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A multi-step rolled forward chance-constrained model and a proactive dynamic approach for the wheat crop quality control problem

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ABSTRACT

Handling weather uncertainty during the harvest season is an indispensable aspect of seed gathering activities. More precisely, the focus of this study refers to the multi-period wheat quality control problem during the crop harvest season under meteorological uncertainty. In order to alleviate the problem curse of dimensionality and to reflect faithfully exogenous uncertainties revealed progressively over time, we propose a multi-step joint chance-constrained model rolled forward step-by-step. This model is subsequently solved by a proactive dynamic approach, specially conceived for this purpose. Based on real-world derived instances, the obtained computational results exhibit proactive and accurate harvest scheduling solutions for the wheat crop quality control problem.

1. Introduction

Both individual farmers and agricultural cooperatives aim to meet uncertainty within sight of the economic consequences on crop production management. The outcome of factors such as climate conditions, yield and agronomic responses to various farming practices has a straightforward incidence on the qualitative and quantitative returns achieved.

So far, since agricultural processes and activities are quite intricate and manifold, many research efforts have been devoted to supporting managerial decision-making. In general, optimization models in most agricultural and crop production applications deal preponderantly with deterministic input data (Gigler, Hendrix, Heesen, van den Hazelkamp, & Meerdink, 2002; Santos, Costa, Arenales, & Santos, 2010; Wang, Li, & O'Brien, 2009, etc.). Nevertheless, several studies have been dedicated to addressing miscellaneous types of uncertainties affecting agri-supply chains. More specifically, various agricultural scheduling and planning problems tackled under uncertainty have been discussed by Borodin, Bourtembourg, Hnaien, and Labadie (2014b), Bohle, Maturana, and Vera (2010), Tan and Cömden (2012), Moghaddam and DePuy (2011), etc. For more details on this topic, one can refer to the survey realized by Ahumada and Villalobos (2009), which reviewed recent studies on the subject and outlined the main contributions related to production and distribution planning models for different commodities of agricultural supply chains.

To the best of our knowledge, there is a lack of flexible and uncertain proactive and/or reactive crop production operational planning tools. By the same token, traditional methods dedicated to solving deterministic optimization are not always suitable to capture the truly dynamic nature of most real-life applications. In order to overcome some of above delineated shortcomings, the seed quality control problem during the harvest season is addressed minutely in this paper.

Two powerful and competing frameworks are well-known for dealing with uncertain and dynamic decision processes: multi-stage and dynamic stochastic programmings. Even if the use of these two paradigms is showing increasing interest, there are still very few real-world implementations. In this article, arising from the background characteristics of a particular problem, we are interested in using some of fundamental concepts of both multi-stage and dynamic stochastic programming approaches and respectively, adapting them in order to better respond to crop quality requirements during the harvest season. Particularly, we make use of the chance-constrained programming approach (Charnes & Cooper, 1959; Dentcheva, Prékopa, & Ruszczynski, 1998, etc.), that allows us to tackle appropriately stochastic optimization problems for which solutions are given jointly with a requested high reliability (confidence) level.

It is worth mentioning our previous work (Borodin et al., 2014b) which only addressed the generic static version of the seed quality control problem during the harvest season *via* a joint

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chance-constrained program. This static version presents a twofold drawback: firstly, the model is intractable for a real-life harvest horizon length (one month and a half, or even more) due to the problem curse of dimensionality, and secondly, no forecasting meteorological data are available for the entire harvest season with a satisfactory accuracy level. On the other hand, looking to treat a real-life case study problem encountered in a typical French agricultural cooperative, the present work proposes a new multi-step joint chance-constrained model rolled forward jointly with a proactive dynamic framework able to: (i) propose proactive solutions during the whole harvest season; (ii) absorb and reflect the harvest process dynamics; (iii) take into account weather and agronomic data updates. In responding to the needs of the case study cooperative, this paper focuses on wheat crop quality degradation, which can be faithfully expressed *via* the Hagberg falling number.

The content of this paper is structured as follows. The next section summarizes the state-of-the-art related to both dynamic and multi-stage stochastic programming paradigms. Section 3 details the problem statement and refers both to its static and rolling forward multi-step models. In Section 4, a proactive dynamic approach is developed. After that, in Section 5, several computational results are reported and discussed. Finally, this paper ends with some concluding remarks including an outline of topics for future research.

2. Related background

Stochastic programming is becoming an increasingly popular tool for modeling decisions under uncertainty. In particular, multi-stage and dynamic programmings have been evolved for solving sequential stochastic optimization problems. Following an independent development, they were initiated approximately in the same period (1955–1965).

Although multi-stage and dynamic stochastic programming paradigms have several similarities, note that in this paper they are distinguished. This is not always the case in the literature. Since stages are just points in time, systems inspected at a finite number of stages are often considered as dynamic (Birge, 1985; Kall & Wallace, 1994; Zhang, Küçükyavuz, & Goel, 2014).

As claimed by Dupačová and Sladký (2002), stochastic dynamic and multi-stage stochastic programming problems with discrete time parameter cope essentially with the same types of problems, i.e. with the dynamic and stochastic decision processes. The main distinction resides in the decision concept, in the different structures used in their formulation and subsequently in different solution procedures:

- for dynamic programming, the definition of *state* is primordial: the structure of the problem is tied to the solution method (the backward/forward recursion is connected with the principle of optimality);
- multi-stage stochastic programs do not use the notion of *state* and their formulation is not connected with any prescribed solution technique. Hence, a variety of stochastic programs exists along with various solution methods.

The classical technique to handle a multi-stage stochastic programming problem is premised on scenario tree construction that branches at each stage. Even with a small number of outcomes per stage, the scenario tree size grows exponentially with the number of stages. As a response to the curse of dimensionality, stochastic dual dynamic programming has been proposed. Decomposition is another well-known solution approach for optimization problems based on the idea of partition, originating with the technical report of Birge (1985). The most common form of decomposition approaches is the L-shaped method drawn-on Benders decomposition or its improvement (Van Slyke & Wets, 1969) and Lagrangian relaxation (Takriti & Birge, 2000). Moreover, Cristobal, Escudero, and Monge (2009) introduced a decomposition methodology, based on a mathematical programming framework, in order to compute the equilibrium path in dynamic stochastic model by decomposing the problem into a set of smaller independent sub-problems.

As regards stochastic dynamic programming, this aims at solving stochastic optimization problems following Markov decision processes, which are the appropriate models for purely endogenous problems (Powell, 2007; Puterman, 1994). An illustrative and eloquent example has been presented by Lin, Chen, and Chu (2014), which focuses on the dynamic multi-site capacity planning problem encountered in the thin film transistor liquid crystal display industry under stochastic demand.

From a practical standpoint, multi-stage and dynamic stochastic programs have applications in many areas. One field in which multi-stage stochastic linear programming is extensively applied, is the long-term scheduling of water resources. More precisely, in order to address the future electricity demand at the lowest expected fuel cost, the problem consists of: (i) establishing a policy of releasing water from reservoirs for hydro-electricity generation, and (ii) determining planning at thermal plant level over a horizon of months or years (Philpott & de Matos, 2012). Among the closest recent studies, the work of Cervellera, Chen, and Wen (2006) can be mentioned, that presented a computational tractable stochastic dynamic programming method for the optimal management of large scale water reservoir networks. Edwards, Ross, Mares, Ellison, and Tomlinson (1989) incorporated time-consistent coherent risk measure into a multi-stage programming model for an application of hydro-thermal scheduling in the New Zealand electricity system.

The increasing complexities of inherent uncertainties in financial markets have led to the need for stochastic mathematical programs to support decision making processes. In this spirit, the portfolio selection problem has received broad interest (Matmoura & Penev, 2013; Topaloglou, Vladimirou, & Zenios, 2008, etc.).

Another field which has received significant attention, concerns vehicle routing problems, as witnessed by the survey of Pillac, Gendreau, Guéret, and Medaglia (2013). On this topic, Powell and Topaloglu (2003) explored the use of concepts from stochastic programming in the context of resource allocation problems arising in transportation and logistics applications. Since transportation problems are often quite large, the research efforts described in Powell and Topaloglu (2003) have been particularly focused on the degree to which some techniques exploit the intrinsic structure of these problems.

3. Problem statement

Consider an agricultural cooperative specializing in cereal production and commercialization, which integrates a union of several hundred farmers, for whom it offers storage, transportation and other customer services. Cereal harvesting represents the pivotal stage for both the agricultural cooperative and growers, on the grounds of its high cost and vulnerability to weather conjuncture. This is particularly notable in the case of wheat gathering, which presupposes substantial crop quality losses in case of any exposure of wheat crops to rainfall after their physiological maturity. Rainfall during the harvest period can lead to sprouting of wheat kernels, which causes alpha-amylase activity. Alpha-amylase is a protein enzyme that decomposes starch and its activity is responsible for the breakdown of starch to a mixture of glucose and maltose, resulting in a reduction of viscosity estimated by the Hagberg falling number (Edwards et al., 1989). Seed sprouting during wet harvest conditions leads to high levels of alpha-amylase, which manifest detrimental effects on the end-use quality and subsequently, the crop's economic returns (Eeden & Labuschagne, 2012).

The Hagberg falling number χ is an internationally standardized and recognized quality metric, which allows the indirect determination of alpha-amylase activity. Low values for χ mean excessive levels of alpha-amylase causing loaves to be discolored, sticky, with poor