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Simulation-based approach for the optimization of a biofuel supply chain

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Abstract

The billion-ton study lead by the Oak Ridge National Laboratory indicates that the U.S. can sustainably produce over a billion ton of biomass, annually. However, the delivery of the biomass required to meet the required goals is particularly challenging. This is mainly because of the physical properties of biomass. This paper focuses on the use of agricultural residues to produce second-generation biofuels. Second generation biomass exhibits more quality variability (e.g., higher ash and moisture contents) than first generation. The purpose of this study is to quantify the cost of imperfect feedstock quality in a biomass-to-biorefinery supply chain (SC) and to develop a discrete event simulation coupled with an optimization algorithm for designing a biofuel SC's. This paper presents a novel optimization approach based on an extended Integrated Biomass Supply and Logistics (IBSAL) simulation model for estimating the collection, storage, and transportation costs. The presented extension of the IBSAL considers the cost incurred for having imperfect feedstock quality and finds the optimal SC design. The applicability of this methodology is illustrated by using a case study in Ontario, Canada. A converging set of non-dominated solutions is obtained from computational experiments. Sensitivity analysis is performed to evaluate the impact of different scenarios on overall costs. Preliminary results are presented.

Keywords
Logistics; Discrete-event Simulation; Simulation-based Optimization; Supply Chain; Renewable Energy; Biofuels.

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1. Introduction

The motivation for moving from fossil to renewable (clean) energy presents some challenges in terms of the high logistical cost and the ability of non-fossil based fuels to become cost competitive. Some of the reasons that motivate this effort are: environmental sustainability, energy security, and agricultural economics. Biomass is the largest single source of renewable energy (3.9 quadrillion out of the 9.6 quadrillion Btu in 2015) [1]. Additional to the production of biofuels, which have been recognized as an alternative source of renewable energy [2], biomass is used in partial replacement processes for the generation of electricity (e.g., co-firing wood pellets in coal plants), and for the production of biomaterials. The billion-ton study lead by the Oak Ridge National Laboratory indicates that the U.S. can sustainably produce over a billion ton of biomass annually without adversely affecting the environment [1]. However, the challenge derives greatly from the logistics (i.e., collecting, storing, and transporting the biomass to the biorefineries at a cost-effective delivered cost) imposed by the physical properties of biomass. Biomass is bulky, widely geographically dispersed, season and weather dependent and has low energy density.

The U.S. government has established a series of goals in the Renewable Fuel Standards (RFS) mentioned in the 2007 Energy Independence and Security Act (EISA) [3] to support the effort of moving from fossil to renewable energy. The goals of RFS (2) are to produce 9 billion gallons of renewable fuel by 2008, and 36 billion by 2022 (no more than 15 billion from corn-starch and a minimum of 16 billion gallons from cellulosic biofuels [4]). Particularly, the RFS requirements for cellulosic biofuel are 230 million gallons for 2016, and 312 (proposed) for 2017 (i.e., increase by 35% (82 million gallons) between 2016 and 2017) [5]. Also, the standard proposes to reduce 60% the lifecycle carbon emission from cellulosic biofuels [5].

Incentives that focus on achieving these goals include feed-in tariffs, tax credits, penalties for carbon emissions, tax exemptions for bioenergy and biomaterials, and the creation of innovative biofuel technologies that allow increasing the production [6]. The government has developed strategies such as *All-of-the-Above*, which are intended to achieve these goals. The delivery of scientific tools that allow strengthening the connection between science and technology [7] is among the objectives that support the *All-of-the-Above Strategy* in the 2014-2018 Plan developed by the Department of Energy (DoE). This objective includes the creation of models that demonstrate that biomass can be viable, sustainable feedstock for hydrogen production for fuel cells and other applications [7]. The models mentioned in Table 1 and the models proposed in this paper are aligned to this overarching goal.

This paper presents a model for estimating the collection, storage, and transportation costs and the cost from having imperfect corn stover quality for the production of bioethanol. The proposed model is based on the I*ntegrated Biomass Supply and Logistic (IBSAL) model* developed by Sokhansanj et al. [8]. The proposed model differs from the IBSAL model in terms of the assumptions, solution methods, and degree of detail for representing the biomass quality (physical and chemical properties) in the SC. The rationale for this research is to test the capability of the proposed novel optimization methodology which communicates with the IBSAL model, and to obtain preliminary results on the effect of the impact of imperfect feedstock quality on the biofuels supply chain planning and design decisions.

This paper is structured as follows: section 2 presents a literature review of: (a) generations of biofuels and lignocellulosic feedstock, (b) imperfect feedstock quality, and (3) models for improving biomass supply chains. Section 3 presents a description of the IBSAL-SimMOpt solution procedure to find near optimal solutions to the biomass-to-biorefinery SC that considers quality-related costs. Section 4 describes the implementation of the IBSAL-SimMOpt procedure to a case study using ExtendSim®™. Section 5 presents the results and concluding remarks. Finally, Section 6 discusses future research.

2. Literature Review

2.1. Generations of Biofuels and Lignocellulosic Feedstock

Biomass can be obtained from energy crops, agricultural and forest residues to produce second-generation biofuels. First-generation biofuels (e.g., biodiesel, corn ethanol, propanol, biodiesel, methanol, among others) produced using edible products (e.g., vegetable oil, sugar, starch, wheat, corn, soybean, sugar cane, among others) have higher energy density, lower ash content, and smaller collection/transportation costs as compared to agricultural and forest waste. However, these types of biomass raised the national debate of *food versus fuel*. This controversy was one of the main reasons for the development of second-generation biofuels (e.g., bio-oil, lignocellulosic ethanol, bioethanol, butanol, Fischer-Tropsch diesel, among others) that use energy crops, non-food plant waste biomass (e.g., agricultural and forest waste). *Second-generation biomass exhibits more quality variability* (e.g., higher ash and moisture contents) *than first-generation biomass*. Recent research that focuses on developing technology that reduces the cost of conversion of second-generation biomass has exponentially grown [2]. The proposed method in this paper provides a decision tool for designing and improving the supply of lignocellulosic feedstock (i.e., corn stover) for the production of a second-generation biofuel. The RFS requirements for cellulosic biofuel have been mentioned in Section 1 of this paper.

Lignocellulose is the most abundant biological material. This material is used for biomass-based heat and power, biofuels, and biomaterials. Lignocellulosic feedstock is obtained from agricultural residues (e.g., corn stover, /sorghum/wheat straw, surgarcane bagasse, among others), hardwood and softwood forest residues, and biofuel crops (switchgrass, miscanthus, energy cane, and woody crops, among others [9], [10]). Mixing biofuel crops currently remain the most viable option in practice for large-scale production.

Corn stover is an important source of biomass in some regions for the production of bioethanol. The long-term demand for corn stover by non-fermentative applications is 23 million dry tons/year. This allows 60-80 million dry tons/year to be potentially available for ethanol production [11]. The case study in this paper considers the SC of *corn stover* for the production of *bioethanol.*

2.2. Imperfect Feedstock Quality

In Section 1, it was mentioned that the challenge is to supply the biomass feedstock to the reactor throat at the biorefinery at a sensible delivery cost. The delivery cost is affected by the production, harvest, storage, handling, preprocessing, and transportation costs [1]. The cost related to the biomass feedstock represents 40% to 60% of the total operating cost of a chain [12,13] that supplies a refinery, which usually has a lifetime of 20 to 25 years. Hence, the viability of a bioenergy project is affected by the delivery cost, which is sensitive to yield of the raw material [14]. The yield of the feedstock is largely determined by the feedstock quality. Castillo-Villar, et al. [15] describe the effect of including in the supply chain operations intended to improve the feedstock quality in terms of moisture and ash content. These operations are: (a) drying in-field to reduce moisture content, and screening to reduce the initial ash concentration; (b) mechanical drying to reduce moisture content, and ash disposal. Operations in (a) are preventive and ensure that the raw material has an acceptable quality when it reaches the refinery. The costs related to the performance of these operations are described as conformance costs. The operations in (b) are considered non-conformance costs, which represent a reactive quality control activity that does not improve the biomass quality and it occurs when the biomass reaches the biorefinery. Finally, the is a penalty cost for reduced yield due to poor biomass quality (i.e., opportunity cost) [15].

This paper presents a model for estimating and improving the cost from having *imperfect corn stover quality* (i.e., uncertain and potentially non-conforming moisture and ash content feedstock) for the production of second generation bioethanol.

2.3. Models for Biomass SC's

Table 1 shows recent research relevant to this paper. Some of these papers provide a description of the technologies and costs that are represented in the harvesting, collection, storage, or transportation blocks in the IBSAL model.

Table 1. Models for biomass SC's

Ref.	Objective / Feedstock	Method
Biomass supply chains		
[16]	Rank alternatives for the collection and transportation of biomass. Feedstock: Biomass (corn stover).	Multi-criteria assessment methodology (PROMETHEE) & IBSAL
[17]	Evaluate collection systems of switchgrass and analyze the related costs, energy input, and carbon emissions. Feedstock: Switchgrass	Discrete event simulation
[18]	Evaluate the impact of residue yield on the biomass delivered cost. Feedstock: Straw and chaff from wheat, barley, and oats.	Discrete event simulation
[19]	Propose supply of corn stover to produce heat and power for a dry mill ethanol plant. Feedstock: Corn stover.	Discrete event simulation
[20]	Minimize the feedstock costs in a logistic system by maximizing highway load and minimizing load/unload times. Feedstock: Cotton (analogously to biomass)	Discrete event simulation
[21]	Optimize the harvest of energy sorghum in the humid southern region by using a modified cotton module builder for the formation of modules. Feedstock: Energy sorghum.	Discrete event simulation
Development of the IBSAL model		
[8]	Describe the development of the IBSAL model. Feedstock: Corn stover.	Discrete event simulation
[22]	Detailed description of the IBSAL model. Feedstock: Corn stover.	Discrete event simulation
[23]	Propose a model for the supply of a mixture of feedstock to a cellulosic ethanol plant. Feedstock: Multi-agricultural.	Discrete event simulation (IBSAL-MC (Multi-crop))
Availability of feedstock and Technology		
[24]	Evaluate technologies for the production, harvest, storage, and transportation. Feedstock: Switchgrass.	Empirical
[21]	Optimize the harvest of energy sorghum in the humid southern region by using a modified cotton module builder for the formation of modules. Feedstock: Energy sorghum.	Discrete event simulation
[25]	Determine the effect of weather on harvested moisture content. Feedstock: Switchgrass and energy sorghum.	Discrete event simulation

3. IBSAL-SimMOpt Approach

The approach presented in this paper is a two-phase model that uses an extension of the IBSAL model [8] in the initial phase, and searches a near-optimal set of solutions in the second phase by using an optimization procedure based on the SimMOpt model. The IBSAL model is a time-dependent discrete event simulation (DES) model with activity-based costing. The model in the proposed approach estimates the cost of imperfect feedstock quality and evaluates its effect on the performance of the SC.

The SimMOpt model is a simulation-based multi-objective optimization approach based on stochastic Simulated Annealing (SA). The solutions for near-optimal quality-related costs are found by using the extension of the IBSAL implemented in ExtendSim®™ and the SimMOpt-based procedure included in written in MS VBA®™ language. Figure 1 shows a diagram of the proposed approach.

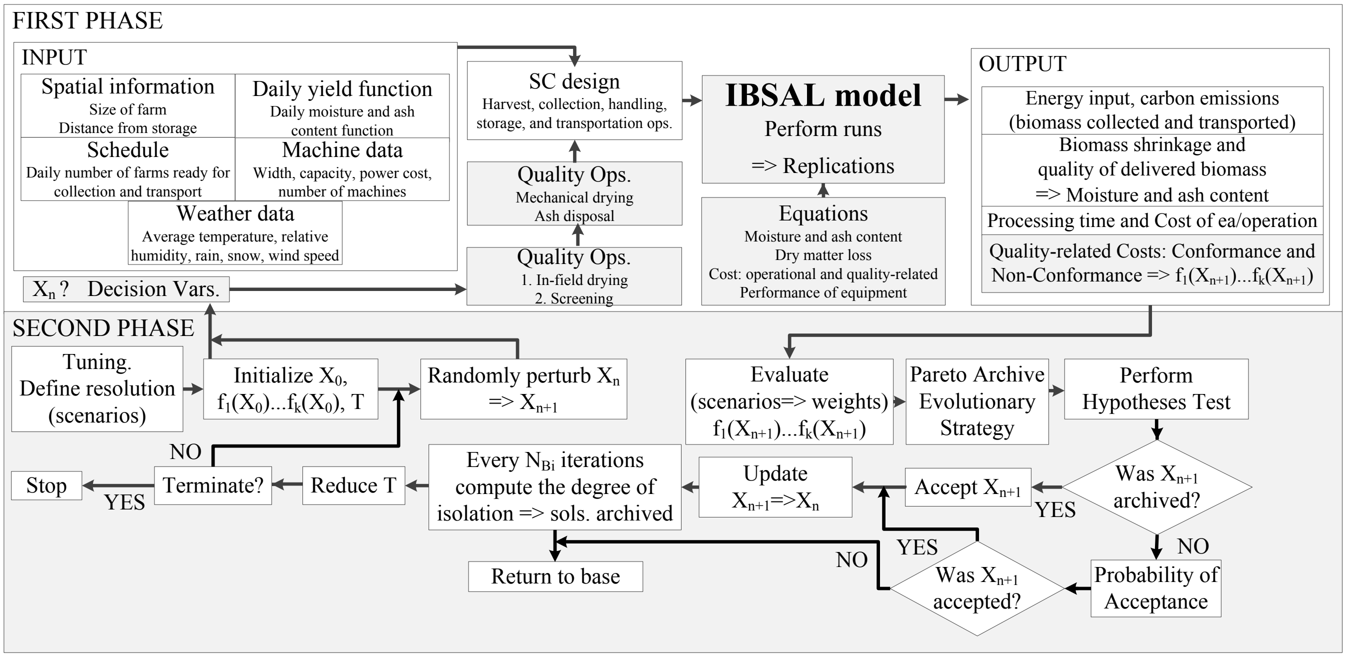

Figure 1. IBSAL-SimMOpt approach

4. Case Study

The characteristics of the system described in this research include a geographical implementation (i.e., Southern and Western Ontario, Canada), crop availability (ac), corn yield (bu/ac), sustainable production (dry tonne/ac), among others. The geographical implementation corresponds to 20 farms located in the following counties: Lambton, Chatam-Kent, Middlesex, and Huron. Figure 2 shows a diagram of the biomass-to-biofuel SC considered in the IBSAL model.

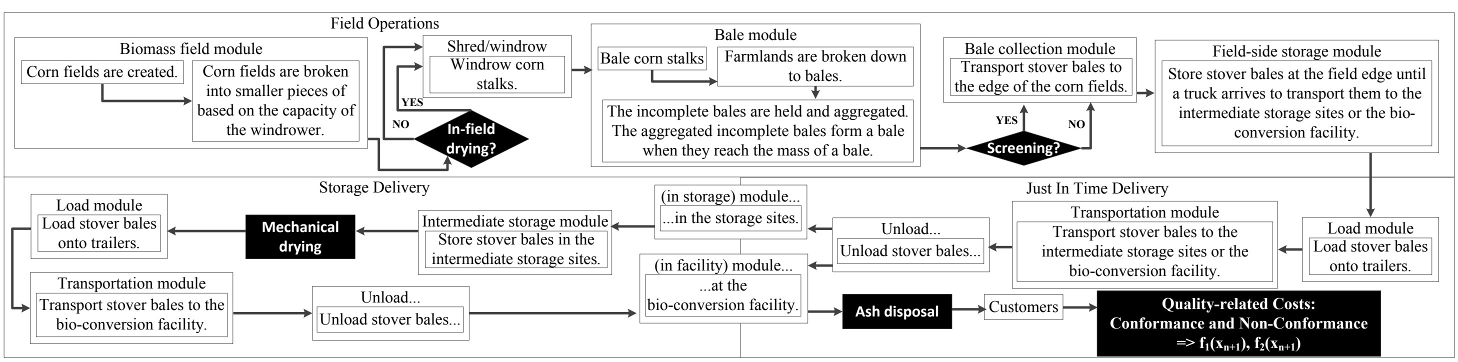

Figure 2. IBSAL model: Corn stover-to-ethanol SC

The initial moisture content is modeled by ~U(0.6, 0.8) [26]. The moisture content after the natural drying process is assumed to follow ~U(0.15, 0.3) [15]. The moisture content requirement for thermochemical processes is 20%. If the content remains above 20% [27], the stover goes through a mechanical drying process. The cost of the natural air drying system is given by (0.014 * (Initial Moisture Content – Final Moisture Content) * 100) + 0.05 per bushel and the in-bin, stirred system is given by (0.033 * (Initial Moisture Content) * 100) + 0.048 per bushel [28]. Similarly, the initial ash content follows ~U(0.08,0.12) [29]. The ash content after the screening process is assumed to follow ~U(0.1, Initial Ash Content). The screening cost is given by 135(Initial Ash Content – Final Ash Content) per dry tonne [15]. The cost of disposing ash is given by 28.86(Final Ash Content) per dry tonne. The binary decision variables in this model represent the decisions of performing the field drying and the screening activities at each farm.

5. Results and Conclusions

The SA was tuned through designed computational experiments. The SA schedules have a relevant effect on the set of these preliminary solutions [30]. Figure 3 shows the Pareto front including four schedules. The non-dominated solution that balances out the conformance and nonconformance costs (i.e., (0.4/0.6) and (0.6/0.4) weights) shows a conformance cost (the cost incurred to prevent biomass poor quality) of $49,899.47 and a non-conformance cost (cost incurred to fixed biomass poor quality) of $16,496.83 for all 20 farms. This non-dominated solution was found when using the schedule that computes the largest number of initial solutions (i.e., Schedule 4 → 50 initial solutions). This preliminary results highlighted the trade-off between conformance and conformance activities implemented into a biofuel SC. The impact of quality-related activities in the SC topology, design and planning decisions will be studied next.

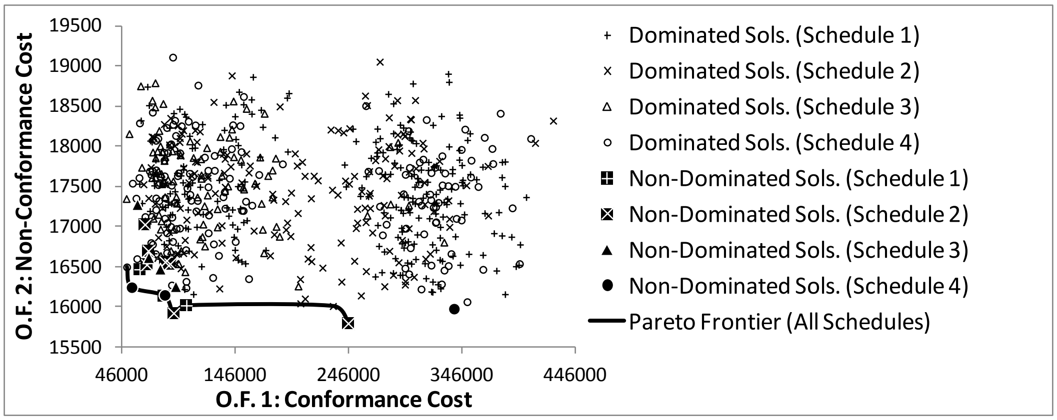

Figure 3. Pareto front from the case study

6. Future Research

Future work involves improving the exploration and exploitation conditions on the second phase of the procedure while reducing computational time by using different population-based and hybrid metaheuristics. Further research considers a full version of the IBSAL model that thoroughly represents the SC system and finds a near-optimal set of solutions for multiple objective functions (e.g., costs related to harvesting, storage, and transportation operations) while considering quality-related activities. The quality of these set of solutions can be evaluated in terms of its rate and time of convergence to the best solution obtained with the ExtendSim®™ Optimizer [31] taken as baseline case.

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