Applied Energy 218 (2018) 266–281

Contents lists available at ScienceDirect

Applied Energy

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

Determining a geographic high resolution supply chain network for a large scale biofuel industry

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HIGHLIGHTS

- Large-scale biofuel industry development with high-resolution spatial information.
- Two-stage optimization model based applying firm location theory.
- The procedure was used to address ultra-high dimensional location problems.
- The proposed approach identified feasible solutions within a reasonable time frame.

ARTICLE INFO

Keywords:
Switchgrass (*Panicum virgatum* L.)
Supply chain
Facility location
Mixed integer programming

ABSTRACT

This research combines Geographic Information Systems (GIS) and Mixed Integer Programming (MIP) model to determine feedstock supply, preprocessing facility, and biorefinery locations at a highly resolved spatial scale with the objective of meeting a large-scale annual biofuel production and demand goal for Tennessee, USA. Simultaneous determination of this supply chain network using MIP is computationally expensive. Memory limitation of typical personal computers constrain the network problem. High Performance Computing environments may require days to solve, and without any assurance of a feasible solution. This paper proposes a two-stage optimization procedure to overcome these computational challenges while maintaining theoretical consistency with conventional firm location theory paradigms. The two-stage procedure assumes that firms first identify biorefinery locations with comparative advantage in terms of supplying biomass. Step two entails determining if costs can be lowered with the addition of preprocessing facilities, and their optimal location relative to the biorefinery sites. In contrast, a single step optimization procedure siting multiple biorefineries and concomitantly preprocessing units and biomass supply areas assumes a different strategy for a single firm. Results suggest that the two-stage optimization approach is able to identify a feasible solution of multiple feedstock areas, feedstock preprocessing and fuel production locations using high-resolution spatial layers over a relatively large geographic region in a fraction of the computer resources required to solve a single, simultaneous location problem. The optimal supply chain network solutions generated from the two-stage and single simultaneous approaches are different. The absolute difference in the smaller scaled models' objective values is less than 1%.

1. Introduction

The United States (US) Energy Policy Act of 2005 established the Renewable Fuel Standard (RFS). The RFS required the domestic production of 28.39 GL of transportation fuels using renewable feedstock. The Energy Independence and Security Act of 2007 (EISA) updated the RFS (RFS2), mandating the annual domestic production of 136.27 GL of biofuels by 2022, with 79.49 GL produced from advanced biofuel technologies [1]. Dedicated energy crops produced on agricultural land are expected to be a significant source of feedstock for achieving the renewable energy mandate. Research suggests that 50% of the RFS2 target could be met by feedstock produced in the southeastern US [2]. This region has comparative advantage in producing cellulosic biomass, such as switchgrass, due to favorable soil and weather conditions [3,4].

Determining the optimal location of facilities, subject to market demand, land suitability for biomass production, and transport costs is

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https://doi.org/10.1016/j.apenergy.2018.02.162
Received 17 November 2017; Received in revised form 7 February 2018; Accepted 24 February 2018
0306-2619/

computationally challenging and has received considerable attention in the supply chain management and engineering literature. Solving large-scale network problems that simultaneously determine optimal locations of biorefinery, feedstock producing areas, and preprocessing units is consistent with an industry dominated by one or a few investment sources with complete information. However, a single "brute force" simultaneous solve is not necessarily consistent with a developmental context of an industry with multiple investors may not have similar information sets or do not coordinate their decisions.

This study proposes an alternative approach to solving a large-scale biofuel supply chain network problem at a high spatial resolution. The proposed methodology is adaptable to a broader class of logistic and supply network problems that schedule the collection and transportation of bulky materials to least-cost production or preprocessing sites. The approach assumes that one or more investors choose least-cost locations for biorefineries such that transport costs from the farm gate to the facility are minimized and industry profit is maximized. Given this solution, the second stage determines an optimal number and profit maximizing configuration of preprocessing units. The empirical example analyzes the *ex-ante* distribution of potential feedstock locations in the state of Tennessee, US. The feedstock is switchgrass and biobutanol is the primary fuel product.

2. Current status of GIS and MIP methods applied to biofuel supply network problems

A challenge to the commercial development of an advanced biofuel industry is the design and location of feedstock and biofuel supply chains, including upstream operations (from farm to biorefineries) and downstream distribution networks (from biorefineries to end users). Large-scale production of cellulosic feedstock, biomass transport, preprocessing, and conversion to biofuel and co-products pose obstacles unlike those of conventional petroleum refinery and distribution systems. Industrial cultivation of cellulosic feedstock materials (for example, switchgrass) requires land currently used in conventional agricultural uses such as pasture or crop production. Biorefinery proximity to end users and feedstock production areas will also affect local transportation systems, environmental quality, regional economies, and the prices paid (received) for inputs (final products) [5–12].

Questions remain, however, including how much feedstock can be reliably produced and where firms will locate with respect to maximizing their net present value, given existing infrastructure and productive resources. High-resolution geographic data that interleaves transportation costs surfaces, feedstock production potential, and demand centers is important for making strategic investment decisions and eventually supporting the long-term sustainability of the industry [13,14]. The transportation of different feedstock types, technology paths, and regional production and distribution problems have been typically investigated using three main approaches: (1) Mixed Integer Programming (MIP) models; (2) Geographic Information System (GIS) based models; and (3) combined GIS and MIP platforms.

The application of MIP models for analyzing the flow of commodities through networks is well-received because of model accuracy, flexibility, and capacity to account for multiple economic constraints and competition for resources among different users. There are numerous applications using MIP models to design optimal bioenergy supply chains (e.g., [6,8,15–32]). Constrained MIP models are usually solvable using commercial optimization packages such as CPLEX, Gurobi, or genetic algorithms [33,34].

Most feedstock distribution and facility location analyses using MIP have focused on the optimal configuration of sequencing of supply chains. Many examples assumed limited production scales because of data constraints, convenience, or solvability (e.g., [7,18,35–37]). Other studies modeled the *ex-ante* development of commercial scale biofuel production at larger regional levels (such as states), but at relatively low levels of spatial resolution. For example, Ref. [38] developed a multi-region and multi-period MIP model for the US state of Oklahoma. Their model was first to combine feedstock supply logistics and feedstock production, biomass dry matter loss, transportation, storage, and feedstock inventory management. Ref. [38]'s spatial resolution was scaled to the county level. Ref. [21] used MIP to optimize a biofuel supply chain in California, considering various feedstocks, commercial scales, and final demand targets. The resolution of their analysis was also at the county (feedstock production) and metropolitan levels (demand centers). Another study of large scale feedstock and multi-location biofuel production disaggregated the United Kingdom into $108\,\text{km} \times 108\,\text{km}$ cells to determine optimal feedstock producing areas, facility locations, and biofuel production capacity [39]. Ref. [39]'s MIP model considered three transportation modes including roads, rail systems, and navigable waterways.

The second type of model uses Geographical Information Systems (GIS) integrating land cover, topography, and built infrastructure coverage to determine biomass supply areas and corresponding facility locations [10,11,34,40–43]. Applications using the GIS approach combine high-resolution spatial layers to project physical features such as road and rail networks, vehicle transportation modes, speed limits, and travel distance. An advantage of stand-alone GIS models is that the production potential, distribution of available feedstock, optimal biorefinery locations, and the distribution paths of biofuel can be determined without explicitly defined objective functions or resource constraints. However, these advantages are also a limitation in terms of model documentation, transferability, replicability, and economic analyses of resource allocation among different entities or locations [43].

The integration of GIS and MIP modeling approaches has obvious advantages. High-resolution geographic features of infrastructure and the routing of resources and end products can be used to structure optimization problems with mixed integer variables and resource availability constraints. For example, Ref. [44] developed a decision-making tool to determine an optimal configuration of biorefinery plant locations and biomass collection activities using GIS and MIP modules for a region in Italy. Ref. [45] used a GIS model to determine a supply chain network in the US state of Michigan. Ref. [45] then used MIP to determine biorefinery capacity, facility numbers, required biomass production amounts, and the transport costs of feedstock to facilities. Ref. [6] combined a MIP cost minimization transport algorithm anchored to GIS surfaces to determine biofuel facility locations, feedstock routing, and feedstock production regions in East Tennessee, US. The primary decision-making units were $13\,\text{km}^2$ hexagons. Ref. [8] conducted a similar analysis at the same resolution for West Tennessee, USA.

The advantages of using combined GIS-MIP models to determine optimal biofuel supply chains configurations is apparent. Higher resolution spatial data adds detailed information about resource constraints, which translates into more precise estimates of feedstock areas and facility locations. However, increased precision comes at computational costs. Simultaneously siting biorefinery facilities, feedstock production units, and possibly preprocessing facility locations is a large-dimension combinatorial problem. Greater numbers of potential facility locations and feedstock growing areas require additional computational resources. Worse, composed models may be too large to be read into most personal computers [19]. In our experience, high performance computing environments may not resolve solve-time problems caused by dimensionality.

Solving high-dimensional biomass-to-biofuel supply chain network problems has received attention in recent years mainly from engineering efficiency and mathematical perspectives. Research has proposed methods to reduce model size and solving time; for example, applying transport distance constraints, limiting the number of potential candidate sites for facilities, and aggregating spatial units [46]; parallel computation has been applied [30] and advanced algorithms proposed (e.g., [28,12,47–49]) to further improve the solving