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Research paper

Planning woody biomass supply in hot systems under variable chips energy content

Alexandra Marques[a,*], Jussi Rasinmäki[b], Ricardo Soares[a], Pedro Amorim[a]

[a] INESC TEC Technology and Science, Campus da FEUP, 4200 - 465 Porto, Portugal
[b] Simosol Oy, Rautatietori 4, 11130 Riihimäki, Finland

A R T I C L E I N F O

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A B S T R A C T

The growing economic importance of the biomass-for-bioenergy in Europe motivates research on biomass supply chain design and planning. The temporally and geographically fragmented availability of woody biomass makes it particularly relevant to find cost-effective solutions for biomass production, storage and transportation up to the consumption facility. This paper addresses tactical decisions related with optimal allocation of wood chips from forest residues at forest sites to terminals and power plants. The emphasis is on a “hot-system” with synchronized chipping and chips transportation at the roadside. Thus, decisions related with the assignment of chippers to forest sites are also considered. We extend existing studies by considering the impact of the wood chips energy content variation in the logistics planning. This is a key issue in biomass-for-bioenergy supply chains. The higher the moisture content of wood chips, the lower its net caloric value and therefore, a larger amount of chips is needed to meet the contracted demand. We propose a Mixed Integer Programming (MIP) model to solve this problem to optimality. Results of applying the model in a biomass supply chain case in Finland are presented. Results suggest that a 20% improvement in the supplier profit can be obtained with the proposed approach when compared with a baseline situation that relies on empirical estimates for a fixed and known moisture content in the end of an obliged storage age.

1. Introduction

Design and planning of biomass-for-energy supply chains (BESC) has been widely studied, as society reinforces the major role of biomass as a global primary energy source. In the case of woody biomass (produced from branches and other by-products of forestry operations), as in other forms of biomass (e.g. residues from agriculture, forestry, fisheries and municipal waste), the availability is temporally and geographically fragmented, which makes it particularly relevant to find cost-effective solutions for biomass production, storage and transportation up to the consumption facility (e.g. Ref. [17]).

In this paper, the company in focus is a biomass supplier that buys the forest residues from forest owners (suppliers) and delivers the wood chips to power plants (customers) in order to meet their contracted demand of energy content, expressed in terms of MWh. The sequence of operations that are responsibility of the company are: 1) Logging, ie., tree felling, delimbing the trunk and cross-cutting into pre-defined lengths with specialized harvesters or manual harvesting with chainsaws; 2) Forwarding the logs and residues with skidders, forwarders or other types of tractors from the logging site up to pre-defined stacking locations at the roadside; 3) Chipping forest residues into smaller size wood chips, with specialized chippers located at the roadside or in terminals for longer term storage; 4) Transporting forest residues or wood chips by truck from the forest sites; and finally 5) Temporary storing and drying the residues and/or chips at the roadside or in terminals. Drying usually occurs under favorable sun and wind open-air conditions, but technical drying systems can be used in terminals, with addition of heat and with forced ventilation in order to reach much lower moisture content levels.

This research focus on planning chipping, transportation and storage operations, especially during the heating season when the power plants are operating. The emphasis is on “hot systems” where wood chipping and transportation operations are synchronized at the roadside. In this case, the trailer-mounted chipper feeds directly a chargeable container mounted in the truck, which will transport the chips ultimately to the plants. The company main decisions with respect to chipping are: *1) when and where to produce the wood chips, to match wood chips availability and plants demand; 2) which chipper to assign to forest residues piles at the forest site.* Main decisions with respect to transportation are: *1) amounts from where, to where, when, what product (flows);*

* Corresponding author.
E-mail address: alexandra.s.marques@inesctec.pt (A. Marques).

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2) transportation capacity needed in each period. In respect to storage, the company main decision is: *3) how long to store/dry forest residues/wood chips and where (roadside or terminals)?* It is noteworthy that, in case of hot systems, there is no intermediate storage of wood chips between these operations, but there is usually storage of forest residues at the logging sites because chipping is done some time after harvesting. Contrarily, the "cold system" encompasses the transport of forest residues to the terminals for later chipping and storage (e.g. Ref. [11]).

The literature shows several examples of mathematical programming techniques to help plan chipping and transportation operations with the aim to minimize the cost per kWh generated (e.g. Refs. [4,6,30]). Previous research from Ref. [19] addressed the case of a large Swedish biomass-supplying entrepreneur. They developed a model to decide when and where forest residues have to be converted into chips, transported and stored in order to satisfy the contracted demand at the sawmill at a minimum cost. They assume that harvesting (and chipping) in each stand occurs in a single period and do not address the assignment of machinery to these operations. Continuous variables determine biomass flows from harvest sites and sawmills to heating plants in each time period and binary variables determine whether forest residues are forwarded or chipped, whether a sawmill has been contracted and a terminal is used in a certain time period (one month) over a planning horizon of one year. The problem was solved with a heuristic approach and applied in six scenarios of possible variations in the supply chain design. In a similar context [14], apply a MIP model to the optimization of inventory planning at the terminals in order to support the choice of chipping technology and location and the route to the heating plants. The model was implemented in a Decision Support Tool called FuelOpt. [23] and [18] also studied the biomass supply in case studies in Austria. The former proposed a Linear Programing model while the latter applies a simple stepwise heuristic approach based on the calculation of available regional forest fuel potential.

Despite these relevant efforts, the dependency between chipping and transportation operations that characterize "hot systems" is still poorly addressed. Previous research (e.g. Refs. [11,12,24]) develop simulation-based approaches to assess productivity issues related with alternative chipping systems as well as to show the importance of balancing chipping and transportation capacity to avoid unnecessary costs related with the trucks waiting time and chippers idle time. In a case similar to this [3], proposes a discrete-event simulation model to find optimal set-ups for the supply chain of crushed material, made from stumps at different road transport distances. Yet, optimization models for jointly planning chipping and transportation remain undone.

Moreover, the impact of wood chips moisture in storage and logistics planning is not yet properly addressed, although it is a key aspect of the business. Usually companies use the chips with lower moisture content as possible, because this corresponds to a higher energy content, meaning that less energy is spent to vapor the water in the wood instead of heating. Moisture content also affects negatively the efficiency of combustion (higher emissions of carbon monoxide, hydrocarbon and fine particles), increases the risk of decay during storage, and increases the transportation costs [27]. Chips moisture content is higher just after harvesting and tends to decrease along the time spent in storage (e.g. Refs. [20,21,28]. Yet, the drying rate depends on the initial moisture content, the weather conditions (specially sun and wind) during the drying period, the drying capacity of the wood, phytosanitary conditions, pile cover type and arrangement, and other features of the storage yard (e.g. dimension, soil drainage capacity) [27].

One of the few studies addressing the impact of moisture content variation in logistics planning was done by Ref. [8]. They apply a simulation model built with a state-task-network approach. Another study by Ref. [31] proposes a 'stochastic programming-robust optimization' model to tackle biomass supply planning, addressing uncertainty in biomass quality and biomass availability. [16] quantifies the impact of incorporating terminals between harvest locations and biorefineries. In this analysis, the decrease in moisture content is one of the considered factors for evaluating the potential benefits of intermediate storage locations. Nevertheless, most planning models for biomass supply fail to effectively capture the impact of the changes in the product properties according to storage time, and do not incorporate the storage age into the model.

The main contributions of this paper are to formulate and solve the tactical biomass supply planning problem, thus extending the work of [14,19] by explicitly considering the variation in chips energy content (or moisture content) over time in storage. Furthermore, it addresses the dependency between chipping and transportation at the roadside that characterize the "hot systems" as well as the space-time continuity of chipping operations.

The remainder of this paper is as follows. Chapter 2 presents the problem description, with emphasis on identifying the impact of the variation of the wood chips energy content in the logistics planning as well as explaining the dependencies between chipping and transportation operations that characterize the hot systems. Chapter 3 presents the proposed modelling approach. It further discusses possible variations to the general Mixed-Integer Programming model for cases where the storage age is not dealt with or the movements of the chippers between piles can be simplified. Chapter 4 presents the computational experiments for a case study of a biomass supply company in Finland. Finally, chapter 5 presents the concluding remarks.

2. Problem description

The woody biomass supply planning problem in hot systems under variable chips energy content can be formulated as follows. Considering a set of power plants (M) with a given demand of energy content (MWh) per week, the problem consists in determine 1) which piles (P) of forest residues should be chipped according to its availability and moisture content; 2) by which chippers (K), and 3) where to transport the chips, considering the possibility to use forest sites and terminals (O) for temporary storage (Fig. 1). The objective is to maximize the operational net profit, considering the revenue from wood chips sales to the plants as well as the costs of chipping, transportation and storage. This is a multi-period flow problem, where the planning periods be half-a-day, one day or even week, and the planning horizon can range from 1 to up to 6 months, the latter corresponding to the expected duration of the heating season, when the power plants are operating.

2.1. Incorporating wood chips energy content variation in logistics planning

The energy demand at the power plants is specified in MWh. This corresponds to the minimum supply during the entire cold season, when the plant is operating, while the maximum supply can be approximated by the plants processing capacity. The price per MWh vary from plant to plant and the supplier was no control over pricing, which is assumed to be fixed within the planning horizon. Depending on the

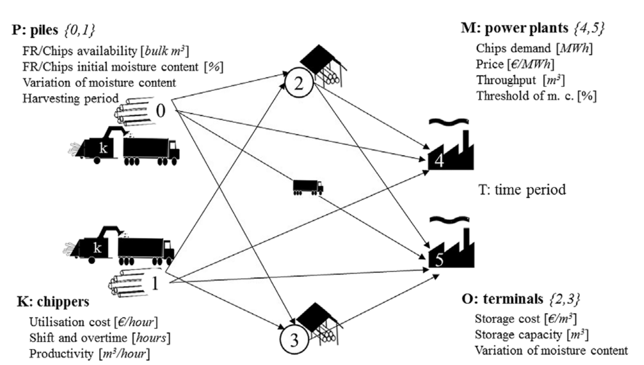

Fig. 1. Graphical representation of the biomass supply planning problem.