-generation platforms, improvements or derivative projects, and alliances or associations in projects. The activities required for PD depend heavily on the development category. The categories differ concerning the product's level of innovation, ranging from novel ideas to similar products with minor adjustments, which can be either in the product or production (and that impact the consumer market).

Regardless of whether it is a radical innovation or a product improvement, PD must consider the characteristics of the market and the customers' expectations and requirements since quality aspects depend on these factors. In this sense, Lüthen *et al.* [32] listed the quality criteria for requirements definition in PD, highlighting the need for the requirements to be understandable to all stakeholders, correctly defined to meet all expectations linked, constantly updated, feasible, measurable, and unambiguous. The authors also mentioned the need for prioritization of requirements during decision-making.

The survey of customer requirements is fundamental to the strategy involving the development of new products [33]. Besides the correct identification of requirements, this article highlights two factors: (a) a single product can be developed for customers with different profiles and expectations; (b) customer requirements may be common. However, the importance assigned by the perspective of each customer profile to each requirement may be different, which thereby requires analysis and weighting that take this factor into account. It is observed that different customer profiles may interfere in the analysis of such requirements.

The definition of *Rc* is performed by consulting customers' expectations. The ways to raise these requirements are diverse. Kärkkäinen, Piippo, and Tuominen [34] list 10 tools considered fundamental in industrial PD (in Business to Business). Despite the focus of the referred study, the tools listed for the definition of requirements are valid for most products. The authors mentioned the need for direct and well-structured interviews, a table for interpreting the VOC and QFD and prioritizing requirements, and Pugh's Matrix for selecting the best product concepts based on customer needs.

The choice of method depends on the amount and type of information needed and the availability, time, and cost of data collection. Ulrich and Eppinger [2] suggest five steps for the survey of customers' needs: search for customers' data, interpretation of the data regarding their needs, ranking of the needs, identification of the relative importance of the needs, and analysis of the results. Crawford and Benedetto [3] refer to the survey of customers' needs as "identifying the problems" of customers considering that they search for a product to solve a pain. With the precise definition of the customers' needs, PD activities survey the necessary technical aspects, i.e., *Rp*.

The method we propose herein relates to both *Rc* and *Rp*. However, unlike other methods widely employed in PD that make this correlation, such as QFD. The relation between these requirements is used to weigh the importance of the product components and direct the decision to those that have a more significant impact on the composition of the proposals resulting from the initial phase of the PDP. Zhang, Simeone, and Hong [35] presented a similar model. However, it resorts to historical product data (BigData of purchases); our method does not depend on historical data, but it is not limited to its use. Another significant difference is that the data-driven models do not distinguish between different customer profiles. Moreover, a model that cites the use of QFD and addresses product requirements in FFE is proposed by Xie, Qin, and Jiang [36]. However, technical design requirements are prioritized.

A single customer requirement can direct to numerous *Rp*, which require distinct options of components, parts, assemblies (*c1, c2, c3, . . . cn*) to build the product. Thus, countless combinations of components create product alternatives; however, not all combinations are ideal or efficient. Fig. 1 represents the hypothetical networks generated from combinations between components for each technical product requirement.

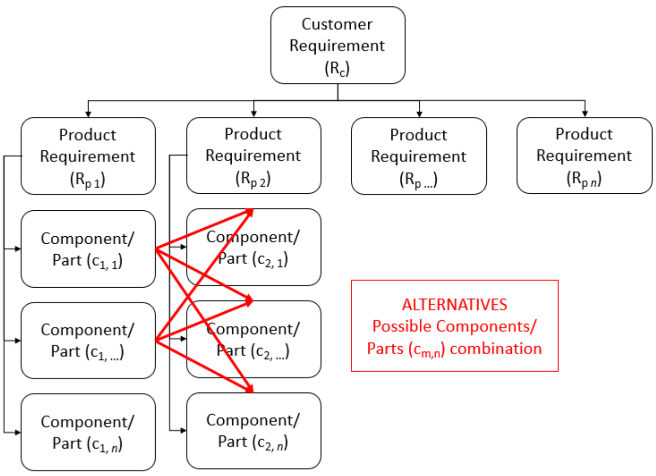


Fig. 1 Relationships between customer requirements and technical product requirements, and the possible combinations of components that meet the requirements

The greater the number of components and their combinations, the greater the difficulty in selecting the combination that best suits the customer requirement. Based on this foundation, the next topic presents the method for prioritizing product components in the FFE phase, considering the relationship between *Rc* and *Rp* and the difference that different customer profiles can cause in weighting.

II. Material and Method

The proposed method consists of 8 steps (Fig. 2), starting with the listing of all *Rc*, where two classes stand out: (a) *Rc* linked to specific customer profiles and their impact on specific *Rp*; (b) customer requirements that impact all *Rp*, which are named Global Customer Requirements (*Rgc*). The weighting of these requirements is obtained through a survey of opinion of a sample of customers, whereas *Rp* is weighted by the technicians in charge of the product's technical development. The impact of *Rc* and *Rcg* weights is then directed to the Rp, generating the Prioritization Values (Vpr), thereby obtaining the ranking of necessary technical resources and the consequent groups of priority components.

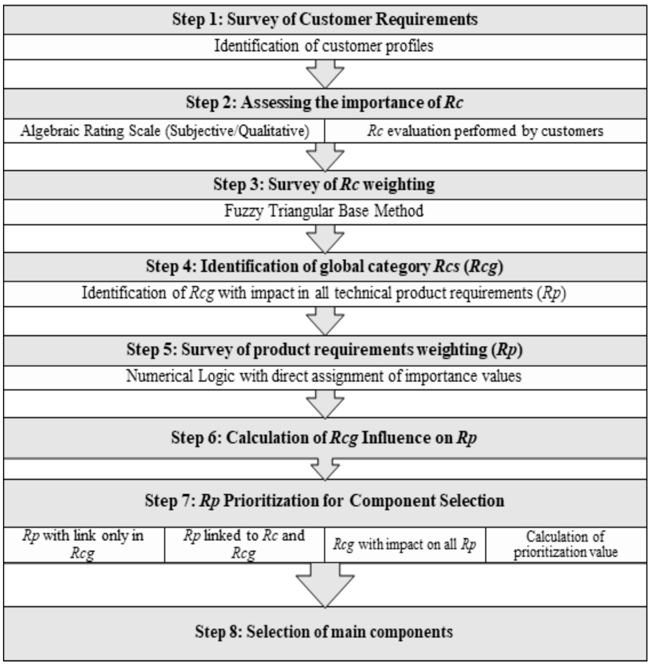


Fig. 2 Stages of the decision method for selection of product components in the FFE phase

A. Step 1 - Survey of Customer Requirements (Rc)

Our method considers changes in the *Rc* when there are different customer profiles. This variation can impact the weighting of the *Rc* performed to define the technical requirements of the product. To exemplify this situation, when considering a group of customers of profile A, a requirement *Rc1* may be more critical than a requirement *Rc2*; however, for a different profile, such as B, *Rc1* may be irrelevant. Furthermore, if most opinions collected to define the technical requirements correspond to profile B, these requirements related to *Rc1* would probably be considered less priority. Thus, customers of profile A could not be met in their expectations. Therefore, identifying them is recommended so that the Rc can be weighted according to the possible variety of customer profiles. We do not address the definition of profiles in this study; it is understood that organizations identify profiles at the beginning of PDP when they define the type of consumer market.

After knowing the profiles, the *Rc* of all of them, or of those representing the majority of the consumer market, should be raised. Our method assumes that the organization has the defined technical, organizational and customer requirements, which were obtained through structured methods (VOC, QFD, and other previously mentioned tools). The focus of the method is on the treatment after the definition of these elements.

B. Step 2 - Assessment of the Importance of Rc

A sample of customers of all profiles evaluated the requirements by grading the importance of *Rc* on a scale survey. In this model, we considered the qualitative scale of judgment used by Wang [37]. The evaluation made by the customer is subjective, and the response is converted quantitatively through triangular-base Fuzzy sets. The Fuzzy Set Theory handles the uncertainty presented in the evaluated elements [38]. Table I presents the qualitative scale of judgment and the respective triangular-base Fuzzy number.

TABLE I
Scale and Fuzzy Number of Triangular Base Used to Obtain the Judgment of Customers Regarding the Importance of Each *Rc*

The scale of judgment on the importance	Fuzzy - triangular base
VP - Very Poor	(0; 0; 0,2)
P - Poor	(0; 0,2; 0,4)
MP - Medium Poor	(0,2; 0,4; 0,5)
F - Fair	(0,4; 0,5; 0,6)
MG - Medium Good	(0,5; 0,6; 0,8)
G - Good	(0,6; 0,8; 1)
VG - Very Good	(0,8; 1; 1)

C. Step 3 - Weighting of Rc

We converted the answers obtained in Step 2 quantitatively through fuzzification. Customers should assess only the requirements that directly impact their profile since the ones that are not related may be marked as null or with low scores, thus impacting the final weighting and the actual representativeness of the expectations of the entire group of customers. For weighting, we performed the following:

1) Built a judgment matrix based on the assessment made by customers, according to Table II.

TABLE II
Matrix Formed by Judgments of Each Customer, or Set of Customers, for Each *Rc*

	Customer 1	**Customer 2**	**Customer (...)**	**Customer *n***
Rc 1	SAsw (1.1)	SAsw (1.2)	SAsw (1...)	SAsw (1.n)
Rc 2	SAsw (2.1)	SAsw (2.2)	SAsw (2...)	SAsw (2.n)
Rc 3	SAsw (3.1)	SAsw (3.2)	SAsw (3...)	SAsw (3.n)
Rc (...)	SAsw (... 1)	SAsw (...2)	SAsw (.. ..)	SAsw (... n)
Rc n	SAsw (n, 1)	SAsw (n, 2)	SAsw (n, ...)	SAsw (n, n)

*SAsw = Subjective answer (VP, P, MP, F, MG, G, VG)

2) Built the fuzzified matrix used in this proposal with triangular based fuzzification (a, b, c);

3) When considering the scores of more than one clients, the averages for each value of the triangular base fuzzy sets are given by Equation 1, where $\bar{a}, \bar{b}, \bar{c}$ (average score of each customer profile), a, b, c (response of each customer), and *n* (number of consulted customers):

$$\bar{a} = \frac{\sum a}{n} \tag{1}$$

The same applies for *b* and *c* to obtain (a, b, c) referring to each *Rc*;

4) Once the averages $\bar{a}, \bar{b}, \bar{c}$ are obtained, the values are defuzzified using Equation 2, with *Rcx* being the defuzzified value:

$$Rcx = \frac{1}{4} . \left(\bar{a} + 2\bar{b} + \bar{c}\right) \tag{2}$$

5) With the defuzzified values, we normalize the results (Equation 3), with the final representation of the weighting of each *Rc* (*Rcwx*) being as follows.

$$Rcw_x = \frac{Rc_x}{\sum Rc} \tag{3}$$

6) The results are sorted in descending order to identify the critical relationship between the requirements (the higher the *Rcwx* value, the greater the attributed importance).

D. Step 4 - Identification of the "Global" Customer Requirements (Rcg)categories

Global Customer Requirements (*Rcg*) refer to the expectations or demands of customers that directly or indirectly impact all or most of the product's technical requirements. The product's selling price, the sustainable aspects, the total size, among others, can be considered *Rcg*. The identification of the weight of *Rcg* is obtained together with the other *Rc* applying Steps 2 and 3.

E. Step 5 - Weighting of Product Requirements (Rp)

At this stage, it is required that the *Rp* are listed and related, directly and indirectly, with each *Rc*; for this, specific tools such as QFD can be applied. Moreover, the importance of *Rp* is highlighted just as it was done for each *Rc*; however, the evaluation of these requirements is performed by the technician in charge of PDP. Ardakani et al. [39] identified that the criteria weighting carried out by experts on the subject, in a decisive action, can be performed using direct methods, such as the Numerical Logic (LN), which comprises pairwise comparisons between criteria. The weighting is directly attributed to the decision-maker and compares how much a criterion is more important than another through a scale covering the interval between 0 and 1. Therefore, qualitative scales, which tend to be subjective methods, are not used in this method. Instead, numerical scales that directly quantify the degree of importance of a criterion regarding another are preferred.

Method [39] is composed of the following steps:

1) Pairwise comparison between criteria and the construction of the matrix: Regarding the construction of the matrix, the requirements of the row (i) will always be compared in function of the column (j) assigning the weights $w_{i,j}$, i.e.: $Rp_{1.1} = 0$; $Rp_{1.2}$ □ $[0 \leq Rp_{i,j} \leq 1]$; $Rp_{1.3}$ □ $[0 \leq Rp_{i,j} \leq 1]$; $Rp_{1.n}$ □ $[0 \leq Rp_{i,j} \leq 1]$. The inverse comparison is given by $Rp_{1,j} = 1 - Rp_{ij}$. Table III summarizes this process.

2) Calculation of the weights of each criterion, Rp, from the comparison matrix: The normalized weights (*Rpw*) calculation is given by Equation 4, where the largest weights refer to the criteria deemed as most important.

$$Rp\overline{w}_{i,1} = \frac{\sum_{i=1}^{n} Rp\ i,j}{\sum\sum_{j=1}^{n} Rp\ i,j} \tag{4}$$

TABLE III
TABLE OF PAIRWISE COMPARISON REFERRING TO THE LN METHOD OF DIRECT NUMERICAL WEIGHTING

	Rp1	Rp2	Rp3	Rpn	Sum Rp	Nor Rp
Rp_1	0	$w_{1,2}$	$w_{1,3}$	$w_{1,n}$	$\sum_{i=1}^{n} Rp\ 1,j$	$Rp\overline{w}_1$
Rp_2	$1 - w_{1,2}$	0	$w_{2,3}$	$w_{2,n}$	$\sum_{i=2}^{n} Rp\ 2,j$	$Rp\overline{w}_2$
Rp_3	$1 - w_{1,3}$	$1 - w_{2,3}$	0	$w_{3,n}$	$\sum_{i=3}^{n} Rp\ 3,j$	$Rp\overline{w}_3$
Rp_n	$1 - w_{1,n}$	$1 - w_{2,n}$	$1 - w_{3,n}$	0	$\sum_{i=n}^{n} Rp\ n,j$	$Rp\overline{w}_4$
					$\sum\sum_{j=1}^{n} Rp\ i,j$	

F. Step 6 - Influence of Rcg on Rp

We analyzed every *Rp* and the direct relations with *Rcg*. The weightings calculated for each *Rp* in the previous were added to Rgc (wRcg) weightings. Then, the final order of importance of the product requirements (*Rpwf*) is given by Equation 5.

$$Rpwf = Rp\overline{w}_i + w_{Rcg} \tag{5}$$

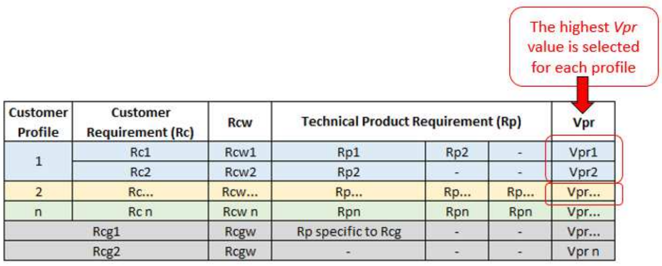
The following conditions must be observed:

- When *Rp* is related to more than one *Rcg*, the average of the weights of *Rcg* is obtained, and this average is then summed with (*Rpw*);
- *Rpwf* values are then normalized by the summation method (Equation 6);

$$(Rp\overline{wf} = \frac{Rpw_{i,1}}{\sum Rpwf_{i,j}}) \tag{6}$$

G. Step 7 - Rp Prioritization for Component Selection

The principal goal of the method is to identify the main product requirements while considering the impact of customer requirements. The following considerations arise from each *Rc*, as illustrated in Fig. 3.



Customer Profile	Customer Requirement (Rc)	Rcw	Technical Product Requirement (Rp)			Vpr
1	Rc1	Rcw1	Rp1	Rp2	-	Vpr1
	Rc2	Rcw2	Rp2	-	-	Vpr2
2	Rc...	Rcw...	Rp...	Rp...	Rp...	Vpr...
n	Rc n	Rcw n	Rpn	Rpn	Rpn	Vpr...
Rcg1		Rcgw	Rp specific to Rcg	-	-	Vpr...
Rcg2		Rcgw	-	-	-	Vpr n

Fig. 3 Relation between customer profile, *Rcw*, *Rp*, and *Vpr*

In this phase, we calculate *Vpr* as a function of each *Rc*. For each customer profile, the highest values of *Vpr* and the respective prioritized *Rp* must be identified. These *Rp* are the requirements for combining components and identifying initial projects that compose the portfolio suggested in the FFE phase. As the identified customer profiles contain *Rcg*, the respective *Vpr* must be considered in the same manner as the others for the choice of the main *Rp*. For this, three distinct situations are taken into account:

1) Technical requirements (*Rp*) that have been included to meet only *Rcg* - named *Rp*(*Rcg*); the prioritization value (*Vpr*) for these requirements needs to be calculated:

- When there is only 1 *Rp* linked to the *Rcg*:

$$V_{pr} = R_{cgw} + R_{pw} \tag{7}$$

- When there is more than 1 *Rp* linked to the *Rcg*:

$$V_{pr} = \frac{\sum_{n}(R_{cgw}+R_{pw})}{n} \tag{8}$$

2) Technical requirements (*Rp*) linked to *Rc* and *Rcg*: calculate the values of *Vpr* the same way as in situation (a). Importantly, do not consider the *Rcg* again as they have already been contemplated in Step 6.

3) Rcg with impact on all *Rp*: global requirements that impact all technical requirements will have the value of *Vpr* = *Rcgw*, as their weighting is mathematically assigned to all analyzed requirements.

H. Step 8 - Selection of Priority Components

With the decreasing ordering of *Vpr* values, we ranked *Rp* according to their respective attributed importance, which was calculated following the proposed method. Based on the *Rc*, the most significant Rp and the consequent product components/parts that have the most significant impact on PD are identified for each customer profile.

Our method does not limit the quantity of *Rp* considered most significant. It is up to the decision-maker to observe *Vpr* values and define how the order of ranking obtained will be considered.

This way, the PDP decision-makers can focus their efforts on the components identified as priorities according to *Rp's* importance, based on the weighting of the *Rc*, which is based on the *Rc* prioritization but not exclusively. The evaluation and weighting of the *Rc* also depend on the judgment of the technicians responsible for the PD.

III. Results and Discussion

We applied the proposed decision-making method to select combinations of product components to design a starting block for running athletes (similar to the one illustrated in Fig. 4). Besides serving as a conventional support platform for a start, the block under development includes sensors and data processing that analyze the athlete's performance. The purpose of this block is to collect information regarding the pressure exerted by the athlete's foot on the block at the moment of start and other variables that can assist in training and performance improvement. The product is already commercialized internationally but not in Brazil. Our goal and motivation to develop this new model is to reduce the cost of production and consequently its sale price in the local market.

Fig. 4 Automated starting block for athletes [40]

A. Stage 1 - Customer Requirements Survey Rc

The product under consideration has three direct customer profiles: the athlete (who uses the equipment), the coach (who guides the athlete based on information collected from the product), and the confederation or club (to which the athlete and coach belong), which buys the product. Each profile has different demands (customer requirements, *Rc*), which are listed in Table IV. The requirements were surveyed directly with a sample of each customer profile.

TABLE IV
Customer Requirements for the Starting Block

Customer	Requirement/Requirement concerning the product	Acronym
Athlete	Footswitch with adjustable angle	Rc 1
	Simple adjustment between pedals	Rc 2
	Block with good fixation	Rc 3
Coach	Response time (first movement)	Rc 4
	Force applied to each pedal unit	Rc 5
	Contact time with the block	Rc 6
	Acceleration (Sprint force)	Rc 7
	Impulse	Rc 8
	Ascent time	Rc 9
	Provision of visual results (graphs)	Rc 10
	Greater number of physical relations between variables obtained	Rc 11
	Simple data handling	Rc 12
Conf./ Inst.	Durability	Rc 13
	Cost	Rc 14

B. Step 2 - Assessment of the Importance of the Rc

The importance of the product requirements was assessed by three athletes who compete in 100-m dash races (and make use of the starting blocks), three physical education professionals who work or have worked with the training of running athletes, and finally, one Brazilian municipal athletics federation and one school in charge of training running athletes. Each client measured the importance of the requirements that directly impacted their decision; athletes evaluated requirements *Rc1*, *Rc2*, and *Rc3*, coaches evaluated requirements from *Rc4* to *Rc12*, and the remaining requirements were evaluated by the confederation or institution responsible for the athlete. The final assessment could be compromised if every customer evaluated all requirements since the importance attributed to requirements that do not directly impact their profile would be very low. Table V presents all performed evaluations.

TABLE V

ASSESSMENT OF THE IMPORTANCE OF THE *RC* ASSIGNED BY CUSTOMERS

Customer Requirements		Assessments of Importance		
		Cust. 1	Cust. 2	Cust. 3
Athlete	Rc1	MP	VP	P
	Rc2	G	VG	MG
	Rc3	G	VG	VG
Coach	Rc4	F	F	VG
	Rc5	MG	G	MG
	Rc6	G	VG	P
	Rc7	G	F	P
	Rc8	F	G	P
	Rc9	P	P	F
	Rc10	G	VG	MG
	Rc11	MG	F	MG
	Rc12	VG	VG	VG
Conf./ Inst.	Rc13	MG	MG	-
	Rc14	VG	G	-

C. Step 3 - Weighting of Rc

After the attribution of the importance of *Rc* by the customers, we built Table VI considering the fuzzification of the values.

TABLE VI

FUZZY MATRIX OF RATINGS ASSIGNED BY CUSTOMERS AND AVERAGE RATINGS, AND CALCULATED *RCW*

Profile		Customer			Mean
		1	2	3	
		(a;b;c)	(a;b;c)	(a;b;c)	(a;b;c)
Athlete	Rc3	(1;1;1)	(1;1;1)	(1;1;1)	(0,73;0,93;1)
	Rc2	(1;1;1)	(1;1;1)	(1;1;1)	(0,63;0,8;0,93)
	Rc1	(0;0;1)	(0;0;0)	(0;0;0)	(0,07;0,2;0,37)
Coach	Rc12	(1;1;1)	(1;1;1)	(1;1;1)	(0,8;1;1)
	Rc10	(1;1;1)	(1;1;1)	(1;1;1)	(0,63;0,8;0,93)
	Rc5	(1;1;1)	(1;1;1)	(1;1;1)	(0,53;0,67;0,87)
	Rc4	(0;1;1)	(0;1;1)	(1;1;1)	(0,53;0,67;0,73)
	Rc6	(1;1;1)	(1;1;1)	(0;0;0)	(0,47;0,67;0,8)
	Rc11	(1;1;1)	(0;1;1)	(1;1;1)	(0,47;0,57;0,73)
	Rc7	(1;1;1)	(0;1;1)	(0;0;0)	(0,33;0,5;0,67)
	Rc8	(0;1;1)	(1;1;1)	(0;0;0)	(0,33;0,5;0,67)
	Rc9	(0;0;0)	(0;0;0)	(0;1;1)	(0,13;0,3;0,47)
Conf./ Inst.	Rc14	(1;1;1)	(1;1;1)	(-;-;-)	(0,47;0,9;1)
	Rc13	(1;1;1)	(1;1;1)	(-;-;-)	(0,33;0,4;0,8)

With the average of the fuzzified values, we applied defuzzification and calculated the final weighting of *Rc* (Table VII).

TABLE VII

DESFUZZY, CALCULATED *RCW* AND *RC* RANKING

Profile		Defuzzy	Rcw	Ranking
Athlete	Rc3	0,9	0,1	1º
	Rc2	0,792	0,09	2º
	Rc1	0,208	0,02	3º
Coach	Rc12	0,95	0,11	1º
	Rc10	0,792	0,09	2º
	Rc5	0,683	0,08	3º
	Rc4	0,65	0,07	4º
	Rc6	0,65	0,07	5º
	Rc11	0,583	0,07	6º
	Rc7	0,5	0,06	7º
	Rc8	0,5	0,06	8º
	Rc9	0,3	0,03	9º
Conf./ Inst.	Rc14	0,817	0,09	1º
	Rc13	0,483	0,06	2º

D. Step 4 - Identification of the "Global" Category Rc's (Rcg)

Amongst all *Rc* raised, two of them impact the majority of the product's technical requirements: durability (*Rc13*) and cost (*Rc14*). Coincidentally, both requirements are assigned to one customer profile; this may not be the case for other types of product. The weights of these requirements were calculated in Step 3 (0.055 and 0.093, respectively).

E. Step 5 - Weighting of Product Requirements (Rp)

The technical requirements were raised by the technical manager of the product development (Table VIII). As the product counts with technology that is new to the local market and will be applied for patent, the inventor of the idea is also the technical manager of the project.

TABLE VIII

DESCRIPTION OF PRODUCT REQUIREMENTS (*RP*)

Product Requirements (*Rp*) - Technical Requirements	
Rp1	Adjustment of the angle between pedals (50° and 70°)
Rp2	Horizontal movement system between pedals
Rp3	System for securing the block on the track
Rp4	Block stiffness
Rp5	Pedal stiffness (plastic deformation)
Rp6	Signal reader
Rp7	Data processing platform
Rp8	Data outputs
Rp9	Material resistant to weather
Rp10	The enclosure of electronic components
Rp11	Conditioning circuit
Rp12	Force sensor

Thus, we evaluated the requirements and calculated the weighting considering only this technical manager's analysis (Table IX).

TABLE IX

PEER REVIEW RESULTS AND WEIGHTING OBTAINED THROUGH THE LN METHOD

	Sum	Rpw	Ranking
Rp1	1,4	0,021	12
Rp2	6,1	0,092	6
Rp3	8,4	0,127	1
Rp4	5,7	0,086	7
Rp5	7,1	0,108	4
Rp6	7,2	0,109	3
Rp7	4,3	0,065	8
Rp8	3,5	0,053	11
Rp9	6,9	0,105	5
Rp10	3,6	0,055	10
Rp11	4,1	0,062	9
Rp12	7,7	0,117	2
Sum	66		

F. Step 6 - Influence of Rcg on Rp

After calculating all the *Rp* weights, in which the impacts of *Rcg* were analyzed and the final weight of each *Rp* assigned, we calculated the *Rcg* weights (Table X).

TABLE X
CALCULATION OF FINAL *RP* WITH THE WEIGHT OF *RCG* ASSIGNED

	Rpw	*Rcg13*	*Rcg14*	*Rpw + Rcgw*	Norm. *Rpwf*	Ranking
Rp1	0,021		0,093	0,068	0,025	12
Rp2	0,092		0,093	0,139	0,052	8
Rp3	0,127		0,093	0,174	0,065	5
Rp4	0,086	0,55	0,093	0,408	0,153	3
Rp5	0,108	0,55	0,093	0,429	0,161	1
Rp6	0,109		0,093	0,156	0,059	7
Rp7	0,065		0,093	0,112	0,042	9
Rp8	0,053		0,093	0,1	0,037	11
Rp9	0,105	0,55	0,093	0,426	0,16	2
Rp10	0,055	0,55	0,093	0,376	0,141	4
Rp11	0,062		0,093	0,109	0,041	10
Rp12	0,117		0,093	0,163	0,061	6
			Sum	2,658		

G. Step 7 - Rp Prioritization of Component Selection

To prioritize the product requirements to be considered for component selection, first, we listed the *Rp* as a function of each *Rc* (Figure 5). With all relations listed, we calculated *Vpr* values as a function of each *Rc*. In the analyzed product, the requirement "cost" (*Rcg14*) has a relation with all *Rp*; thus, *Vpr* of *Rcg* is equal to *Rcw*, (0,094). The other *Vpr* values are listed in Table XI.

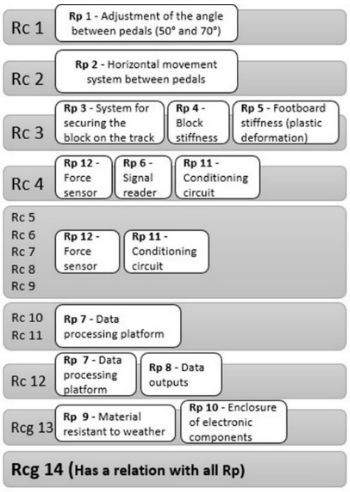


Fig. 5 Relation between *Rp*, *Rc* and *Rcg*

TABLE XI
SUMMARY ON SELECTION AND WEIGHTING OF *RP*, CONSIDERING *RC* AND *RCG*, AND *VPR* VALUES

Customer Req. (Rc)	Rcw	Rp (considering Rcg) mean	Vpr	Selected Rp
Rc1	0,024	0,025	0,049	Client Profile 1: Rc3 (Rp3; Rp4; Rp5)
Rc2	0,09	0,052	0,142	
Rc3	0,102	0,127	0,229	
Rc4	0,074	0,054	0,127	Client Profile 2: Rc12 (Rp7; Rp8)
Rc5	0,078	0,051	0,129	
Rc6	0,074	0,051	0,125	
Rc7	0,057	0,051	0,108	
Rc8	0,057	0,051	0,108	
Rc9	0,034	0,051	0,085	
Rc10	0,09	0,042	0,132	
Rc11	0,066	0,042	0,108	
Rc12	0,108	0,04	0,148	
Rcg13	0,055	0,134	0,134	Client Profile 3: Rc13 (Rp9 and Rp10)
Rcg14	0,093	0	0,093	

H. Step 8 - Selection of priority components

We identified seven technical product requirements for product development that should guide product options at the end of the FFE phase. The diagram in Fig. 6 shows the components of each *Rp* that must be combined to build the portfolio of options that finalizes the FFE phase.

With the application of the proposed method, the decision-maker of a project has a reduced set of requirements and components to combine and form the product options that compose the portfolio. Without applying the method, the decision-maker would have a large number of options to be analyzed (14 customer requirements, 12 product requirements and 33 components that would be combined). Using the method we suggest, it was possible to select the most important requirements and restrict the number of combinations (3 customer requirements, 7 product requirements, and 10 main components) in a reliable.

Regarding these product requirements, the technician in charge of PDP must select the components of the product proposals with greater detail and based on the analysis of the risks involved. Other components may be selected less sensibly considering that they do not impact the requirements of customers and the product.

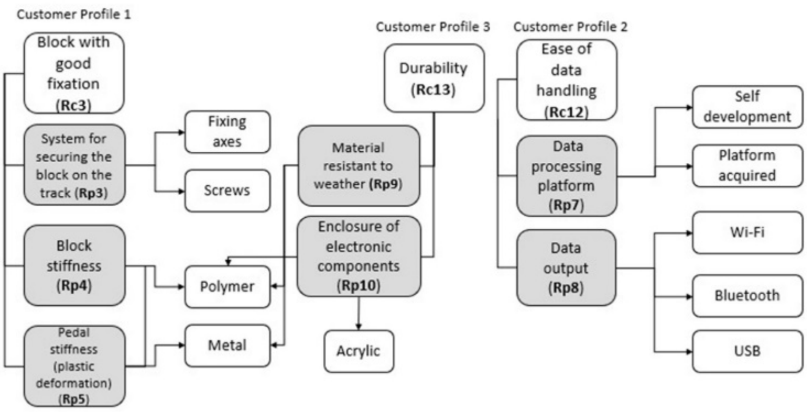


Fig. 6 Relation between customer requirements, product requirements, and components

IV. Conclusion

We proposed a new method to help multi-criteria decision in the FFE phase of product development. and it was applied to a product under development and presented a satisfactory result. The method was tested to build an electronic starting block for running athletes and presented satisfactory results. The main goal was to reduce the number of possible combinations of components that form the initial product proposals. For this, we used the importance attributed to the expected customer requirements and to the technical requirements necessary for the product's construction and operation.

In the analyzed case, the possibility of combinations of items was reduced by approximately 69%. It does, in fact, show to the decision-maker that only the highlighted items have significant relevance in the product design, which eliminates the need for in-depth studies or unnecessary concerns with items that do not have a significant impact. Such assurance is achieved because the decision on the design considers the importance of both customers' and technical requirements.

Our method is aimed at the first definitions of the PDP. The specific analysis of each product developed is up to those responsible for the execution of the other stages of the process (conceptual design).

As a suggestion for future studies, we propose the following: Specific studies on the relation between customer profiles and the impact on PDP. Improvement of the method regarding possible and not valid combinations between technical product requirements; A study on a specific method to identify global customer requirements; Validation of the method in products with a higher number of components; Validation of the method with a product in advanced stages of development, and with satisfactory results, in order to analyze if the resulting combinations confirm what was decided in the PDP; The application of the proposed method in various products.

Acknowledgment

The Federal Institute of Education supported this study, Science and Technology of Rio Grande do Sul (IFRS).

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