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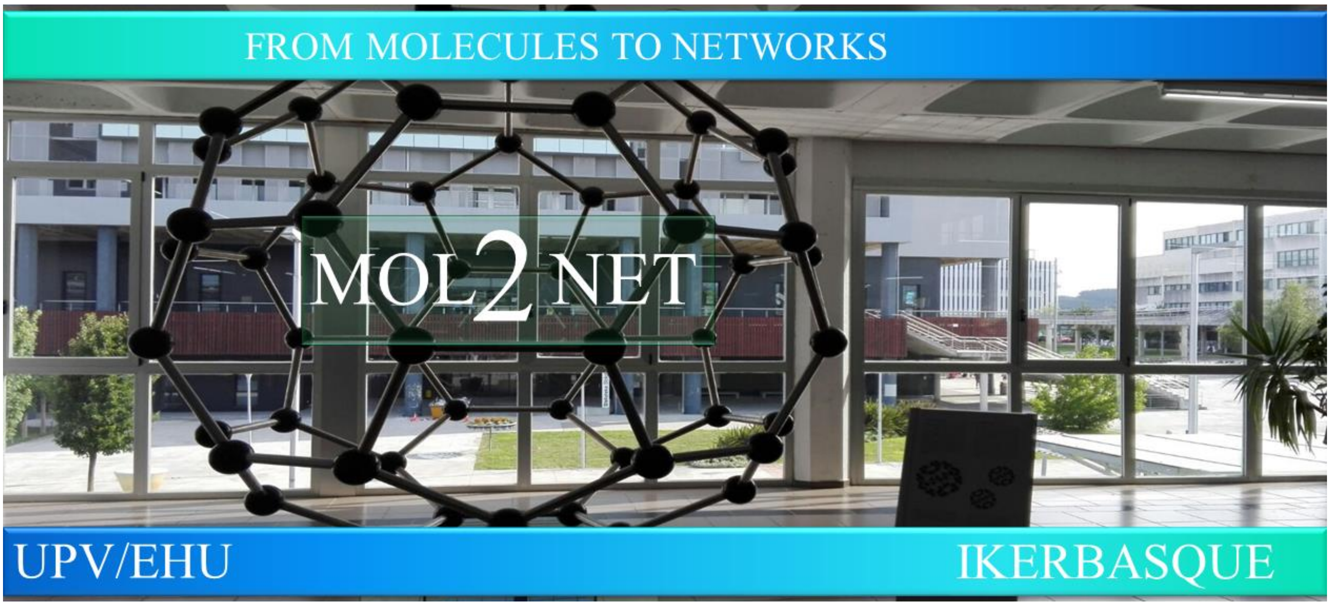

A new method to project portfolio selection with multiple interacting criteria hierarchically structured

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Graphical Abstract	Abstract.
Insert grafical abstract figure here	Project portfolio selection is very complex. Often the multiple criteria used to assess projects are hierarchically structured and show interaction. Most of these criteria are also used at portfolio level to assess the supported projects as a whole; however, additional criteria must be considered to define the conformity of the decision maker with the portfolios. Here, we present a novel method to comprehensively address all the characteristics

	of the problem. The method uses a generalization of the outranking approach and value functions to aggregate the criteria scores, and evolutionary algorithms to define the most preferred portfolio.

Introduction

Project portfolio selection is one of the most important problems faced by senior managers of large enterprises and public organizations. Although the overall quality of most candidate projects is frequently acceptable, resource limitations make their support impossible, and the Decision Maker (DM), (either a top manager or a collective entity in charge of the decision process), has to choose the subset of projects to be supported. This subset is called project portfolio. The problem of identifying the "best" project portfolio is called project portfolio selection (PPS) problem.

Since projects and portfolios are generally described by several (or many) evaluation criteria, multiple criteria decision making (MCDM) methods, perhaps combined with single or multi-objective optimization tools, are the way to address PPS. However, the vast majority of the methods generally focus only on some of the features of the problem and do not provide a comprehensive approach to deal with the overall problem's complexity.

Fundamental characteristics that add complexity to the PPS problem are listed below:

- Large number of project proposals and/or criteria;
- Interdependence (either positive or negative synergy) between projects;
- Interacting criteria at project level;
- Interacting criteria at portfolio level;
- The preferences of the DM must be considered to set values of projects and portfolios, or to find the best compromise when multiple objectives are optimized at portfolio level;
- Imprecise, vague, or even missing values for criteria scores, resource requirements and preference parameters; this is particularly true when the DM is a non-homogeneous group or a hardly accessible person (e.g., the CEO of a large enterprise).
- Hierarchically structured criteria;
- The DM wants to assess the projects with respect to several criteria within the hierarchy. For example, Research and Development projects can be classified as poor, middle or high regarding the project's probability of success, not only regarding its overall quality.
- At portfolio level, the DM wants to optimize a set of criteria assessing the final portfolio, which result from an aggregation of the supported projects' features. For example, the DM would like to maximize the number of supported projects classified as "High " regarding their probability of success. This kind of criteria are used to assess the built portfolio, as opposed to the more traditional criteria used to assess individual projects; we will refer to them as "conformity criteria";
- The DM may impose some hard constraints related to the conformity of the DM with the built portfolio. For instance, the DM would like any project whose probability of success is classified as low to be supported.

- The DM may want the portfolio to respect the order of project qualities to a certain extent. That is, the DM may be willing to partially improve the overall quality of the portfolio even when that means supporting worse projects than some very expensive projects. Or supporting interacting projects that are worse than others, but whose interaction contributes more to the overall quality of the portfolio.
- The preferences of the DM are relevant regarding what she calls a balanced portfolio (see e.g., Barbati *et al.*, 2018; Korotkov and Wu, 2020); that is, where poor scores of the portfolios on some criteria cannot be compensated by good scores on other criteria.

A comprehensive decision support approach should bring flexibility to incorporate any subset of these characteristics depending on the specific context. However, to the best of our knowledge, there are no published approaches that achieve this.

This contribution summarizes a novel approach that addresses all the complexity of the PPS problem as described before. The novelty/originality provided by this work concerns its abilities to: i) handle interacting and heterogeneous criteria that are hierarchically structured; ii) assess the performance of projects and/or portfolios at different levels of the hierarchy; iii) optimize many criteria and conformity criteria; iv) deal with cardinal information in some criteria and ordinal and qualitative scales in other criteria; v) handle veto situations, incomparability and non-transitive preferences; vi) guarantee balanced portfolios; and vii) handle imperfect knowledge on criteria performance levels, parameters of the decision model, and available and required resources.

Materials and Methods

The overall quality of a portfolio is assessed by using a set of criteria. This set is generally composed of two subsets. The first subset contains criteria that contribute to the impact of the portfolio; the scores of these criteria usually result from an aggregation of the impacts produced by the supported projects. The second subset contains the conformity criteria. The PPS problem is addressed as a multiple objective optimization problem.

Conformity criteria are often defined in terms of certain features of the supported projects. This is the case, for example, when the DM wants to maximize the number of R&D projects with high probability of success. This probability is a non-elementary criterion within the hierarchical structure which arises when a project is evaluated. To assess the probability of success is equivalent to assigning each project's probability of success to a category like "High", "Middle", or "Low". This is a multiple criteria ordinal classification statement. In this work, we use as fundamental tool the hierarchical interval outranking approach proposed by Fernández et al. (2022a). This method allows:

- To deal with hierarchical and interacting criteria;
- To assign actions (project features) to ordered classes or categories, regarding either the overall project quality or any project feature;
- To handle imprecise criteria performance levels either as interval numbers or pseudo-criteria:
- To deal with imprecision, arbitrariness or ill-definition in setting the parameters of the decision model
- The PPS problem is approached by a combination of classification and optimization tools. Ordinal classification is used to determine acceptable projects, and also to evaluate some conformity criteria (e.g. minimize the number of non-supported projects that are assigned to a

better class than supported projects). An optimization tool able to handle several (even many) criteria is required to find the "best" portfolio.

- Once the problem has been formalized, the proposed approach first models the preferences of the DM using a novel eclectic approach that combines both the hierarchical interval outranking and value function approaches; an interval-based value function is used following the idea presented by Fernández et al. (2022b). Our proposal uses this novel approach to aggregate criteria scores to compare a project to other projects or to reference profiles. The preferences of the DM are then used to evaluate the projects such that each project can be assigned to preferentially ordered classes regarding some non-elementary criteria given by the DM.
- Following the idea presented by Fernández et al. (2022c), we use an interesting way of exploiting the preferences of the DM to transform a multi-objective optimization problem into a single-objective one, ensuring selective pressure towards the region of interest (the privileged zone in the Pareto frontier according to the preferences) .
- At the final step, a canonical genetic algorithm is adapted to the specific characteristics of the addressed problem and the best overall portfolio is determined.
- Balance of the final portfolio is guaranteed as follows. First, the DM builds a prototypical portfolio; this can be done by taking advantage of the experience of the DM, who will directly provide the criteria scores that she considers acceptable. After, the prototypical portfolio is used as a reference that must be outranked; since the prototype portfolio provides acceptable criteria scores, a portfolio that outranks it will ensure balance in its criteria scores if these criteria has veto power; an unbalanced portfolio will not outrank the prototypical portfolio as low criteria scores will veto that result. Therefore, outranking the prototypical portfolio is a hard constraint that the final portfolio must fulfill.

Results and Discussion

One thousand Research and Development projects were randomly simulated, using thirty four elementary and non-elementary criteria. Interval numbers were used to simulate imprecise assessments. 189 projects were classified as acceptable by HI-INTERCLASS-nC (Fernández et al., 2022a). At portfolio level, twenty one elementary, non-elementary and conformity criteria were considered and optimized. The best portfolio contains 123 projects, and outperforms two very popular heuristics based on prioritizing best projects according to either their quality or ranking.

Conclusions

This proposal is perhaps the most comprehensive approach to address the PPS problem. A popular heuristic way when selecting projects consists of assessing them, then supporting the best ones until the resources are exhausted. Among other limitations, this way does not consider synergies between projects nor the preferences of the DM regarding her conformity with the chosen portfolio. The alternative way is to use optimization methods at the portfolio level, after performing an aggregation of the contributions or values of the supported projects. However, assessing portfolio-level criteria that neglect the individual quality of projects can lead to proposals that reduce the acceptability of the portfolio for the decision maker.

The proposed approach combines ordinal classification at project level with evolutionary optimization at portfolio level. A hierarchy of interacting criteria is used to assess the projects, and conformity criteria are defined and optimized at portfolio level to ensure the acceptability of the portfolios. Imprecision and uncertainty in both criteria performance levels (including costs) and preference model parameters are handled by interval numbers. Non-compensatory preferences and veto and modeled by using the hierarchical interval outranking approach, whereas an interval-based value function is used to represent. compensatory preferences.

One of the main advantages of the proposal consists of its capacity to handle many objectives and candidate projects through a novel way to incorporate the preferences of the decision maker into the evolutionary search. Other important advantages concern i) the handle of conformity criteria at portfolio level, and ii) its ability to ensure the balance of the chosen portfolio.

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