A Forest Biomass-to-Hydrogen Supply Chain Mathematical Model for Optimizing Carbon Emissions and Economic Metrics

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ABSTRACT

This study introduces a mathematical programming approach to optimize biomass-to-hydrocarbon supply chain design and planning, aiming to balance economic and environmental outcomes. The model incorporates a range of residual biomass types from forestry, sawmills, and the pulp and paper industry, with the option to establish various processing facilities and technologies over a multi-period planning horizon. The analysis involves selecting forest areas, identifying biomass sources, and determining the optimal locations, technologies, and capacities for facilities converting wood-based residues into methanol and pyrolysis oil, which can be further refined into biodiesel and drop-in fuels. Using Life Cycle Assessment (LCA) in a gate-to-gate analysis, forest supply chain carbon emissions are estimated and integrated into the optimization model, extending previous research. A multi-objective framework is employed to minimize CO_2-equivalent emissions while minimizing present costs, with efficient Pareto points evaluated in a case study focused on the Argentine forest industry.

Keywords: Supply Chain, Life Cycle Analysis, Biomass, Optimization.

INTRODUCTION

Forest supply chains (FSCs) are critical for achieving decarbonization targets [1]. FSCs are characterized by abundant biomass residues, offering an opportunity to add value to processes while contributing to the production of clean energy products. One particularly interesting aspect is their potential integration with oil refineries to produce drop-in fuels, offering a transformative pathway to mitigate traditional refinery emissions [2].

In this article, a disjunctive mathematical programming approach is presented to optimize the design and planning of the FSC for the production of hydrocarbon products from biomass, optimizing both economic and environmental objectives. Various types of byproducts and residual biomass from forest harvesting activities, sawmill production, and the pulp and paper industries are considered. Alternative processing facilities and technologies can be established over a multi-period planning horizon. The design problem scope involves selecting forest areas for exploitation, identifying biomass sources, and determining the locations, technologies, and capacities of facilities that transform wood-based residues into methanol and pyrolysis oil, which are further processed in biodiesel and petroleum refinery plants, respectively. This problem is challenging due to the complexity of the supply chain network, which involves numerous decisions, constraints, and objectives. In particular, in the case of large geographical areas, transportation becomes a crucial aspect of supply chain design and planning because the low biomass density significantly impacts carbon emissions and costs. Thus, the scope of planning the problem includes selecting connections and material flows across the supply chain. A multi-objective approach is proposed to assess economic and environmental objectives. A set of efficient Pareto points is

obtained and compared in a case study of the Argentine forest industry.

PROBLEM STATEMENT

A supply chain superstructure is considered in this paper formed by three echelons: the feedstock areas where pine and eucalyptus logs, forest residues, and sawmill residues are obtained; the processing facilities, where biomass is converted into fuels and intermediates; and the consumer nodes (biodiesel plants or petroleum refineries). Logs are used for the paper industry, i.e., the kraft pulping process, while residues from all sources are transformed into fuel products. Stand-alone and integrated plants can be selected to produce intermediate or final products (hydrogenated pyrolysis oil for petroleum refineries and methanol for biodiesel plants).

Process alternative pathways are presented in Figure 1.
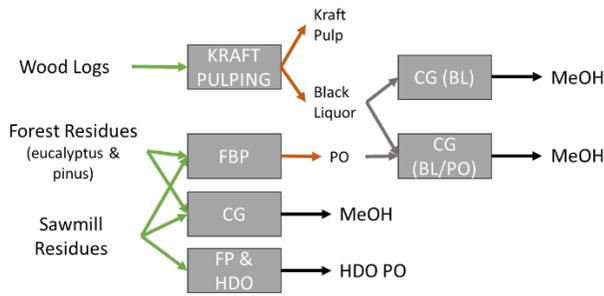
References: BL: black liquor; CG: catalitic gasification; FBP: fluidised bed pyrolysis; FP: fast pyrolysis; PO: Pyrolysis oil; HDO: Hydroxygenation; HDO PO: Hydroxygenated pyrolysis oil.

Figure 1. Process alternatives.

The problem studied can be stated as follows, given: processing, investment and transportation costs; environmental impact of each process, measured in equivalent carbon emissions; products' demand; capacity levels and economy scale factors; biomass availability and allowed capacity expansions in forest nodes; processing yields. The model must select over a multi-period timeframe: (i) The extent of land and types of tree species to be harvested at each forest location and within each time period; (ii) The processing facilities to be established at each location over time, including their technology, scale, and degree of integration; (iii) The output levels for each technology and processing plant in every time period; (iv) The capacity outlines for each supply chain processing facility across the entire timeline; (v) The transport flows of all materials and supply chain linkages across each time period. The goal is to minimize the present costs and the environmental impact of the supply chain.

MULTI-OBJECTIVE APPROACH

As mentioned, this article extends previous work from Piedra-Jimenez et al. [3], where the supply chain is optimized assuming an economic objective function (minimizing total present costs). The deterministic formulation presented there is reformulated as a bi-objective model to include the minimization of the CO_2 equivalent emissions.

The Life Cycle Assessment (LCA) methodology is used to estimate FSC carbon emissions. A gate-to-gate analysis is carried out for each activity in the FSC and combined with the optimization problem to obtain a cradle-to-gate LCA. The predicted LCA results are then integrated as input parameters into a mathematical programming model for FSC design and planning to optimize the bi-objective problem. This formulation is solved by assuming the Ɛ-constraint approach to obtain a set of Pareto optimal points. The total impact is presented in Eq. (1). Transportation emissions are estimated in Eq. (2), and emissions from processing facilities are estimated in Eq. (3). Due to space limitations, the rest of the formulation is not transcribed here, as it can be found in Piedra-Jimenez et al. (2024), resulting in a generalized disjunctive model (GDP) implemented as a mixed integer linear programming (MILP) model using Big M reformulation.

$$CO_2e = TCO_2e + PCO_2e \qquad (1)$$

$$TCO_2e = \sum_{\substack{r,s,j,k,m,t \\ (r,s)\in M_{RS}}} \zeta1_{r,s} \cdot \rho1_{j,k} \cdot F1_{r,s,j,k,m,t} +$$

$$\sum_{\substack{i,k',m',k,m,t \\ (i,m)\in M_I \\ (i,m')\in I_M}} \zeta2_i \cdot \rho2_{k,k'} \cdot F2_{i,k,m,k',m',t} + \sum_{\substack{o,k,m,l,t \\ (o,m)\in M_O}} \zeta3_o \cdot \rho3_{k,l} \cdot$$

$$F3_{o,k,m,l,t} \qquad \forall \, t \qquad (2)$$

$$PCO_2e = \sum_{\substack{r,s,j,k,m,t \\ (r,s)\in M_{RS}}} \vartheta1_{r,s,m} \cdot F1_{r,s,j,k,m,t} +$$

$$\sum_{\substack{i,k',m',k,m,t \\ (i,m)\in M_I \\ (i,m')\in I_M}} \vartheta2_{i,m} \cdot F2_{i,k,m,k',m',t} \qquad (3)$$

Parameters

$\zeta1_{r,s}$ carbon dioxide equivalent emission for the transportation truck used for raw material (r,s) from sources j to plants k (t CO2 Emission/ t-km)

$\zeta2_i$ carbon dioxide equivalent emission for the transportation truck used for intermediate product i from plants k to other facilities k (t CO2 Emission/ t-km)

$\zeta3_o$ carbon dioxide equivalent emission for the transportation truck used for product o from plants k to clients l (t CO2 Emission/ t-km)

$\vartheta1_{r,s,m}$ carbon dioxide equivalent emission from processing raw material r from tree species using technology m (t CO2 Emission/ t feedstock)

$\vartheta2_{i,m}$ carbon dioxide emission from processing intermediate product i using technology m (t CO2 Emission/ t feedstock)

$\rho1_{j,k}$ distance between raw material nodes j and processing plants k (km)

$\rho2_{k,k'}$ distance between processing plants k and k' (km)

$\rho3_{k,l}$ distance between processing plants k and clients l (km)

Positive variables

$F1_{r,s,j,k,m,t}$ amount of raw material r of tree species s from node j to facility node k produced with technology m in period t

$F2_{i,k,m,k',m',t}$ amount of intermediate product i produced from processing node k which applying technology m that is consumed by node k´ for further processing with technology m´ in period t

$F3_{o,k,m,l,t}$ amount of final product o produced with technology m in location k to satisfy demand node l in period t

TCO_2e carbon equivalent emissions from transportation activities

PCO_2e carbon equivalent emissions from processing facilities

CO_2e total carbon equivalent emissions

The resulting formulation is a linear generalized disjunctive model that is reformulated with Big-M relaxation.

CASE STUDY AND RESULTS

Open LCA and EcoInvent 3.11 were used to estimate the equivalent CO_2eq emissions from processes and transportation following ISO 14040 and ISO 14044 [4, 5]. The processes characteristics regarding energy consumptions, efficiency, yields, were obtained from the literature [6 - 13]. Power energy matrix from Argentinean case study is estimated considering reports from the country [14]. A 15-year horizon planning (HP) is assumed.

The resulting emissions from each process and the input and output characteristics are presented in Table 1.

Regarding transportation, EURO 3 truck technology is assumed. The capacity assumed is based on typical cargo transportation options in Argentina (28.5 t for all type of products and an additional limitation of 37 m³ for liquids). Since no data for this country is available in LCA database, the rest of the world (RoW) reported emission from the EcoInvent is assumed. This value is estimated considering an average capacity load of 5.8 t.

In the Argentinean case study, the average load is quite larger than the one reported in the EcoInvent database. Therefore, the transportation emissions per ton-km are estimated according to the Argentinean load factor. This type of procedure is supported, for instance, in [15]. It is assumed that the trucks are used with 90% of the full load of a one-way trip and an empty return is considered. This estimation is presented in the last line of Table 2. For the different products, their density is used to calculate if the capacity restriction is determined by the volume or the weight of the truck. Except for the saw-mill residues, in all cases, the maximal weight is the active limitation. The calculated emission for each type of product is presented in Table 2.

The supply chain nodes considered are located in the northeast and center regions from Argentina as depicted in Figure 2. The FSC superstructure consists of 25 supply sources, 3 operational kraft pulp mills, 13 potential biorefinery locations, and 26 demand nodes (21 soybean-based biodiesel plants and 5 petroleum refineries).

Table 1: Process characteristics and estimated emissions from LCA analysis.

Material Input	Flowrate input (t/h)	Technology	Material Output	Flowrate Output (t/h)	Emission (t CO2eq /t input)
Saw-mill residues	43.29	Fast Pyrolysis	FP Oil	21.65	0.42627
FP Oil	21.65	Hydroxgenation (HDO)	HDO Bio-oil	14.29	0.20465
Forest Residues	52.70	Catalytic Gasification (1)	Methanol	22.7	0.18654
Forest Residues	20.90	Fluidised Bed Pyrolysis	FBP Oil	7.56	0.26788
FBP Oil + Black Liquor	43.4 + 173.6	Catalytic Gasification (2)	Methanol	62.5	0.62199
Black Liquor	173.60	Catalytic Gasification (3)	Methanol	40.1	0.26254

Table 2: Estimated emissions for transportation alternative and material.

Type of truck	Emission*	Saw-mill residues	Forest residues	Forest logs	FBP Oil	HDO Bio-oil	Methanol
Euro 3 16-32 Tons	0.196	0.1183	0.0885	0.0885	0.0885	0.0885	0.0885
Average load in t		10	13	13	13	13	13

* Data from EcoInvent Database 3.11 for RoW assuming 5.8 t of average capacity use

All reported units are in (kg CO2eq/t-km)

The model was implemented in GAMS and executed using solver CPLEX on a 32GB RAM machine with Intel Core i9-11900K 3.50GHz CPU. The problem consists of 4,968 integer variables, 88,016 continuous variables and 59,654 constraints. Each iteration (one per Pareto point) was executed to global optimality (gap 0%) in less than 9 minutes.
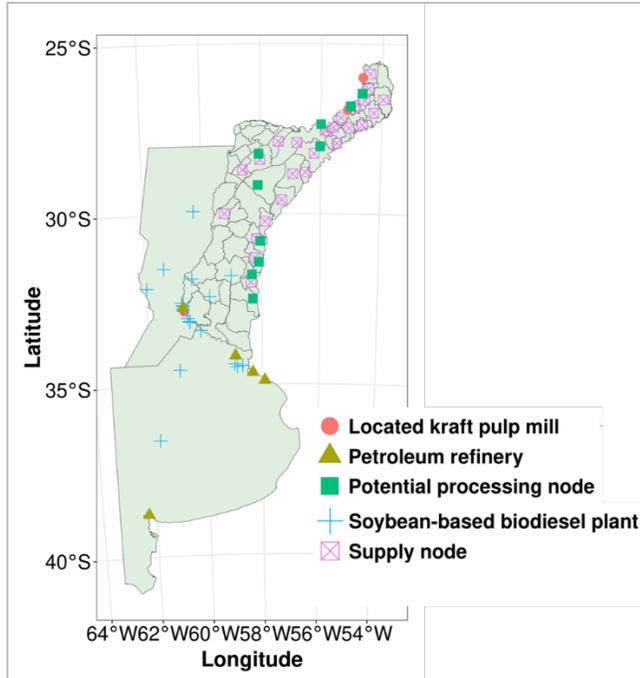

Figure 2. Locations for supply chain nodes.

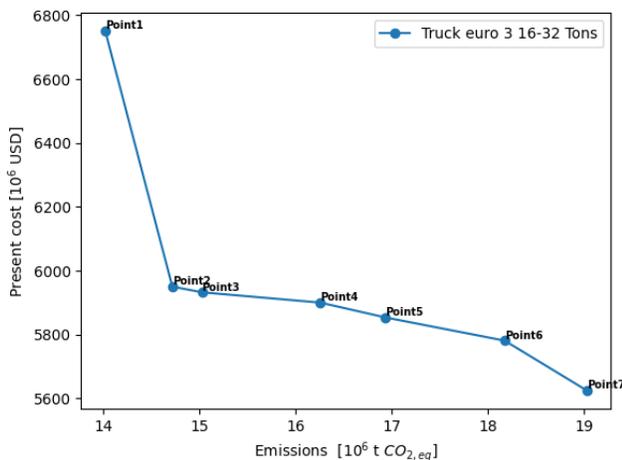The optimal solutions obtained are depicted in Figure 3, showing the compromise between the two proposed objectives.

Figure 3. Pareto front.

Considering the relative difference between points, the best compromise solution is given in point 2, i.e. a relevant decrease in present cost is shown at an expense of small increment in CO2 emissions. In this point, total emissions for the 15-year HP are 14,719,296 ton of CO2eq while total present costs are USD 5,949,789,094.

Figures 4 and 5 present the environmental and cost functions breakdown, respectively. In all cases, process emissions are larger than the ones from transportation. Particularly, processing forest biomass is the one that most contributes to the CO2 equivalent emissions. Regarding transportation, the larger emission from transportation of final products can be explained by the distances between nodes. Considering all solutions, the main difference in the emissions scheme is observed from point 1 to 2. In the first solution, only sawmill residues and forest biomass are consumed as raw materials. To improve costs, the use of intermediate products (such as black liquor and pyrolysis oil) is increased while sawmill residues consumption diminishes.
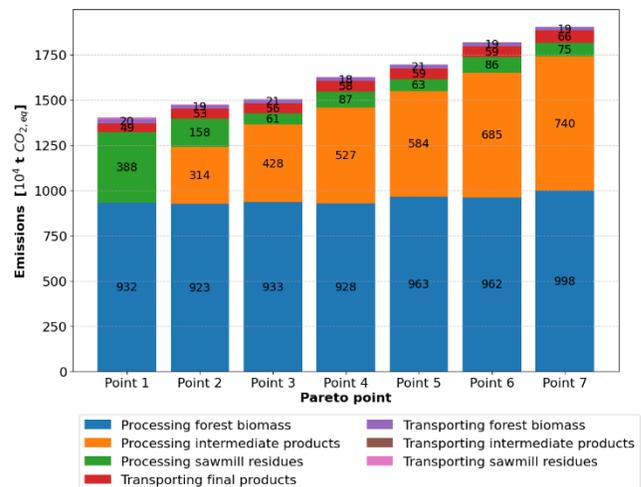

Figure 4. Emissions breakdown for all points

In the case of present costs, main component is given by investment cost in new plants followed by the variable cost for processing forest biomass. Except for the first point as mentioned before, the cost breakdown does not significantly change among points.

The selected technologies and plant locations are presented in Figure 6 for point 2 that is considered the best compromise solution. Two plants for producing HDO PO are installed, one located near 3 petroleum refineries and the other placed in the biomass sourcing area. Two plants are integrated to Kraft mills for producing methanol from black liquor via catalytic gasification. Another stand-alone plant is installed for producing methanol from forest residues using catalytic gasification technology.
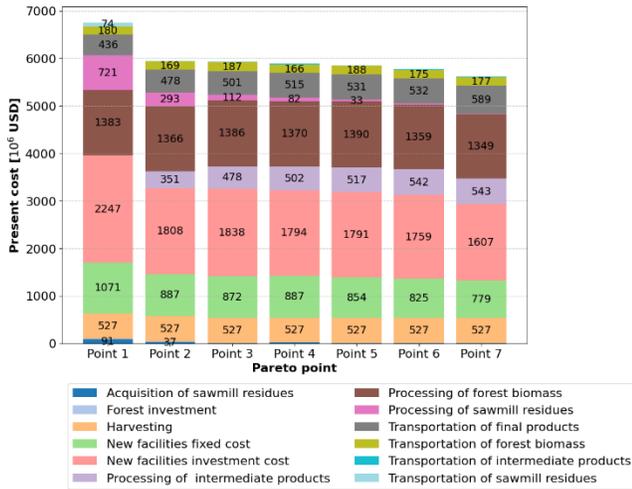
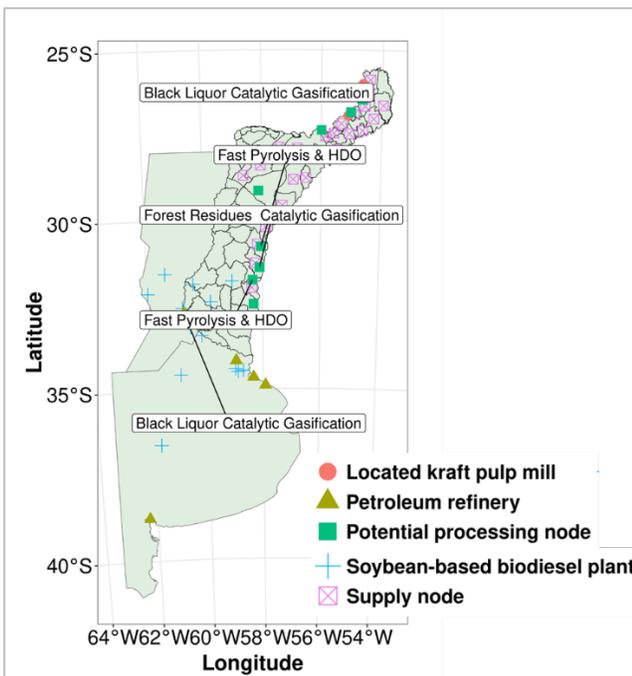**Figure 5.** Present costs breakdown for all points

Figure 6. Technologies and locations selected.

Table 3: Carbon intensity mean values.

Product	Co2 intensity (ton Co2eq/ton product)	Co2 intensity (g Co2eq/MJ)
HDO PO	1.65129	55.04
Methanol	0.98780	43.52

Table 3 presents the average carbon intensity for the produced bio-methanol and hydroxigenated pyrolysis oil. The fluctuations between points on the Pareto curve in unit emissions for hydrogenated pyrolysis oil are negligible. Only very small changes are observed. In the case of methanol, although there are variations between points, the maximum difference is less than 30%.

CONCLUSIONS

This article extends previous work by incorporating carbon emissions in the forest supply chain as a second optimization objective. The LCA methodology was applied to assess the environmental emissions of each activity within the supply chain's scope. A clear compromise solution can be selected, maintaining a good balance between present costs and total emissions.

The proposed model serves as a valuable tool for guiding the decision-making process, considering both economic and environmental perspectives in a supply chain that could reshape the wood-based industry in Argentina. The results indicate that residual biomass from this sector can be converted into value-added products, replacing their fossil-based alternatives. Future work includes testing the model computational performance for other instances considering other regions, input data and increasing problem size.

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