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Optimal running and planning of a biomass-based energy production process

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Abstract

We propose mathematical programming models for solving problems arising from planning and running an energy production process based on burning biomasses. The models take into account different aspects of the problem: determination of the biomasses to produce and/or buy, transportation decisions to convey the materials to the respective plants, and plant site locations. Whereas the ''running model'' is linear, we propose two ''planning models'', both of which are mixed-integer nonlinear programming problems. We show that a spatial branch-and-bound type algorithm applied to them is guaranteed to converge to an exact optimum in a finite number of steps.

Keywords: Renewable energy; Biomass exploitation; Mathematical programming

1. Introduction

Producing energy derived from fossil carbon-based fuels is proving costly to both the environment (in terms of pollution) and society (in terms of monetary investment). As the prices of crude oil increase, governments and other institutions are researching the most cost-efficient ways to produce energy from alternative sources (Inyang, 2005). One of the most popular contendents is energy produced by biomasses of several kinds (Regional Wood Energy Development Programme, 1998). In (McCarl et al., 2000) the competitiveness of biomass-based fuel for electrical energy opposed to carbon-based fuel is examined using a mathematical programming model. Among the advantages of this type of energy production, there is the potential for employing waste materials of biological origin, like used alimentary fats and oils, agricultural wastes and so on. A factory producing energy with such materials would benefit from both the sales of the energy and the gains obtained by servicing waste (Aringhieri et al., 2004). In (Fiorese et al., 2005) a mathematical program is proposed to localize both energy conversion plants and biomass catchment basins in provincial areas. Other mathematical models for specific biomass discrete facility location problems are developed in Freppaz et al. (2004) and Koukios et al. (2001). A model that combines detailed energy conversion plant optimization with energy/heat transportation cost is given in Söderman and Pettersson (2006).

This paper describes an optimization problem arising from the deployment of such an energy production process in central Italy. This involves several processing plants of different types (for example, a liquid biomass plant, a squeeze plant and a fermentation–distillation plant). Some of these plants (e.g. liquid biomass plant) produce energy; others (e.g. the fermentation–distillation plant) produce intermediate products which will then be routed to other plants for further processing. There are several possible input products (e.g. agricultural products, biological waste), obtained from different sources (e.g. direct farming or acquisition on the markets) at different unit costs. Apart from the energetic output, there may be other output products which are sold in different markets (e.g. bioethanol obtained from the fermentation–distillation plant and sold in the bioethanol market). See Fig. 1 for a typical process flowsheet.

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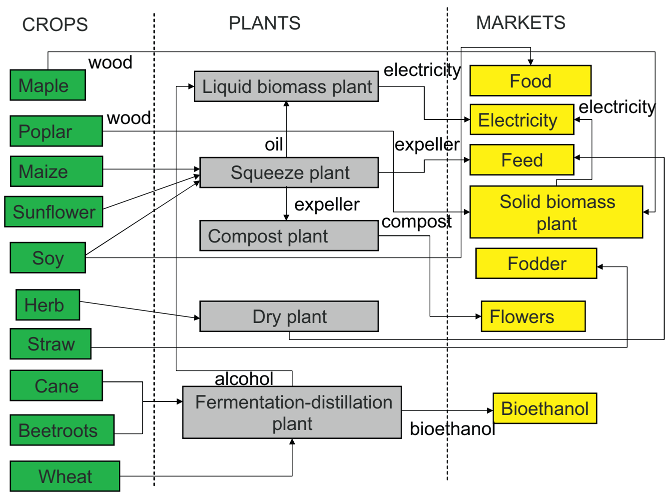

Fig. 1. A typical process flowsheet.

There are in fact three optimization problems relating to this description. The first (and simplest) is that of modelling the production process as a net gain maximization supposing the type of plants involved and the end product demands are known. The second is that of deciding the type of plants to involve in the process to maximize the net gain, subject to known end product demands. Although post-optimal sensitivity analysis may be used to gather hints on how to improve the process, an optimization model provides the ultimate process planning tool. The second model is in fact a simple variant of the first, in that we simply let some of the parameters of the first (linear) problem be decision variables in the second. The third problem is an evolution of the second, taking into account plant installation costs, some features of electricity production plants, and transportation issues (Lund and Andersen, 2005; Lund and Münster, 2006; Möller, 2005). We remark that we only carried out computational experiments on the first and second model, since the practical needs of the industry that commissioned the research were limited. The third model is supplied to show that this modelling approach can be extended to a more complicated and realistic setup.

Section 2 describes the model relating to the production process when the plant types are known ("running model"). Section 3 describes the model relating to the process planning ("planning model"), an exact mixed-integer linear reformulation thereof, and shows that an application of a standard spatial branch-and-bound (sBB) algorithm (Sahinidis and Tawarmalani, 2005; Smith and Pantelides, 1999) yields a finitely convergent exact method. In Section 4 we discuss the application of the production process and planning models to a real-life case. Section 5 discusses the third model, and Section 6 concludes the paper.

2. Optimizing the production process

Modelling a flowsheet as that presented in Fig. 1 presents many difficulties. Notice that the products can be inputs, intermediate, outputs, or both (like alcohol, which is both an output product and an intermediate product). Likewise, processing plants can be intermediate or final or a combination (like the fermentation–distillation plant). Consider also that the decision maker may choose to buy an intermediate product from a different source to cover demand needs, thus making the product a combination of intermediate and input. Of course the input products may be acquired or produced at different locations and at different prices. Moreover, each flow arrow has an associated transportation cost. The time horizon for the optimization process is one year.

The central concept in our model is the process site. A *process site* is a geographical location with at most one processing plant and/or various storage spaces for different types of goods (commodities). A place where production of a given commodity occurs is represented by a process site with a storage space. Thus, for example, a geographical location with two fields producing maize and sunflower is a process site with two storage spaces and no processing plant. The fermentation–distillation plant is a process site with no storage spaces and one processing plant. Each output in Fig. 1 is represented by a process site with just one storage space for each output good. In this interpretation the concepts of input, output and intermediate products, and those of intermediate and final process, lose importance: this is appropriate because, as we have emphasized earlier, these distinctions are not always well defined. Instead, we focus the attention on the material balance and on the transformation process in each process site. Furthermore, we are able to deal with the occurrence that a given commodity may be obtained at different costs depending on whether it is bought or produced directly.

We represent the process sites by a set V of vertices of a graph $G=(V,A)$ where the set of arcs A is given by the logistic connections among the locations. To each vertex $v\in V$ we associate a set of commodities $H^-(v)$ which may enter the process site, and a set of commodities $H^+(v)$ which may leave it. Thus, for example, the fermentation–distillation plant is a process site vertex where $H^-(\text{fermentation}-\text{distillation plant})=\{\text{cane, beetroots}\}$ and $H^+(\text{fermentation}-\text{distillation plant})=\{\text{alcohol, bioethanol}\}$. Furthermore, we let $H=\bigcup_{v\in V}(H^-(v)\cup H^+(v))$ be the set of all commodities involved in the production process, and we partition $V=V_0\cup V_1$ into V_0, the set of process sites with an associated processing plant, and $V_1=V\backslash V_0$.

Fig. 2 is the graph derived from the example in Fig. 1.

The following parameters define the problem instance:

- c_{vk}: cost of supplying vertex v with a unit of commodity k (negative costs are associated with output nodes, as these represent selling prices; a negative cost may also be associated to the input node "waste", since waste disposal is a service commodity);
- C_{vk}: maximum quantity of commodity k in vertex v;
- τ_{uvk}: transportation cost for a unit of commodity k on the arc (u,v);