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Online and stochastic optimization for the harvesting of short rotation coppice

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ABSTRACT

Facing an increasing need of biomass and an expected gap between production of wood and utilization, wood from short rotation coppice offers great potential to cover the demand of renewable resources. Short rotation coppice is a form of agricultural land use to provide woodchips for energy supply or wood for industrial applications in a relatively short time.

The economic profitability is the most important factor for the adoption of short rotation coppice for energy from biomass. Further on, the profitability of short rotation coppice was found to be most sensitive to the price for biomass and biomass yield. In this work, we present a simplified model for the problem of finding the optimal harvesting and selling policy with respect to a maximum profit by incorporating price and biomass yield as uncertain factors. Since we are dealing with renewable resources, the uncertain nature of these factors (e.g. due to insect infestation, annual weather conditions or unsteady prices) is taken into consideration and the model is especially designed to deal with these uncertainties.

In order to incorporate the uncertainties inherent in the determining factors of the problem, the concepts of online optimization and stochastic optimization are applied to a simplified model of the problem. We then derive optimal policies and give explicit results. By means of these mathematical optimization techniques we can prove that our policies are best possible or produce results that are close to an optimal solution.

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1. Introduction

The use of wood biomass for wood products and energy supply is increasingly gaining in importance, especially for meeting regional demands of heat and electricity supply (Gonzáles-García et al., 2014).

1.1. Short rotation coppice

Short rotation coppice (SRC) is a form of agricultural land use to provide woodchips for energy recovery or wood for industrial applications in a relatively short time (Knust et al., 2009). Hybrids of fast growing tree species with a high annual growth rate of biomass, e.g., poplar (Populus spp.) and willow (Salix spp.), are intensively cultivated via cuttage and stump shooting (cf. Knust et al., 2009; Ceulemans and Deraedt, 1999; Hauk et al., 2014). The trees are planted in rows at a space of 0.5–1.0 m and harvested manually or mechanically (depending on stem diameter) after a rotation period of one to 15 years. The profitability of SRC depends on maximizing the yield of biomass per unit area (Sage, 1999). The biomass yield depends on planting density, rotation time, and site-related factors like soil condition, rainfall, competing vegetal overgrowth, and pests. To foster the biomass accumulation and enhance tree growth, land development measures can be applied, i.e., mechanical soil preparation, fertilization, irrigation, and weed control (cf. Knust et al., 2009; Ceulemans and Deraedt, 1999; Sage, 1999; Bilodeau-Gauthier et al., 2011).

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Different types of wood exhibit varying growth properties, which determine among other things planting density and rotation times. While the cultivation of industrial wood requires a lower planting density and longer rotation times (10–15 years) (Knust et al., 2009), trees for energy recovery can be planted at a high density and at short rotation periods (usually 3 years for poplar). Furthermore, an increased rotation period leads to higher yields and better wood quality (increased wood/bark ratio) for each individual tree, but requires a lower planting density per unit area (Hauk et al., 2014).

The economic profitability is singled out as the most important factor for the adoption of SRC for energy from biomass and the profitability of SRC was found to be most sensitive to the price for biomass and biomass yield. In this work, we model the problem of finding the optimal harvesting and selling policy with respect to a maximum profit by incorporating price and biomass yield as uncertain factors. Since we are dealing with renewable resources, the uncertain nature of these factors, e.g., due to pest infestation, annual weather conditions, or unsteady prices, is taken into consideration and the model is especially designed to deal with these uncertainties.

1.2. Motivation and limitations of the model

We consider the problem of finding the optimal harvesting and selling policy by incorporating uncertain factors. In this work, this question is approached from a mathematical point of view, more precisely by means of online optimization (see Section 3) and by stochastic optimization (see Section 4).

We follow the overall approach of applying optimization methods for problems with uncertainties that guarantee optimality of the solution (rather than heuristics whose solutions are in general not optimal). Within the field of optimization under uncertainty, the methods of online, stochastic, and robust optimization represent the most well-known approaches. Since robust optimization does not consider the dynamic aspect of the problem but rather all decisions are made in the beginning, we focus on online and stochastic optimization.

The main goal of this work is to introduce these concepts to the field of renewable resources and to point out how these concepts may be of help to understand such problems in a better way. In order to achieve a model that is analyzable by means of these methods, we (over-)simplify the real-world problem and focus on the defining aspects of the problem. It is *not* our aspiration to reflect the real-world situation one-to-one in our model, but rather to focus on few main aspects and obtain an easily comprehensible model. Thus, the idea of how to apply the methods of online and stochastic optimization comes to the fore and we make a first step to applying these methods to more complex models.

The cornerstones of our model are given as follows: We consider discrete time periods. In each time period, the amount of available wood, in the following referred to as resources, is increased by additional biomass yield and decreased by the amount sold by the manager. The selling options for the manager in each time period are determined by requests of potential buyers featuring a purchase quantity and an offered price the potential buyer is willing to pay for this quantity. Now, the question of the optimal harvesting and selling policy with respect to a maximum profit arises.

As mentioned above, this is obviously a simplified model for the problem, which allows for a first analysis within the context of online and stochastic optimization. The model does not incorporate many aspects that certainly have an influence in the real-world problem, consider for example market dominance (“Is the market entirely dominated by the buyers?”), variable biomass increase, time discounting on the revenue or cost streams, behavioral assumptions, etc.

In the following, the problem of finding the optimal harvesting and selling policy is analyzed within the simplified model. We apply the concept of online optimization and present an optimal online algorithm. Furthermore, a stochastic optimization model for the problem is presented and explicit results are given, which demonstrate the power of additional stochastic information.

2. Online and stochastic optimization

In classical combinatorial optimization, it is assumed that the input data of a problem instance is fully available. Based on this complete knowledge of data, an algorithm computes an optimal solution.

In *online optimization*, an algorithm has to make a sequence of decisions, based on successively revealed information, that will have an impact on the final quality of its overall performance. Each of those decisions must be made without secure information about the future. Such an algorithm is called an *online algorithm*, in contrast to an offline algorithm that is aware of all relevant information in advance and computes a solution based on the full data set (cf. Borodin and El-Yaniv, 1998, Section1.1.1).

Online algorithms are applied to decision problems that require decisions to be made immediately after new bits of information for the problem are revealed and no knowledge about future events is available. Considering the harvesting decision with respect to SRC, in each time period the decision about selling or waiting has to be made: The manager either harvests (parts of) the wood and sells it for the current price, or waits for a better price in the future (and a possible growth in biomass). However, there is no knowledge about future prices. The price of renewable resources, in this case SRC, is highly dependent on uncontrollable external influences such as weather conditions or pest infestations. The same holds true for the growth in biomass. Therefore, a worst-case analysis such as the concept of competitive analysis is appropriate in this case.

In order to measure the quality of online algorithms, we use the well-known concept of *competitive analysis*, where, for each request sequence, the value obtained by an online algorithm is compared to the optimal value achievable on that sequence. We denote the value obtained by an online algorithm on a sequence σ by $\mathrm{ALG}(\sigma)$ and the optimal value achievable on that sequence by $\mathrm{OPT}(\sigma)$. For an overview on the topic of competitive analysis for online problems we refer to the textbook by Borodin and El-Yaniv (1998).

For maximization problems as studied in this paper, deterministic competitive algorithms are formally defined as stated in the following definition:

Definition 2.1. (Deterministic Competitive Algorithm) *A deterministic online algorithm ALG is called c-competitive for a constant* $c \geq 1$ *if* $\mathrm{ALG}(\sigma) \geq 1/c \cdot \mathrm{OPT}(\sigma)$ *for all request sequences* σ.

The *competitive ratio* of a deterministic online algorithm is defined as the infimum over all c such that the algorithm is c-competitive.

Competitive analysis often yields very pessimistic results which is due to the worst-case nature of this analysis. For many practical problems, stochastic information about the unknown data is available. This can be incorporated in *stochastic optimization* (or *stochastic programming*), where piece by piece, some of the random variables are realized, and the task is to design a

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