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A two-stage stochastic programming model for lot-sizing with onsite generation of renewable energy

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Abstract

One way to achieve energy efficiency in manufacturing consists of equipping plants with on-site renewable energy generation systems to partially power industrial processes. However, renewable energy sources are highly intermittent and their availability is difficult to predict accurately. We thus investigate an integrated industrial production and energy supply planning problem under uncertain renewable energy availability. We propose a two-stage stochastic programming model for this problem. The first decision stage consists of building a production plan for a proportional lot-sizing and scheduling problem in a single-machine multi-item setting. The second decision stage considers a discrete set of scenarios representing potential realizations of the stochastic generation of renewable energy over the planning horizon and aims at building an energy supply plan for each scenario. Computational experiments will be presented to show the practical efficiency of the proposed approach.

1 Introduction

Industrial companies are increasingly under pressure to mitigate the CO₂ and pollution emissions linked to the manufacturing of industrial products. They are also confronted with a sharp rise in the price of conventional energy sources (gas, grid electricity...) so that the availability and affordability of energy is becoming a critical parameter in manufacturing. One way to deal with these two challenges consists in powering industrial processes with electricity generated on-site from renewable sources.

However, the intermittence of renewable energy sources (wind, sun...) makes it impossible to accurately predict the amount of energy they will provide. Thus, an integrated energy supply and industrial production planning problem under uncertain renewable energy availability needs to be solved. This work is an attempt at modeling and solving such a problem by using a two-stage stochastic programming approach.

2 Problem description and modeling

Problem description We seek to plan production in an industrial plant producing several types of item to satisfy a time-varying external market demand. Backlogging is not allowed and demand must be met on time. The plant comprises a single production resource. This resource may produce only one type of item at a time. Changing the type of item in production requires to carry out startup operations. These operations incur a fixed startup cost but the startup time is assumed to be negligible.

Energy is consumed during both startup operations and manufacturing. The amount of energy consumed during a startup depends on the product that the machine will be setup for. The energy consumed during manufacturing is proportional to the number of items produced. No energy is consumed when the machine is idle or when it is setup for a given product but not producing.

The energy supply system comprises three main elements: the onsite power generation devices (photovoltaic panels) converting a renewable energy source into electricity, the on-site energy storage system (a set of batteries) and the main electricity grid from which electricity may be bought at a given time-varying buying price. The amount of electricity produced by the onsite power generation devices depends on the availability of the corresponding energy source and is thus subject to many uncertainties.

Problem modeling We propose to model the resulting stochastic lot-sizing problem via a two-stage stochastic programming approach. This approach relies on the assumption that the energy supply planning decisions do not have to be made 'here-and-now' but may rather be postponed to a later point in time at which more detailed

information about the actual amount of the generated green energy over the whole planning horizon becomes available.

Thus, the first stage decisions consist of building a production plan for a single-machine multi-product system. To this aim, the planning horizon is divided into a set of planning periods sufficiently short to track the variations in the green energy availability and grid electricity buying price with the necessary accuracy. The resulting small-bucket lot-sizing problem is modeled as a Proportional Lot-sizing and Scheduling Problem (PLSP). The startup and lot-sizing decisions embedded in the resulting production plan translate in an energy demand for each period of the planning horizon.

In order to represent the uncertainties on the available renewable energy, we use a finite set of randomly generated discrete scenarios. A scenario gives a potential realization of the quantity of energy generated by the PV (photovoltaic) panels for each period of the planning horizon. The second-stage decisions thus consist of building, for each considered scenario, an energy supply plan capable of meeting the energy demand of the system in each period. For each scenario, this energy supply plan determines the amount of energy to be bought from the grid, stored in or retrieved from the battery at each time period.

This modeling approach results in the formulation of a large-size mixed-integer linear program (MILP).

3 Solution approach and preliminary computational results

This MILP is solved by a Benders decomposition approach. This approach decomposes the problem into a master problem and a set of linear sub-problems. The master problem comprises the first-stage production planning decisions and is thus an MILP solving a deterministic PLSP. Each sub-problem corresponds to a second-stage scenario and is a small linear program taking as input data the energy demand coming from the first-stage decisions and building a minimal-cost feasible energy supply plan.

More precisely, we develop a branch-and-Benders-cut algorithm. A primal acceleration technique called the in-out stabilization method [1] is used to accelerate the Benders procedure by generating more efficient Benders cuts. Extended valid inequalities, derived from the classical (l, S) inequalities in the lot-sizing problems, are also added to the MILP formulation at the root node of the branch-and-bound algorithm.

We carried out some numerical experiments to evaluate the performance of the proposed branch-and-Benders-cut algorithm. Numerical instances were randomly generated using data available in [2, 3, 4]. Regarding the scenarios, we generated them with the following procedure. First, for each time period, we randomly generated

a value for the predicted PV generation quantity, by using a Gaussian process with means equal to the deterministic PV generation quantities given in [2]. We then used an Auto-Regression and Moving Average (ARMA) model to generate auto-correlated prediction errors.

The algorithm was implemented in Python and each instance was solved with the mathematical solver CPLEX 20.10. We compare the computational performance of our algorithm with the one of the Benders algorithm embedded in CPLEX as well as the one of a classical Benders approach. Our preliminary computational results first show that for small-size instances involving 3 products, 32 micro-periods and 1000 scenarios, the proposed Branch-and-Benders-Cut algorithm can find a relative good feasible solution with smaller MIP gap compared to the other Benders approaches. For the medium-size instances involving up to 5 products, 64 microperiods and 1000 scenarios, the other two Benders algorithms can hardly find a feasible solution within the time limit while the proposed method finds a feasible solution of acceptable quality.

Compared to the deterministic approach where we assume to be able to find the optimal solutions for each scenario, i.e., wait-and-see solutions, which is defined as the expected value of optimal solutions with perfect foresight of PV electricity obtained, we proved also the need to implement the aforementioned two-stage stochastic approach by calculating the Value of the Stochastic Solution (VSS). It was shown that the more the product-specific energy-consumption varies for different products and the PV-availability varies among scenarios, the more the necessity of implementing the stochastic approach is apparent.

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