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Decision support system integrating GIS with simulation and optimisation for a biofuel supply chain

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ABSTRACT

A range of economic and societal issues has resulted from fossil fuel consumption in the transportation sector in the U.S. These include health related air pollution, climate change, dependence on imported oil, and other oil related national security concerns. Biofuels production from various lignocellulosic biomass types, such as wood, forest residues, and agriculture residues, have the potential to replace a portion of the total fossil fuel consumption. This study focused on locating biofuel facilities and designing the biofuel supply chain to minimise the overall cost. For this purpose, an integrated methodology was proposed by combining the Geographic Information System technology with simulation and optimisation modelling methods. The GIS-based method was used as a precursor for selecting biofuel facility locations by employing a series of decision factors. The identified candidate sites for biofuel production served as inputs for simulation and optimisation modelling. The simulation/optimisation model and identified locations provided an integrated decision support system for decision makers to determine the optimal cost, energy consumption, and emissions for candidate locations. This novel methodology development extends prior research.

1. Introduction

A range of societal issues have been caused by fossil fuel consumption in the transportation sector in the U.S., including health related air pollution, climate change, dependence on imported oil, and other oil related national security concerns [1]. Biofuels production from various forms of lignocellulosic, biomass materials such as wood, forest residues, and agriculture residues have the potential to replace a portion of the total fossil fuel consumption [2]. This study focused on locating biofuel facilities and designing the biofuel supply chain to minimise the overall cost. For this purpose an integrated methodology was proposed by combining the Geographic Information System (GIS) technology with simulation and optimisation modelling methods. The GIS-based method was used as a precursor for selecting biofuel facility locations by employing a series of decision factors. The identified candidate sites for biofuel production served as inputs for simulation and optimisation modelling.

There is a stream of literature on modelling biofuel supply chains and facility location problems by using one of the three modelling approaches or by combining two of the methods. However, literature on the integrated approach by combining all three methods is less extensive. GIS has proved to be an effective tool to address issues related to biofuel facility location selection, biomass availability, and biomass logistics [3–6]. Simulation models had been developed to track flows of a given supply chain network [7]. For example, the integrated biomass supply analysis and logistics model (IBSAL) for supplying corn stover to a biorefinery [8,9]; and the Straw Handling Model (SHAM) built for delivering straw to a heating plant [10,11]. The optimisation modelling method had been widely used for biofuel supply chain design [12–17]. Walther et al. [18] built a multi-period MIP-model for integrated location, capacity and technology planning for the design of production networks for second generation bio-diesel.

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Dekker et al. [19] presented a review that highlights the contribution of Operations Research (OR) to green logistics, focussing on design, planning and control in a supply chain for transportation, inventory of products and facility decisions.

Simulation combined with optimisation was demonstrated to be an effective method to identify the optimal combination of biomass feedstock type, transportation mode, and number of biorefineries before actual plant construction [20]. Two studies, Elia et al. [20] and Leduc et al. [21] used simulation results as input for optimisation modelling to evaluate biofuel production. Elia et al. [20] built a MILP formulation to assess hybrid coal, biomass, and natural gas supply network for liquid biofuel production in the U.S. A total of 270 simulation runs were conducted for various combinations of feedstock types (e.g. biomass, natural gas and coal) and biorefinery capacities. The simulation results, such as the to-be-delivered amount of feedstock to a plant and the amount of biofuel produced, were used as input for the MILP model and the optimal supply network was determined [20]. Leduc et al. [21] developed a simulation-based optimisation model to evaluate combined ethanol, power, heat, and biogas production in Sweden. The simulation results were used as inputs for the optimisation model in terms of yields of ethanol, electricity, heat and biogas produced from biomass feedstock [21]. The optimal location of building an ethanol facility was identified and the ethanol price was computed [21].

De Mol et al. [22] created both simulation and optimisation models for the logistics of biomass fuel collection. The two models share similarities and also have some differences. The simulation model is preferred when the network structure of the logistics is pre-defined. The optimisation model is more effective to determine the optimal network structure, including the optimal mixture of biomass types [22]. Since the actual transports were determined by the simulation model, it allows for tracking of time-dependent parameters, such as moisture and dry matter losses through the collection network. In optimisation modelling it is difficult to include the time-dependent effects because they are based on the annual flows [22]. The simulation model used cost and energy consumption as performance indicators while the optimisation model determined calculated cost [22].

There is limited work in the area of modelling woody biomass supply chains using optimisation and simulation simultaneously [20–22]. Additionally as a precursor to optimisation or simulation modelling, the GIS-based facility location analysis considers a series of factors simultaneously. To date, we are unaware of the application of these three methods integrated into a single research study. The benefit of integrating all three methods is its capability of addressing several issues that add complexity to the supply chain model, such as biomass harvesting and transport. For northern climates with snow and ice, the spring breakup period imposes weight limits on transportation vehicles. This is because of the thawing and freezing cycle of the roadways in the spring that subject them to damage if heavily travelled by vehicles with full loads. It is not economically viable to travel with partially loaded vehicles. The variability of spring breakup timing introduced uncertainties into the supply chain. The simulation model was designed to focus on these uncertainties. The spring break-up time could be specified as scenarios input to each harvest area in order to allow representation of the time dynamics of the system [23]. The simulation model could show how the given supply system works during the spring breakup.

2. Integrated methodology

The proposed integrated methodology, that combines the GIS technology with simulation and optimisation modelling methods, is illustrated in Fig. 1. The GIS-based methodology was applied as a first step for selecting biofuel facility locations by employing a series of decision factors to include accessibility to biomass, railway/road transportation network, water body, and workforce. The resulting candidate sites served as inputs for the simulation and optimisation modelling. Using additional data including biomass availability, cost factors, energy factors, and emissions factors, the simulation model tracks flows of a given supply chain network, whilst the optimisation model identifies the optimal supply chain network. Both models can be applied to determine the optimal cost, consisting of the delivered feedstock cost, inventory holding cost, energy consumption cost, and GHG emissions cost for candidate locations.

Whilst the simulation model provided detailed outputs for specified scenarios, strategic questions such as how many harvesting areas should be included, when and where to acquire harvesting contracts, and what is the operating plan for spring breakup were addressed by simulating multiple scenarios over multiple years. The optimisation model was developed to inform these strategic decisions. The annual optimisation results were disaggregated and synchronized with the required weekly simulation input. After several replications (or several years) of a simulation run, the simulation model showed statistical results for the outputs. The simulation outputs provided feedback to the optimisation model in the form of refined parameter values. The optimisation model was then run again to provide updated strategic plans to the simulation model. This process can be repeated as necessary in order to develop a robust solution to the scenario being considered.

2.1. GIS-based methodology for preselecting biofuel facility locations

As a precursor to simulation or optimisation modelling, the GIS-based methodology was used to preselect potential biofuel facility locations for biofuel production from forest biomass. Fig. 2 presents an overview of the GIS-based methodology, which considered eight decision factors [7]: (a) county boundaries, (b) a railroad transportation network, (c) a state/federal road transportation network, (d) water body (rivers, lakes, etc.) dispersion, (e) city and village dispersion, (f) a population census, (g) biomass production, and (h)

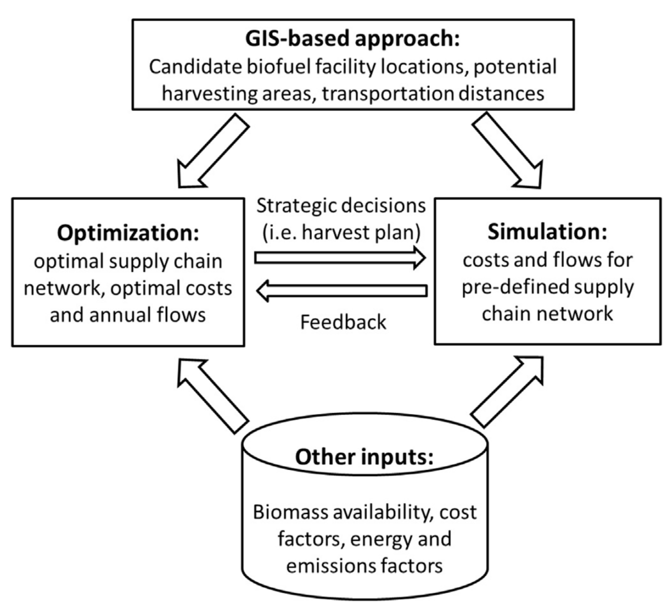

Fig. 1. Overview of the integrated methodology.