Mathematical modeling to assess the strategic impact of energy generation on forestry supply chains

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Abstract. Significant quantities of biomass and waste are generated in forestry supply chains during harvesting and processing operations. These materials can be used to produce thermal and electrical energy, simultaneously improving economic performance and environmental sustainability. This paper presents a mixed-integer linear programming (MILP) model designed to strategically assess the impact of incorporating a biomass-fired power plant into a forestry supply chain over a multi-decade horizon. The model's primary contribution is the evaluation of power plant capacity considering the addition of supplementary equipment, while simultaneously optimizing the chain's topology, material flows, and energy generation decisions. The objective function maximizes the system's Net Present Value (NPV) by determining the optimal configuration of forestry operations, industrial production, waste management, transportation, and power generation. The model was applied to a real-world industrial case study to analyze the installation of power plants with varying generation capacities. The results demonstrate the importance of a coordinated approach between energy generation and the production of primary products and byproducts.

Keywords: Mathematical modeling, forest supply chain, biomass, strategic planning, power generation.

1 Introduction

The global economy continues to exhibit a strong dependence on fossil fuels, within a context characterized by oil price volatility, projected depletion of reserves, and a sustained increase in energy demand. In this scenario, the search for renewable and sustainable alternatives has gained increasing relevance. Among these, biomass stands out as a renewable energy source derived from residues and byproducts of biological origin generated in agricultural and industrial activities, particularly within the forestry sector. However, its efficient utilization faces challenges related to availability, collection and transportation costs, resource quality, and energy conversion performance (Malladi et al., 2018).

In the forestry sector, the supply chain encompasses interrelated activities ranging from resource management and harvesting to industrial processing and distribution. These value creation networks include multiple associated chains (such as sawn timber, bioenergy, biorefinery products, and other forest-based outputs) that require efficient strategic, tactical, and operational coordination (Audy et al., 2016; Ramage et al., 2017). In recent years, studies such as Siyu et al. (2022) have underscored that integrating and planning all processes from raw material extraction to final product delivery is crucial to overcoming traditional operational silos. Current literature increasingly emphasizes the common factor of addressing these highly interrelated tasks simultaneously across strategic, tactical, and operational decision horizons (Rönnqvist et al., 2023). For instance, through a comprehensive MILP framework, Luo et al. (2021) combined strategic decisions (such as harvesting, bucking, and sales scheduling) with tactical operations, including facility location, production yields, external sourcing, and the entire distribution network from forest to consumer. Furthermore, Gomes et al., 2026 introduced an integrated decision-support framework that bridges environmental risk modeling with tactical supply chain operations within the forest-to-bioenergy value chain. The framework synchronizes upstream biomass availability and post-disturbance resource utilization with downstream processing capacity and delivery commitments to bioenergy facilities.

In this context, the valorization of forest residues for energy generation not only contributes to reducing the accumulation of residual biomass but may also enhance the overall profitability of the production system. The bioenergy supply chain configuration addressed by Rafique et al. (2021) introduces a distinctive problem structure that shifts away from typical forestry-centric systems. The model operates as an integrated system where demographic factors directly dictate energy demand and consumption over multiple periods. To minimize the resulting energy deficit, an MILP formulation balances budget and multi-source biomass limits (including municipal and food wastes alongside wood and crops) are considered.

This study develops a mixed-integer linear programming (MILP) model to optimize the configuration and material flows of a forest-industrial supply chain. While previous work (Rodriguez et al., 2025) overlooked energy plant scaling, the primary contribution of this paper is the explicit determination of the power plant's optimal capacity, evaluating alternative levels to maximize supply chain efficiency. The model simultaneously determines the optimal network structure, sourcing decisions, and product flows to customers, with the objective of maximizing the NPV. Different operational scenarios are analyzed to assess how the integration and scale of an energy plant—considering biomass availability—impact the economic and operational performance of the system.

2 Problem description

In this work the addressed problem involves the strategic and tactical management of an integrated forestry supply chain, requiring a synchronized approach to coordinate resources from the forest to the final consumers. The challenge begins with the selection of internal and third-party forest stands and the determination of specific exploitation methods. These decisions dictate the availability of log types for direct sale or internal processing, while simultaneously requiring the establishment of the appropriate number and capacity of equipment (such as chippers) to convert residues and biomass into fuel. The problem also takes into account industrial operations, where the flow of raw materials (including cant and pulpable logs) must be managed across internal and third-party sawmills. This necessitates deciding which volumes are processed for traditional customers and which are diverted as feedstock for energy production, alongside the optimized selection of third-party sawmills and the acquisition of their waste to balance supply and demand. Finally, the scale of energy generation is determined by evaluating the strategic integration of a power plant with a predefined capacity. The operation must successfully balance the processing of internal and third-party waste to meet these production targets.

Thus, as part of the problem, the following decisions were considered: a) Stand Selection and Exploitation: Decision-makers must identify which internal and third-party forest stands to select for harvesting; b) Harvesting Methods: The specific type of exploitation for each selected stand must be determined to optimize resource recovery; c) Log Allocation: Decisions are required regarding the quantities and types of logs to be sold directly to customers versus those kept for internal processing; d) Third-Party Integration: The process involves selecting external stands and determining the volume of logs to be purchased from third-party suppliers; e) Sawmill Feedstock: Coordination is needed to decide the specific quantities and types of logs to process in the sawmills; f) Byproduct Valorization: Decisions must be made regarding the equipment capacity needed to process cant and pulpable logs for use as power plant fuel or for sale to customers; g) External Industrial Support: This includes the selection of third-party sawmills and determining the quantity of waste and biomass to be purchased from them; h) Output Management: the volume of processed products delivered from the sawmills to each specific customer segment must be defined; i) Generation Scale: A key decision involves determining the total quantity of energy to be generated by the plant; j) Feedstock Mix: The operation must balance the quantity of internal versus third-party waste processed for energy generation; k) Logistics and Distribution: Finally, the system must define the quantity of products and byproducts to be transported from the sawmills to each targeted market.

The decisions mentioned indicates that the capacity and quantity of the following essential machinery must be taken into account: i) Portable Chippers: For in-forest biomass processing; ii) Pulpable Chippers: For converting specific log diameters into paper-grade chips; iii) Waste Chippers: For valorizing industrial edges (cant logs); iv) Energy Plant Infrastructure: To convert the accumulated waste into a revenue-generating utility. Figure 1 shows an aggregated description of the supply chain structure and material flows considered.

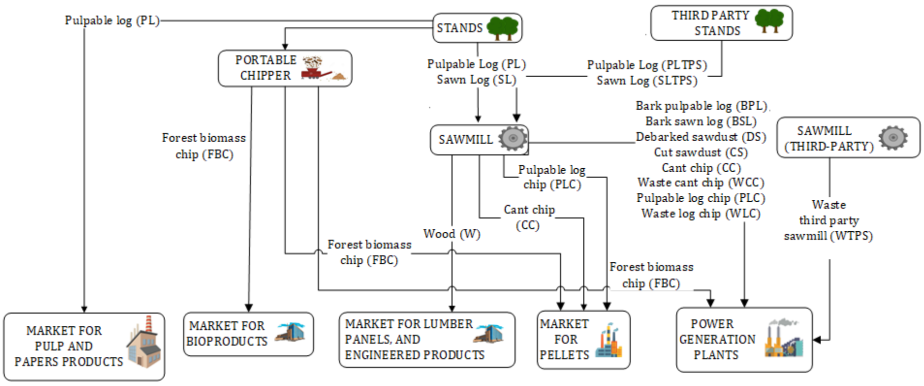

Fig. 1: The FSC considered.

3 Mathematical model

Tables 1 to 4 show sets/indices, decision variables and parameters used in the formulation.

Table 1: Sets/Indices.

Set/ Indices	
A_P	Company's sawmills
A_T	Third-party sawmills
I	Chipper machines, sawing and drying units
I_D	Sawn wood drying units
I_{POR}	Chipper machines that can be moved to the harvest areas in order to process forest biomass (portable chippers)
I_{PULP}	Chipper machines for processing pulpable logs
I_W	Chipper machines for waste
IN	Interventions
J	Destinations
J_{FBC}	Customers who buy chips of forest biomass
J_P	Power generation plants
K	Raw material, waste, products and byproducts
K_{BS}	Bark and sawdust: Bark Sawn Log (BSL), Bark Pulpable Log (BPL) and Debarked Sawdust (DS).
K_C	Cant (C)
K_{DPL}	Debarked pulpable log (DPL)
K_{FBC}	Forest biomass chip (FBC)
K_{PL}	Pulpable log from own stands (PL)
K_{SL}	Sawn log from own stands (SL)
K_{WTPS}	Waste third-party sawmill (WTPS)
K_{CW}	Chip and Waste: Cant Chip (CC), Waste Cant Chip (WCC), Pulpable Log Chip (PLC), Waste Log Chip (WLC) and Cut Sawdust (CS).
K_{PR}	Products required by the energy plants: BPL, BSL, DS, CS, CC, WCC, PLC, WLC, FBC and WTPS.
R	Stands
T	Time-periods

Table 2: Continuous variables.

Continuous Variables	
$\boldsymbol{C_{AL_t}}$	Annual cost of land at period t
$\boldsymbol{C_{FC_t}}$	Total fixed cost at period t
$\boldsymbol{C_{FR_t}}$	Fixed cost of stands at period t
$\boldsymbol{C_{FCC_t}}$	Fixed cost of the chipper machines at period t
$\boldsymbol{C_{FS_t}}$	Fixed cost of sawmills in period t
$\boldsymbol{C_{FE_t}}$	Fixed cost of the power generation plants at period t
$\boldsymbol{C_{P_t}}$	Variable cost associated with the use of chipper machines at period t
$\boldsymbol{C_{VAPL_{j,t}}}$	Variable cost associated with the use of energy plant j at period t
$\boldsymbol{C_{RM_t}}$	Cost of waste purchased from third-party sawmills and logs purchased from third-party stands at period t
$\boldsymbol{C_{T_t}}$	Transportation cost at period t
$\boldsymbol{COST_t}$	Cost obtained at period t
$\boldsymbol{IC_{E_t}}$	Income from the sale of energy at period t
$\boldsymbol{IC_{FBC_t}}$	Income from the sale of chip of biomass at period t
$\boldsymbol{IC_{PL_t}}$	Income from the sale of pulpable logs at period t
$\boldsymbol{IC_{TC_t}}$	Income from the sale of trunk chips (PLC and CC) at period t
$\boldsymbol{IC_{W_t}}$	Income from the sale of wood at period t
$\boldsymbol{I_{I_t}}$	Initial investment at period t
$\boldsymbol{NPV}$	Net present value
$\boldsymbol{REV_t}$	Revenue obtained at period t
$\boldsymbol{X_{API_{ap,i,k,t}}}$	Quantity of product k transported from own sawmill ap to chipper i at period t
$\boldsymbol{X_{APJ_{ap,j,k,t}}}$	Quantity of product k transported from own sawmill ap to destination j at period t
$\boldsymbol{X_{ATJ_{at,j,k,t}}}$	Quantity of raw material k transported from third-party sawmill at to destination j at period t
$\boldsymbol{X_{B_{j,k,t}}}$	Quantity of biomass k in destination j at period t
$\boldsymbol{X_{IJ_{i,j,k,t}}}$	Quantity of the product k transported from chipper, sawing and drying units i to destination j at each period t
$\boldsymbol{X_{RAP_{r,in,ap,k,t}}}$	Quantity of the product k transported from stand r with the intervention in to own sawmill ap at time period t
$\boldsymbol{X_{RJ_{r,in,j,k,t}}}$	Quantity of product k transported from stand r with the intervention in to destination j at period t

Table 3: Binary variables.

Binary Variables	
$\boldsymbol{Y_{ADQ_{i,t}}}$	Equal to 1, if chipper machines i is acquired at period t
$\boldsymbol{Y_{AT_{at,t}}}$	Equal to 1, if third-party sawmill at supplies raw material at period t
$\boldsymbol{Y_{P_j}}$	Equal to 1, if plant j is activated in the planning horizon

The objective function is presented below, followed by the primary constraints governing biomass-fired power plant selection and material flow allocation over a strategic multi-decade horizon. This model builds upon the formulation proposed by Rodriguez et al. (2025). To maintain conciseness, we present only the novel and modified constraints that diverge from the base formulation, focusing specifically on equations related to energy generation.

Table 4: Parameters.

Parameters	
$C_{AM_{j,t}}$	Fixed cost of amortization in the destination j at period t
CC	Minimum amount of product that can be transported per period
$C_{FA_{i,t}}$	Fixed acquisition cost of chipper machine i at period t
$C_{FIP_{j,t}}$	Equivalent periodic cost of the total fixed installation cost in the destination plant j at period t
$C_{FMANT_{j,t}}$	Fixed cost of maintenance in the destination j at period t
$C_{FO_{j,t}}$	Fixed cost of operators in the destination j at period t
$C_{O_{j,t}}$	Number of operators in the destination j at period t
$CTPS_{MAX_{at,k,t}}$	Maximum amount of waste k that can be purchased to third-party sawmill at period t
$C_{VAI_{i,t}}$	Variable cost of using chipper machine i at period t
$C_{VAP_{ap,t}}$	Variable cost of sawmill ap at period t
C_{VAPI_j}	Variable unit cost of energy plant j
$D_{max_{J,k,t}}$	Maximum demand of destination j of product k at period t
$D_{min_{J,k,t}}$	Minimum demand of destination j of product k at period t
M	A large number
ma	Months of the year
EP_t	Selling price of energy at period t
RB_k	Energy generated (MWh) per ton of product supplied
V_E	Proportion of generated energy designated for commercialization
$\emptyset$	Discount rate

3.1 Objective function

Equation (1) presents the objective function, which seeks to maximize the company's NPV by balancing periodic profits (REV_t-$COST_t$) against the specified discount rate.

$$Max\ NPV = \sum_{t \in T} \frac{REV_t - COST_t}{(1 + \emptyset)^t} \qquad (1)$$

3.2 Incomes

Equation (2) determines the total revenue as the aggregate income generated from the sale of all products. This includes revenue from wood (IC_{W_t},), energy (IC_{E_t}), pulpable logs (IC_{PL_t}), as well as proceeds from trunk chips (IC_{TC_t}) and biomass chips (IC_{FBC_t}).

$$REV_t = IC_{W_t} + IC_{E_t} + IC_{PL_t} + IC_{TC_t} + IC_{FBC_t} \qquad \forall\, t \in T \qquad (2)$$

3.3 Energy incomes

Equation (3) computes the revenue from energy sales by multiplying the volume of biomass intended for energy generation ($X_{B_{j,k,t}}$) by the prevailing market price (EP_t) per MWh generated. This quantity is derived from the volume of byproducts and waste transferred to the power plant, adjusted by a energy-to-mass conversion factor RB_k (MWh per ton) and the specific fraction of generated energy designated for sale (V_E).

$$IC_{E_t} = \sum_{j \in J_P, k \in K_{PR}} X_{B_{j,k,t}} * EP_t * RB_k * V_E \qquad \forall\, t \in T \tag{3}$$

3.4 Costs

Equation (4) determines the total cost as the sum of all fixed and variable expenditures. This comprehensive cost structure incorporates raw material procurement (C_{RM_t}), production (C_{P_t}), and transportation (C_{T_t}), alongside fixed operating costs (C_{FC_t}), cultivated land expenses (C_{AL_t}), and the initial capital investment (I_{I_t}) for each period. The total fixed cost aggregates expenditures across harvest sites, sawmills, and the power generation facilities. These are categorized into: (i) stand-level costs, which encompass initial interventions, administrative overhead, and taxation tied to the specific silvicultural plan; (ii) facility-specific costs for chipping units, sawmills, and the generation plant; and (iii) operational overheads, including equipment amortization, labor requirements, and routine maintenance expenditures.

$$COST_t = C_{RM_t} + C_{P_t} + C_{T_t} + C_{FC_t} + C_{AL_t} + I_{I_t} \qquad \forall\, t \in T \tag{4}$$

3.5 Production costs

The total production cost is formulated in Equation (5) as the sum of four primary operational components. The first term accounts for the costs incurred during the processing of pulpable and saw logs within the sawmills. The second and third terms represent the production expenses associated with chipping operations, specifically covering residue and pulpable chippers, as well as portable chipping units. Finally, the fourth term considers the operating costs at the energy plant.

$$C_{P_t} = \sum_{r \in R, in \in IN, ap \in AP, k \in K_{PL} \cup K_{SL}} X_{RAP_{r,in,ap,k,t}} * C_{VA\,ap,t} + \sum_{ap \in AP, i \in I_W \cup I_{PULP}, k \in K_C \cup K_{DPL}} X_{API_{ap,i,k,t}} * C_{VA\,i,t} + \sum_{r \in R, in \in IN, i \in I_{POR}, j \in J_{FBC}, k \in K_{FBC}} X_{RJ_{r,in,j,k,t}} * C_{VAI\,i,t} + \sum_{j \in J_p} C_{VAP\,j,t} \qquad \forall\, t \in T \tag{5}$$

3.6 Fixed costs

The total fixed costs, encompassing the processing of trunks and residues across harvest areas, internal sawmills, and the power generation facility, are formulated in Equation (6). This aggregate cost is composed of four primary elements: the fixed costs associated with forest stands (C_{FR_t}), chipping operations ($C_{FCC\,t}$), sawmill facilities (C_{FS_t}), and the power generation plant ($C_{FE\,t}$).

$$C_{FC_t} = C_{FR_t} + C_{FCC_t} + C_{FS_t} + C_{FE_t} \quad \forall\, t \in T \tag{6}$$

Equation (7) determines the fixed cost associated with the power plant, which is calculated by summing the equipment amortization, workforce costs, and maintenance costs, respectively.

$$C_{FE_t} = \sum_{j \in J_P} \left(C_{AM_{j,t}} + C_{O_{j,t}} * C_{FO_{j,t}} * ma + C_{FMANT_{j,t}} \right) * Y_{P_j} \quad \forall\, t \in T \tag{7}$$

3.7 Initial investment costs

The initial investment includes the acquisition of equipment and machinery required for the operation particularly the installation costs of the chippers and the power generation plant. This investment is considered in Equation (8) through binary variables. In this constraint, the parameter $C_{FA_{i,t}}$ corresponds to the acquisition cost of chipper machine *i* in period *t*, whereas $C_{FIP_{j,t}}$ is the equivalent periodic cost of the total fixed cost to install plant *j*. The equivalent periodic cost at each period *t* ($C_{FIP_{j,t}}$) is obtained spreading both the capital and accrued interest over the planning horizon. When the installation of a chipper or a power generation plant is activated, the corresponding binary variable takes the value of 1; otherwise, it takes the value of 0.

$$I_{I_t} = \sum_{i \in I_W \cup I_{PULP} \cup I_{POR}} C_{FA_{i,t}} * Y_{ADQ_{i,t}} + \sum_{j \in J_p} C_{FIP_{j,t}} * Y_{P_j} \quad \forall\, t \in T \tag{8}$$

3.8 Product flow constraints

Equation (9) determines lower and upper bounds of the amount of waste available (K_{WTPS}) that a given third-party sawmill can supply, in the case that it provides residues ($Y_{AT_{at,t}} = 1$). The lower limit established in restriction (9) imposes the minimum amount required from any active third-party sawmill per full period *t*.

$$\left\{ \begin{array}{l} \sum_{j \in J_P} X_{ATJ_{at,j,k,t}} \geq CC * Y_{AT_{at,t}} \\ \sum_{j \in J_P} X_{ATJ_{at,j,k,t}} \leq CTPS_{MAX_{at,k,t}} * Y_{AT_{at,t}} \end{array} \right\} \quad \forall\, at \in AT, \forall\, t \in T, \forall\, k \in K_{WTPS} \tag{9}$$

3.9 Power plant requirements constraints

To satisfy the operational requirements of the energy generation facilities, Equation (10) defines the lower and upper bounds for the volume of products delivered to the power plant during any given period. The activation of power plant *j* in period *t* is governed by the binary variable $\boldsymbol{Y_{P_j}}$. When the plant is operational ($\boldsymbol{Y_{P_j}} = 1$), the delivered feedstock must strictly fall within the specified minimum and maximum demand limits. Conversely, when the plant is inactive $\boldsymbol{Y_{P_j}} = 0$), a Big-M formulation is employed to relax these constraints, ensuring that the demand limits are only enforced when the plant is active.

$$\begin{Bmatrix} X_{B_{j,k,t}} \geq D_{min_{j,k,t}} - M * (1 - \boldsymbol{Y_{P_j}}) \\ X_{B_{j,k,t}} \leq D_{max_{j,k,t}} + M * (1 - \boldsymbol{Y_{P_j}}) \end{Bmatrix} \qquad \forall\, j \in J_P, \forall\, k \in K_{PR}, \forall\, t \in T \tag{10}$$

As power plants can be fed with different types of fuels, Equation (11) determines the total biomass utilization. The type of product that may be used are residues from third-party sawmills (K_{WTPS}), biomass chips (K_{FBC}), products and residues obtained from the chippers (K_{CW}), as well as bark and sawdust transported from sawmills (K_{BS})within each time period .

$$\sum_{at \in AT, k \in K_{WTPS}} X_{ATJ_{at,j,k,t}} + \sum_{r \in R, in \in IN, k \in K_{FBC}} X_{RJ_{r,in,j,k,t}} + \sum_{i \in I_W \cup I_{PULP} \cup I_D, k \in K_{CW}} X_{IJ_{i,j,k,t}} + \sum_{ap \in AP, k \in K_{BS}} X_{APJ_{ap,j,k,t}} = \sum_{k \in K_{PR}} X_{B_{j,k,t}}$$

$$\forall\, j \in J_P, \forall\, t \in T \tag{11}$$

Equation (12) ensures that at most one energy plant is activated within the planning horizon.

$$\sum_{j \in J_P} Y_{P_j} \leq 1 \tag{12}$$

Equation (13) defines the variable cost of the energy plant *j* when the plant is activated ($\boldsymbol{Y_{P_j}} = 1$). The variable cost $\boldsymbol{C_{VAPL}}_{j,t}$ is determined based on the amount of biomass processed at plant *j* and the corresponding unit variable cost.

$$\boldsymbol{C_{VAPL}}_{j,t} \geq \sum_{k \in k_{PR}} X_{B_{j,k,t}} {*} C_{VAPI_J} + M * \left(\boldsymbol{Y_{P_j}} - 1 \right) \qquad \forall\, j \in J_p, \forall\, t \in T \tag{13}$$

4 Numerical results

To assess the model's performance, a case study of a vertically integrated forestry company located in north of Misiones, Argentina was considered. The organization coordinates forest management, sawmill processing, and bioenergy production, managing 132 stands of Pinus taeda over a 30-year planning horizon. For each stand, 90 distinct management regimes are evaluated, which dictate the annual yields of biomass, sawn logs (large diameter), and pulpable logs (small diameter). The availability of these forest resources is assumed to be known throughout the entire planning period.

The forestry supply chain considers four equipment units: the two existing waste chippers (i_1, i_2) and the proposed integration of a pulp log chipper (i_3) and a mobile unit for stand-level biomass (i_4). In addition, the problem involves evaluating the potential integration of three power plant alternatives with different capacities. Plant 1 (P_1): Designed for an annual generation of 35,040 MWh, requiring 70,080 tons of biomass by year. Plant 2 (P_2): Designed for 52,560 MWh per year, with a corresponding consumption of 105,120 tons. Plant 3 (P_3): Designed for 70,080 MWh per year, requiring 140,160 tons of feedstock. Currently, fuel availability is restricted to residues from the company's internal sawmill and 20 third-party facilities, as the system lacks the machinery to process forest residues (branches and leaves) and has limited capacity for other byproducts. Consequently, to address these limitations, the problem includes the strategic evaluation of acquiring portable forest chippers, pulp log chippers, and additional waste chippers.

4.1 Scenario Analysis

In order to analyze the impact of different configurations, multiple scenarios were defined. The goal is to identify operational trade-offs and derive managerial insights by studying how changes in the system impact the overall economic performance.

Scenario S_1 serves as the baseline case, representing the traditional supply chain configuration that does not include a power generation plant. Scenarios $S_{2.1}$ through $S_{2.3}$ evaluate the integration of a power generation plant under varying capacity assumptions: $S_{2.1}$ to $S_{2.3}$ analyze the system performance under fixed, incremental capacity levels. Scenarios $S_{3.1}$, $S_{3.2}$, $S_{4.1}$, and $S_{4.2}$ examine the system's sensitivity to the availability of third-party biomass in conjunction with variations in the equipment used for waste processing. In all four scenarios, external sawmill waste is reduced to 89,957 t/year ($S_{3.1}$/$S_{3.2}$) and 0 t/year ($S_{4.1}$/$S_{4.2}$). The key distinction is that while $S_{3.1}$ and $S_{4.1}$ maintain the current equipment set, $S_{3.2}$ and $S_{4.2}$ evaluate the inclusion of the pulp log chipper (i_3) and the mobile forest biomass chipper (i_4) into the supply chain structure. These scenarios assess how fluctuations or restrictions in the supply of external waste impact the optimal configuration and overall profitability of the network. Table 5 summarizes the main characteristics of the proposed scenarios.

The mathematical formulation was implemented in GAMS 35.2.0 and solved with CPLEX 20.1.0.1 on a personal computer, with Intel Core i7-11700 2.50 GHz and 32 GB RAM memory, for a 0.1 % gap tolerance.

Table 5: Scenarios characteristics.

Scenarios	i_3	i_4	P_1	P_2	P_3	Third-party sawmills – Capacity [t/year]
S_1	*	*	-	-	-	179,914
$S_{2.1}$	*	*	1	-	-	179,914
$S_{2.2}$	*	*	-	1	-	179,914
$S_{2.3}$	*	*	-	-	1	179,914
$S_{3.1}$	-	-	*	*	*	89,957
$S_{3.2}$	*	*	*	*	*	89,957
$S_{4.1}$	-	-	*	*	*	0
$S_{4.2}$	*	*	*	*	*	0

* The selection of the power generation plant or chipper machines is determined by the model.

- Power generation plant or chipper machine not considered

4.1.1 Incorporation of power generation plants

The economic and computational results for the scenarios evaluating individual generation alternatives are summarized in Tables 6 and 7, respectively. As detailed in Table 6, introducing the power plant in $S_{2.1}$–$S_{2.3}$ adds exactly 243 continuous variables, 3 binary variables, and 337 equations to the baseline case (S_1). Within the integration scenarios, these dimensions remain completely constant. The variations in CPU time is attributed to the fact that larger plant capacities increase profitability through energy sales, which allows the solver to identify highly dominant economic solutions and converge much faster, reducing the time from 7,115 seconds in $S_{2.1}$ to just 92 seconds in $S_{2.3}$

Table 6. Mode size, resolution time and GAP for S_1 and $S_{2.1}$ to $S_{2.3}$

Scenario	Variables		Equations	GAP [%]	CPU Time [s]
	Continuous	Binary			
S_1	253,990	6,378	79,534	0.1	4,223
$S_{2.1}$	254,233	6,381	79,871	0.1	7,115
$S_{2.2}$	254,233	6,381	79,871	0.1	2,067
$S_{2.3}$	254,233	6,381	79,871	0.1	92

Table 7. Revenues and costs for S_1 and $S_{2.1}$ to $S_{2.3}$

Scenario	NPV [$]	Total Revenue [$]	Total Cost [$]	Energy Plant Costs [$]		
				Fixed	Variable	Installation
S_1	40,400	185,218	37,069	0	0	0
$S_{2.1}$	38,925	261,377	103,196	3,839	61,224	5,000
$S_{2.2}$	41,851	297,240	114,609	3,993	68,591	10,000
$S_{2.3}$	48,694	344,546	124,414	4,151	60,970	15,000

As shown in the revenue and cost in Table 7, compared to the base case of operating without an energy plant (S_1), incorporating a small-scale plant ($S_{2.1}$) is economically suboptimal (resulting in a lower NPV). Conversely, implementing the larger plant ($S_{2.3}$) is the most economically viable option and delivers the highest NPV. These findings demonstrate that power generation integration optimizes both economic returns and biomass utilization, with the largest plant capacity providing the best results under current conditions. On the other hand, it is important to note that $S_{2.3}$ exhibits lower total variable costs than $S_{2.2}$ due to economies of scale, as the unit variable cost of the largest plant capacity (P_3) is half that of the smallest configuration (P_1). This reduction in unit operational costs effectively offsets the increased processing volumes, resulting in a lower total variable cost.

Figure 2 illustrates the biomass supply to the power generation plant across the evaluated scenarios, considering both internally generated waste and third-party sources. The variations observed between scenarios are driven exclusively by the shifting requirements for specific categories: forest biomass chips (FBC), pulpable log chips (PLC), and Waste Log chips (WLC), Bark Pulpable Log (BPL) and Cant Chip (CC). In contrast, the demand for all other byproducts (including WCC, CS, DS, BSL, and WTPS) remains constant across the entire scenario set.

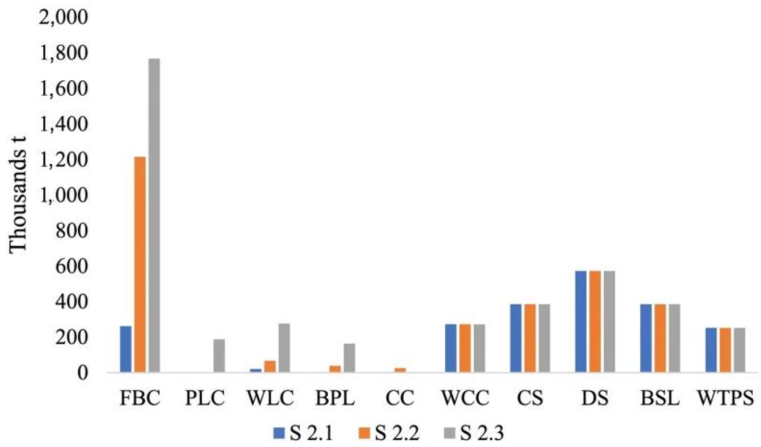

Fig. 2. Power plant requirements per year for $S_{2.1}$ to $S_{2.3}$.
Note: FBC: Forest Biomass Chip; PLC: Pulpable Log Chip; WLC: Waste Log Chip; BPL: Bark Pulpable Log; CC: Cant Chip; WCC: Waste Cant Chip; CS: Cut Sawdust; DS: Debarked Sawdust; BSL: Bark Sawn Log; WTPS: Waste Third-party Sawmill.

4.1.2 Different levels of waste availability

This subsection evaluates the impact of variations in third-party biomass availability on both the system configuration and its overall economic performance. The economic and computational results for the scenarios evaluating variations in third-party biomass availability are summarized in Tables 8 and 9, respectively.

Table 8. Mode size, resolution time and GAP for $S_{3.1}$, $S_{3.2}$, $S_{4.1}$ and $S_{4.2}$

Scenario	Variables		Equations	GAP [%]	CPU Time [s]
	Continuous	Binary			
$S_{3.1}$	254,233	6,381	79,871	0.1	9
$S_{3.2}$	254,233	6,381	79,871	0.1	54
$S_{4.1}$	254,233	6,381	80,471	0.1	7
$S_{4.2}$	254,233	6,381	80,471	0.1	21

Table 9. Revenues and costs for $S_{3.1}$, $S_{3.2}$, $S_{4.1}$, and $S_{4.2}$

Scenario	NPV [$]	Total Revenue [$]	Total Cost [$]	Energy Plant	Energy Plant Costs [$]		
					Fixed	Variable	Installation
$S_{3.1}$	37,888	274,085	104,724	P2	3,993	68,591	10,000
$S_{3.2}$	48,695	344,518	124,493	P3	4,151	60,970	15,000
$S_{4.1}$	36,265	246,467	97,259	P1	3,834	60,970	5,000
$S_{4.2}$	48,003	341,725	123,882	P3	4,151	60,970	15,000

As presented in Table 9, scenarios $S_{3.1}$ and $S_{3.2}$ maintain the same dimensions as the previous integration cases, whereas $S_{4.1}$ and $S_{4.2}$ add 600 equations due to the total restriction of external waste, while keeping variable counts constant. Despite these structural changes, computational times remain consistently low across all scenarios, ranging from 7 to 54 seconds. Mathematically, the restriction on external biomass limits the feasible routing and sourcing combinations. This reduction in alternative paths, combined with the high profitability of the larger plant capacities (P_3) in $S_{3.2}$ and $S_{4.2}$, allows the solver to rapidly isolate dominant economic configurations and reach rapid convergence.

A comparison of the results in Table 9 reveals that when waste availability is restricted and additional processing equipment is unavailable ($S_{3.1}$ and $S_{4.1}$), the NPV decreases by 22.19% and 25.52% relative to $S_{2.3}$. However, when allowing for in-house waste processing ($S_{3.2}$ and $S_{4.2}$), these losses are significantly mitigated, resulting in only marginal changes to the NPV. In the latter scenarios, the modifications in the NPV are primarily driven by the substitution of external waste with the company's primary products. Diverting these products to power generation creates an opportunity cost, as they are consumed internally rather than sold at a higher market.

Regarding the energy plant selection, supply constraints in $S_{3.1}$ and $S_{4.1}$ initially favor medium (P_2) and small (P_1) capacities, respectively. This preference shifts significantly with the introduction of on-site processing modules (i_3 and i_4) in $S_{3.2}$ and $S_{4.2}$. The added pre-processing capability restores the economic viability of larger plant configurations, effectively reversing the downward trend in capacity selection.

Figure 3 illustrates the biomass supply to the power generation plant across the scenarios $S_{3.1}$, $S_{3.2}$, $S_{4.1}$, and $S_{4.2}$, considering both internally generated waste and third-party sources. As illustrated in the figure, the lack of processing equipment in scenarios $S_{3.1}$ and $S_{4.1}$ precludes the utilization of several feedstocks, specifically Forest Biomass Chip (FBC), Pulpable Log Chip (PLC), Waste Log Chip (WLC), and Bark Pulpable Log (BPL). Because the production infrastructure for Cant Chip (CC) remains operational, it becomes the dominant feedstock in scenarios $S_{3.1}$ and $S_{4.1}$. The variance in consumption between these two cases is capacity-driven: $S_{4.1}$ requires less volume due to its small plant (P_1) selection, while $S_{3.1}$'s higher intake is a direct result of utilizing the larger P_2 plant.

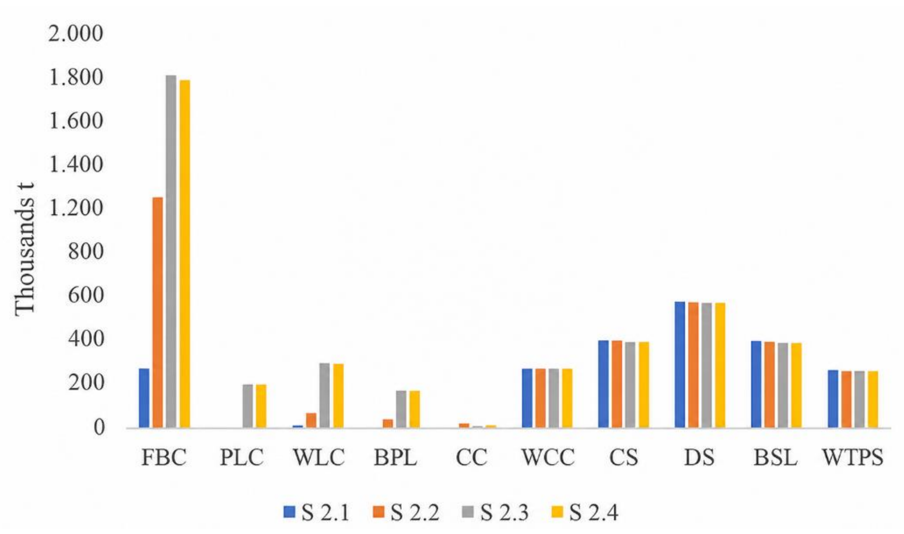

Fig. 3. Power plant requirements per year for $S_{3.1}$, $S_{3.2}$, $S_{4.1}$ and $S_{4.2}$

Note: FBC: Forest Biomass Chip; PLC: Pulpable Log Chip; WLC: Waste Log Chip; BPL: Bark Pulpable Log; CC: Cant Chip; WCC: Waste Cant Chip; CS: Cut Sawdust; DS: Debarked Sawdust; BSL: Bark Sawn Log; WTPS: Waste Third-party Sawmill.

Results demonstrate that integrating a power generation plant is economically viable across the entire range of waste availability, ensuring continuous operation throughout the planning horizon. While plant capacity scales with waste availability (leading to economic benefits) external waste remains an important factor for system efficiency. Although third-party resources are not strictly required for power generation, their availability allows the company to divert a larger share of its primary products toward direct sales, thereby optimizing overall profitability.

5 Conclusions

This paper presents a MILP model designed to strategically assess the integration of a biomass-fired power plant within a forestry supply chain over a multi-decade horizon. Moving beyond previous literature, the primary contribution of this work is the explicit determination of the power plant's optimal capacity. By internalizing these structural choices, the proposed approach effectively optimizes supply chain topology, material flows, and energy generation decisions to maximize the NPV. The model serves as an effective strategic planning tool, enabling the evaluation of investment decisions, capacity scaling, and supply strategies across various operational scenarios.

The formulation was applied to a real-world case study, where the results highlight significant economic and operational impacts resulting from shifts in generation scale and the volatility of third-party biomass availability. Furthermore, the model exhibits a good computational performance, reaching optimal solutions within a 0.1% optimality gap in at most 7,120 seconds. Findings indicate that incorporating a power generation plant significantly improves economic performance compared to a supply chain without energy integration. Specifically, the plant with the highest energy production capacity achieved the greatest NPV (20.53 % higher than the baseline scenario S_1) demonstrating that NPV growth outweighs the increase in total costs. Sensitivity analysis regarding third-party residue availability reveals that profitability does not vary significantly as long as all available processing equipment (residue chippers, pulpwood chippers, and forest biomass chippers) is considered. In the absence of third-party biomass, fuel demand is offset by increased utilization of internal resources (residues and pulpwood chips); while this leads to a marginal reduction in revenue, it does not significantly compromise the system's overall economic viability.

Future research will focus on transitioning the current model into a stochastic programming or robust optimization framework to explicitly account for inherent volatilities, such as fluctuations in product demand, climatic impacts on forest stand development, and supply chain disruptions. Additionally, given the increasing scrutiny of the environmental footprint of forestry projects, the objective function could be expanded into a multi-objective approach. This would enable stakeholders to balance the maximization of NPV with critical environmental and social metrics, providing a more holistic tool for sustainable strategic planning.

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