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Sustainable production technologies which take into account environmental constraints

Marius Rădulescu [a,*], Sorin Rădulescu [a], Constanţa Zoie Rădulescu [b]

[a] Institute of Mathematical Statistics and Applied Mathematics, Casa Academiei Române, Calea 13 Septembrie nr. 13, RO-050711, Bucharest 5, Romania
[b] National Institute for Research and Development in Informatics, 8-10 Averescu Avenue, 011455, Bucharest 1, Romania

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Abstract

We formulate and study a multiobjective programming approach for production processes which implements suitable constraints on pollutant emissions. We consider two alternative optimization problems: (a) minimum pollution risk; (b) maximum expected return. For each pollutant, we define three different contamination levels: (a) the desirable or the target pollution level, (b) the alarm (warning or critical) level and (c) the maximum admissible (acceptable) level, and introduce penalties proportional to the amounts of pollutants that exceed these levels. The objective function of the minimum pollution risk problem is not smooth since it contains positive parts of some affine functions, resulting in mathematical difficulties, which can be solved by formulating an alternative linear programming model, which makes use of additional variables and has the same solutions as the initial problem. We investigate various particular cases and analyze a numerical example for a textile plant.

Keywords: Multiobjective programming; Production planning; Environmental constraints; Pollutant emission

1. Introduction

An undesired effect of industrial manufacturing is the pollution of the environment. The transition from an agrarian to an industrial manufacturing economy and technological progress results in aggravating the pollution risk. Government agencies of advanced countries try to implement and enforce consistent pollution policies. For example, the European Directive CE 61/96 "Integrated Pollution Prevention and Control" (IPPC) requires that the industrial sectors EU change their production methods according to best available techniques (BAT), with the objective of reducing the impact on the environment as a whole.

Various strategies have been developed to mitigate the effects of pollution. Unfortunately, these strategies are expensive to implement and may take years to have the desired effect. In the past, most approaches to handling pollution could be summed up by the phrase "dilution is the solution to pollution". However pollution levels have increased so much in amount and toxicity that this approach is no longer acceptable. The key is pollution prevention, rather than clean up or control, although the alternative approach of source reduction may be a good starting point to the prevention process. The "Polluter-pays principle", where the polluter should bear the costs of avoiding pollution, or remedying its effects, is increasingly being applied successfully all over the world.

* Corresponding author.
E-mail addresses: mradulescu.csmro@yahoo.com (M. Rădulescu), radulescu@ici.ro (C.Z. Rădulescu).

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Many governmental programs and policy instruments were implemented in order to reduce or to achieve certain environmental standards. The firm managers become more and more aware of the potential benefits of the integrated production–planning decision support systems.

In reality the compliance with environmental standards can only be achieved with a certain probability.

2. Research in mathematical modeling for environment protection and sustainable industrial development

The concept of sustainable development supposes harmonization or simultaneous realization of the objectives connected to economic growth and environment.

Reiborn et al. (1990) has shown that, in the long run, the investments in systems for environment management are smaller than the benefits of the firms.

The importance of the problems connected with environment protection and pollution prevention is a stimulus for research in mathematical modeling of production processes.

There are many papers dealing with various mathematical models of production systems and related sustainable technologies (Bloemhof-Ruwaard et al., 1995; Chakraborty et al., 2004; Cheng et al., 2003; Clarke, 1987; Daniel et al., 1997; Dohin and Kaios, 1995; Grauer et al., 1984; Klassen and McLaughlin, 1996; Klassen and Whybark, 1999; Letmathe and Balakrishnan, 2005; Linninger et al., 2000; Melnyk et al., 1999; Nijkamp and van den Bergh, 1997; Penkuhn et al., 1997; Qiu et al., 2001; ReVelle, 2000; Ulhoi, 1995; Wirl, 1991; Wirl et al., 1987; Wu and Chang, 2004, 2003). Interesting references, environmental standards and several mathematical models can be found in Klassen and Whybark (1999). In Melnyk et al. (1999) and Steven and Letmathe (1996), the authors suggest the integration of output related material and energy flows such as waste, sewage and pollutants into bills of materials. This integration refers to the coefficients that characterize different operating procedures.

A great number of decisions about industrial production are made under uncertainty. Uncertainity governs the market price of industrial products, the price of raw materials and energy, the attempts of the firms to comply with environmental constraints, etc. Mathematical modeling of the decision problems under uncertainty is much more difficult than that of the deterministic decision problems. Decision problems under uncertainty generate difficult large scale optimization problems. Often these problems are complicated by the presence of integer decision variables which are used to model the logical restrictions or cardinality restrictions. Their complexity degree increases very much when several periods are taken into account (multiperiod models). Operating in a changing and uncertain environment, firms must make strategic and operational decisions while trying to satisfy many conflicting goals. For example, in order to maximize expected profit and minimize risk, they must periodically decide when and by how much to expand capacity and even more often how much to produce, all in the face of unknown future demands, available technology, and so on. We refer to this class of problems as multi-objective decision processes under uncertainty.

The interested reader may find several decision making models for the industrial production which take into consideration the uncertainty in the following papers (Chakraborty et al., 2004; Cheng et al., 2003; Ierapetritou et al., 1996; Linninger et al., 2000; Wu and Chang, 2004, 2003). An overview on the problems connected with optimization in the presence of uncertainty may be found in Sahinidis (2004).

3. Formulation of the model

In what follows a sustainable production plan means a production plan that satisfies suitable environmental constraints. We shall formulate several optimal production planning models that take into account various environmental constraints. A general multiobjective stochastic programming problem is formulated where the objective functions are the expected return of the production plan and the penalties for the case when the cumulative effect of each emission overcomes some environmental levels. The manager tries to find a production plan that maximize the expected return, minimize the pollution penalties and satisfies the environmental constraints.

Suppose that an industrial firm has the possibility to manufacture the products $P_1, P_2, \ldots, P_n$. Here by a product we understand not only the product, but the product together its production technology. Let (Ω, K, P) be a probability space and c_i: $\Omega \times \mathbf{R}_+ \to \mathbf{R}_+$, $i = 1, 2, \ldots, n$. Suppose that $c_i(\cdot, S)$: $\Omega \to \mathbf{R}_+$ are random variables for every $i = 1, 2, \ldots, n$ and $S \in \mathbf{R}_+$. If the manager invests the sum S in the manufacture of product i then he will obtain a return equal to $c_i(\cdot, S)$. A unit of the product P_i is defined as an amount of the product P_i for which the manager invested one monetary unit, say one euro. The manufacture of a product generates none, one or several pollution emissions $F_1, F_2, \ldots, F_m$ and requires p resources $R_1, R_2, \ldots, R_p$. We denote by b_{ij} the amount of pollution emission F_j per unit of product P_i and by c_{ik} the amount of resource R_k required per unit of product P_i. Denote by r_k the maximum availability of resource R_k. Since b_{ij} depends on several random factors, including the conditions of the experiment in which the measurement of it is performed, we shall consider that b_{ij} is a random variable. Consequently, we shall suppose that all b_{ij}: $\Omega \to \mathbf{R}_+$ are random variables (measurable functions). b_{ij} are random variables because repeated measurements of the same quantity yield slightly different