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Integrating multimodal transport into forest-delivered biofuel supply chain design

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ABSTRACT

An integrated multi-stage, mixed integer programming (MIP) model using multimodal transport was designed for a forest biomass biofuel supply chain to manage logistics. The two transport modes are rail and truck. The objective was to minimize the total cost for infrastructure, feedstock procurement harvest, transport, storage and process. The model coordinated strategic and tactical decisions. Strategic decisions include the number, capacity, and location of storage yards and biorefineries. Tactical decisions included the amount of biomass shipped, processed and inventoried during a time period. The model was validated using the state of Michigan, in the Midwest United States, as the base case. It was uncovered that trucks are preferred over rail for short-haul deliveries while rails are more effective for long-haul transport. Taking advantage of these benefits, the multimodal transport model provided more cost effective solutions.

1. Introduction

Strong demand for oil in the United States (U.S.) for the transportation industry, multiple societal issues, including climate change concerns, heavy air pollution, high dependence on imports, and a multitude of security concerns have driven the evaluation of different alternatives [1]. In 2011, the transportation industry used over 28% of the total U.S. energy which equates to 70% of the nation's oil consumption [2]. This generated one-third of total greenhouse gas (GHG) emissions in the U.S. Biofuel, using renewable lignocellulosic biomass feedstock such as agricultural residues, wood, and forest residues, provides a limited replacement for, or complement to, gasoline [3]. Additionally, as MTBE (Methyl Tertiary Butyl Ether) is substituted with ETBE (Ethyl Tert-Butyl Ether) in gasoline; this is another source of demand for biofuels. The biomass resource is geographically distributed which contributes to cost and complexity associated with the removal operations; this poses challenges that may hinder the increased utilisation of biomass in the production of biofuels [4,5]. Developing a financially feasible and consistent feedstock supply chain system that includes diverse harvesting and collection methods, multiple storage options and multi-modal transport scenarios, is key to long-term viability of a biorefinery.

A biofuel system represents a typical biofuel supply chain, including location setup, feedstock procurement, transport and storage, biofuel production and distribution. Prior research studies notably suggest some common techniques to include optimisation with mixed integer programming (MIP) [6–24], geographic information systems (GIS) [25,26], and simulation [27,28]. Some methods were used in combination with other methods. Other methods with less frequency included spatial analysis, multi-criteria selection, regression, honey bee foraging, and spatial clustering [29].

There is an extensive body of knowledge applying optimisation and mixed integer programming methods to address biofuel supply chain design and logistical questions, including economic performance [6–8], financial risk [6], feedstock production [9] and cost uncertainty [6], potential biofuel supply [8], and fuel price uncertainty [6,10]. Based on the breadth of geographical regions studied, the methods applied not only to small areas such as single U.S. states [11–18] and small countries [6], but also to medium areas that included a few U.S. States [6–8] or countries [19], as well as to large regions of the U.S [20,21]. Multiple types of biomass were investigated including agricultural [6,8], forest [8], urban waste [8], and energy crop biomass [8,9]. Multi-period MIP models integrating spatial and temporal dimensions were built for long-term

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strategic planning of biofuel supply chain systems [22,23], and for managing the logistics of a refinery over a specific period of time [24].

A new decision support systems (DSS) tool integrating cost, energy reductions, GHG considerations, sensitivity analysis and GIS was developed to provide all-inclusive analysis of alternative systems for optimising biomass energy production [25]. Parker et al. [26] built an integrated model based on GIS and mathematical programming to evaluate the economic potential and infrastructure requirements for hydrogen production from agricultural residues.

The Integrated Biomass Supply Analysis and Logistics (IBSAL) model provided a time-dependent simulation of biomass feedstock supply system including operations, collection, storage, and transport [27]. Based on the IBSAL framework, a simulation model was developed to evaluate the delivery cost of forest biomass, moisture content, and carbon emissions from the logistics operations for a power plant in Quesnel, BC, Canada [28]. Life Cycle Assessment on biofuels production on local scale in other countries (e.g. Italy) has also been reported in literature. For example, environmental advantages of bioenergy production on local scale was evaluated in Ref. [30] when there is a need for improving a farmers' agricultural budget by means of even a small income or savings from bioenergy production.

As a result of the literature review, research gaps in the area of modelling biofuel supply chain were identified as follows.

(1) There is limited work integrating multimodal transport into biofuel supply chain design. The majority of prior studies only considered truck transport, which is usually used for short-haul delivery. Rail transport is more efficient for long-haul and high volume transport because of economies of scale [31]. In addition to economic incentives, multimodal transport offers greater flexibility in handling feedstock seasonality, coupled with feedstock storage in the supply chain [32].

(2) Prior published research lacks the investigation of forest biomass storage when it is characterized by seasonal feedstock availability [33]. A few studies focused on agricultural biomass storage, such as corn stover [32], wheat straw [34], and cotton stalks [33]. Less focused on woody biomass, such as forest residues [32] and almond tree prunings [33]. Zhang et al. initially designed a pulpwood storage system at a biorefinery to address road weight restriction problems during the spring breakup period, which is exclusive to northern climates with snow and ice [35].

(3) To the best of our knowledge, intermediate storage built at rail spurs or along Class A highways has not been reported except the Feedstock Supply Chain Center of Energy Excellence (CoEE) study [36]. Class A highways are all-season roads which can be used during spring breakup [36]. In the literature, three commonly used feedstock storage systems are on-field/roadside storage, intermediate storage, and storage near/at biorefineries [33]. On-field/roadside storage would result in large number of distributed, small storage facilities near harvesting areas, which complicates the transport operations followed [34]. Storage near/at biorefineries usually only has two-months of inventory [32]. For example, Zhang et al. designed a storage system at biorefinery for the spring breakup period (about two-month duration from the beginning of March through the end of April each year for most counties in the Lower Peninsula of Michigan) [35]. Storage that occurs at an intermediate location between harvesting areas and biorefineries could handle and store large volume of biomass feedstock. Xie et al. placed intermediate storage at transshipment hubs [32]. These could also be railroad landings/spurs, which is common in the Upper Peninsula of Michigan. Others employed satellite storage (SS) with fixed or variable hauling distance to determine the intermediate storage locations [34,37].

This study fills the gaps of previous research by developing a multi-stage, mixed integer model integrating multimodal transport into the biofuel supply chain design. Two transport modes considered are truck and rail and they are differentiated by costs and delivery scheduling. To ensure year-round delivery of forest biomass to biorefineries, intermediate storage is placed at rail spurs with rail access (hereafter referred to as “rail yards”) and along Class A highway without rail access (hereafter referred to as “truck yards”). This is because both rail and Class A highway transport is not subject to spring breakup restrictions. Interstate highways are Class A roads with higher speed limit [36] (65 mph and 70 mph on major truck lines) and are used to locate truck yards in this study. We assumed no inventory of biomass was located along the harvesting.

The study is organized as follows. In Section 2 a description of biofuel supply chain components is presented as well as a network representation. The mathematical formulation is in Section 3. The application of our models is a case study of Michigan's Lower Peninsula (or the L.P. of Michigan) located in Section 4. Model inputs were collected from different sources. The optimisation results are presented and discussed in Section 5. Section 6 concludes the paper with discussions on research findings, major contribution, and potential future research.

2. Problem description

A multimodal-based cellulosic biofuel supply chain is illustrated in Fig. 1. Forest biomass is harvested and forwarded to roadside landing and then transported to intermediate storage yards or biorefinery directly by trucks. The forest biomass feedstock stored at truck yards is shipped to biorefineries via truck. Biomass stored at rail yards is shipped to biorefineries by rail.

To mathematically model the biomass supply chain, a network was developed to depict the flow (Fig. 2). This allows for representation of a dynamic model that is composed of three infrastructure layers: harvesting areas, storage yards, and biorefineries. The length of a time period for this network is fixed at one month, with the planning horizon consisting of one year. For example, he feedstock supply uncertainty is denoted by successive time periods t and t+1 in Fig. 2

The objective is to minimize the cost of supplying biofuel facilities while meeting necessary delivery requirements. The model is briefly described as: given (i) facility capital cost, feedstock stumpage unit cost, harvesting/forwarding unit cost, storage unit cost, and transport unit cost, (ii) monthly feedstock supply by county, (iii) geographic distributions of harvesting areas, storage yards, and biofuel facilities, and (iv) transport modes in different segments of the network. The model allows for strategic decisions related to:

- The number, capacity and location of biorefineries needed to make use of the biomass available in the region;
- The number and location of storage yards;
- Harvesting areas that serve a particular storage yard; and
- Storage yards that serve a particular biorefinery;
  On the other hand, managing the logistics of a biorefinery consists of a number of tactical decisions related to:
- The amount of biomass harvested in a time period;