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Logistics Management of Agri-Industrial Waste for Energy Valorization in Uruguay

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ABSTRACT

The energy recovery of agro-industrial residual biomass offers a pathway to reduce fossil fuel emissions in thermal processes while valorizing waste. In practice, however, the primary bottleneck is logistical: feedstocks are geographically dispersed, with low bulk density and high moisture content, driving up collection, pretreatment, and transport costs. This work combines geospatial processing with mathematical optimization to design a multi-stage logistics network. The model incorporates intermediate densification options and technology selection (chipping, pelletizing, or briquetting) to supply one or more final waste-to-energy plants. The case study focuses on Northeastern Uruguay, considering forestry residues, meat-processing waste, and rice husks. We formulate a multi-period Mixed-Integer Linear Programming (MILP) model aimed at minimizing the total annualized cost, encompassing transportation, logistical operations, capital investment, and plant O&M, subject to supply constraints, capacities, and maximum transport distances. Results show that the optimal configuration corresponds to the briquetting scenario, which includes a fixed densification facility and processes 200, 160 t/y of biomass from 18 sawmills. Under this configuration, the system generates 276, 954 MWh, with a net margin of USD 5.77/MWh and a net profit of USD 1, 596, 662 over the planning horizon. Sensitivity analysis indicates that the electricity selling price is a critical parameter, with a tolerance margin of only 8%, while mobile densification is not economically viable under current market conditions. Beyond the specific case study, the main contribution of this work is the optimization model itself, whose general and configurable formulation allows its application to other regions, residue types, and market conditions without reformulating its mathematical structure.

Keywords: Biomass, Supply Chain, Energy Systems, Modelling and Simulations, Optimization, Technoeconomic Analysis

INTRODUCTION

The energy valorization of agro-industrial residues is a key strategy for industrial decarbonization, yet its implementation is often limited by logistical costs. Because of dispersed biomass availability, low bulk density, and high moisture content, the expenses associated with collection and transport can be prohibitive. While densification addresses these issues by increasing volumetric energy density, it introduces significant design challenges: determining where densification should occur, at what scale, and how to optimize biomass flows to the end-user. Optimizing these interrelated decisions requires a spatially explicit framework that integrates road-network data with operational and geographic constraints.

This work proposes a multi-stage logistics network design for residual biomass with intermediate densification. The model is applied to the Tacuarembó–Rivera corridor in Uruguay, evaluating pre-treatment alternatives to identify cost-efficient configurations for facility locations, capacities, and flow allocations. Regarding the state of the art, O'Neill, Geissler, and Maravelias (2024)

Residue	Generation rate (t/year)	Recoverable fraction (%)	Heating value (kcal/kg w.b.)	Bulk density (kg/m³)	Moisture content (% w.b.)	Harvest period / Seasonality
Rice husk	261,200	80%	3,520.9	125	8.50%	February – June
Sawmill residues	412,027	54.40%	4,269.0	275	15.5%	Annual
Rumen content	81,195	100%	2,153.0	770	76–82%	Annual

Table 1. Characteristics for the studied residues

integrated logistics networks with biorefinery location and design, demonstrating high sensitivity to spatial variables and incentives. O'Neill et al. (2025) compared bioenergy landscape configurations and logistics networks under transport constraints and mitigation targets, while Zervopoulou et al. (2025) formulated a spatially explicit MILP model to locate plants and allocate flows in biomass-to-fuel supply chains. Similar to our work, these studies address network design and highlight the dependence on resource geography and logistical constraints. Our contribution differs by including intermediate densification as a core design decision, incorporating mobile alternatives with period-by-period relocation, pre-treatment technology selection, and a multi-period planning horizon.

CONTEXT

Residual biomass can be understood as any organic matter of animal or plant origin that can be valorised for energy or material recovery. This classification facilitates the analysis of agro-industrial residues with different properties and seasonal patterns, all sharing a common objective: their transformation into energy carriers or chemical feedstock.

Nevertheless, the existence of a residue does not guarantee its logistical feasibility. Therefore, this study narrows its scope to three specific streams characterized by high availability, concentration and low current market value: sawmill residues, slaughterhouse rumen content, and rice husks

Sawmill residues

Sawmill operations produce byproducts such as bark, trimmings, and wood shavings, which are characterized by low moisture content and relatively concentrated generation points. National surveys estimate annual production of approximately 412, 000 tonnes on a dry basis (Gutiérrez et al., 2017).

Slaughterhouse rumen content

Bovine rumen content stands out among slaughterhouse waste due to its high volume, estimated at 36 kg per head. Its primary logistical constraint is a high moisture content (80%), which significantly inflates transportation costs and limits conditioning alternatives. In 2024, Uruguay processed 2, 256, 123 cattle (INAC, 2024), consolidating beef as the country's primary slaughter category. A local benchmark is the ONTILCOR meat-packing plant, where rumen content is co-fired in boilers alongside firewood without additional drying. This facility reportedly valorizes its entire waste generation (440 t/month), achieving a substitution ratio of 2 kg of residue for every 1 kg of firewood while maintaining steady steam production.

Rice husk

Generated during the dehulling process, rice husk is concentrates at milling facilities, which provides favorable collection logistics. This residue represents represents roughly 20% of the grain weight and has a reported HHV of 3, 300 kcal/kg (Faroppa, 2010). Its main drawback is a low bulk density (120–130 kg/m³), making the evaluation of densification alternatives essential (Díaz Tovar, 2019). In Uruguay, irrigated rice cultivation maintains average yields of 9, 000 kg/ha, with a harvested area of nearly 150, 000 hectares during the 2023/2024 season (MGAP-OPYPA, 2024).

Table 1 summarizes the key characteristics of the three residues, which are used to parameterize availability and the conditioning and densification alternatives within the model.

Densification

The model evaluates three densification alternatives. None of these densification alternatives are compatible with rumen content due to its high moisture content.

Shredding/Grinding

This is included as a lower-complexity option, though it yields lower improvements in density, heating value, and moisture reduction. It is a particularly relevant technology for processing sawmill residues.

Pelletizing

A compaction process that transforms biomass into

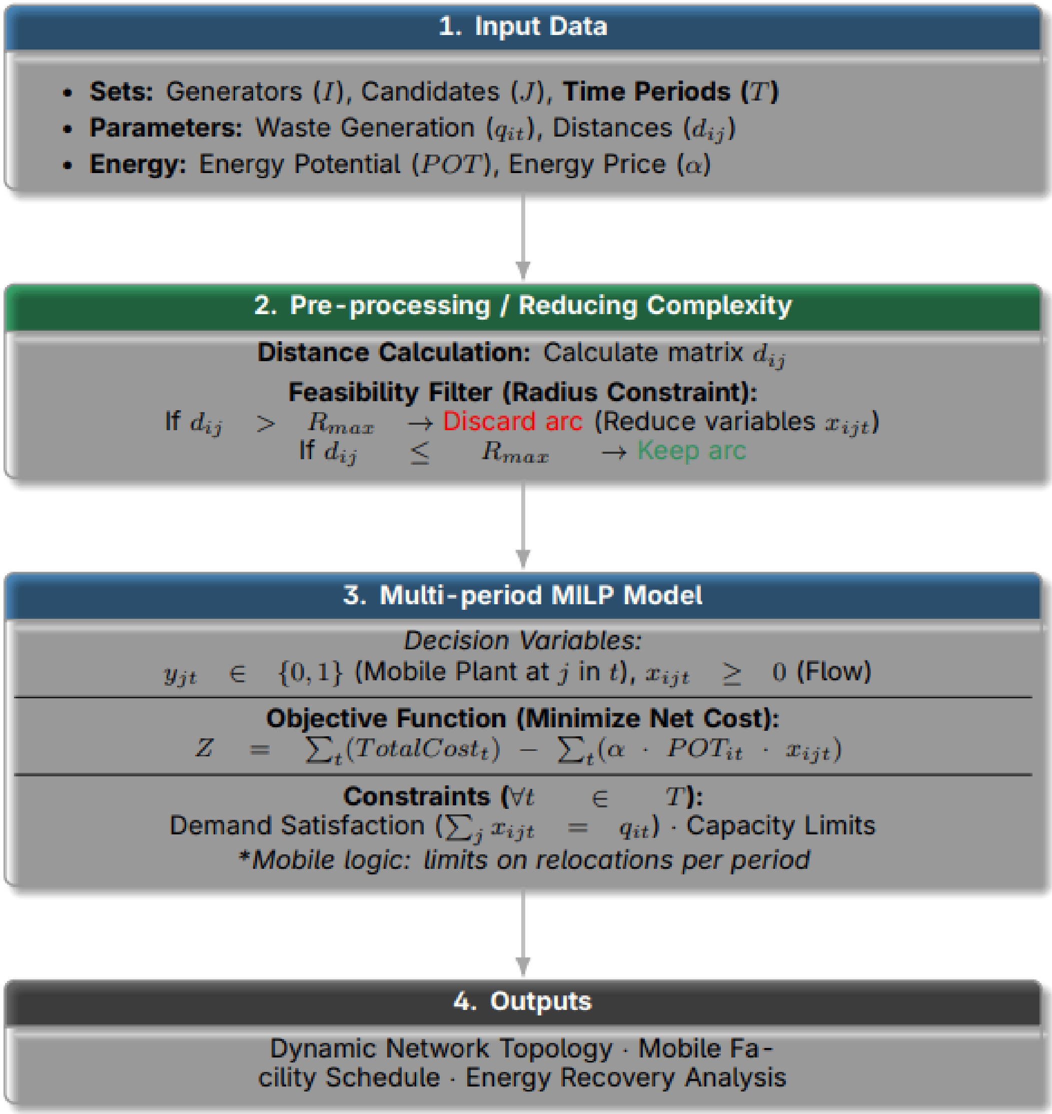

Figure 1. Structure of the multi-period optimization framework for mobile plant location.

pellets, significantly increasing both bulk density and volumetric energy density. This alternative requires higher capital investment and more rigorous operational control than the others, often necessitating strict feedstock moisture ranges to achieve acceptable quality standards (Hernández et al., 2017).

Briquetting

A compaction technology similar to pelletizing but resulting in a larger final product. The mechanical quality of the densified material depends heavily on compaction pressure and the specific properties or blending of the biomass. These factors are critical for technology selection and the definition of operating parameters (Forero-Núñez et al., 2014).

STUDY CASE

Based on the initial residual biomass survey in Uruguay, a nationwide georeferenced database was developed. This database includes all surveyed meat-packing plants, sawmills, and rice mills, recording specific coordinates and monthly residue generation for each facility. The next step involved identifying regions characterized by both high concentrations of generation points and the logistical viability required to supply a centralized plant. To achieve this, a computational procedure was implemented to analyze spatial clusters within a predefined radius, calculating the aggregate energy potential by residue type and prioritizing areas with the highest supply density.

The clustering radius was defined based on energy viability criteria for transport: for each residue, the energy content of a fully loaded truck was compared to the energy consumed during transit, yielding a maximum feasible transport distance specific to each material. Among the identified regions, the Tacuarembó-Rivera corridor was selected as the primary case study, with its logistical axis centered on the national highway traversing the area.

Once the region was defined, potential land parcels for an energy valorisation plant were evaluated. Key watercourses within the study area were mapped, and candidate parcels were pre-selected using a weighted multi-attribute scoring scheme. In general terms, the attributes considered included road accessibility for heavy-duty vehicle traffic, proximity to water sources, available water flow, and topographical characteristics. Based on this assessment, the five highest-scoring parcels were selected as candidate sites for the model.

Network Structure

The study case is defined by the following components, which constitute the input data for the mathematical model developed in the following section. A total of 22 georeferenced generation points are considered: 18 sawmills, 2 rice mills, and 2 slaughterhouses, located in the northeastern corridor of Uruguay between the departments of Tacuarembó and Rivera, with National Route 5 as the main logistical axis. The logistics network includes 6 candidate locations for the final energy recovery plant, 16 candidate nodes for fixed densification plants, and up to 4 mobile densification units. The three densification alternatives evaluated are shredding, pelleting, and briquetting, while the selected valorization pathway is electricity generation through biomass combustion in a steam boiler coupled to a power generation turbine. Biomass transport is carried out using standard trucks.

METHODOLOGY

The logic of the proposed model is illustrated in Figure 1. The framework is structured as a multi-period Mixed-Integer Linear Programming (MILP) problem, designed to capture the temporal variability of seasonal feedstock supply and to allow for the relocation of mobile plants between periods according to the spatial availability of resources. The model considers three decision levels: generation points ($p \in P$), fixed ($n \in N$) or mobile ($k \in K$) densification plants, and final energy plants ($f \in F$), across time periods ($t \in T$). It incorporates 35 parameters describing costs, capacities, distances, process yields, energy consumption, operational times, and transport factors, assuming trucking as the sole transport mode available in the study region.

The primary decision variables are:

- tp, t- tons of biomass utilized at generation point *p* in period *t* [ton]
- zp, n, f, t binary variable; 1 if residues from generation point *p* are densified at location *n* and sent to final plant *f* in period *t* ; 0 otherwise.
- mk, n, t binary variable; 1 if mobile densification unit kkk is operating at location nnn in period ttt, and 0 otherwise.
- yp, f, t binary variable; 1 if residues are sent directly from generation point *p* to final plant *f* in period *t*; 0 otherwise.
- un, t binary variable; 1 if a fixed densification plant is activated at location nnn, and 0 otherwise.
- dd binary variable; 1 if densification method ddd is selected, and 0 otherwise.
- ff binary variable; 1 if the final energy plant is activated at location fff, and 0 otherwise.

The objective function (see Figure 1) seeks to minimize the total net system cost while accounting for the energetic valorization of the available biomass. The formulation includes the revenues associated with energy production together with the annualized costs of the supply chain. These costs comprise transportation and logistical operations, truck fleet requirements, mobile plant relocation, and the CAPEX and O&M of both densification and final waste-to-energy facilities. As a result, negative objective-function values indicate economically viable configurations in which energy revenues exceed total system costs over the planning horizon.

The model incorporates a comprehensive set of balance, capacity, and technological compatibility constraints to ensure the physical and operational consistency of the network. This includes mass balances at each node and period—accounting for yields and losses associated with densification—alongside capacity limits for fixed plants, mobile units, and the transport fleet. Spatial constraints define maximum allowable distances based on the type and state of the residue. Furthermore, the formulation enforces exclusivity and unique flow allocation conditions, as well as technological compatibility rules; specifically, only sawmill and rice mill residues are eligible for densification, while rumen content is restricted to drying. These constraints guarantee system feasibility and accurately capture the interplay between transport, densification, and energy recovery.

The model was implemented in Python 3.13 using the Pyomo algebraic modeling framework and the HiGHS

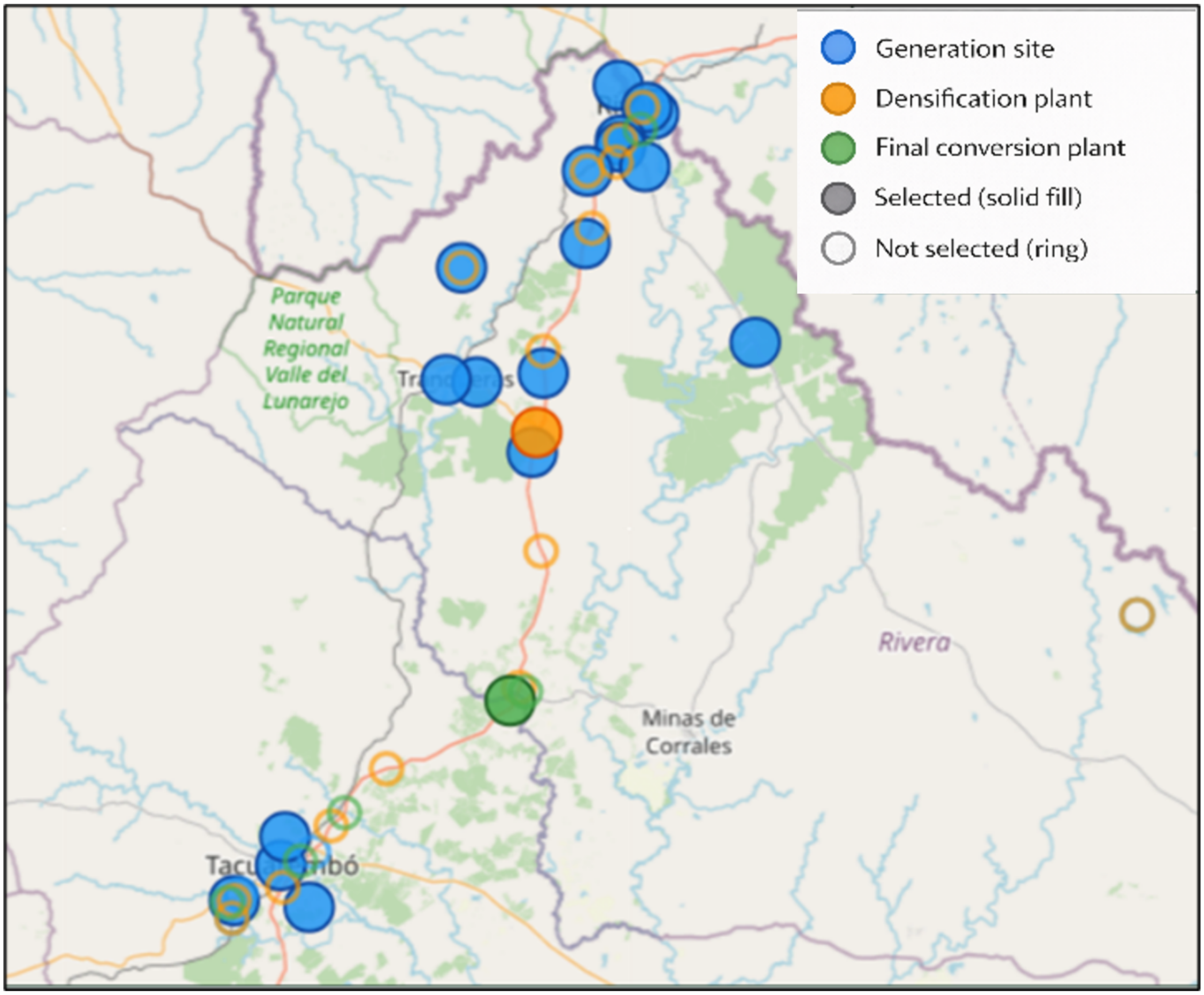

Figure 2. Location of the selected plants and active generation points.

MILP solver. Input data are provided through Excel files containing biomass generation points, candidate plant locations, and model parameters. Based on these data, the optimization model is executed to provide the following outputs: the selection of collection points, optimal flow allocation, the location and activation of both densification and final plants, and an estimation of the total energy potential.

Results

The optimal solution corresponds to the briquetting scenario, in which the model selects the opening of one fixed densification plant and one final energy recovery plant. The resulting logistics network combines direct flows to the final facility with flows requiring an intermediate densification stage, depending on distance and overall network configuration. Under this solution, the system processes 200, 160 tons of biomass per year from 18 active sawmills and generates 276, 954 MWh over the annual planning horizon. The objective function reaches –USD 1, 596, 662, indicating that revenues from energy sales exceed total system costs. Mobile densification is not economically viable under current market conditions.

CONCLUSION

This work developed and applied a mathematical optimization model to evaluate logistics strategies for the energy valorization of residual biomass in Uruguay. A key finding is that densification is not justified primarily by its direct energetic benefit, but by its logistical role within the supply chain: it expands the effective reach of the network and enables the incorporation of biomass that would otherwise remain outside the feasible system.

The analysis also shows that transport, although not dominant in the base-case cost structure, becomes much more influential as biomass sources become more geographically dispersed. In addition, the economic viability of the system is highly sensitive to the electricity selling price and to the conversion efficiency of the final plant, with a tolerance margin of only 8%. Under the evaluated conditions, mobile densification does not constitute a viable alternative due to its higher operating cost and limited processing capacity. Beyond the specific results of the case study, the main contribution of this work lies in the optimization model itself, whose general and configurable formulation makes it applicable to other regions, residue types, and market conditions without requiring changes to its mathematical structure.

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