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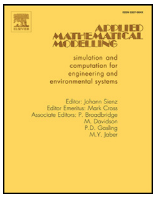

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A non-probabilistic methodology for reliable sustainability planning: An application to the Iraqi national irrigation system

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ABSTRACT

This study describes the use of quadratically constrained linear programming with box and complementarity constraints, combined with a relative 1-norm distance measure, to determine the extent to which the relative weights (w) attached to three sustainability criteria (economic, social, and environmental features) could affect the choice of projects to be implemented. To do so, this paper analyzes alternative proportions of the total projects (m) that should be implemented (e.g., 50% and 25% of the total number of projects) as well as alternative standards (c) to be achieved, on average, for some indices (e.g., 100% and 150% of the average standard values, which represent the mean value of these indices for all projects). The overall analytical results are presented for both linearly and exponentially weighted constraints, using partial derivatives to perform local sensitivity analyses (i.e., for each selected or rejected project), and the results account for the effects of w, c, and m. Next, level curves are prepared over the whole domain for w to produce two-dimensional graphs that support a global sensitivity analysis (i.e., for all selected and rejected projects) and to account for the effects of w, c, and m for both linearly and exponentially weighted constraints. Application of this approach to the Iraqi national irrigation system as a case study showed that the results are less robust if a smaller proportion (25%) of the total projects is chosen, with a change of up to 30% in the projects selected. In this context, an increase in the smallest weights for sustainability criteria also affected project choices. If the average standard to be achieved is made stricter (150% of the average standard), the results become more robust, with a change of less than 5% in the selected projects. In this context, increases in the smallest weights for sustainability criteria did not affect the project choices. The results were less robust with linearly weighted constraints than with exponentially weighted constraints.

1. Introduction

Planning requires the identification of which projects should be prioritized [1,2]. If there is no sequence constraint, the sequence of project implementations or the movements of resources from times t to $t+1$ can be disregarded [3], and if there are no risks from projects, the attitude of decision-makers towards risk is irrelevant [4]. In this context, the planning problem consists of providing a list of n non-dominated projects. Alternatively, we could search for a ranked list of n projects

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[5], although this approach could lead to an endless discussion among stakeholders about the inclusion or exclusion of any given project.

Sustainability is an increasingly important criterion in project selection. In this context, sustainability planning implies that the projects are characterized based on the many features that affect sustainability (i.e., the ability to continue the project economically without detrimental long-term environmental impacts, but with beneficial long-term social impacts) and that can be grouped based on previously proposed criteria [6] or based on specified standards that should be met [7]. In this context, stakeholder participation [8] affects how the features will be grouped and weighted as well as how standards are specified and how adherence to the standards is weighted. Thus, sustainability planning requires a multi-criteria analysis (MCA), with relative weights attached by stakeholders both to the categories of criteria and to the standards for each criterion. This is preferable to a preference-ratio approach, in which projects are ranked according to percentage scores for some indicators [9], and preferable to a cost-benefit analysis, in which projects are ordered according to monetary achievements for all indicators. If there are no qualitative indicators, so that crisp rather than fuzzy analysis can be applied [10], and if all indicators are continuous, so that normalized percentages [11] can be used rather than binary values [12], the problem consists of maximizing a linear sum of weighted percentage scores for the first n projects, subject to linearly or non-linearly weighted constraints [13]. Alternatively, it would be possible to use genetic algorithms [14], although this approach produces solutions based on numerical simulations rather than based on analytical results.

However, a non-dominated selection of projects crucially depends on the weights attached to the criteria by stakeholders, the standards to be achieved for each criterion (on average), and the number of projects to be chosen.

The purpose of the present study was to develop an optimization methodology with box and complementarity constraints, combined with a relative distance algorithm that shows the extent to which the relative weights attached to MCA categories (w_{eco}, w_{soc}, and w_{env} for economic, social, and environmental factors, respectively) will affect the choice of projects to be implemented. The reference values of the relative weights are estimated by applying factor analysis and conditional means to data from stakeholder surveys. In particular, this paper will analyze the effects of alternative proportions of a larger set of projects to be chosen (m) as well as the effects of alternative standards to be achieved on average (c). To do so, this study will use quadratically constrained linear programming [15] combined with linearly or exponentially weighted constraints [16] to determine the choice of projects, which must meet an average standard value for each criterion. In particular, this paper will use box and complementarity constraints [17], which represent, respectively, the degree of implementation of each project and the interdependency among projects [18]. These frameworks will be described and justified in Section 2.1. Examples include a monetary budget or spatial linkages [19], and a relative 1-norm distance measure to compare the chosen projects [20] or to depict the relative change in project choices [21].

This approach will solve the problem analytically and then perform a local sensitivity analysis for decisions about each project in terms of its dependency on w_{eco}, w_{soc}, w_{env}, c, and m; that is, it will analyze the extent to which the selection or rejection of a project is affected by an increase in w_{eco}, w_{soc}, w_{env}, c, or m.

Next, the main characteristics of the solution algorithm are defined in terms of its dependency on the abovementioned weights: in particular, the values are unknown but crisp numbers that are bounded so that they include all feasible values, without *ex ante* identification of the worst values, while allowing for potential interdependencies among the weights, and without assumptions on their probability distributions. This permits the construction of level curves, in which one factor is held constant (i.e., the percentage change in the selected projects) and the others are varied (e.g., two relative weights attached to the MCA categories). This is possible because of the complementarity of these relative weights (i.e., because they must total 1.0, increasing one weight requires decreasing one or more of the other weights). These assumptions will be described and justified in Section 2.5. Examples include intuitive visual analysis of the solution space defined by the analytically derived equations for the decision whether to preserve an offshore research platform to support sustainable development within an ecosystem services framework [22].

This approach allows the construction of a three-dimensional simplex contour plot that can be used to carry out a non-stochastic global sensitivity analysis to account for uncertainties arising from the weight-estimation methods applied by experts, the potential lack of mutual understanding achieved by experts and stakeholders, and the representative-selection procedures implemented by stakeholders. That is, this approach will reveal the extent to which the overall decision about projects to implement will change if each parameter is modified in a given direction (e.g., an increase in relative weights attached to social and environmental categories) or whether it will not change if the weights are modified within an identified safe area (i.e., the part of the solution space in which the overall project choice does not change).

To illustrate this approach, the optimization methodology will be applied to a case study of the Iraqi national irrigation plan.

This paper provides two main contributions to the literature: First, it shows how sustainability planning can be tackled by means of an objective procedure such as quadratically constrained linear programming to prioritize project selection (see Section 2.3), which can be linearly or exponentially dependent on criteria weights (see Section 2.2). Second, this mathematical formulation enables sensitivity analysis at both a local scale (i.e., for each selected or rejected project; see Section 2.4) and a global scale (i.e., for all selected and rejected projects; see Section 2.5). This approach is both direct and intuitive because it is based on graphs (for stakeholders), and is accurate and comprehensive because it is based on formulas (for experts).

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