ARTICLE IN PRESS

Renewable Energy xxx (2015) 1–13

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Models for optimization and performance evaluation of biomass supply chains: An Operations Research perspective

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ARTICLE INFO

Article history:
Received 26 March 2015
Accepted 16 July 2015
Available online xxx

Keywords:
Biomass
Logistics
Supply chain
Modeling
Optimization
Bioenergy

ABSTRACT

The production of biofuels, bioenergy and chemical intermediates from biomass is a promising solution to reduce the consumption of fossil fuels and greenhouse gas emissions. While a significant research effort has been devoted to biomass production and conversion processes, the importance of logistics was detected more recently. Indeed, efficient supply chains are essential to provide conversion facilities with sufficient quantities of quality biomass at reasonable prices. As large territories and hundreds of biomass producers are involved, quantitative models are very useful to evaluate and optimize the resources required, the associated costs, the energy consumptions and the environmental impacts. This article surveys the recent research on models for biomass supply chains, from an Operations Research perspective. 124 references, including 72 published since 2010, have been analyzed to present the structures and the activities of these chains, a typology of decisions in three levels (strategic, tactical and operational), and a review of models based either on performance evaluation techniques (e.g., simulation) or mathematical optimization. A conclusion underlines the contributions and shortcomings of current research and suggests possible directions.

1. Introduction

Simply speaking [114], *biomass* is any material of biological origin, *biofuels* are fuels produced directly or indirectly from biomass, and *bioenergy* refers to the energy produced from biofuels. For instance, forest wood can be chipped and incinerated to produce heat and power, while sugar cane can be fermented to produce bioethanol. The last two decades have seen a growing interest in biomass as a means of reducing dependence on fossil fuels and developing a clean and renewable energy. For instance, the Ref. [40] issued a directive to achieve, by 2020, 20% of renewable energy, including from biofuels, with a target of 10% in transport.

While research on crop production and conversion processes is well developed, the actors concerned realized only recently that the Achilles' heel of the planned bioenergy production systems could be logistics. For instance, each crop is harvested during a short period in the year while conversion plants have to work continuously. Hence, an efficient supply chain must be implemented, to act as intermediate buffer and supply conversion units without shortage. Moreover, as the biomass itself is relatively cheap, the economic equilibrium of the whole system critically depends on logistic costs. Operations Research (OR) is an adequate approach to bring quantitative models for these biomass supply chains, evaluate their performance and optimize criteria such as their total cost, their energy consumption and their GHG (greenhouse gas) emissions.

The goal of this contribution is to depict the OR models proposed for biomass supply chains and to provide good entry points for readers having a general OR culture without being specialists in biomass. We have read more than 170 research articles, published from 1989 to 2014, to select 124 significant references in terms of modeling. This review demarcates from the few existing surveys by adopting an OR perspective, insisting on the types of models and solution methods employed, and gathering very recent references, with 72 papers published from 2010 onwards. It also highlights the gaps in the existing research and proposes a few possible directions for improvement.

The paper is organized in four sections. Section 2 is a general presentation of biomass supply chains (structures, activities, decision levels) and comments the few existing surveys. Section 3 describes performance evaluation models based on spreadsheets, geographical information systems, or simulation. Section 4

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http://dx.doi.org/10.1016/j.renene.2015.07.045
0960-1481/

considers optimization models based on mathematical programs, before a critical conclusion in Section 5.

2. Biomass supply chains

2.1. Structure and activities

A biomass supply chain includes various activities, such as cultivation, harvesting, pre-processing, transportation, handling, and storage. It stops usually at the gates of a *conversion unit*, in general a *biorefinery*, producing biofuels and chemical intermediates, or a *bioenergy conversion plant*, generating electricity, heat and/or cooling. A few papers add the distribution stage, from conversion facilities to end-users. Compared to industrial supply chains, several differences must be underlined:

- Biomass supply chains cover a vast collection territory, with many scattered cultivation areas;
- Long planning horizons are considered, because most crops have a one-year cultivation cycle;
- Inputs (biomass productions) and outputs (conversion activities) are desynchronized;
- Because of degradations, the crops cannot wait and must be harvested quickly when ready.

Both industrial and biomass supply chains can be modeled as *networks* (graphs) where the nodes correspond to the locations of interest while the arcs represent product flows. However, biomass supply chains involve specific activities that require various resources:

- *Harvesting activities* are possible in a limited time window at the input nodes devoted to biomass production, when the crop is ready, and they compete for a limited fleet of machines, like combine harvesters. The yield is not perfect, with a typical 10–20% loss.
- *Storage* is required in practice to synchronize the biomass production calendar with the production plan of conversion plants. It can take place in the fields or forests as simple stacks, in the farms, in centralized storage sites, or before the processes in conversion facilities.
- *Pre-processing* is useful to improve preservation (drying) and handling (baling, pelletization) and to reduce transportation costs by increasing density. For instance, switchgrass density is 60–80 kg/m^3 when harvested, 140–180 after baling and 700–800 for pellets [102]. The simplest treatments like baling can be done on the field. Stronger compressions and other transformations like roasting are possible, but using heavier equipment and/or dedicated sites.
- *Transport.* Like in industrial logistics, several transport modes can be used, the fleet of vehicles is often limited and the number of travels per period is restricted by vehicle range and driving time regulations. However, road transport is often the only solution for production sites with limited accessibility (forests), and truckload operations are systematic due to the large amounts handled.

The designers of such chains need modeling tools to cope with this complexity. Before coming to a total cost, they must understand the dynamics of the chain and determine many variables, like the amounts harvested (which crop, where, when, in which amount), the network flows (quantities transported), the advisable stock levels, and the resources consumed (harvesting equipment, vehicles, energy, manpower). Subtle tradeoffs must be found. For instance, densification can be done on the field, using balers, or in a more efficient densification plant. The second option adds a transport step to the plant, but then transport costs are cheaper thanks to the higher density.

2.2. Sustainability concepts

Sustainable development consists in meeting the current needs of humanity by combining the rational use of natural resources, environmental protection, economic prosperity and quality of life, without compromising the ability of future generations to meet their own needs. Sustainability must be analyzed taking into account the environmental, economic and societal aspects [7,32].

Environmental sustainability aims to prevent environmental degradation. The environmental impact of human activity is characterized by three main ecological footprints, affecting atmosphere (greenhouse gas emissions, GHG), water, and soils [104]. However, the implementation of good practices, like the ones recommended by the International Energy Agency [59], can limit the degradations induced by biomass industries.

Biofuel production may promote economic development, for example by attracting investors, favoring biomass sources which are currently unused, increasing and diversifying farmers' incomes, and boosting associated industries such as agricultural machinery [28].

However, it raises many societal issues, such as social acceptability, impact on rural populations, land use, and territorial development, potential for job creation, and poverty reduction. Hence, according to [108], relevant energy indicators for a developing economy should not be limited to environmental and economic issues: they must integrate social criteria such as poverty.

A few authors have presented analyses of supply chains which take into account these sustainability concepts, see for instance [42,23].

2.3. Decision levels

Like in production management and industrial logistics, the decisions in biomass supply chains can be conveniently classified in three levels, according to the time horizon concerned.

2.3.1. Strategic decisions

Strategic decisions are long-term decisions which involve important financial investments and engage companies over 1 year at least, such as the construction of a new factory or the design of a new aircraft. In bioenergy context, such decisions include for instance the selection of accepted biomass types, the location and size of pre-processing plants and conversion facilities, the transportation modes used, and the long-term supply contracts. Due to the lack of precise information several years in advance, strategic decisions are often based on aggregated data. Most authors consider a single time period [37], but multi-period horizons are sometimes useful to model long-term demand fluctuations, e.g., 5 periods of 3 years in Ref. [15].

2.3.2. Tactical decisions

Tactical decisions are medium-term decisions applied to a multi-period horizon, over a few months. In industry, production planning is based on such decisions, e.g., determining the number of products manufactured in each period, under aggregate resource constraints. Examples in biomass supply chains include the amount to harvest in each farm and each period, the number of vehicles to be purchased (fleet size), and the definition of safety stock levels. The time period considered may vary between one day [99] and one month [24].

Please cite this article in press as: B.H. Ba, et al., Models for optimization and performance evaluation of biomass supply chains: An Operations Research perspective, Renewable Energy (2015), http://dx.doi.org/10.1016/j.renene.2015.07.045