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Peat and pots: An application of robust multiobjective optimization to a mixing problem in agriculture

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ABSTRACT

In horticultural settings, mixing problems arise when choosing a suitable growth substrate for potted plants. The aim of practitioners is to choose a pot and a growth substrate mixture such that environmental emissions and costs are simultaneously minimized. The impact of the plant's quality on the selling price should also be considered. The decision problem outlined here is affected by two types of uncertainty. First, the problem parameters are uncertain due to the nature of the input data. For example variations in the agronomic characteristics of the growth media and in the weather conditions lead to imprecision. Second, the composition of the growth media is generally not implemented exactly due to variability in the mixing process itself. If these uncertainties are ignored, the problem can be addressed using deterministic multiobjective optimization. If these uncertainties are to be considered, the problem can be addressed by means of robust multiobjective optimization. In this paper, we apply both a deterministic and a robust approach to the problem, with and without uncertainty. We present a case study of an Italian plant nursery and we compare deterministic and robust solutions. Our results show that the robust solutions are preferable to the deterministic ones, and that the robust approach is indeed worth considering for horticultural mixing problems and might also be used effectively in other settings where similar mixing decisions arise.

1. Introduction

Over the years, Operations Research has been used extensively to optimize environmentally friendly production planning in agricultural supply chain management (Crespo et al., 2010; Bohle et al., 2010; Doole, 2012). Multiobjective optimization is particularly helpful, since objectives other than profitability must also be taken into account (for a survey on multiobjective optimization in agriculture, see Hayashi, 2000). A specific challenge in handling renewable resources is the fluctuation in their quantity, quality, and material properties arising from the multiple-usage of by-products. Here, typical decision problems can be formulated as mixing problems, which have been quite thoroughly investigated (Ashayeri et al., 1994; Shih and Frey, 1995). In this work, however, we consider a specific mixing problem that is currently a challenge in the horticulture sector: replacing peat substrate and plastic pots with more environmentally-friendly alternatives.

Peat is a non-renewable resource widely used in horticulture due to its agronomic characteristics, which guarantee the quality of plants to be sold in the market. Although peat can indeed be replaced by compost—an agricultural by-product—the compost's variable agronomic properties determine different quality levels of a potted plant. Therefore, only a certain percentage of peat can be substituted in a blending process. A second way to improve the sustainability of horticulture would be to replace planter pots made of conventional plastic with innovative, biodegradable pots.

In mathematical terms, this problem thus comprises a binary decision between two types of pots and a decision about the share of compost used to partially replace the peat. Two objective functions are considered, one for the economic consequences and one for the ecological consequences:

- The economic consequences are the additional costs due to the processing steps associated with compost handling. The selling price of agricultural and horticultural products depends on their quality, a multi-faceted assessment often based on sampling, scoring, and quality ratings.
- The ecological consequence is the greenhouse gas reduction achieved by replacing peat (in part) with compost and plastic pots

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with biodegradable pots. This reduction can be determined by calculating the global warming potential (GWP) in kg CO_2 equivalents (IPCC, 2007).

The problem is characterized by two types of uncertainty that are typical in renewable resource processing: parameter uncertainty and decision uncertainty. The former is clearly caused by fluctuations in quality, quantity and material properties, but inaccuracies in experimental data and measurements also contribute (Lowe and Preckel, 2004; Geldermann et al., 2016). The latter occurs whenever solutions are not implemented exactly as calculated, but only within a range of the computed values. For example, the targeted share of compost is generally not achieved exactly, due to imprecisions in the mixing process.

In these situations, robust optimization provides a suitable framework for decision support, since it seeks solutions that are feasible for all scenarios and that perform best with respect to the worst case. Classic robustness concepts are minmax robustness (Ben-Tal et al., 2009) and regret robustness (Kouvelis and Yu, 1997). Other concepts such as Bertsimas and Sim (2004) and Schöbel (2014) are reviewed in Goerigk and Schöbel (2016). Robust optimization has been applied to various problems in agriculture. For example, Bohle et al. (2010) applied it to the scheduling of wine grape harvesting in Brazil; Doole (2012) applied it to compare deterministic and robust approaches to evaluating perennial pasture species in Australia by using uncertain parameters within intervals; Munhoz and Morabito (2014) applied it to orange juice production; Alvarez and Vera (2014) applied it to a sawmill planning problem; Rocco and Morabito (2016) applied it to the tomato processing industry; and Hombach et al. (2018) applied a robust and multiobjective optimization model with integrated risk attitude to a biodiesel supply chain in Germany.

In this paper, we consider a minmax robustness approach for both parameter and decision uncertainty in multiobjective optimization (see Ehrgott et al., 2014; Kuroiwa and Lee, 2012 for parameter uncertainty and see Eichfelder et al., 2017 for decision uncertainty).

Robust minmax multiobjective optimization results in rather complicated (sometimes set-valued) optimization problems (for recent surveys, see Ide and Schöbel, 2016; Wiecek and Dranichak, 2016). Here, we use robust multiobjective optimization to determine solutions to our uncertain problem; the theoretical background for this work can be found in Krüger (2018). We also describe the managerial implications in a real-world multiobjective problem from the agricultural industry.

The paper is structured as follows. Section 2 describes the problem, which is initially analyzed and mathematically formulated without taking uncertainty into account. Section 3 illustrates a case study with its input data (environmental emissions and costs). In Sections 4 and 5, the model is described in detail and a deterministic solution approach for the problem without uncertainty and a robust solution approach for the uncertain problem are displayed. In Section 6, we compare the deterministic and robust results and draw some conclusions about current horticulture management practices and promising avenues for further research.

2. Problem description

A major environmental problem in European horticulture is the greenhouse gas (GHG) emissions caused by potted plant cultivation using peat and plastics (Lazzerini et al., 2014).

Peat accumulates under anaerobic conditions over thousands of years from partially decayed sphagnum, grasses, and other plants. It is a very flexible material that can be adapted for most plants, since it is generally low in nutrients, pH, and bulk density. Moreover, it exhibits favorable cation exchange capacity and air-filled porosity characteristics (Robbins and Evans, 2001). Taken together, these parameters define the quality level of peat as a growth medium in horticulture. However, peatlands (or bogs) are important carbon sinks, and peat extraction results in significant emissions of carbon dioxide, methane, and nitrous oxide (Waddington et al., 2009). Consequently, peatland protection aims to maintain both biodiversity and such ecosystem services as climate protection and nutrient retention. To reduce the environmental impacts of the sector, alternative materials (e.g., compost, bark, wood, rice hulls, animal manure) made of renewable resources or by-products can be substituted for peat.

In horticulture settings, peat could be best replaced by *compost*. Beyond a certain replacement percentage, however, the agronomic quality of the potted plant becomes unacceptable (Papafotiou et al., 2005). Agricultural supply chains generate a great variety and quantity of waste and by-products that could be used as compost, including the by-products from the olive oil industry (Raviv, 2014).

In horticulture, *plastic pots* are widely used because of their low cost, durability, and versatility. Since they cannot be recycled easily due to soil and vegetable matter contamination, agrochemical residues, and additives, they are generally landfilled after one usage (Schettini et al., 2013). In the United States, an estimated 750 thousand tons of plastic pots are disposed of annually (Nambuthiri et al., 2015); in Italy, 91 thousand tons of plastic pots, sheets, and twines used in agriculture are disposed of annually (Scarascia-Mugnozza et al., 2011). Here, *biodegradable pots*, which can be embedded in the soil with the plant or disposed of in composting facilities, represent a viable alternative to plastic pots.

From a responsible management perspective, it makes sent to consider both peat substitution and the replacement of plastic pots with biodegradable ones. The resulting reduction in GHG emissions can be determined by a Life Cycle Assessment (LCA), which looks at environmental impacts from all stages of a products life, including raw material extraction, materials processing, manufacturing, distribution, use, repair, maintenance, and disposal or recycling (Geldermann et al., 1999; Brandenburg et al., 2014).

Along with the goal of minimizing GHG emissions, one would also like to minimize the additional costs associated with substituting for peat and plastic pots. The additional costs comprise only those costs which are relevant for the decision, and that vary from the initial situation (i.e., the only use of peat and plastic containers to grow plants). This leads to a biobjective optimization problem, which is complicated by the two types of uncertainty mentioned in Section 1. Parameter uncertainty arises from lack of exact knowledge of cost and emission parameters. Here, one must work with intervals. Decision uncertainty arises from variations in the implementation of the calculated solution. For instance, the calculated share of compost cannot be mixed exactly using manual labor.

2.1. Mathematical formulation of the problem

In mathematical terms, we have a binary decision about whether or not to replace the plastic pot with a biodegradable pot, along with a decision about how much compost to mix with the peat. We let one potted plant be the functional unit of the problem and assume it is representative of all plants of the same species cultivated in a given nursery. For each potted plant, we must decide on

- the share of compost $\gamma \in [0, 1]$ used to replace peat,
- which type of pot to use. This decision is modeled by introducing the pot variable $\beta \in \{0, 1\}$, where $\beta = \begin{cases} 1 & \text{if a biodegradable pot chosen} \\ 0 & \text{if a plastic pot chosen} \end{cases}$.

Using the two decision variables γ and β, the optimization problem for a specific plant species can be written as the following biobjective minimization problem with two objective functions and one constraint: