A multiobjective fuzzy model for selecting and planning a project portfolio in a public organisation

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Abstract: Our purpose in this paper is to assist decision-makers in the task of selecting project portfolios to satisfy their requirements and guarantee profitable growth. This task usually involves decision-makers having to face multiple objectives and constraints, as well as the uncertainty associated with certain parameters of the problem. Therefore, in this paper, we propose a multiobjective programming model, which includes uncertainty through the use of fuzzy parameters and allows us to represent information not fully known by the decision-makers. The resulting model has been applied to a project portfolio selection process in a public organisation.

Keywords: project portfolio selection; fuzzy numbers; multiobjective programming; public organisations.

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1 Introduction

Selecting the projects that best match the needs, requirements and objectives of an organisation is a complex task. Several quantitative techniques have been developed in recent decades to address this need. However, many of these techniques have been developed under the hypothesis of deterministic environments, without taking into account the issue of uncertainty involved in the process.

Organisations typically pursue a wide variety of objectives that cannot easily be achieved by a single project. Therefore, groups of projects (i.e., portfolios) that share a limited number of resources over a given period of time have to be selected (Archer and Ghasemzadeh, 1999; Martinsuo, 2013).

There is a wealth of literature on many methods used in this field (Heidenberger and Stummer, 1999; Iamratanakul et al., 2008). One set of widely used techniques focuses on ranking the investment required for each proposal, and the budget is then distributed until it is fully spent (e.g., financial methods (Silvola, 2006), scoring methods (Lawson et al., 2006), analytical hierarchy process (Feng et al., 2011) and multiple attribute utility theory (Duarte and Reis, 2006)). However, these approaches are not always feasible, for four main reasons:

- They only take budget constraints into account. However, organisations have to deal with other constraints (Mavrotas et al., 2008).
- The dynamic nature of the process is not taken into account (Archer and Ghasemzadeh, 1999).
- There may be complementarity and incompatibility relationships as well as synergies between the candidate projects (Chien, 2002).
- Organisations seek the best outcomes in relation to various criteria (maximise profits, minimise risk, use the fewest resources, etc.); thus, the multiobjective nature of the problem is patent (Mavrotas et al., 2008; Carazo et al., 2010; Ballestín and Blanco, 2011; Cruz et al., 2014).

All this has led to growing interest in other techniques derived from mathematical programming owing to their ability to incorporate a greater degree of complexity. Our study is framed within mathematical programming methods.

A final key issue in project selection is that some aspects of the problem may in fact be vague or even unknown. Thus, given that projects are selected before they are actually implemented, the information available may be characterised by imprecision and uncertainty.

In recent years, there has been an increase in studies on scheduling and selecting project portfolios that use fuzzy techniques to deal with uncertainty. Because of the lack of historical data, it has become usual to resort to experts who, based on their experience, suggest modal values and the expected variation interval regarding unknown parameters (Wang and Hwang, 2007). In this context, the literature provides two main approaches to this problem. Certain authors use flexible programming (Pereira, 1988; Kuchta, 2000; Machacha and Bhattacharya, 2000; Mohamed and McCowan, 2001; Carlsson et al., 2007; Ke and Liu, 2007; Pérez et al., 2013, among others). On the other hand, some apply possibilistic programming (Wang and Hwang, 2007; Hasuike et al., 2009, among others).

However, none of the described studies simultaneously include other constraints in the models, such as precedence relationships, which are of great relevance to this problem. In this context, our aim was to apply a model that brings together as many features as possible, while taking into account different types of constraints and the uncertainty associated with certain parameters.

The paper is structured as follows: in Section 2, we formalise the fuzzy model used; in Section 3, a real application in a public organisation is presented and the conclusions are drawn in the final section.

2 Fuzzy model

Let us assume an organisation has to select the best group of projects from a set of I project proposals. The organisation also needs to know when each project will start within a given planning horizon divided into T periods. Therefore, the decision variables are denoted by:

$$x_{it} = \begin{cases} 1 & \text{if project } i \text{ starts at } t \\ 0 & \text{otherwise} \end{cases} \tag{2.1}$$

where $i = 1, 2, \ldots, I$; $t = 1, 2, \ldots, T$.

The vector $x = (x_{11}, x_{12}, \ldots, x_{1T}, x_{21}, x_{22}, \ldots, x_{2T}, \ldots, x_{I1}, x_{I2}, \ldots, x_{IT})$, with $T \cdot I$ binary variables, represents a project portfolio.

The organisation needs to evaluate the candidate projects according to a set of attributes at every period of the planning horizon, and, at the same time, the organisation needs to include multiple constraints in the process. In particular, one major issue in this process is the awareness of the exact amount of resources needed for each project at each execution time. However, these amounts are not fully known at the time they are included, and thus we need a procedure to include uncertainty. In this case, we formulate this uncertainty using triangular fuzzy numbers (Zimmermann, 1996). To this end, experts must provide the most likely value (modal value) of these numbers and their variation interval. We chose triangular fuzzy numbers not only because they are easy to handle and they reflect situations involving uncertainty very well (Zimmermann, 1996; León et al., 2003), but also because they have been successfully used in situations similar to those presented here (Chang and Lee, 2012).

Therefore, we assume that $r_{i,u,v}$ represents the modal value for the resources that project i needs at the time of execution v, for the resource category u, and $\underline{r}_{i,u,v}$ and $\overline{r}_{i,u,v}$ are, respectively, the left and right spreads these resources can have. On the other hand, we assume that the maximum and minimum amount of resource u the organisation can spend at time k are also triangular fuzzy numbers. When a confidence level is set such that $\alpha \in [0, 1]$, we obtain the variation interval for the number associated with a given confidence level within which the decision-maker (DM) considers that all values are likely.

Therefore, the objective functions and the constraints can be defined as follows:

$$F_q(x) = \sum_{k=1}^{T} W_{qk} \cdot \left(\sum_{i=1}^{I} \sum_{t=1}^{K} c_{q,i,k+1-t} \cdot x_{it} + \sum_{j=1}^{s} g_{jk}(x) \cdot a_{qjk} \right) \quad q = 1, 2, \ldots, Q \tag{2.2}$$

s.t.:

$$\widetilde{LR}_{uk} \leq \sum_{i=1}^{I}\sum_{t=1}^{k}\tilde{r}_{i,u,k+1-t}\cdot x_{it} + \sum_{j=s+1}^{\hat{s}} g_{jk}(x)\cdot\tilde{h}_{juk} \leq \widetilde{UR}_{uk}$$
$$+(1+\text{rate}_u(k))\cdot\left(\widetilde{UR}_{u,k-1} - \sum_{i=1}^{I}\sum_{t=1}^{k}\tilde{r}_{i,u,k+1-t}\cdot x_{it} + \sum_{j=s+1}^{\hat{s}} g_{j,k-1}(x)\cdot\tilde{h}_{j,u,k-1}\right) \quad (2.3)$$
$$u\in\{1,2,\ldots,U\},\ k\in\{1,2,\ldots,T\}$$

$$\underline{b}(k) \leq B(k)\cdot\begin{pmatrix}\sum_{t=k-d_1+1}^{k} x_{1t}\\ \vdots\\ \sum_{t=k-d_I+1}^{k} x_{It}\end{pmatrix} \leq \overline{b}(k) \quad k=1,2,\ldots,T \quad (2.4)$$

$$\underline{b} \leq B\cdot\begin{pmatrix}\sum_{t=1}^{T} x_{it}\\ \vdots\\ \sum_{t=1}^{T} x_{It}\end{pmatrix} \leq \overline{b} \quad (2.5)$$

$$CL_i \leq \sum_{t=1}^{T} x_{it} \leq 1 \quad i=1,2,\ldots,I \quad (2.6)$$

$$\alpha_i\cdot\sum_{t=1}^{T} x_{it} \leq \sum_{t=1}^{T} t\cdot x_{it} \leq \beta_i \quad i\in E \quad (2.7)$$

$$\sum_{t=1}^{T} x_{lt}\left(\sum_{t=1}^{T} t\cdot x_{it} + h_i\right) \leq \sum_{t=1}^{T} t\cdot x_{lt} \leq \sum_{t=1}^{T} t\cdot x_{it} + H_i \quad i\in P_l \quad (2.8)$$

which represent:

- (2.2) Objective functions. Each objective function is defined by adding two aspects together: the individual contributions of the projects selected for the portfolio according to the period of implementation in which each project is at that time and the additional positive or negative effects that result from the synergies that may exist between some of the projects selected. Therefore:
  - $C_{q,i,k+1-t}$ are the values from the function q in the period k, for project i, if this project is selected and started at t.
  - A_j, $j = 1,2,\ldots, s$, are sets of independent projects in which the decision-maker sets the minimum (m_j) and maximum (M_j) number of projects that must be active for the variation generated at an amount a_{qjk}. Thus, technical constraints are included in the model to ensure the functions $g_{jk}(x)$ take value 1 if the number of active projects in set A_j, at a point in time k, is between the values m_j and M_j; otherwise, they take the value 0.
  - w_k are weights that enable the aggregation of time-related information.
- (2.3) Renewable resource constraints. These limit the amount of each type of resource (budget, labour, etc.) spent at each point in time. Therefore:

- $\tilde{r}_{i,u,k+1-t}$ represents the fuzzy amount of resources required by project *i*, for the resource *u* if this project is selected at *t*.
- $A_j,\ j = s+1, \ldots, \hat{s},$ are sets of independent projects as in (2.2). In this case, the variation generated is represented by $\tilde{h}_{ujk}$ (also a triangular fuzzy number).
- $\widetilde{UR}_{uk}$ and $\widetilde{LR}_{uk}$ represent, respectively, the maximum and minimum fuzzy amount of resource *u* that the organisation can spend at time *k*.
- $\text{rate}_u(k)$ is the interest rate used to transfer unused resources to the next point in time.

- (2.4) Temporary linear constraints. Constraints on the active projects included in the portfolio at period *k* that do not depend on their execution time. In these constraints, $\underline{b}(k)$ and $\overline{b}(k)$ are the lower and higher bounds defined, respectively, and $B(k)$ is the coefficient matrix.
- (2.5) Global linear constraints. These constraints are the same as those immediately before, but do not depend on the period. Therefore, $\underline{b}$ and $\overline{b}$ are the lower and higher bounds defined, respectively, and *B* is the coefficient matrix.
- (2.6) Mandatory and uniqueness constraints. These constraints ensure that each project starts only once, and CL_i can be used to force the mandatory execution of certain projects.
- (2.7) Constraints on the starting period. The decision-makers may wish to force the starting period of certain projects. Therefore, *E* is a subset of all projects, and α_i and β_i represent the lower and upper time bounds, respectively, for the *i*th project.
- (2.8) Precedence constraints: P_l is a subset of predecessor projects to project *l*. Project *l* cannot begin until at least h_i periods have passed since its predecessors began, and project *l* must begin within H_i periods since its predecessors began.

However, to operate with fuzzy constraints (2.3), the fuzzy numbers have to be compared. The literature provides a vast range of techniques that can be used to make comparisons (Campos and Verdegay, 1989). In this case, we perform the comparison by using one of the α-cuts, suggested by Chang and Lee (1994). This approach rapidly provides results and for this reason it is a widely used approach (Leon et al., 2003). We use the comparison method introduced by Tanaka et al. (1984), which permits fuzzy numbers to be compared using α-cuts without creating elements that cannot be compared or that lead to ambiguities.

3 A real application

In this section, we illustrate the potential of the approach by applying it to a real case in a Spanish state university. The university's Department for the Strategic Planning of Infrastructure (DSPI) needs to plan, at the beginning of the period and for a given time horizon, the budget available to fund a project portfolio by choosing from among all the candidate projects. The aim is to select the best project portfolio to implement, given the resources available, and to decide when to start each project in the portfolio while taking into account the organisation's needs, objectives and priorities and several strategic and political constraints.

The information provided by the university can be summarised as follows (a more detailed description of the problem can be found in Carazo et al. (2012)):

- There are 52 *alternative projects* ($i = 1, 2, \ldots, 52$), and the time planning *horizon* consists of five consecutive semesters ($k = 1, 2, 3, 4$).
- The *objectives* considered by the organisation are as follows:
  - *Maximise the positive impact*. This objective function is defined as the sum of positive effects that the selected projects have on the organisation. To calculate this function, the management team of the DSPI has to assign a score to each project based on the percentage of individuals who would benefit from it.
  - *Minimise the risk*. To calculate this second objective function, the management team assigns risk scores to each project.
  - *Maximise the number of active projects in at least three periods within the time horizon.* This objective function is based on the desire to encourage the selection of projects within major infrastructures.
- The constraints considered by the organisation are as follows:
  - There is one renewable resource: monetary resources available. Moreover, in this constraint, the organisation sets eight synergies between projects.
  - There is one global resource: projects 1, 2 and 3 are very similar, and hence only one can be selected in one portfolio.
  - Some projects are mandatory.
  - In addition, there are four precedence relationships.

The university's selection system starts with the proposals made by the various university departments according to their needs in the areas they represent. These proposals are analysed by the DSPI management team, which decides which project portfolio to fund and implement. This selection is based solely on the DMs' experience: it neither uses mathematical model nor includes the uncertainty of the data. With this system, DMs have to manage a large amount of information: multiple objectives, restrictions, interdependencies between the projects and a planning horizon. These issues make it very difficult to obtain efficient solutions, and can lead to suboptimal solutions. The solution adopted by the university department (Initial Portfolio), using this traditional selection system, included 38 projects, and reached the values of the objective functions as shown in Table 1 (first column).

On the other hand, our alternative approach involves selecting projects by using the mathematical model proposed in Section 2. The main advantage of this approach is that uncertainty in the data can be included in the model. To this end, DMs have to provide information about the variation of the coefficients involved in constraints (2.3). In this case, DMs set a specific variation for each coefficient, by considering the particular project and semester involved.

Table 1 Comparison between selected portfolios

Initial portfolio	*Efficient portfolio 1*	*Efficient portfolio 2*	*Efficient portfolio 3*
38 projects	41 projects	41 projects	42 projects
Impact: 291	Impact: 294	Impact: 292	Impact: 291
Risk: 165	Risk: 164.75	Risk: 163	Risk: 161.75
Duration: 3	Duration: 4	Duration: 4	Duration: 4

The complexity of the model proposed in Section 2 necessitates the use of a computational tool to carry out the mathematical calculations. In this case, we use a method based on an evolutionary algorithm named Scatter Search for Project Portfolio Selection (SS-PPS) (Carazo et al., 2010), whose good problem-solving abilities in this field have been previously proven. This method has been modified to include uncertainty. Therefore, by solving the resulting problem with this modified method, we obtain an efficient frontier formed by 414 project portfolios.

We remark here that, when solving multiobjective problems, it is usual to obtain efficient frontiers formed by a high number of points. The usual procedure is to include the DMs' preferences in the process to obtain the efficient point that best suits their requirements. However, in our case, we intend to show that the proposed model can provide a better solution than that obtained by the traditional method and also provides greater stability with respect to changes that may occur to monetary data. Thus, by analysing the 414 efficient portfolios obtained, we find three project portfolios (Table 1) that improve the objective function values achieved by the portfolio initially proposed by DMs.

These project portfolios obtained are similar to those obtained using the traditional selection system, but they differ regarding the number of projects and the schedule. Thus, efficient project portfolios 1 and 2 execute 41 projects, and efficient project portfolio 3 executes 42 projects. In all cases, the number of projects executed is greater than that obtained in the initial project portfolio (38).

On the other hand, regarding the stability of the solution, the three project portfolios obtained are stable against the possible changes in the monetary data of the problem. In particular, whatever the value set for the confidence level, efficient project portfolios 1 and 2 will always belong to the efficient frontier of the problem. In the case of efficient project portfolio 3, it belongs to the efficient frontier on the condition that the confidence level set by the decision-makers is greater than or equal to 0.02. This information is very useful to DMs because it ensures the efficiency of the project portfolio chosen, even when coefficient values in constraints (2.3) vary.

Therefore, the main advantage presented by the results of the model we propose is, on the one hand, the certainty of always attaining project portfolios that belong to the efficient frontier of the problem, and, on the other hand, the stability of these portfolios against any changes that may affect the resource constraints concerning monetary data. Therefore, for each project portfolio, we offer decision-makers an associated confidence level that reports on the variation interval permitted of the parameters so that the portfolio remains efficient.

However, when the problem is solved using the traditional method, decision-makers have no assurance concerning the efficiency of the portfolio of selected projects. That is, there may be another project portfolio that meets the constraints and obtains better values in the target functions than does the selected portfolio. Furthermore, if the monetary data of the problem suffers variations, then the selected project portfolio may even fail to meet budgetary constraints. This would mean that the portfolio could not be carried out.

In this regard, the decision-makers involved fully appreciated the usefulness of the tool offered, since it not only provides efficient portfolios but also offers a measure of the stability of each portfolio against monetary variations. Furthermore, the time required by DMs to obtain the portfolio of selected projects using the traditional method ran into several months of intense meetings, owing to the amount of information to take into account. However, the presented approach provided them with the solution of the problem, thereby assuming a saving of considerable time and effort.

Therefore, when some of the initial information is characterised by a certain degree of uncertainty, the proposed model not only provides information about the objective function values obtained for each project portfolio, but also provides the confidence level at which the portfolio is efficient. This enables the DMs to be more confident concerning the solution chosen to be carried out.

4 Conclusions

Selecting a project portfolio is a complex process involving many factors and considerations, from the time it is proposed to the time the project portfolio is finally selected. Given that making a good selection is of crucial importance, it is essential to develop well-founded mathematical models to lead the organisation, without fail, to their final goal. To achieve this selection, such models have to reflect, as closely as possible, both the real situation of the organisation as well as its targets and preferences. However, since the process of selecting and implementing project portfolios occurs in real environments and not in laboratories, uncertainty and a lack of knowledge regarding some data is always an issue.

In this study, uncertainty has been included in the model in the form of triangular fuzzy numbers to represent the coefficients in the renewable resource constraints. We, therefore, worked with fuzzy numbers according to the confidence levels associated with their respective membership functions.

In practical terms, we have tested an empirical application, including uncertainty, of the process of selection and planning of project portfolios in a Spanish university and concluded that the model proposed provides better solutions than the solution originally reached by the university's DSPI. Furthermore, it also provides information regarding how reliable the solutions might be, since it bears in mind the uncertainty in the initial information.

Introducing fuzzy elements into the problem of scheduling and selecting project portfolios is very useful since it enables the uncertainty associated with some of the parameters of the problem to be addressed. This approach does not require excessive information from the decision-makers, and its results are easily understood. Furthermore, studying the variability in the solutions to the problem allows decision-makers to deeply analyse the complexity of the problem they are dealing with.

Finally, the output of the proposed multiobjective model is a set of efficient portfolios. To assist the decision-makers to select one single project portfolio, it is necessary to somehow include their preferences into the model. This issue constitutes our current line of research.

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