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Optimization of sawmill residues collection for bioenergy production

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HIGHLIGHTS

- A real-life stochastic vehicle routing problem is presented and solved.
- The goal is to optimize the collection of biomass residues from a set of sawmills.
- A model that optimizes the energy returned on energy invested (EROEI) is proposed.
- Accounting for the randomness in the input parameters makes the model more robust.
- Our solution is shown to be more accurate and precise than a deterministic one.

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ABSTRACT

The collection of sawmill residues is an important logistic activity for the pulp and paper industry, which uses the biomass as a source of energy. We study a vehicle routing problem for a network composed of a single depot and several sawmills. The sawmills serve as potential suppliers of biomass residues to the depot, which in turn processes and distributes the residues to the pulp and paper mills. This problem consists of identifying the best daily routing schedule for a fixed number of trucks. The objective is to maximize the ratio of energy returned on energy invested, while satisfying a minimum daily amount of dried biomass residues. There are several random components in the problem, including the availability and moisture content of the biomass residues. We use a combination of scenario analysis and heuristics to solve this stochastic vehicle routing problem. A performance comparison of the proposed method reveals an estimated daily energy savings of 6 GJ over the benchmark method.

1. Introduction

The deleterious impacts of climate change coupled with the ongoing urbanization of countries around the world have led to a global effort to reduce greenhouse gas emissions for energy production, especially in the transportation sector. The transport sector is responsible for approximately one quarter of greenhouse gas emissions in both Europe and America, making it the second largest emitting sector after energy [1,2]. A plethora of studies show that urban freight transport could be vastly more efficient. According to the European Commission, 24% of commercial trucks that operate in Europe are empty [2]. In the United States, commercial trucks drive an estimated 19 billion needless miles each year [3]. Thus, significant economic and environmental savings may be achieved by reducing truck transport.

This paper presents a modeling framework to optimize the collection of biomass residues from sawmills in the presence of uncertainty. Recognizing that the goal of procuring the biomass is for the production of energy, we cast the problem as an energy optimization task.

Biomass feedstocks that are brought to a combined heat and power (CHP) plant for conversion into energy must meet certain specifications in order for the process to be safe and successful. The wet basis moisture content is used to describe the water content of biomass and is defined as the percentage equivalent of the ratio of the weight of water to the total weight of the biomass. The most important property of biomass feedstocks with regard to transport and energy conversion is its moisture content. This is for two reasons. First, the biomass feedstock might have to undergo drying if the moisture content exceeds that accepted by the facilities boiler, with an ensuing energy expense. Second, the unnecessary transportation of water embedded in the biomass feedstock increases the energy utilized for transportation. Hence, our objective is to schedule the collection activities and identify

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collection routes that maximize the total energy returned on energy invested (EROEI) taking into consideration the transportation and drying of the biomass feedstock. The EROEI is defined as the ratio of the amount of usable energy acquired from a particular energy resource to the amount of energy expended to obtain that energy resource.

Many processes in the biomass supply chain may randomly vary each time they are performed. For example, the availability and quality of the biomass residues as well as the time required to load, unload and transport will vary on a case by case basis. These disturbances can be caused by spatial and temporal variations in a seemingly unpredictable fashion that can be best represented in the model with the use of random variables. A main source of uncertainty driving these random variations can be attributed to weather, such as precipitation, wind, and exposure to the environment. In the context of biomass procurement for bioenergy, variability in the biomass quality (i.e. moisture content, calorific value, etc.) and availability can have a significant impact on the cost of energy production and the energy conversion efficiency. As such, the modeling of these activities should consider both the biomass quality and availability as random parameters with probability distributions. Modeling such variations is often done using specified stochastic distributions with mean and variance estimated from historical data. The sampled values of the random variables were obtained using random number generators. All other model input parameters (i.e. number and location of sawmills, travel distances, number of trucks, truck capacities, etc.) are considered fixed. The values assigned to the fixed parameters were established per the study criteria or derived from the literature.

Our motivating case study deals with the planning of truck routes for the collection of sawmill residues (or waste) in the Lower Mainland region of British Columbia, Canada [4]. A symbiotic relationship exists between sawmills and pulp mills. Approximately 50% of a log, by volume, gets turned into lumber at a sawmill. The waste residues from the process are utilized by the pulp mills to produce both pulp and excess green energy. The majority of pulp mills rely on purchased sawmill residue chips for most, if not all, of their chip supply. Consequently, the sale of residue chips has become an essential revenue stream for the sawmills. The pulp mills have the necessary expertise, infrastructure and potential to be future large scale producers of biomass based transportation fuels [5].

The real-life sawmill residues collection problem under consideration may be described as follows. There are a total of 25 sawmills in the region and a single depot. The location of the sawmills and the depot are given along the streets of a defined road network. The biomass residues produced by the sawmills must be collected by a fleet of trucks with known capacities. The average daily amount of biomass residues produced by each sawmill are subject to variability. Each truck may collect biomass residues from several sawmills before returning to the depot to unload. Truck drivers work 8 h shifts that start at 9 am and end at 5 pm. The trucks leave the depot at the start of the day at 9 am and are allowed to make several, potentially different, routes in a single day. A truck must return to the depot to unload after completing a route. In addition, all trucks must return to the depot before the end of the day at 5 pm. The amount of biomass residues that should be collected on a daily basis is determined by the energy demand from the pulp mills that are being supplied by the depot.

Information regarding the mass, measured in green tonnes (gt), and energy content, measured in gigajoules per tonne (GJ t^{-1}), of the biomass residues available at each sawmill are unknown and highly variable. The energy content of the biomass residues depends on the moisture content, which is known to play a significant role in the optimization of biomass supply chains [6].

The biomass residues collection problem can be viewed as a stochastic vehicle routing problem (SVRP). The vehicle routing problem (VRP) is a very well known and widely studied problem in combinatorial optimization. The general objective is to route the vehicles, with each route starting and ending at the depot, so that all customer supply demands are met and the total travel distance is minimized. As this is a computationally very hard problem, which cannot be solved by exact methods, in practice heuristics are typically used for this purpose [7]. The SVRP arises when some of the elements of the VRP are not known exactly, such as the travel times, product availability and customer demand.

Prevalent techniques used to solve the SVRP minimize the expected cost of the assigned routes, including those incurred by recourse actions, while satisfying a set of chance constraints. In most cases, simplifying assumptions are used in order to fit probabilistic models that rely on mathematical theorems and lemmas [8]. In our experience these techniques generally result in computationally demanding and unscalable models [9]. Moreover, the explicit use of the expected value in solving the SVRP implies that the decision maker is primarily interested in the average performance of the solution and is not concerned with its variance and other features of its random behavior. To avoid these drawbacks, the SVRP presented in this paper is solved using the quantile-based scenario analysis (QSA) approach [9]. The QSA approach analyzes the performance of solutions obtained from solving deterministic realizations of the stochastic problem and identifies the solution that optimizes chosen quantiles of the stochastic objective function, subject to satisfying conditions on given quantiles of the constraint distribution. An advantage of this approach is that it requires only that each deterministic version (i.e. scenario) of the stochastic problem be solvable.

The contributions of this paper are threefold. First, it demonstrates the methodological and practical advantages of addressing the problem of procurement planning for bioenergy production in a stochastic manner in comparison to a purely deterministic approach. Second, it is shown that the procurement of biomass for energy production can be presented in a mathematical framework that accounts for both the energy utilized for procurement and the energy obtained during conversion. Third, it illustrates how randomness can be directly incorporated into any existing deterministic VRP, often encountered in energy production, and solved as an SVRP by a direct application of the QSA approach.

The remainder of this paper is organized as follows. A review of the literature on SVRP studies is discussed in Section 2. The sawmill residue collection model and its input requirements are presented in Section 3.1. The heuristic routing and scheduling methodologies are explained in Section 3.2, followed by the presentation and discussion of results in Section 4. Main conclusions are provided in Section 5.

2. Literature review

The deterministic VRP has received some attention in recent years in the area of energy efficiency, production and management. For example, Araujo et al. [10] studied the collection of waste frying oil for the production of biodiesel in Rio de Janeiro, Brazil. Juan et al. [11] investigated several open research problems related to the introduction of electric vehicles in logistics and transportation, including strategic and planning challenges associated with hydrogen-based electric vehicles. Shao et al. [12] studied an electric vehicle routing problem in Beijing to address some operational issues such as range limitation and charging demand. Jokinen et al. [13] present a mathematical model that minimizes the total costs