Expert Systems With Applications 42 (2015) 8432–8444

Contents lists available at ScienceDirect

Expert Systems With Applications

journal homepage: www.elsevier.com/locate/eswa

A fuzzy hybrid project portfolio selection method using Data Envelopment Analysis, TOPSIS and Integer Programming

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ARTICLE INFO

Keywords:
Project portfolio selection
Data Envelopment Analysis
Fuzzy TOPSIS
Linear Integer Programming
Augmented scores

ABSTRACT

Project selection and resource allocation are critical issues in project-based organizations. These organizations are required to plan, evaluate, and control their projects in accordance with the organizational mission and objectives. In this study, we propose a three-stage hybrid method for selecting an optimal combination of projects. We obtain the maximum fitness between the final selection and the project initial rankings while considering various organizational objectives. The proposed model is comprised of three stages and each stage is composed of several steps and procedures. We use Data Envelopment Analysis (DEA) for the initial screening, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) for ranking the projects, and linear Integer Programming (IP) for selecting the most suitable project portfolio in a fuzzy environment according to organizational objectives. Finally, a case study is used to demonstrate the applicability of the proposed method and exhibit the efficacy of the algorithms and procedures.

1. Introduction

Most organizations often need to evaluate multiple program proposals or projects competing for scarce resources (e.g., money, manpower, equipment) and subsequently select those projects that best satisfy conflicting objectives or opposing group interests (Zanakis, Mandakovic, Gupta, Sahay, & Hong, 1995). As the number of projects increases, the decision process becomes much more complicated because of (Belton & Stewart, 2002; Kirkwood, 1997):

- Multiple and contradictory goals (criteria)
- Contrasting qualitative and quantitative goals
- Dependent projects
- Uncertainty in the data with regards to specific criteria
- Organizational requirements and constraints, and/or
- A large number of feasible portfolios.

A stand-alone multiple-criteria ranking method may not be sufficient to solve complex real-life problems with specific requirements and constraints (Badri, Davis, & Davis, 2001; Santhanam, Muralidhar, & Scniederjans, 1989). In addition, these methods do not generally consider the interaction among projects with common resources. Several methods have been proposed in the literature to overcome these problems. Most of these methods are classified as Integer Programming (IP), or, more specifically, 0–1 programming methods (a binary variable is assigned to each project so that if the project is selected, $x_i = 1$; otherwise, $x_i = 0$). IP and mixed IP (MIP) models are usually used to solve single objective problems (Kyparisis, Gupta, & Ip, 1996; Melachrinoudis & Kozanidis, 2002; Pisinger, 2001; Santhanam & Kyparisis, 1995).

Zero-one goal programming is generally used to combine the evaluation criteria when applying multiple-criteria ranking methods (Albright, 1975; Badri et al., 2001; Fandel & Gal, 2001; Kwak & Lee, 1998; Mukherjee & Bera, 1995; Santhanam & Kyparisis, 1996; Santhanam et al., 1989; Zanakis et al., 1995). Some researchers also have used Data Envelopment Analysis (DEA) to solve these problems (Cook & Green, 2000; Oral, Kettani, & Cinar, 2001; Oral, Kettani, & Lang, 1991). Another method commonly used to solve these problems is a two-phase approach where a multi-criteria evaluation is carried out in the first phase to evaluate each project individually.

An IP model is then applied to the project evaluation data in order to calculate the objective function and constraints (Abu-Taleb & Mareschal, 1995; Golabi, Kirkwood, & Sicherman, 1981; Mavrotas, Diakoulaki, & Caloghirou, 2006; Mavrotas, Diakoulaki, & Capros, 2003).

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http://dx.doi.org/10.1016/j.eswa.2015.06.057
0957-4174/

These models however tend to solve the last phase in the portfolio selection process without ensuring that the final selected portfolio fits the organizational objectives and requirements. In summary, a general framework is needed to address the following gaps in the project portfolio selection (PPS) literature:

(1) Several methods have been proposed in the existing literature for project evaluation and portfolio selection that are not comprehensive and are only used for specific phases of the evaluation and selection process.
(2) There is no method reported in the literature that can ensure the compatibility of the selected portfolio with the organizational mission and objectives.
(3) The IP model proposed in this study can be considered a knapsack problem with several constraints. Stewart (1991) constitutes one of the first applications of a (non-linear) knapsack model to address multi-criteria optimization problems. The main weakness of this type of approach is that it does not preserve the ranking of the projects based on their multi-criteria scores. This ranking is not preserved because the budget constraints and the objective function which search for the best combination of projects are not considered when the ranking is determined. Projects with low scores and low costs may be preferred to the projects with higher costs (Cook & Green, 2000; Mavrotas et al., 2006; Tobin, 1999).

The main objective of the method introduced in this paper is to adapt standard multiple-criteria decision making methods to the information transmission and decision processes taking place at different levels within an organization. That is, the intuitive initial selection of processes via DEA together with the TOPSIS valuations are included to mimic different information and decision making stages within the PPS process of an organization. However, we are also aware of the fact that, due to this flexibility, inconsistencies can easily arise between the objectives defined in the initial evaluation stages and any additional modifications implemented by other members of the organization afterward.

For example, assume that projects *A*, *B* and *C* have multi-criteria scores of 0.65, 0.4 and 0.3 and costs of \$50,000, \$20,000 and \$25,000 respectively. Assuming that the multi criteria scores are the objective function coefficients, the combination of projects *B* and *C* is preferred to project *A* because their aggregate score is $0.3 + 0.4 > 0.65$ and their aggregate cost is $25{,}000 + 20{,}000 < 50{,}000$.

IP modeling selects projects *B* and *C* instead of project *A* although their individual scores are lower than the score of *A*. This is because using IP's formulation one can compare a combination of projects with a single project. In order to apply the IP method to the problem under consideration in this study, we adjust the final result using the multi-criteria score obtained for each project. Therefore, if option *A* is not selected, while other options with the same criteria (same type of evaluation, same department) and multi-index scores are selected, the promoter of option *A* can raise a logical objection to the process.

The method proposed in this study defines the individual scores of each project as the main selection criterion and prevents the inevitable integration caused by the interaction of the objective function and the constraints in the IP model. This will be achieved by replacing the scores of the main criteria with augmented scores. The proposed three-stage approach provides the maximum fitness between the final selection and the project initial ranking by considering the relevant organizational objectives and requirements.

That is, our model accounts explicitly for the information received at different levels within an organization. Lengthy evaluation processes, with information and constraints introduced at different levels of the organization during the decision process, tend to distort the initial organizational objectives. Our main contribution, besides the systematic design of the organizational decision process, is given by the novel algorithm defining the augmented scores that preserve the initial rankings assigned by the decision makers (DMs) when new constraints are introduced at a second level within the organization. These additional constraints, together with the knapsack structure of the final IP optimization problem, would lead to a set of portfolio solutions composed by projects other than those highly valued based on the initial organizational objectives. We have defined the entire decision structure so that the initial objectives are emphasized and maintained throughout the process.

The rest of this paper is organized as follows: in Section 2, the PPS literature is discussed. The proposed method is introduced in Section 3. In Section 4, a case study is used to demonstrate the applicability of the proposed method and exhibit the efficacy of the algorithms and procedures. Finally, in Section 5, basic conclusions and further research directions are presented.

2. Project portfolio selection

A project is a complex effort with well-defined objectives, schedule, and budget, and is composed of interrelated tasks performed by various organizational units (Archibald, 1992). A project portfolio is a collection of projects that are put together for a particular organization. These projects generally compete for scarce resources (e.g., people, finances, and time). PPS is the process of selecting a portfolio of projects from available project proposals without exceeding available organizational resources or violating organizational constraints and requirements. A wide range of divergent techniques have been proposed in the literature for estimating, evaluating, and choosing individual projects (e.g., economic return, decision tree, simulation, etc.). Salo, Keisler, and Morton (2011) review extensively the literature on portfolio decision analysis, which provides a sound methodological basis to account for the complex environment faced by DMs while allowing for the best possible resource allocation decision.

PPS methods involve the simultaneous consideration and ranking of a number of projects according to particular criteria. The most highly ranked projects are then selected for a portfolio without exceeding available organizational resources. Archer and Ghasemzade (1999) have classified these methods into five distinct groups including: ad hoc methods, comparative approaches, scoring methods, portfolio matrices, and optimization methods. They emphasize that portfolio selection is usually a committee process, often associated with multiple and conflicting criteria, and projects may be highly interdependent. They also argue that among the published project portfolio section methodologies, little progress has been made toward achieving an integrated framework and decomposing the selection process into a structured and logical series of activities that involve participation of a committee. Similarly, Iamratanakul, Patanakul, and Milosevic (2008) also categorized the project selection models into several groups including: scoring methods, economic methods (e.g., payback method, net present value, and internal rate of return), mathematical programming, real options analysis, simulation modeling, and heuristics methods. They emphasize that each methodology alone does not address all of the aspects of PPS. For more information about PPS models, the interested reader is referred to Archer and Ghasemzade (1999), Ehrgott, Klamroth, and Schwehm (2004), Graves and Ringuest (2003) and Iamratanakul et al. (2008).

3. Proposed method

The method proposed in this study is a comprehensive framework that integrates fuzzy TOPSIS, DEA and linear IP in a very structured and systematic framework. The proposed hybrid framework covers all the necessary steps in PPS from project creation to the final selection. The general multi-stage framework proposed in this study is adopted from the PPS research conducted by Archer and Ghasemzade (1999). Fig. 1 presents a schematic view of the hybrid

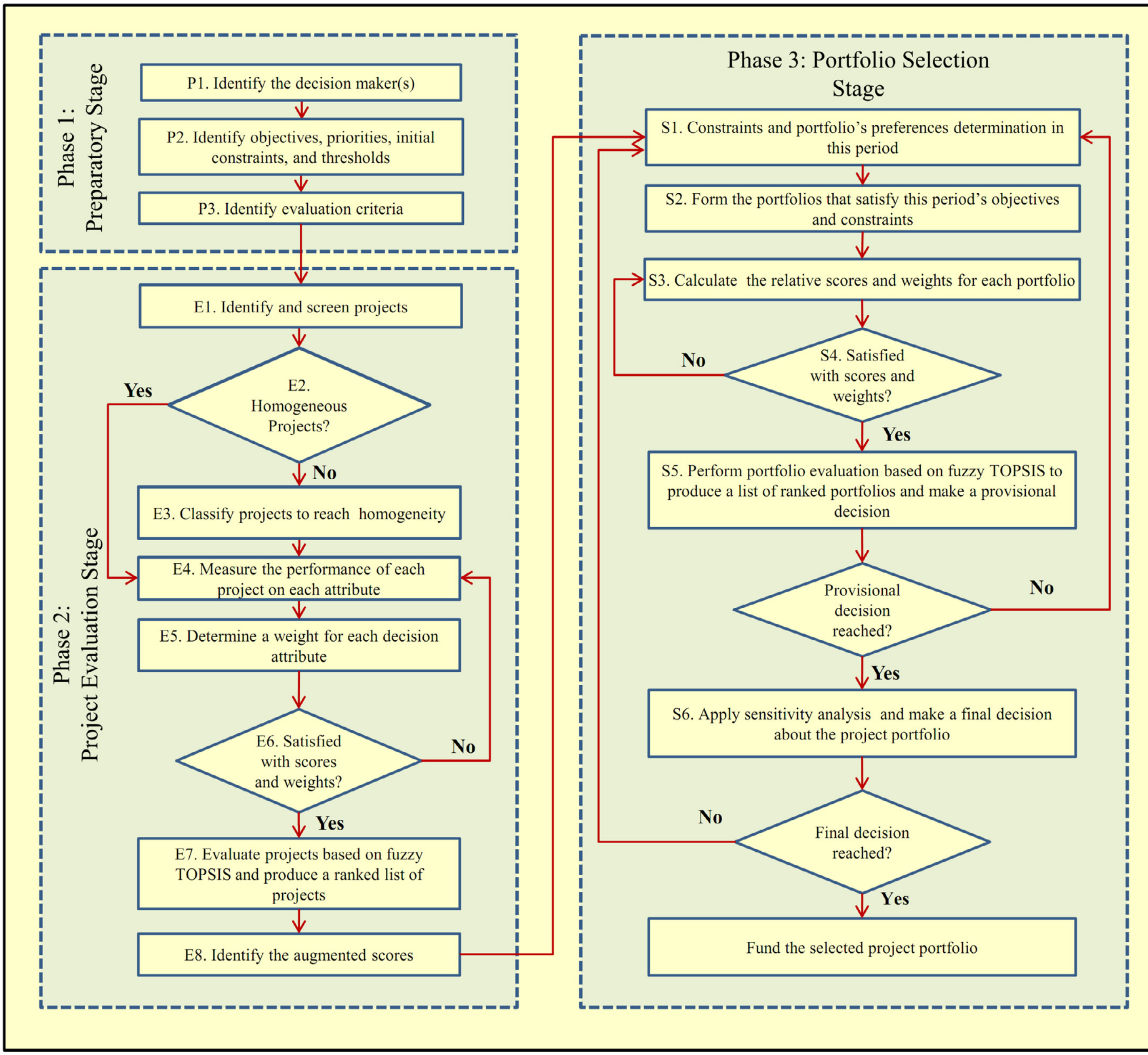

Fig. 1. Proposed PPS framework.

framework proposed in this study which is composed of three main phases including: a preparatory stage, a project evaluation stage, and a portfolio selection stage. A detailed description of each phase composing the suggested PPS framework together with each one of their corresponding steps is presented in Sections 3.1–3.3.

Some intuition summarizing the main structure of the framework proposed follows. Consider the framework proposed from an information transmission perspective. The three-stage approach introduced in this paper and described in Fig. 1 includes an *initial evaluation stage* in which the projects are evaluated individually. The information available and the requirements imposed when determining the initial ranking should ideally be maintained as we move into the next stage to build the project portfolio. To this end, we include a *transition stage*, where a knapsack model is applied to the individual evaluations of each project in order to generate augmented scores. These scores prevent the linear IP problem applied to evaluate the potential portfolios from bundling inferior projects over more effective ones. Once the augmented scores are calculated, additional requirements are introduced at a *final decision stage* within the organization. Given these additional requirements, a new ranking based on the potential interactions of the projects within a portfolio is defined. In this way, we are able to generate a set of portfolios ensuring that the final one selected fits the initial organizational objectives and requirements to the greatest possible extent.

That is, in real life settings, decisions are made at different levels within an organization and the evaluation criteria must therefore be modified and applied accordingly. The objectives imposed initially are subject to modifications throughout the design process of the portfolio. Discrepancies may easily arise between the organizational objectives and requirements defined when determining the initial ranking of individual projects and those imposed on the final portfolio. The PPS method introduced in the current paper accounts for this fact. Fig. 2 complements the PPS framework described in Fig. 1, concentrating on the information transmission process

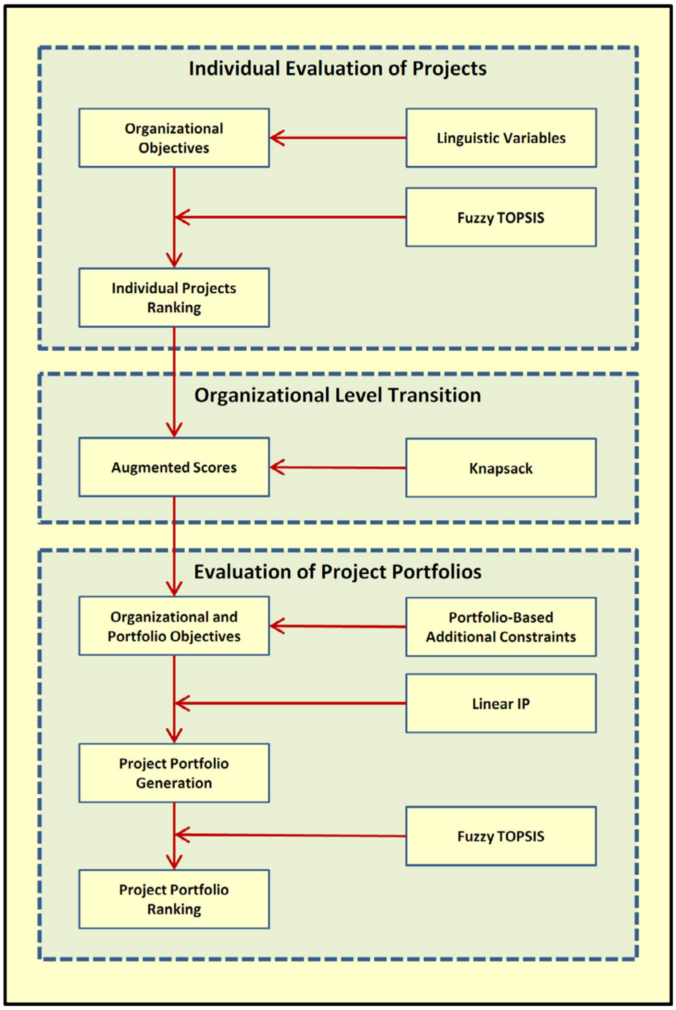

Fig. 2. Information transmission process within the organization and PPS.

within the organization. The main stages described in Fig. 2 are the following ones.

- Individual evaluation of projects: the initial objectives and constraints imposed by the organization are generally provided in the form of linguistic variables. The crucial importance of these initial variables through the different evaluation stages has determined our choice of a fuzzy TOPSIS method to elaborate the initial ranking of individual projects and that of the final portfolios.
- Organization level transition: as already stated, the known trade-off existing between the TOPSIS multi-criteria scores achieved by each individual project and their costs when determining the final portfolio leads to our definition of augmented scores. The initial ranking of projects (obtained using fuzzy TOPSIS) provides important information that must be preserved during the remaining stages of the PPS process. The augmented scores assigned to each project aim at preserving this information when defining the final portfolio.
- Evaluation of project portfolios: after defining the augmented scores, we propose a linear IP model that accounts for additional constraints. Note that these constraints were not available during the initial stage of the PPS process and must be inserted afterward. These constraints are imposed at a different organizational level, preventing their inclusion in the initial TOPSIS evaluation, and affect the whole portfolio, not only the individual projects. For example, the final portfolio may be required to include a particular project, even if was not considered in the initial selection stage. This imposition must be accounted for in the evaluation process and determines the composition of the final project portfolio.

3.1. Phase 1: preparatory stage

The preparatory stage is composed of the following three steps:

P1. Identify the decision makers (DMs): in this step, all the DMs or committee members involved in the PPS process are chosen.
P2. Identify objectives, priorities, initial constraints, and thresholds: in this step, all the organizational objectives, requirements, and constraints concerning the PPS process are formulated.
P3. Identify evaluation criteria: in this step, the DMs identify and formulate all the criteria relevant to the PPS problem. These criteria can be organized into a hierarchical or network structure for further processing.

3.2. Phase 2: project evaluation stage

The initial step in the project evaluation stage is to identify and define the relevant projects and proposals for further consideration.

E1. Identify and screen projects: DEA is used in this step to evaluate the performance of each project and identify inefficient projects for elimination. The basic intuitive guidelines describing a standard DEA problem are provided below.

DEA is widely used to measure the relative efficiency of a set of operating units that use multiple inputs to produce multiple outputs. Originally proposed by Charnes, Cooper, and Rhodes (1978), Farrell (1957) popularized the non-parametric frontier analysis when they proposed the first DEA model. Numerous developments of both theory and applications have been proposed over the past three decades. DEA models have two states: input-oriented and output-oriented. Let us consider n decision making units (DMUs) ($\mathrm{DMU}_1, \mathrm{DMU}_2, \ldots, \mathrm{DMU}_n$) that consume m-type inputs to produce s-type outputs. In this case, DMU j consists of $(x_{1j}, x_{2j}, \ldots, x_{mj})$ inputs and $(y_{1j}, y_{2j}, \ldots, y_{sj})$ outputs. Therefore, the matrix of inputs, X, and the matrix of outputs, Y, can be constructed as follows:

$$X = \begin{bmatrix} x_{11} & x_{12} & \ldots & x_{1n} \\ x_{21} & x_{22} & \ldots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \ldots & x_{mn} \end{bmatrix} \qquad Y = \begin{bmatrix} y_{11} & y_{12} & \ldots & y_{1n} \\ y_{21} & y_{22} & \ldots & y_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ y_{s1} & y_{s2} & \ldots & y_{sn} \end{bmatrix}$$

In this study, we use the standard CCR model proposed by Charnes et al. (1978) to evaluate the efficiency of the projects and remove the inefficient projects from further consideration. The mathematical details of the CCR model used in this hybrid framework are as follows:

$$\begin{aligned} &\operatorname{Min} \theta = \theta_p \\ &\text{s.t.}: \\ &\sum_{j=1}^{n} x_{ij}\lambda_j \le \theta_p x_{ip} \quad i = 1, \ldots, m, \\ &\sum_{j=1}^{n} y_{rj}\lambda_j \ge y_{rp} \quad r = 1, \ldots, s, \\ &\lambda_j \ge 0 \qquad j = 1, \ldots, n. \end{aligned} \tag{1}$$

The decision variables λ_j represent the weights or intensity variables of the DMUs. The resulting linear combinations in the constraints define the frontier points that are compared with the values achieved by the DMU being assessed. Let us consider point (P) in Fig. 3. For evaluating the efficiency of this point, point (B) is available horizontally and parallel to point (P). Point (P) uses x_p units of input to produce y_p units of output. On the other hand, point (B) uses x_B units of input, which is less than the input used by point (P), but produces y_B units of output, which equals the output for point (P).

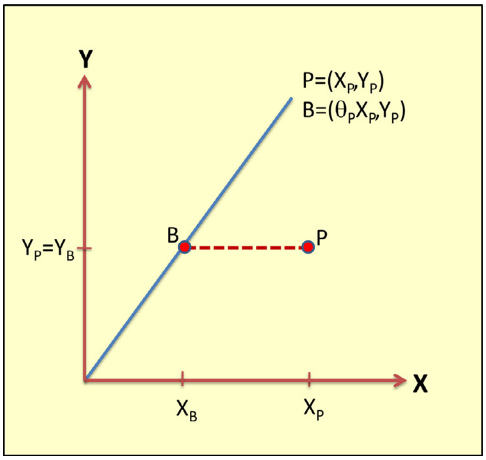

Fig. 3. Efficiency border for the input-oriented CCR.

Now for point (P) to reach the efficient point, the amount of input must be reduced. In optimal condition, the efficiency of (P) will be increased if the reduction required in the amount of input is low. We indicate the amount of input reduction by $\theta \cdot \theta_p$ is a fraction of the input for P that also represents the efficiency of P.

The aim of this step is to decrease the evaluation time, computational expenses and the size of the problem. In this step, the knowledge of the DMs' is increased through their direct involvement in the evaluation and selection process, which allows them to discard those projects deemed to be inefficient from further evaluation when creating the different portfolios in the final stage of the PPS process. Also, we make the methodology more acceptable and applicable for the managers. This is made possible by removing inefficient alternatives and continuing the process with the remaining efficient ones.

E2. Check project homogeneity: in order to evaluate the projects, the DMs must verify that all projects are homogeneously classified, which would allow them to move directly to the E4 step. However, if this were not the case, then the DMs must proceed with the next step.

E3. Classify projects to reach homogeneity: projects are not always naturally homogenized and the DM sometimes needs to classify them in homogenized groups. There are different criteria for the classification of projects (e.g., research and development criteria, project size, project time, technology type) that can be applied in order to do so.

E4. Measure the performance of each project on each attribute: if the DM determines a unit for each criterion, he or she can evaluate each project based on that criterion. For instance, the cost and rate of return of the project can be displayed as monetary values. But criteria such as strategic alignment and competition are hard to quantify. Therefore, the following three approaches are proposed to evaluate the projects based on these criteria: the direct rating approach, the value function, and the performance scale. Kabli (2009) provides a description of the main characteristics of each approach.

E5. Determine a weight for each decision attribute: in order to evaluate the projects the group of DMs must measure each project's value based on various criteria.

E6. Satisfaction with the scores and weights: this step ensures the satisfaction of the group members with the weights and scores. Some group members may change the assigned scores and weights after viewing the evaluation results. If the group is not satisfied with the weights and the scores, steps E4 and E5 should be repeated until all DMs are comfortable with these results.

E7. Evaluate projects based on fuzzy TOPSIS and produce a ranked list of the projects: the main stages composing the TOPSIS ranking process within a fuzzy evaluation environment are described below.

Assume $A_1, A_2, \ldots, A_m$ are m possible alternatives and $C_1, C_2, \ldots, C_n$ are criteria and $\tilde{x}_{ij}$ is the performance of alternative A_i based on criteria C_j where x_{ij} a fuzzy number. The following represents the fuzzy decision matrix for this problem:

$$
\begin{array}{ccccc}
 & C_1 & C_2 & \ldots & C_n \\
A_1 & \tilde{x}_{11} & \tilde{x}_{12} & \ldots & \tilde{x}_{1n} \\
A_2 & \tilde{x}_{21} & \tilde{x}_{22} & \ldots & \tilde{x}_{2n} \\
\vdots & \vdots & \vdots & & \vdots \\
A_m & \tilde{x}_{m1} & \tilde{x}_{m2} & \ldots & \tilde{x}_{mn}
\end{array}
$$
$$\tilde{W} = [\tilde{w}_1, \tilde{w}_2, \ldots, \tilde{w}_n]$$

where $\tilde{w}_j$ is the weight of criteria j.

Next, the following processes are used to rank the alternatives:

Process E7.1. Determining the evaluation criteria.

Process E7.2. Determining the alternative courses of action.

Process E7.3. Evaluating each alternative on each criteria. Note that the alternative performance scores are represented by fuzzy numbers.

Process E7.4. Determining the criteria weights.

Process E7.5. Constructing the fuzzy decision matrix (where each $\tilde{x}_{ij}$ is a triangular fuzzy number).

Process E7.6. In this step, the normalized fuzzy matrix is calculated. There are several methods for normalizing a fuzzy decision matrix. Among them, we emphasize those of Jahanshahloo, HosseinzadehLotfi, and Izadikhah (2006), who proposed an α-cut approach to convert fuzzy numbers into intervals, and Jahanshahloo, HosseinzadehLotfi, and Izadikhah (2005), who proposed a method for normalizing interval numbers and converting the normalized interval numbers into fuzzy numbers.

In order to construct the normalized fuzzy matrix, we calculate the maximum and minimum for each column and perform the following calculations:

$$\tilde{n}_{ij} = \begin{cases} \dfrac{\tilde{x}_{ij}}{\tilde{x}_j^+} = \left(\dfrac{a_{ij}}{c_j^+}, \dfrac{b_{ij}}{b_j^+}, \dfrac{c_{ij}}{a_j^+}\right) & \text{if criteria } j \text{ is positive} \\ \dfrac{\tilde{x}_j^-}{\tilde{x}_{ij}}\left(\dfrac{a_j^-}{c_{ij}}, \dfrac{b_j^-}{b_{ij}}, \dfrac{c_j^-}{a_{ij}}\right) & \text{if criteria } j \text{ is negative} \end{cases} \tag{2}$$

where $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ is a triangular fuzzy number, and $\tilde{x}_j^+ = (a_j^+, b_j^+, c_j^+)$ and $\tilde{x}_j^- = (a_j^-, b_j^-, c_j^-)$ are the maximum and minimum scores, respectively.

Process E7.7. In this step, the weighted normalized matrix is calculated based on the importance of the criteria and their corresponding weights.

$$\tilde{v}_{ij} = \tilde{n}_{ij} w_j \tag{3}$$

where w_j is the weight for criterion j and the respective normalized values $\tilde{n}_{ij}$ have been defined in Eq. (2).

Process E7.8. In this step, the ideal positive and negative fuzzy solutions can be determined as follows. Given that each $\tilde{v}_{ij}$ is a normalized fuzzy number defined within the interval [0, 1]:

$$\begin{aligned} \tilde{A}^+ &= \left(\tilde{v}_1^+, \ldots, \tilde{v}_n^+\right) \\ \tilde{A}^- &= \left(\tilde{v}_1^-, \ldots, \tilde{v}_n^-\right) \end{aligned} \tag{4}$$

Process E7.9. In this step, the distance between each alternative and the ideal positive and the ideal negative solutions is calculated as follows:

$$\begin{aligned} \tilde{d}_i^+ &= \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^+\right) \quad i = 1, \ldots, m \\ \tilde{d}_i^- &= \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^-\right) \quad i = 1, \ldots, m \end{aligned} \tag{5}$$

where $j = 1, \ldots, n$, $\tilde{v}_j^+ = (1, 1, 1)$ and $\tilde{v}_j^- = (0, 0, 0)$ for all criteria. Assuming that $\tilde{A} = (a_1, b_1, c_1)$ and $\tilde{B} = (a_2, b_2, c_2)$ are two triangular fuzzy numbers, the distance between them is calculated as follows:

$$d\left(\tilde{A},\tilde{B}\right)=\sqrt{\frac{1}{3}\left[(a_1-a_2)^2+(b_1-b_2)^2+(c_1-c_2)^2\right]} \tag{6}$$

Process E7.10. After $\tilde{d}_i^+$ and $\tilde{d}_i^-$ are determined for each alternative, the proximity ratio is calculated in order to rank the alternatives. The relative proximity of alternative A_i is defined as follows:

$$\tilde{R}_i=\frac{\tilde{d}_i^-}{\tilde{d}_i^++\tilde{d}_i^-}\quad i=1,\dots,m \tag{7}$$

As shown in Eq. (7), $\tilde{R}_i\in[0,1]$ represents the distance between alternative i and the negative-ideal. Therefore, a higher value of $\tilde{R}_i$ represents a farther distance from the negative ideal and a higher rank compared to the other options. In the best-case scenario, A_i is consistent with $\tilde{A}^+$ so $\tilde{R}_i=1$. Furthermore, in the worst-case scenario A_i is consistent with $\tilde{A}^-$ and $\tilde{R}_i=0$.

E8. Identify the augmented scores: this step aims at strengthening the consistency between the results obtained from the linear IP model applied in the portfolio selection stage and the rankings from the initial multi-criteria approach. As suggested by Kabli (2009), multiple-stage approaches should aim at remaining consistent through their PPS process.

In order to do so, we replace the initial multi-criteria scores of each alternative i, $\tilde{R}_i$, with augmented scores in the IP objective function. By applying the augmented scores, the problem of underestimating good projects (with high cost) is solved and the complete preorder of the projects obtained in the previous step is considered. Therefore, by applying the augmented scores in the objective function we are able to remove this deficiency from the model without distorting the complete preorder of the individual projects.

A simple approach is to assign scores to the projects so that the augmented score of the ith project is greater than the sum of the scores of all the projects which are worse than i based on the complete preorder derived from the TOPSIS evaluation stage. Therefore, if we assign a score of 1 to the worst project, the next project score is $(1+1)=2$, the one after that is $1+2+1=4$, and so on. Clearly, all the augmented scores consist of natural numbers. Following this approach for n projects, the score of the best project will become 2^{n-1}. Thus, there is a high variation in the objective function ratios for more than 20 projects.

This basic condition must also account for the cost of the projects, since the knapsack optimization problem applied in the next stage of the process will bundle projects in terms of both their scores and costs. When bundling projects together, the IP method does not necessarily select those that are actually preferred due to their higher multiple-criteria scores determined by the initial objectives of the organization.

Our algorithm prevents this outcome by assigning new augmented scores to all the projects such that they cannot be replaced from a portfolio combining less individually preferred but cheaper ones. That is, we want to prevent the DMs from prioritizing any combination of projects with higher combined multiple-criteria scores but lower combined cost over an initially preferred (though more costly) one.

Thus, the augmented score assigned to a preferred project must be higher than the sum of all the augmented scores received by all those projects with lower multi-criteria scores but whose combination of costs and scores makes them preferable to the initially preferred one.

In order to determine the score of project k, we only consider those projects which are lower than k in cost and rank. Therefore, in order to find the augmented score (as_i, $i=1,\dots,m$), the projects are first ranked in increasing order according to their multiple-criteria score ($\tilde{R}$) basis ($\mathrm{ms}_{k+1}\geq \mathrm{ms}_k$, $k=1,\dots,m$). (ms) is an index assumed equal to 1 for the worst project, which is assigned an $\mathrm{as}_1=1$. Then for project k, $k=2,\dots,m$, a standard knapsack problem is solved as follows:

$$\begin{aligned}&\mathrm{Max}\, Z_k=\sum_{i=1}^{k-1}\mathrm{as}_i x_i\\&\text{s.t.}:\\&\sum_{i=1}^{k-1}c_i x_i\leq c_k\\&x_i\in\{0,1\}\end{aligned} \tag{8}$$

In the knapsack problem (8) defined above, as_i and c_i are the augmented scores and costs of the ith project, respectively. Z_k is the highest possible score that can be achieved from the projects which are worse than k and have a cumulative cost lower than c_k. If $Z_k<\mathrm{as}_{k-1}$, then, as_{k-1} is increased one unit to obtain as_k. On the other hand, if $Z_k>\mathrm{as}_{k-1}$, then as_k must be set equal to Z_k+1. The flowchart of the algorithm for calculating the augmented scores is presented in Fig. 4.

3.3. Phase 2: portfolio selection stage

After evaluating and ranking the projects, the budget cannot be assigned to the higher score projects without taking other constraints and preferences into account.

S1. Constraints and portfolio's preferences determination in this period: the primary preferences and constraints were determined in the second step, leading to the initial ranking generated throughout the second stage of the PPS process. In S1, the DMs decide to remove or add constraints to the problem. For example, the project manager may add one particular project (known as a 'golden project') in the final portfolio. As already stated, these constraints are imposed at a different level within the organization and are not considered when performing the initial TOPSIS evaluation. Examples of potential constraints that can affect the portfolio selection process are as follow:

$$(i)\ \sum_{i\in S_A}x_i\leq K \tag{9}$$

x_i is a zero-one variable ($x_i=1$ if project i is selected, $x_i=0$ otherwise). S_A is a set of homogenized projects that belong to a special department and K is a constant number.

$$(ii)\, x_i=1 \tag{10}$$

Project i is a golden project (a necessary project to be included in the final portfolio).

$$(\mathbf{iii})\, x_A+x_B\leq 1 \tag{11}$$

Projects A and B cannot be simultaneously in the final portfolio.

$$(\mathbf{iv})\ \sum_{i=1}^{n}c_i x_i\leq \mathrm{budg} \tag{12}$$

c_i is the cost of project i, budg is the total available budget and n is the total number of projects.

$$(\mathbf{v})\, x_B\leq x_i,\quad i\in P_B \tag{13}$$

P_B are the total requirements of project B (if the requirements of a project are not satisfied, the project cannot be selected). Requirements are projects that must be selected together with a given project, in this case B, if the latter is considered within a portfolio. If known beforehand, this constraint would modify the scores assigned to project B by TOPSIS in the initial evaluation stage, particularly so if the requirements were to receive very different scores from those assigned to B.

Note that in order to obtain a feasible solution the constraints should not be contradictory.

S2. Form the portfolios that satisfy this period's objectives and constraints: a large number of project portfolios can be created, particularly when the number of constraints is low and the number of

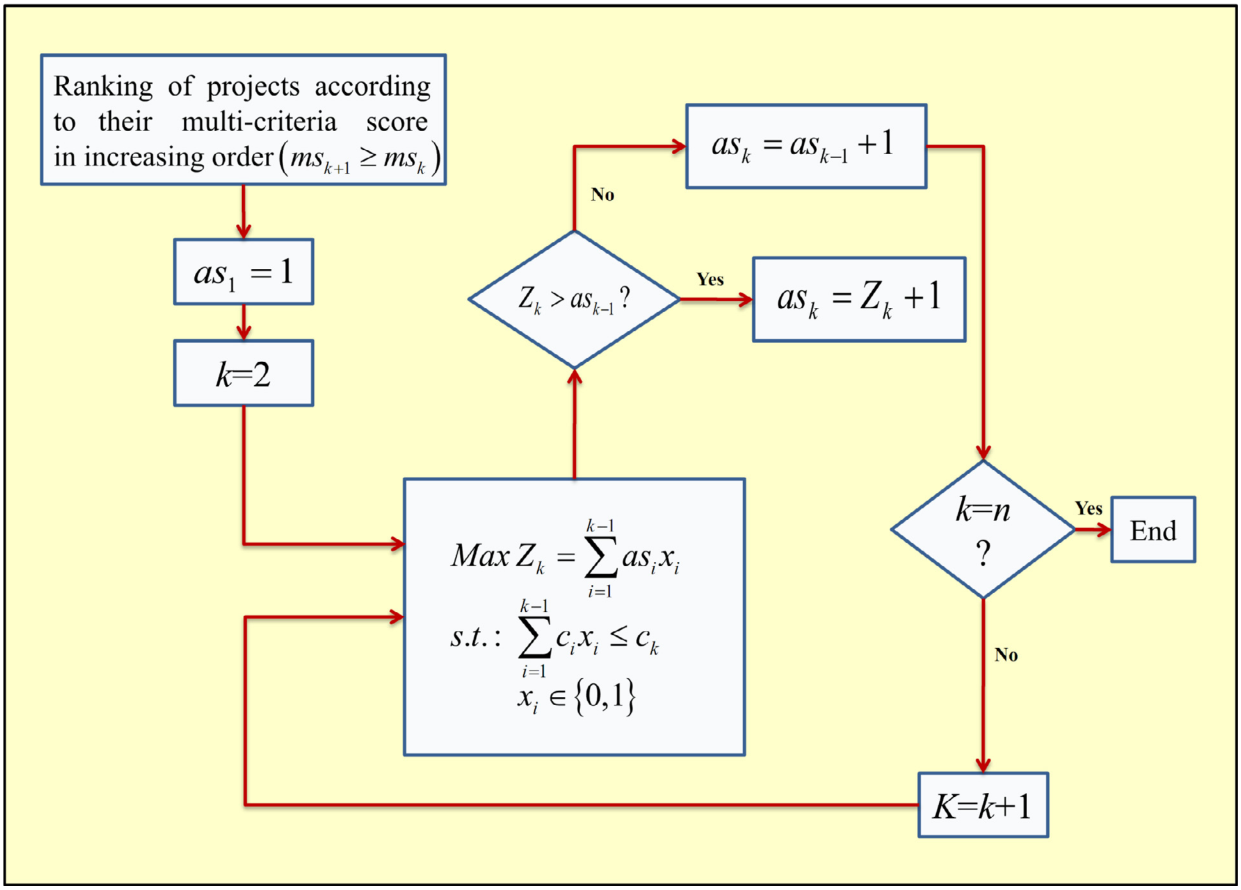

Fig. 4. Flowchart of the algorithm for calculating the augmented scores.

projects is large. Due to this fact, the DM applies a linear IP model for creating different portfolios and considering different preferences and constraints. The objective function of this model is as follows:

$$\text{Max}\, Z = \sum_{i=1}^{n} \text{as}_i x_i \tag{14}$$

where n is the total number of projects and as_i is the augmented score calculated for the ith project.

It is clear that the linear IP model provides an optimal solution. Sometimes, this result is accepted as the final portfolio (Mavrotas, Diakoulaki, & Kourentzis, 2008). However, in this study, we generate a larger set of solution portfolios in order to let DMs choose the best one available. The intuition justifying the generation of multiple solution portfolios comes from the inclusion of a new set of constraints in step S1. That is, the optimal solutions derived from the current optimization problem combine the initial weights assigned by the DMs through the initial TOPSIS analysis performed during the project evaluation stage with the new constraints introduced in step S1. These new constraints were not considered by the DMs when assigning the subjective weights and scores to the projects before performing the initial TOPSIS evaluation.

Thus, the augmented scores introduced in step E8 preserve an order of projects determined by the DMs that could be modified if they would have known about the constraints imposed in step S1. As a result, and in order to choose the best portfolio in terms of the initial evaluations and the new constraints, a set of optimal portfolios is generated. In this way, the DMs can apply again the TOPSIS method to the resulting portfolios and choose the best among them, considering both the initial objectives of the organization together with the new constraints imposed at a different organizational level and initially unavailable to the DMs.

Consequently, the initial result is entered in the problem as a new constraint and the problem is solved again in order to create a second portfolio. This process is repeated until the model is stopped. For instance, assume that in a first solution, projects 1, 2 and 4 are selected. We add these projects to the model as the constraint $x_1 + x_2 + x_4 \leq 2$ and solve the model again. Note that the current step generates a set of optimal portfolios that may be potentially chosen and whose relative position in the final ranking will be based on the TOPSIS scores obtained by each portfolio. If the model does not produce results in this initial phase, the DMs must revise the constraints introduced in the previous step and solve the model all over again.

Note also that the PPS method proposed in the paper is deterministic. That is, we have not considered any stochastic dependence between the projects or parameters when forming the portfolios. Any dependence has been reduced to the additional information and constraints introduced by managers or other organizational DMs in step S1 before the IP method is applied during the final portfolio selection stage.) The importance of correlation has been repeatedly emphasized in the literature and different approaches have been proposed to address the issue including the entropy method (Bickel & Smith, 2006, different copulas methods (Clemen & Reilly, 1999; Wang & Dyer, 2012), and the contingent portfolio programming method (Gustafsson & Salo, 2005). In this regard, a stochastic version of the augmented score algorithm could be developed based on the initial evaluations received together with the potential requirements that may follow from these evaluations and take place in between decision stages. As a result, the augmented scores assigned to a given project would depend on the (conditional) probability of selecting different projects based on the initial and expected requirements of DMs.

S3. Calculate the relative weights and scores for each portfolio: after creating the feasible models, the DMs can consider new weights for the criteria. Note that the importance of each criterion for a project is different from their importance for a portfolio. Thus, the interaction among projects within the portfolio will determine the results from the TOPSIS evaluation applied in step S5 below.

S4. Check satisfaction with the scores and weights: in this step, the DMs review the criteria weights and the portfolio score if their required level of satisfaction is not met. In this case, they might return to the previous step and do the necessary revision. If the required level of satisfaction is met, they will continue to the next step.

S5. Perform portfolio evaluation based on fuzzy TOPSIS to produce a list of ranked portfolios and make a provisional decision: in this step, portfolios are evaluated and ranked using fuzzy TOPSIS. It is often possible that the DMs select portfolios that are higher in the rank as a temporary decision. If the group agrees on the temporary decision, they continue to the next step; otherwise, they return to steps S1 to S4 and do the necessary revisions to the constraints, scores and proposed portfolio weights.

S6. Apply sensitivity analysis and make a final decision about the project portfolio: in this step, we measure the effect on the model results caused by a change in the variables and the model's parameters. Sensitivity analysis answers the question "How the results can be affected by changing values?" (Clemen et al., 2001). If a small shift leads to a significant change in the portfolio, the DMs must agree on whether to keep the current portfolio or make another decision.

It should be noted that sensitivity analysis is a crucial component of linear IP problems because a small change in a ratio can lead to a significant change in the problem solution. At the end of this step, it is decided whether to accept the selected portfolio or return to steps S1 to S6. Once the selected portfolio satisfies the DMs, it is accepted as the final decision.

4. Case study

In this section we demonstrate the applicability of the proposed method and exhibit the efficacy of the algorithms and procedures with a case study adopted from Kabli (2009). Indeed, we will replicate the main results obtained by Kabli (2009) within a fuzzy setting. In order to do so, we will fuzzify the evaluations provided for each project within the different criteria categories considered. We will also generate the corresponding augmented scores in order to verify the consistency of the results obtained with respect to the initial objectives of the organization. Moreover, given the initial numerical evaluations provided by Kabli (2009), DEA will not be applied in the initial stages of the process. In this regard, all the projects analyzed will be assumed to be efficient.

4.1. Preparatory stage

The objectives and constraints for the activities in this portfolio selection problem are related to: (1) clean fuel, (2) hydrogen production, (3) production of petrochemicals feedstock and chemicals from the refined products, and (4) upgrading low-value refined products. Another constraint is that each one of these areas should be represented with projects in the selected portfolio. The project portfolio has a given budget which determines a budget constraint of 10 million pounds.

In this study, we considered 13 sub-attributes classified into the five categories of opportunity, potential risks, technology, finance, and employment as shown in the hierarchical structure described in Fig. 5.

(i) Opportunity attributes represent two qualitative potential benefits including environmental friendliness and partnership. Environment friendliness measures the ability of the project to have minimum adverse effects on the environment. Partnership reflects the opportunities for establishing partnerships with other

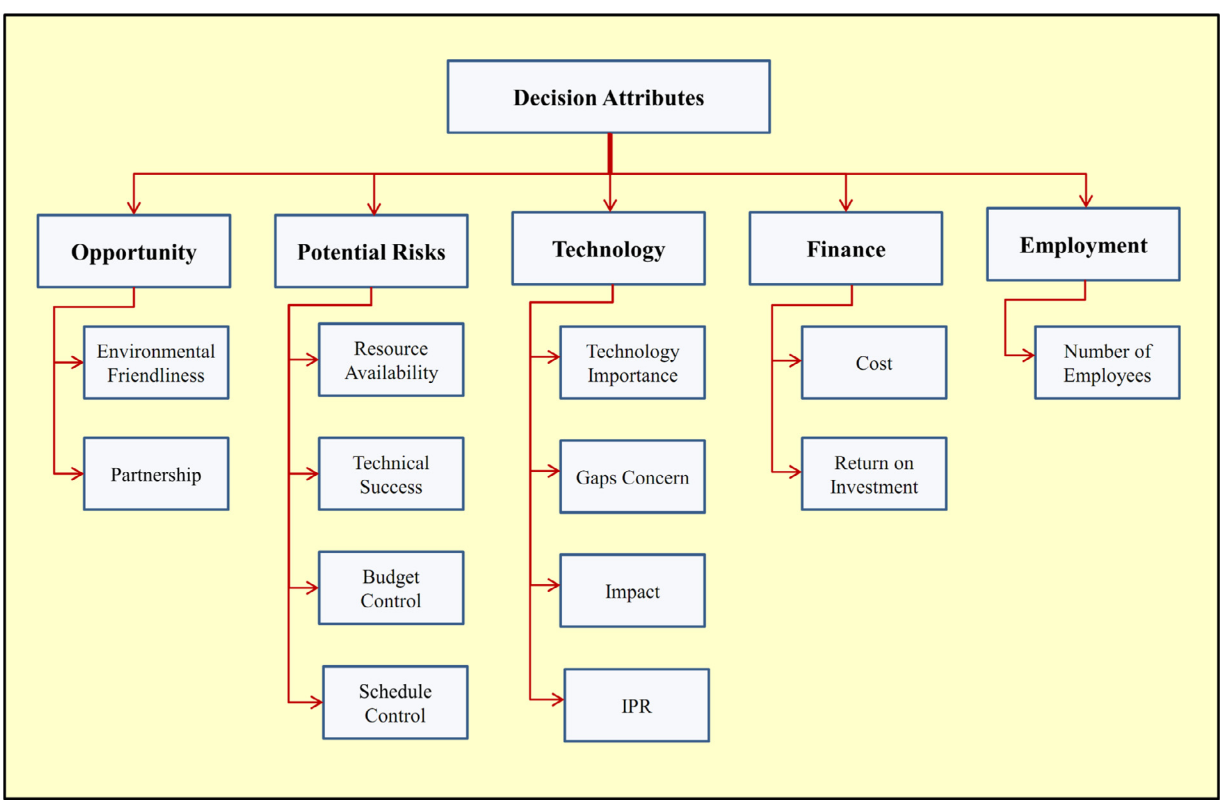

Fig. 5. Decision attributes used in the project evaluation process.

Table 1
Project matrix.

Project set	Activity type
P_1 to P_8	Clean fuel
P_9 to P_{16}	Developing quality recycled products
P_{17} to P_{23}	Producing primary petrochemical products and chemical materials from recyclable materials
P_{24} to P_{30}	Producing hydrogen

companies for the purpose of technology development, cost cutting, etc.

(ii) Potential risks are captured by the four sub-attributes of resource availability, technical success, budget control, and schedule control. Resource availability considers the availability of people, equipment, and material. Technical success measures the probability that a project will be able to achieve its established goals. If the project goals and objectives are not well defined, the probability of technical success is considered low. Budget control refers to the probability that a project can be completed with its specified budget. Schedule control reflects the probability that a project can be successfully completed within its expected completion time.

(iii) The technology attribute is used to assess the ability of the project to enhance technological developments in the company. Four subcriteria of this attribute are technology importance, gap concern, impact, and intellectual property rights (IPRs). Technology importance reflects the relevance of a project to technology in general. Gap concern considers the technological gap between the company and its competitors. Projects are expected to bridge this technological gap. Impact assesses the scope of the impact of technology on different research areas or different company products. A project is more attractive if the technology utilized has a positive influence on multiple projects company-wide. IPR assesses the ability of a project to develop its own technologies and to patent them for future commercial use.

(iv) Financial attributes such as cost and return on investment measure the expected monetary gain (or loss) from undertaking specific projects.

(v) The employment attribute assesses the expected number of employees to be employed from implementing a project. Reducing the number of contract employees is one of the main objectives of the company.

4.2. Project evaluation stage

In this study, we evaluated 30 non-homogeneous projects. Initially, we divided these projects into four groups of homogeneous projects according to the four activity types presented in Table 1.

As shown in Table 1, projects 1–8 were grouped according to the clean fuel activity type. Projects 9–16 were projects related to developing quality recycled products. Projects 17–23 were projects for producing petrochemical products and chemical materials from recyclable materials. Finally, projects 24–30 were concerned with producing hydrogen.

Next, we initiated the evaluation process whereby these projects were evaluated according to the attributes and sub-attributes presented in Fig. 5. Each attribute consisted of one or more decision elements, making it impossible to determine the score of each attribute directly. The weighted scores for the various decision

Table 2
Fuzzy decision matrix.

Project	Criteria and weight				
	F 0.36	*E* 0.14	*T* 0.14	*O* 0.32	*R* 0.04
1	(70 60 50)	(30 20 10)	(18 13 8)	(70 65 60)	(47 42 37)
2	(70 60 50)	(30 20 10)	(56 51 46)	(69 64 59)	(61 56 51)
3	(0 0 0)	(100 100 100)	(78 73 68)	(15 10 5)	(58 53 48)
4	(100 90 80)	(100 100 100)	(100 95 90)	(100 100 100)	(100 100 100)
5	(70 60 50)	(50 40 30)	(50 45 40)	(41 36 31)	(62 57 52)
6	(50 40 30)	(0 0 0)	(47 42 37)	(86 81 76)	(29 24 19)
7	(40 30 20)	(60 50 40)	(52 47 42)	(100 96 91)	(49 44 39)
8	(100 100 100)	(100 90 80)	(100 97 92)	(100 99 94)	(100 100 100)
9	(70 60 50)	(0 0 0)	(34 29 24)	(12 7 2)	(36 31 26)
10	(100 90 80)	(100 100 100)	(100 100 100)	(100 99 94)	(100 100 100)
11	(60 50 40)	(100 90 80)	(52 47 42)	(49 44 39)	(56 51 46)
12	(100 90 80)	(100 100 100)	(100 100 100)	(100 100 100)	(100 95 90)
13	(0 0 0)	(60 50 40)	(66 61 56)	(77 72 67)	(36 31 26)
14	(70 60 50)	(100 100 100)	(59 54 49)	(37 32 27)	(27 22 17)
15	(100 100 100)	(100 100 100)	(100 97 92)	(100 100 100)	(100 95 90)
16	(80 70 60)	(0 0 0)	(59 54 49)	(81 76 71)	(86 81 76)
17	(80 70 60)	(0 0 0)	(49 44 39)	(48 43 38)	(61 56 51)
18	(100 90 80)	(100 100 100)	(100 98 93)	(100 100 100)	(100 97 92)
19	(0 0 0)	(100 100 100)	(48 43 38)	(59 54 49)	(62 57 52)
20	(80 70 60)	(70 60 50)	(58 53 48)	(9 4 0)	(81 76 71)
21	(100 100 100)	(100 100 100)	(100 98 93)	(96 91 86)	(100 97 92)
22	(100 90 80)	(100 100 100)	(100 96 91)	(100 99 94)	(100 100 100)
23	(100 90 80)	(50 40 30)	(20 15 10)	(41 36 31)	(35 30 25)
24	(50 40 30)	(40 30 20)	(70 65 60)	(9 4 0)	(62 57 52)
25	(0 0 0)	(80 70 60)	(61 56 51)	(65 60 55)	(42 38 32)
26	(100 90 80)	(100 100 100)	(100 95 90)	(96 91 86)	(100 99 94)
27	(50 40 30)	(0 0 0)	(56 51 46)	(100 100 100)	(78 73 68)
28	(100 100 100)	(100 100 100)	(100 95 90)	(100 100 100)	(100 100 100)
29	(50 40 30)	(50 40 30)	(53 48 43)	(68 63 58)	(78 73 68)
30	(40 30 20)	(60 50 40)	(38 33 28)	(90 85 80)	(61 56 51)

Table 3
Project rankings according to fuzzy TOPSIS.

Project	$\tilde{d}^+$	$\tilde{d}^-$	$\tilde{d}^+ + \tilde{d}^-$	$\tilde{R}_i$	Rank
1	4.513	0.6067	5.1204	0.1184	**14**
2	4.4587	0.6612	5.1199	0.1291	**11**
3	4.6922	0.4670	5.1592	0.0922	**24**
4	4.0436	0.9584	5.002	0.1916	**7**
5	4.5278	0.5986	5.1264	0.1167	**15**
6	4.259	0.4752	4.7343	0.1003	**22**
7	4.2208	0.5728	4.7936	0.1194	**13**
8	4.0267	0.9740	5.0007	0.1947	**3**
9	4.7092	0.2974	5.0066	0.0594	**30**
10	4.0423	0.9579	5.0002	0.1915	**8**
11	4.4681	0.5368	5.0049	0.1072	**18**
12	4.0386	0.9633	5.0019	0.1925	**5**
13	4.6020	0.3998	5.0018	0.0799	**26**
14	4.4579	0.5460	5.0039	0.1091	**17**
15	3.9749	0.9929	4.9678	0.1998	**1**
16	4.3976	0.6055	5.0031	0.1210	**12**
17	4.5271	0.4792	5.0063	0.0957	**23**
18	4.0422	0.9598	5.0020	0.1918	**6**
19	4.6043	0.3967	5.0010	0.0793	**27**
20	4.5518	0.4548	5.0066	0.0908	**25**
21	4.0346	0.9660	5.0006	0.1931	**4**
22	4.0502	0.9519	5.0021	0.1903	**9**
23	4.4726	0.5323	5.0049	0.1063	**19**
24	4.6870	0.3227	5.0097	0.0641	**29**
25	4.6116	0.3846	4.9962	0.0769	**28**
26	4.0434	0.9290	4.9724	0.1868	**10**
27	4.4359	0.5678	5.0037	0.1134	**16**
28	4.0070	0.9931	5.0001	0.1986	**2**
29	4.5027	0.5028	5.0050	0.1004	**21**
30	4.4821	0.5242	5.0063	0.1047	**20**

Table 4
Augmented scores.

ms	$\tilde{R}_i$	Project	Cost/budget	Augmented score
1	0.0594	9	4/2	1
2	0.0644	24	3/2	2
3	0.0769	25	2	3
4	0.0793	19	1/2	4
5	0.0799	13	7/1	5
6	0.0908	20	8/1	9
7	0.0922	3	2	10
8	0.0957	17	1	11
9	0.1003	6	5/1	12
10	0.1004	29	1/2	13
11	0.1047	30	5/2	24
12	0.1063	23	4/1	25
13	0.1072	11	1	26
14	0.01091	14	5/1	27
15	0.1134	27	6/1	28
16	0.1167	5	1	29
17	0.1184	1	2/1	30
18	0.1194	7	2	56
19	0.1210	16	3/1	57
20	0.1291	2	5/1	58
21	0.1868	26	8/1	59
22	0.1903	22	4/1	60
23	0.1915	10	6/1	61
24	0.1916	4	5/2	88
25	0.1918	18	2/2	89
26	0.1925	12	2/1	90
27	0.1931	21	2	91
28	0.1947	8	6/1	92
29	0.1986	28	8/1	93
30	0.1998	15	1/1	94

attributes considered were calculated as follows:

$$
\begin{aligned}
O &= [(W_{EF} * EF_{\text{Score}}) + (W_P * P_{\text{Score}})]\\
R &= [(W_{RA} * RA_{\text{Score}}) + (W_{TS} * TS_{\text{Score}}) + (W_B * B_{\text{Score}})\\
&\quad + (W_S * S_{\text{Score}})]\\
T &= [(W_G * G_{\text{Score}}) + (W_{TI} * TI_{Score}) + (W_I * I_{Score})\\
&\quad + (W_{\text{IPR}} * IPR_{\text{Score}})]\\
F &= [(W_C * C_{\text{Score}}) + (W_{RE} * RE_{\text{Score}})]\\
E &= (W_E * E_{\text{Score}})
\end{aligned}
\tag{15}
$$

The W parameters represent the weights of each decision element within an attribute (O = opportunity, R = risk, T = technology, F = finance, and E = employment). The remaining parameters represent the scores of the corresponding sub-attributes described in Fig. 5.

Then the DM assigns a weight to each criterion that indicates its importance. The methods used to determine the weights of the criteria and sub-criteria (decision elements) are described extensively in the Appendix E of Kabli (2009). Afterward, in accordance with the above equations, a total score for each project is obtained by considering all the criteria and weights presented in Table 2.

Kabli (2009) emphasizes his limited access to the numerical data necessary to obtain the scores and weights required to implement the PPS process. Thus, he uses the random number generator in the MS Excel spreadsheet to "mimic the steps of eliciting projects' scores and attributes' weights done by the decision makers to evaluate R&D projects and select the portfolio" (pp. 135) through Monte Carlo simulation.

As shown in Table 3, projects 15, 28, 8, 21 and 12 are ranked from first to fifth, respectively. Before entering the next stage, their augmented scores are calculated applying model (8), while taking into account the project rankings and the budget consumed. These scores, described in Table 4, are used for each project in the objective function of the IP model instead of the multi-criteria ones.

Table 5
A limited project matrix example.

Project set	Budget (%)
P_1 to P_8	40
P_9 to P_{16}	20
P_{17} to P_{23}	20
P_{24} to P_{30}	20

It should be noted that even though the augmented score algorithm has been applied only once through the current decision process, it could be implemented more times through the different stages of a more complex decision making process. That is, the algorithm could be applied at each decision point determined by different information levels after a given ranking is obtained. This could be done to preserve a sufficiently stable ranking based on the objectives defined within each decision point and those objectives defined by managers and other organizational DMs at further information levels.

4.3. Portfolio selection stage

The primary organizational constraints and preferences considered by the DMs were determined in the second step. Another tool for introducing constraints is the project matrix. That is, an additional set of constraints that can be introduced at a later stage within the organization is given by the project matrix, where different project activity sets are allocated different percentages of the total organizational budget. Table 5 provides an example of a limited project matrix.

In this case, the clean fuel constraint can be described as follows:

$$x_1b_1 + x_2b_2 + x_3b_3 + x_4b_4 + x_5b_5 + x_6b_6 + x_7b_7 + x_8b_8 \leq 0.4B$$

where x represents the zero-one project variables, b is the budget or cost of the respective projects and B is the total available budget. We have applied the linear IP model to create the portfolios considering all the constraints. It should be noted that the current model does not account for partial investment or multiple portfolio selection, implicit constraints that, if loosened, would modify the outcomes obtained from the PPS method (Salo, Gustafsson, & Ramanathan, 2003). As stated at the end of the previous subsection, the augmented score algorithm could be implemented again to the ranking values obtained by each portfolio in order to create a new knapsack problem based on the augmented portfolio scores together with any new constraints added afterward.

The objective function for the current IP model is defined as follows:

$$\text{Max } Z = \sum_{i=1}^{30} \text{as}_i x_i$$

x_i is a zero-one variable, where $x_i = 1$ means that the ith project has been selected and $x_i = 0$ means that it has not been selected. The total number of projects is 30 and as_i is the calculated augmented score for the ith project.

The following constraints were formulated for this problem:

- ***Budget constraints*:** the total investment required by the selected portfolios must not exceed the available budget (10 million pounds).

$$\sum_{i=1}^{30} b_i x_i \leq 10$$

Table 6
Criteria attribute weights and an example of a portfolio's total score.

Criteria Weight		Opportunity 0.32	Potential risks 0.04	Technology 0.14	Financial 0.36	Employment 0.14
Projects	P_8	(94 99 100)	(100 100 100)	(92 97 100)	(100 100 100)	(80 90 100)
	P_{12}	(100 100 100)	(90 95 100)	(100 100 100)	(1009080)	(100 100 100)
	P_{18}	(100 100 100)	(92 97 100)	(93 98 100)	(80 90 100)	(100 100 100)
	P_{22}	(94 99 100)	(100 100 100)	(91 96 100)	(80 90 100)	(100 100 100)
	P_{26}	(86 91 96)	(94 99 100)	(90 95 100)	(80 90 100)	(100 100 100)
	P_{28}	(100 100 100)	(100 100 100)	(90 95 100)	(100 100 100)	(100 100 100)
Portfolio 1		(574 589 596)	(576 591 600)	(556 581 600)	(520 560 600)	(580 590 600)

Table 7
Portfolio scores and portfolio rankings.

Portfolio	Projects of portfolio	Criteria and weight					Rank
		Opportunity 0.32	Potential risks 0.04	Technology 0.14	Financial 0.36	Employment 0.14	
1	28–26–22–18–12–8	(596 589 574)	(600 591 576)	(600 581 556)	(600 560 520)	(600 590 580)	33
2	28–26–22–18–15–8	(596 589 574)	(600 591 576)	(600 578 548)	(600 570 540)	(600 590 580)	24
3	28–26–22–21–15–8	(592 580 560)	(600 591 576)	(600 578 548)	(600 580 560)	(600 590 580)	40
4	28–26–22–21–12–8	(592 580 560)	(600 591 576)	(600 581 556)	(600 570 540)	(600 590 580)	23
5	26–22–15–10–8–4	(598 588 568)	(600 594 584)	(600 580 555)	(600 560 520)	(600 590 580)	36
6	28–22–15–10–8–4	(600 597 582)	(600 595 590)	(600 580 555)	(600 570 540)	(600 590 580)	18
7	26–22–18–12–10–8	(594 588 568)	(600 591 576)	(600 586 566)	(600 550 500)	(600 590 580)	38
8	28–22–18–12–10–8	(600 597 582)	(600 592 582)	(600 586 566)	(600 560 520)	(600 590 580)	25
9	26–18–15–12–10–8	(596 589 574)	(600 586 566)	(600 587 567)	(600 560 520)	(600 590 580)	27
10	28–18–15–12–10–8	(600 598 588)	(600 587 572)	(600 587 567)	(600 570 540)	(600 590 580)	8
11	26–22–15–12–10–4	(596 589 574)	(600 589 574)	(600 583 563)	(600 550 500)	(600 600 600)	39
12	28–22–15–12–10–4	(596 598 588)	(600 590 580)	(600 583 563)	(600 560 520)	(600 600 600)	26
13	26–22–15–12–8–4	(596 589 574)	(600 589 584)	(600 580 555)	(600 560 520)	(600 590 580)	35
14	28–22–15–12–8–4	(600 598 588)	(600 590 580)	(600 580 555)	(600 570 540)	(600 590 580)	17
15	26–21–15–12–10–8	(600 580 560)	(600 586 566)	(600 587 567)	(600 570 540)	(600 590 580)	13
16	28–21–15–12–10–8	(600 580 574)	(600 587 572)	(600 587 567)	(600 580 560)	(600 590 580)	2
17	26–22–21–12–10–8	(892 579 554)	(600 591 576)	(600 586 566)	(600 560 520)	(600 590 580)	32
18	28–22–21–12–10–8	(596 588 568)	(600 592 582)	(600 586 566)	(600 580 540)	(600 590 580)	10
19	26–22–15–12–10–8	(596 588 568)	(600 594 574)	(600 585 565)	(600 560 520)	(600 590 580)	28
20	28–22–15–12–10–8	(600 597 582)	(600 590 580)	(600 585 565)	(600 580 540)	(600 590 580)	9
21	28–26–21–12–10–8	(592 580 560)	(600 591 576)	(600 585 565)	(600 570 540)	(600 590 580)	16
22	28–26–21–15–12–8	(592 581 566)	(600 586 566)	(600 582 557)	(600 580 560)	(600 590 580)	5
23	28–26–21–15–10–8	(592 580 560)	(600 591 576)	(600 582 557)	(600 580 560)	(600 590 580)	6
24	28–22–21–15–12–4	(596 590 580)	(600 587 572)	(600 581 556)	(600 570 540)	(600 600 600)	12
25	26–22–21–15–12–4	(592 581 566)	(600 586 566)	(600 581 556)	(600 560 520)	(600 600 600)	34
26	28–21–18–15–12–8	(596 590 580)	(600 584 564)	(600 585 560)	(600 580 560)	(600 590 580)	1
27	26–21–18–15–12–8	(592 581 566)	(600 583 558)	(600 585 560)	(600 560 540)	(600 590 580)	15
28	28–22–21–15–12–8	(596 589 574)	(600 587 572)	(600 583 558)	(600 580 560)	(600 590 580)	3
29	26–22–21–15–12–8	(592 580 560)	(600 586 566)	(600 583 558)	(600 560 540)	(600 590 580)	19
30	28–22–21–15–10–8	(596 588 568)	(600 592 582)	(600 583 558)	(600 580 560)	(600 590 580)	4
31	26–22–21–15–10–8	(592 579 554)	(600 591 576)	(600 583 558)	(600 560 540)	(600 590 580)	22
32	28–26–22–15–12–4	(596 590 580)	(600 589 574)	(600 578 553)	(600 540 520)	(600 600 600)	37
33	28–26–18–15–12–8	(596 590 580)	(600 586 566)	(600 582 557)	(600 560 540)	(600 590 580)	14
34	28–26–22–15–12–8	(596 589 574)	(600 589 574)	(600 580 555)	(600 560 540)	(600 590 580)	20
35	28–26–22–15–10–8	(596 588 568)	(600 594 584)	(600 580 555)	(600 570 540)	(600 590 580)	21
36	26–22–18–15–12–8	(596 589 574)	(600 586 566)	(600 583 558)	(600 560 520)	(600 590 580)	11
37	28–22–18–15–12–8	(600 598 588)	(600 587 572)	(600 583 558)	(600 570 540)	(600 590 580)	29
38	26–22–18–15–10–8	(596 588 568)	(600 591 576)	(600 583 558)	(600 560 520)	(600 590 580)	31
39	28–22–18–15–10–8	(600 597 582)	(600 592 582)	(600 583 558)	(600 580 540)	(600 590 580)	7
40	28–26–22–12–10–8	(600 596 576)	(600 595 590)	(600 584 564)	(600 560 520)	(600 590 580)	30

- ***Classification constraint***: at least one project from each activity type must be included in the portfolio.

$$x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8 \geq 1$$
$$x_9 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14} + x_{15} + x_{16} \geq 1$$
$$x_{17} + x_{18} + x_{19} + x_{20} + x_{21} + x_{22} + x_{23} \geq 1$$
$$x_{24} + x_{25} + x_{26} + x_{27} + x_{28} + x_{29} + x_{30} \geq 1$$

- Constraints related to Table 5 (limited project matrix) regarding the maximum percentage of the budget that can be allocated to each project set.

We have used LINGO software to solve the model described above. The first solution of the model is a portfolio of projects 8, 12, 18, 22, 26 and 28 with an investment equal to 10 million pounds. This portfolio is entered into the model as the following constraint in order to create other portfolios: $x_8 + x_{12} + x_{18} + x_{22} + x_{26} + x_{28} \leq 5$.

The next portfolio consists of projects 8, 15, 18, 22, 26 and 28 with 9.9 million pounds of investment. These projects are also entered into the model as a constraint together with the other constraints. This process continues until the model cannot produce any more results.

We consider a total number of 40 portfolios among those created. This has been done for comparability purposes with the results provided by Kabli (2009). At the same time, the DM can calculate the relative score of each portfolio created. In this paper, we have calculated each portfolio's score using the sum of the projects' scores within each portfolio for each criterion. For instance, Table 6 presents the fuzzy scores of the projects composing the initial portfolio together with the subjective weights assigned by the DMs to each attribute. At the same time, the last row is given by the sum of the project scores obtained by the portfolio for each fuzzy attribute. The resulting fuzzy evaluation of each attribute together with the subjective weights assigned by the DMs will determine the score of the portfolio through the final stage of the process.

We then evaluated and ranked the portfolios created by applying the TOPSIS method. The final scores assigned by the DMs to each portfolio are presented in Table 7. As shown in this table, portfolio 26 (consisting of projects 8, 12, 15, 18, 21 and 28, and requiring 9.9 million pounds of investment) has the highest rank.

Sensitivity analysis can then be applied in order to check the impact of different changes in the model parameters. The results from modifying the weight of the financial criterion, i.e. the most important one, on the ranking of portfolios are identical to those of Kabli (2009, pp. 143–146) and have therefore been omitted. Portfolio 26 remains as the final selection that should be made by the DM.

5. Conclusion and further research directions

Selecting projects and optimizing the project portfolio that best aligns with the organization's strategic priorities is a difficult task. We have proposed a three-stage hybrid method for PPS problems. We have preserved the maximum fitness between the final portfolio selection and the projects' initial rankings while considering various organizational objectives. The model proposed is comprised of three stages and each stage has been divided into several steps and procedures. We used DEA for initial screening, TOPSIS for ranking projects, and integer linear programming for selecting the most suitable project portfolios in a fuzzy environment according to organizational objectives.

The method proposed in this study helps the DMs: (1) think systematically about complex PPS problems; (2) decompose the PPS problems into manageable steps and integrate the results to arrive at a solution consistent with organizational goals and objectives; (3) carefully consider the element of uncertainty within a structured framework; and (4) account for several quantitative and qualitative goals, constraints, and DMs' preferences. Managerial judgments and accurate data are integral components of PPS problems. Our approach enables DMs to assimilate project-related judgments and data within a formal and systematic approach.

The DMs can apply sensitivity analysis to check the impact of different parameter alterations in the final solution. In addition, the proposed approach allows the DMs to revise the optimal solution by selecting or removing a particular project and to check the impact of these modifications on the solution and the available resources consumed by a particular portfolio. Some challenging issues experienced during the development of the model can be proposed as further studies. These issues are listed as below:

1. Sometimes the benefits of implementing two or more projects were higher than their sum. A mathematical formulation could be integrated in the proposed framework to model these types of dependencies.
2. The proposed methodology consists of a number of tools and techniques that require a great deal of time and effort. An automated decision support system could significantly reduce the time and efforts required and, at the same time, improve transparency.

Acknowledgments

The authors would like to thank the anonymous reviewers and the editor-in-chief for their constructive comments and suggestions.

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