Optimal design of the supply chain for cogeneration of energy from forest biomass

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Abstract. In the forestry industry, residues are generated when the stands are exploited and during the production of wood. The residues can be used to obtain incomes and generate thermal and electrical energy. This work presents a MILP formulation aimed at optimizing the topology of the supply chain and the material flows of a forestry-industrial company that has a power generation plant. The objective function of the formulation aims at maximizing the company profit while its constraints set the supply chain configuration. Optimal material flows within the chain are consequently fixed. The model of the supply-chain was solved with GAMS and the optimal configuration and flows for several scenarios were obtained. Analyzing these variations, it can be affirmed that considering a new structure in the supply chain allows improving the profitability of the organization.

Keywords: forestry biomass, cogeneration, supply chain topology, optimal material flows.

1 Introduction

The global economy depends strongly on the fossil fuels, the oil price volatility, the projected long-term decline in global oil reserves, and the rising energy consumption. Due to the aforementioned, the study of “green” and sustainable alternatives trying to reduce dependency is receiving considerable research efforts. Green energy sources should ideally be renewable and sustainable. Biomass originates from biodegradable products, waste, and residues of biological origin from agriculture, forestry and aquaculture, and from a wide range of raw materials (wood, agricultural crops, byproducts of wood processing, manure and the organic processing of waste). Although the consumption of biomass for generating energy presents several advantages [1], some difficulties such as availability, cost and quality, conversion performance, and transport costs must be overcome for its efficient use as fossil-fuels replacement. Forest biomass is usually dispersed geographically and needs to be transported to plants in a cost-effective way. Nowadays, there are underutilized large quantities of residues in countries with intensive forestry management because the cost of collecting and transporting them is greater than the market value [2]. The main source of forest biomass is waste derived from the harvest, which represents in Argentina, 264.000 t per year and arises mainly from implanted forests. The biomass generated from forest harvests is basically composed of branches, canopies and sections of stem outside commercial standards. In addition, waste is generated in the sawing process, such as sawdust, cants chip, pulp chip and other. This study develops a mathematical model for optimizing the structure and the material flows of a supply chain of a forestry industrial complex. The approach presented in this paper improves the model presented by Bragado et al. [3] by considering additional practical aspects of the problem. In this way, the new formulation takes into account, in a more precise way, the flows of products, byproducts and residues that go across the network. The feasibility of operating a 4MW cogeneration plant (which consumes biomass as raw materials) jointly with the computation of optimal flows of products to clients is researched. The objective function aims at setting the supply chain configuration that maximizes profits and selects the best biomass supply-sources and source to customer's flows. The MILP model of the supply chain is solved with GAMS and its optimal configuration in several scenarios is presented and discussed.

2 Problem description

The vertically integrated forestry-industrial company located in the north of Misiones province owns forests, a cogeneration plant (which produces bioenergy by using biomass as fuel), and sawmills (that produce timber products). Let $R = \{r_1, r_2, \ldots, r_{100}\}$ the set of forests from where products K^{st} = {*PL: pulpable logs, SL: sawn logs, FB: forest harvest biomass*} are obtained. Thus, if a stand is exploited, a given amount of any product is obtained depending on the stand area and the characteristics of the corresponding intervention on the stand. Pulpable logs and sawn logs are transported from forests to a debarking area, where the barks are removed by a debarker machine. Biomass is used as fuel for the power generation plant. Let $I = \{I_{op} \cup I_{pot}\}$ the set of chipper machines (hereinafter referred to as "chippers") defined as the union of the subset of operative chippers $I_{op} = \{i_1, i_2\}$ and potential chippers $I_{pot} = \{i_3, i_4\}$ that may become operative just after and the acquisition decision has been made. Chipper i_3 would allow to process pulpable logs and would have a bigger processing capacity than the current machines (I_{op}). Chipper i_4 would be a mobile device that can be placed in forests for processing branches, leaves and fine stem, e.g., forest harvest biomass. The set of destinations is defined by $J = \{p_1, J_2, J_3, J_4, J_5, J_6\}$. Pulpable logs can be sold directly to customers type 2, $J' = \{J_2\}$, or sent to the own sawmill, $A_P = \{ap_1\}$, where the first processing step is the debarking. The debarked pulpable logs are transferred to chippers that process them in order to obtain byproducts. In the case of pulpable logs processed by the potential chipper i_3, the obtained product would be pulpable log chip. Sawn timber, log outlines and sawdust are obtained from sawn logs. The outlines of sawn logs are sent to the chippers $I_{op} = \{i_1, i_2\}$ which process these so called cant in order to obtain cant chips. Through sawing on these machines, several types of chips are produced according to customer specifications (K^c = {*PLC: Pulpable Log Chip, CC: Cant Chip, FBC: Forest Biomass Chip*}, which are subsequently marketed. Cant-chips and pulpable log chips satisfy customers` requirements in the same way, therefore they are added together and called trunk chips (*TC: Trunk Chip*). Chips produced out of specifications, waste-chips (*WC*), and wastes (*Ws*) from the different process stages (for example, bark and *SD*: Sawdust) are fed as fuel (*B: Biomass*) to the power generation plant $\{JP = p_1\}$. Furthermore, residues (W_{at}) can be purchased from third-party sawmills $A_T = \{at_1, at_2, \ldots, at_{20}\}$ in order to supply the plant and complement the flux sent from the chippers. Sawn wood and the surplus of chips and pulpable logs can be directly sold to certain destinations named general customers $JC = \{J_2, J_3, J_4, J_5, J_6\}$. It is clarified that the client J_2 is placed in two sets, since chips and pulpable logs can be sold to it. The power generation plant produces 4 MWh while consuming 192 *t* of biomass per day and operates continuously every day Thus, the objective of this work is to determine the optimal structure of the supply chain considering the incorporation of relevant equipment and the optimal flows of products in order to maximize the profits of the company for a period of one year while satisfying the demand of the power generation plant and customers' demands of company products. Figure 1 illustrated the researched problematic.

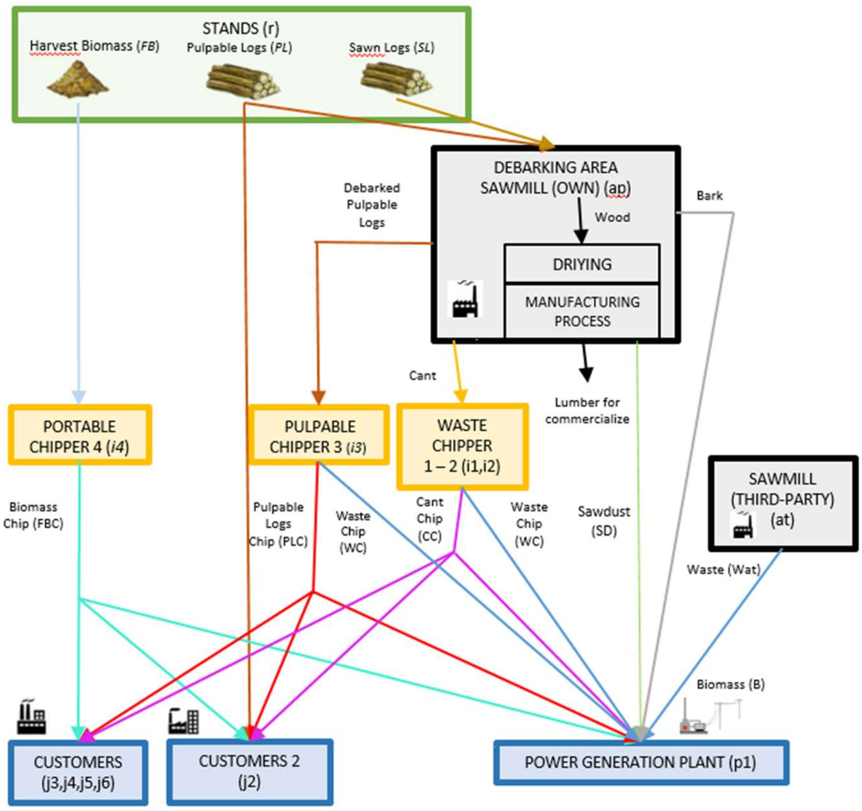

Fig. 1: Diagram of the addressed problem.

3 Mathematical model of the supply chain

Sets

A_T	Third-party sawmills
A_P	Company's sawmill
I	Chipper machines
I_{op}	Operative chippers
I_{pot}	Potential chippers
J	Destinations
J'	Customers type 2
JP	Plant
JC	Customers who can buy chip
K	Products
Kst	Products obtained from stands
Kc	Products obtained after being processed in chipper machines
Ksw	Products obtained after being processed in the own sawmill
R	Stands

Parameters

$C_{R_{r,k}}$	Capacity of stand *r* for producing product *k (t).*
$C_{MIN_{i,k}}$	Minimum capacity of chipper machine *i* for processing product *k* (*t*).
$C_{MAX_{i,k}}$	Maximum capacity of chipper machine *i* for processing product *k* (*t*).
$D_{J,k}$	Demand of destination *j* of product *k* (*t*).
$D_{RC_{r,ap}}$	Distance between stand *r* and own sawmill *ap* (*km*).
$D_{CD_{i,j}}$	Distance between chipper machine *i* and destination *j* (*km*).
$D_{CD2_{i,r,j}}$	Distance between portable chipper machine *i* and destination *j* (*km*).
$D_{RD_{r,j}}$	Distance between chipper stand *r* and destination *j* (*km*).
$D_{ATJ_{at,j}}$	Distance between third party sawmill *at* and destination *j* (*km*).
PP_k	Selling price of product *k ($/t).*
$C_{AT_{at,k}}$	Cost of raw material *k* purchased from third party sawmill *at ($/t).*
C_{FC_i}	Fixed cost of chipper machine *i ($).*
C_{FA_i}	Fixed acquisition cost of chipper machine *i ($).*
C_{VA_i}	Variable production cost of chipper machine *i ($/t).*
$C_{TRC_{r,ap}}$	Transportation cost between stand *r* and sawmill *ap ($/km).*
$C_{TRD_{r,j}}$	Transportation cost between stand *r* and destination *j ($/km).*
$C_{TATC_{at,j}}$	Transportation cost between third party sawmill *at* and destination *j ($/km).*
$C_{TCC_{i,j}}$	Transportation cost for moving materials from chipper machine *i* to destination *j ($/km).*
$C_{TCC2_{i,r,j}}$	Transportation cost for placing portable chipper *i* in location *j ($/km).*
R_{TC}	Processing yield of product on chipper-machine.

C_c	Vehicle capacity *(t)*.
m_r	Minimum number of truckloads sent from stand *r (t)*.
M	A large number
R_{SCANT}	Transformation yield of sawn logs to cants.
R_{SDS}	Transformation yield of sawdust produced by the company sawmills.
R_{LBARK}	Transformation yield of bark obtained from the debarking of pulpable and sawn logs.
R_{SW}	Transformation yield of sawn logs to wood
R_{SDSW}	Transformation yield of sawdust from wood processing.
V_E	Quantity of sold energy
R_B	Yield of t of biomass per MWh *($/MWh)*.
P_E	Energy sale price per MWh *($/MWh)*.
P_W	Selling price of wood after drying *($/t)*.

Continuous variables

$X_{RAP_{r,ap,k}}$	Quantity of products *k* transported from stands *r* to own sawmills *ap*
$X_{API_{ap,i,k}}$	Quantity of products *k* transported from own sawmill *ap* to chipper *i*
$X_{ATJ_{at,j,k}}$	Quantity of products *k* transported from third-party sawmills *at* to destination *j*.
$X_{APJ_{ap,j,k}}$	Quantity of products *k* transported from own sawmills *ap* to destination *j*.
$X_{RJ_{r,j,k}}$	Quantity of products *k* transported from stands *r* to destination *j*.
$X_{IJ_{i,j,k}}$	Quantity of the products *k* transported from chipper *i* to destination *j*.
$X_{RI_{r,i,k}}$	Quantity of the products *k* transported from stands *r* to chipper *i*.
$X_{B_{j,k}}$	Quantity of produced k biomass.
Z	Objective function.
REV	Revenue.
I_{PL}	Income from sale of pulpable logs.
I_E	Income from sale of energy.
I_{TC}	Income from the sale of trunk chips
I_{FBC}	Income from sales of biomass chips.
I_W	Income from the sale of wood.
$COST$	Total costs.
C_{RM}	Cost of raw material purchased from sawmills.
C_{FC}	Fixed chipper machine installation cost.
C_{UC}	Utilization cost of chippers *i* (i_3 or i_4).
C_P	Variable production cost of chippers

C_T Total transportation cost.

Binary variables

Y_{R_r}	Equal to 1, if the stand *r* is harvested on the planning period
$Y_{AP_{ap}}$	Equal to 1, if the own sawmill *ap* is used.
$Y_{AT_{at}}$	Equal to 1, if the third-party sawmill *at* supplies raw material.
Y_{I_i}	Equal to 1, if chipper *i* is used.
Y_{J_j}	Equal to 1, if customer *j* receives products.

Objective function

The objective function seeks the maximization of the company' profit. Profit is defined as the difference between revenues and the summation of fixed and variable costs.

$$Z = REV - COST \tag{1}$$

Flow and balance constraints

Eqs. (2)–(16) define the balance and flows between the different nodes in the supply chain and ensure the flow between them.

Equation (2) establishes that if a stand is exploited, the amount of pulpable log sent to customers and the own sawmill must be equal to the capacity of the stand.

$$\sum_{j=j'} X_{RJ_{r,j,k}} + \sum_{ap=ap_1} X_{RAP_{r,ap,k}} = C_{R_{r,k}} * Y_{R_r} \qquad \forall\, r \in R,\ \forall\, k = PL \tag{2}$$

For the sawn log, equation (3) shows that, if a stand is exploited, the amount of sawn log sent to the own sawmill must be equal to the capacity of the stand.

$$\sum_{ap=ap_1} X_{RAP_{r,ap,k}} = C_{R_{r,k}} * Y_{R_r} \qquad \forall\, r \in R,\ \forall\, k = SL \tag{3}$$

Equation (4) connects the amount of forest biomass sent to the portable chipper with the capacity of this product in the stands, if that stand is exploited.

$$\sum_{i=i_4} X_{RI_{r,i,k}} = C_{R_{r,k}} * Y_{R_r} \qquad \forall\, r \in R,\ \forall\, k = FB \tag{4}$$

Equations (5)-(11) determine the amount of different products obtained after certain operations. In these constraints, several conversion factors, such as R_{SCANT}, are used. Equation (5) calculates the number of cants that are sent to the waste chippers from the own sawmill considering the amount of sawn logs received from the stands.

$$\sum_{r,ap=ap_1,k=SL} X_{RAP_{r,ap,k}} * (1 - R_{LBARK}) * R_{SCANT} = \sum_{ap=ap_1,i=i_{op},k=Cant} X_{API_{ap,i,k}} \quad (5)$$

Equation (6) specifies the amount of pulpable logs that is sent to the pulpable log chipper.

$$\sum_{r} X_{RAP_{r,ap,k}} * (1 - R_{LBARK}) = \sum_{i=i_3} X_{API_{ap,i,k}} \qquad \forall\, ap \in AP, \forall\, k = PL \quad (6)$$

Equation (7) determines the amount of cant-chips and pulpable log chips obtained after cants and pulpable logs are processed on the operative chippers.

$$\sum_{ap,k=Cant,PL} X_{API_{ap,i,k}} * R_{TC} = \sum_{j,k=CC,PLC} X_{IJ_{i,j,k}} \qquad \forall\, i \in i_1, i_2, i_3 \quad (7)$$

Equation (8) determines the amount of waste chips obtained after cants and pulpable logs are processed on operative chippers.

$$\sum_{ap,k=Cant,PL} X_{API_{ap,i,k}} * (1 - R_{TC}) = \sum_{j=p_1,k=WC} X_{IJ_{i,j,k}} \qquad \forall\, i \in i_1, i_2, i_3 \quad (8)$$

Equation (9) shows the relationship between the amount of forest biomass and the amount of forest biomass chips.

$$\sum_{r,k=FB} X_{RI_{r,i,k}} = \sum_{j,k=FBC} X_{IJ_{i,j,k}} \qquad \forall\, i = i_4 \quad (9)$$

Equation (10) determines the amount of bark obtained from the processed logs that is sent to the power generation plant.

$$\left(\sum_{r,k=PL} X_{RAP_{r,ap,k}} + \sum_{r,k=SL} X_{RAP_{r,ap,k}}\right) * R_{LBARK} = \sum_{j=p_1,k=Bark} X_{APJ_{ap,j,k}} \qquad \forall\, ap \in AP \quad (10)$$

Equation (11) defines the amount of sawdust obtained from the processed logs that is sent to the power generation plant.

$$\sum_{r,ap,k=SL} X_{RAP_{r,ap,k}} * (1 - R_{LBARK}) * R_{SW} * R_{SDSW} + \sum_{r,ap,k=SL} X_{RAP_{r,ap,k}} * (1 - R_{LBARK}) * R_{SDS} = \sum_{ap,j=p_1,k=SD} X_{APJ_{ap,j,k}} \quad (11)$$

Equation (12) determines the total amount of biomass (B) used in the power plant. The biomass is obtained from residues of third party sawmills, biomass chips, pulpable log chips, cant-chips, waste chips, bark and sawdust.

$$\sum_{at,k=Ws} X_{ATJ_{at,j,k}} + \sum_{i,k=CC,PLC,FBC,Ws} X_{IJ_{i,j,k}} + \sum_{ap,k=Bark,SD} X_{APJ_{ap,j,k}} = \sum_{k=B} X_{B_{j,k}} \qquad \forall\, j \in JP \qquad (12)$$

Equation (13) shows that the sum of cant-chips and pulpable log chips is equal to the log chip that can be sold to customers.

$$\sum_{i=i_1,i_2,i_3,k=CC,PLC} X_{IJ_{i,j,k}} = \sum_{i=i_1,i_2,i_3,k=TC} X_{IJ_{i,j,k}} \qquad \forall\, j \in JC \qquad (13)$$

Eq. (14)-(15) impose upper and lower bounds on the quantity of products *k* transported from stands *r* to the own sawmills *ap*. Similar constraints must be imposed to variables $X_{RJ_{r,j,k}}$, $X_{API_{ap,i,k}}$, $X_{RI_{r,i,k}}$ and $X_{ATJ_{at,j,k}}$. Due to space limitations, they are not written in this work.

$$\left\{\begin{aligned} \sum_{ap,k=SL,LP} X_{RAP_{r,ap,k}} &\le M * Y_{R_r} \\ \sum_{ap,k=SL,LP} X_{RAP_{r,ap,k}} &\ge m_R * Y_{R_r} \end{aligned}\right\} \qquad \forall\, r \in R \qquad (14)$$

$$\left\{\begin{aligned} \sum_{r,k=SL,LP} X_{RAP_{r,ap,k}} &\le M * Y_{AP_{ap}} \\ \sum_{r,k=SL,LP} X_{RAP_{r,ap,k}} &\ge m_R * Y_{AP_{ap}} \end{aligned}\right\} \qquad \forall\, ap \in A_P \qquad (15)$$

Demand and production constraints

Eq. (16) defines the minimum and maximum production capacity for products processed in each chipper machine. For waste chippers (i_1, i_2), the constraint imposes maximum and minimum bound on the quantity of cant chips that can be obtained. Regarding the chipper processing pulpable log (i_3), a similar constraint limits the maximum and minimum quantity of pulpable log chips that can be processed. Finally, another similar constraint states the maximum and minimum amount of biomass chip processed by the portable chipper (i_4).

$$\left\{\begin{aligned} \sum_{j} X_{IJ_{i,j,k}} &\ge C_{MIN_{i,k}} * Y_{I_i} \\ \sum_{j} X_{IJ_{i,j,k}} &\le C_{MAX_{i,k}} * Y_{I_i} \end{aligned}\right\} \qquad \forall\, i \in I, \forall\, k = CC, PLC, FBC \qquad (16)$$

Equations (17)–(19) determine the quantities of product *k* necessary to cover both the internal and external demands.

$$\sum_{r} X_{RJ_{r,j,k}} \le D_{J,k} * Y_{J_j} \qquad \forall\, j \in J', \forall\, k = PL \qquad (17)$$

$$X_{B_{j,k}} = D_{J,k} * Y_{J_j} \quad \forall j = p_1, \forall k = B \tag{18}$$

$$\sum_{i} X_{IJ_{i,j,k}} \leq D_{J,k} * Y_{J_j} \quad \forall j \in JC, \forall k = TC, FBC \tag{19}$$

Income constraints

Equations (20) – (25) define the revenues obtained from the sale of different products. Therefore, while eq. (20) computes the total incomes as the sum of revenues associated to the sale of each product, eqs. (21) to (25) define the profits associated to selling pulpable logs, energy, trunk chip, biomass chip and wood, respectively.

$$REV = I_{PL} + I_E + I_{TC} + I_{FBC} + I_W \tag{20}$$

$$I_{PL} = \sum_{r,j=J'\ k=PL} X_{RJ_{r,j,k}} * PP_k \tag{21}$$

$$I_E = \sum_{j=p_1\ k=B} X_{B_{j,k}} * P_E * (1/R_B) * V_E \tag{22}$$

$$I_{TC} = \sum_{i,j=JC,k=TC} X_{IJ_{i,j,k}} * PP_k \tag{23}$$

$$I_{FBC} = \sum_{i=4,j,k=FBC} X_{IJ_{i,j,k}} * PP_k \tag{24}$$

$$I_W = (\sum_{r,k=SL} C_{R_{r,k}} * Y_{R_r}) * (1 - R_{LBARK}) * R_{SW} * P_w \tag{25}$$

Cost computing constraints

Eq. (26) computes the total costs as the sum of all costs. In this way, the cost for purchasing raw materials is defined by eq. (27), chipper-machines fixed costs are defined by eq. (28), amortization of acquired chipper-machines are given by eq. (29), production costs are defined by eq. (30) and transportation cost by eq. (31).

$$COST = C_{RM} + C_{FC} + C_{UC} + C_P + C_T \tag{26}$$

$$C_{RM} = \sum_{\text{at},j=p_1,k=W_{at}} X_{ATJ_{at,j,k}} * C_{AT_{at,k}} \tag{27}$$

$$C_{FC} = \sum_{i=i_{op}} C_{FC_i} + \sum_{i=i_{pot}} C_{FC_i} * Y_{I_i} \tag{28}$$

$$C_{UC} = \sum_{i} C_{FA_i} * Y_{I_i} \tag{29}$$

$$C_P = \sum_{\text{ap},i=i_1,i_2,i_3,k=Cant,PL} X_{API_{ap,i,k}} * C_{VA_i} + \sum_{r,i=i_4,k=B} X_{RI_{r,i,k}} * C_{VA_i} \tag{30}$$

$$C_T = \sum_{\text{r,ap,k=PL,SL}} X_{RAP_{r,ap,k}} * D_{RC_{r,ap}} * \frac{C_{TRC_{r,ap}}}{C_c} + \sum_{i=i_1,i_2,i_3,j,k=CC,PLC} X_{IJ_{i,j,k}} * D_{CD_{i,j}} * \frac{C_{TCC_{i,j}}}{C_c} + \sum_{i=i_1,i_2,i_3,j=p_1,K=WC} X_{IJ_{i,j,k}} * D_{CD_{i,j}} * \frac{C_{TCC_{i,j}}}{C_c} + \sum_{r,j=j\prime,k=PL} X_{RJ_{r,j,k}} * D_{RD_{r,j}} * \frac{C_{TRD_{r,j}}}{C_c} + \sum_{at,j=p_1,k=W_{at}} X_{ATJ_{at,j,k}} * D_{ATJ_{at,j}} * \frac{C_{TATC_{at,j}}}{C_c} + \sum_{i=i_4,j,r,k=FBC} X_{IJ_{i,j,k}} * D_{CD2_{i,r,j}} \frac{C_{TCC2_{i,r,j}}}{C_c} \tag{31}$$

4 Numerical Results

The convenience of using the proposed formulation is demonstrated by solving different scenarios of the case study. Table 1 shows the main characteristics of the scenarios considered in this section. From S_1 to S_4, they consider alternative configurations for the chippers, while the demand of forest biomass for the power energy plant (70.080 *t/year*, necessary to generate 4 *MWh*) as well as the maximum amount and the price of the waste delivered by third-party sawmills (179.914 *t/year* and 392 *$/t*) are the same in all scenarios. S_1 represents the current situation of the company where just the chippers used for processing cants (i_1 and i_2) are available. The pulpable logs chipper (i_3) and the forest biomass chipper (i_4) are not present. On the other hand, S_4 is the most general situation where the possibility of reconfiguring the supply chain and all product flows is considered. S_4 considers that each chipper (i_1 to i_4) may or may not be included on the supply chain configuration. Scenarios $S_{5.1}$ to $S_{7.4}$ deal with different situations of practical interest to the company. In these cases, the variations are considered with respect to the values of scenario S_4.

Table 1. Case scenery characteristics.

Case Scenery	**Waste Chippers (i_1 & i_2)**	**Pulpable Chipper (i_3)**	**Portable Chipper (i_4)**	**Biomass Demand [t/year]**	**Waste of third-party sawmills**	
					Maximum mount [t/year]	Average Price [$/t]
S_1	Yes	No	No	70.080	179.914	392
S_2	Yes	No	Yes	70.080	179.914	392
S_3	Yes	Yes	No	70.080	179.914	392
S_4	*	*	*	70.080	179.914	392
$S_{5.1}$	*	*	*	**87.600**	179.914	392
$S_{5.2}$	*	*	*	**105.120**	179.914	392
$S_{5.3}$	*	*	*	**122.640**	179.914	392
$S_{5.4}$	*	*	*	**140.160**	179.914	392
$S_{6.1}$	*	*	*	70.080	**107.948**	392
$S_{6.2}$	*	*	*	70.080	**80.961**	392
$S_{6.3}$	*	*	*	70.080	**53.974**	392
$S_{6.4}$	*	*	*	70.080	**26.987**	392
$S_{7.1}$	*	*	*	70.080	179.914	**490**
$S_{7.2}$	*	*	*	70.080	179.914	**588**
$S_{7.3}$	*	*	*	70.080	179.914	**686**
$S_{7.4}$	*	*	*	84.600	179.914	**785**

* The inclusion {0;1} is determined by the model.

$S_{5.1}$ to $S_{7.4}$ take into account changes related to biomass demand as well as the maximum amount and price of waste supplied by third-party sawmills. In the first cases, $S_{5.1}$ to $S_{5.4}$, an increase in biomass demand by the power generation plant is considered, ranging from 87.600 t/year to 140.160 t/year. On the other hand, in cases $S_{6.1}$ to $S_{6.4}$, a gradual decrease in the supply of waste provided by third-party sawmills is taken into account, ranging from 107.948 t/year to 26.987 t/year. Finally, scenarios $S_{7.1}$ to $S_{7.4}$ consider the price increase of waste purchased to third-party sawmills (ranging from 490 $/t to 785 $/t).

The formulation was implemented in GAMS 34.3.0 and solved with CPLEX 20.1 on a personal computer, with Intel Core i3-9100F 3.60 GHz and 32 GB RAM memory, for a 0 % gap tolerance. It is important to note that all scenarios are solved in short CPU times. Optimal results are obtained using between 0,09 and 0,19 seconds of CPU time. For the cases considered, the model involves 656 continuous variables,131 binary variables, and 1.062 constraints.

4.1 Results for different equipment considerations (S_1 to S_4)

Table 2 and Figures 2 to 5 show relevant characteristics of the solutions obtained for scenarios S_1 to S_4. For example, Table 2 indicates the number of harvested stands, the amount of raw materials (pulpable log, sawn log and forest biomass) sent from stands to the different supply chain entities, the number of produced chips, as well as the amount of waste supplied by third-party sawmills.

Table 2. Results for scenarios S_1 to S_4

Case Scenery	Stands	Pulpable Logs [t/year]	Saws Logs [t/year]	Harvest Biomass [t/year]	Pulpable Log Chip [t/year]	Cant Chip [t/year]	Biomass Chip [t/year]	Third-party sawmills	Waste third party sawmills [t/year]
S_1	10	4.966	38.729	0	0	12.417	0	12	59.175
S_2	8	4.877	33.416	1.555	0	10.714	1.555	12	59.116
S_3	71	61.924	121.089	0	44.515	38.824	0	1	237
S_4	27	15.633	108.786	8.468	8.315	34.879	8.468	9	28.663

From the table and figures, it can be seen that the most rentable case is S_3. Nevertheless, when the solution is analyzed, it is observed that the biomass from the stands is not used, therefore more stands must be exploited to cover the demand of raw material for the power generation plant (44 stands more than in S_4). Apparently, S_3 involves an economically advantageous situation in the analyzed period, however, it has negative consequences in the future because constrains the company capacity to obtain raw materials due to the overexploitation of stands carried out in the current planning period. In addition, it implies wasting the available forest biomass and leaving it in the forests. In order to avoid this situation, the costs of exploiting stands must be taken into account.

The solution obtained for S_4 establishes that all the chipper machines must be used to maximize the economic benefit. Figure 5 shows the network structure obtained for S_4. Compared with the solutions obtained for cases S_1 and S_2, the solution of S_4 presents greater profit mainly due to two factors: the increased production and the sale of chips and lumber, as well as, a decrease in the purchasing cost of waste from external sawmills. It is important to note that the increase in profit occurs despite the significant increase in transportation costs.

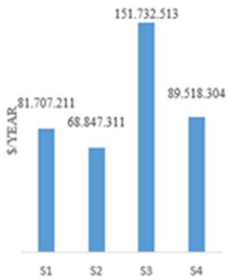

Fig. 2. Objective function value for S1 to S4

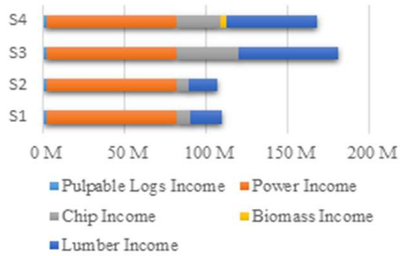

Fig. 3. Revenues for S1 to S4 [Millions $/year].

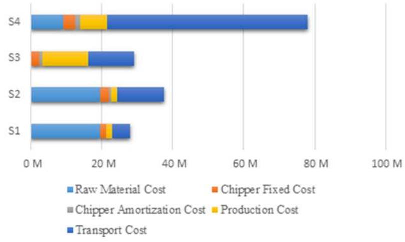

Fig. 4. Cost for S1 to S4 [Millions $/year].

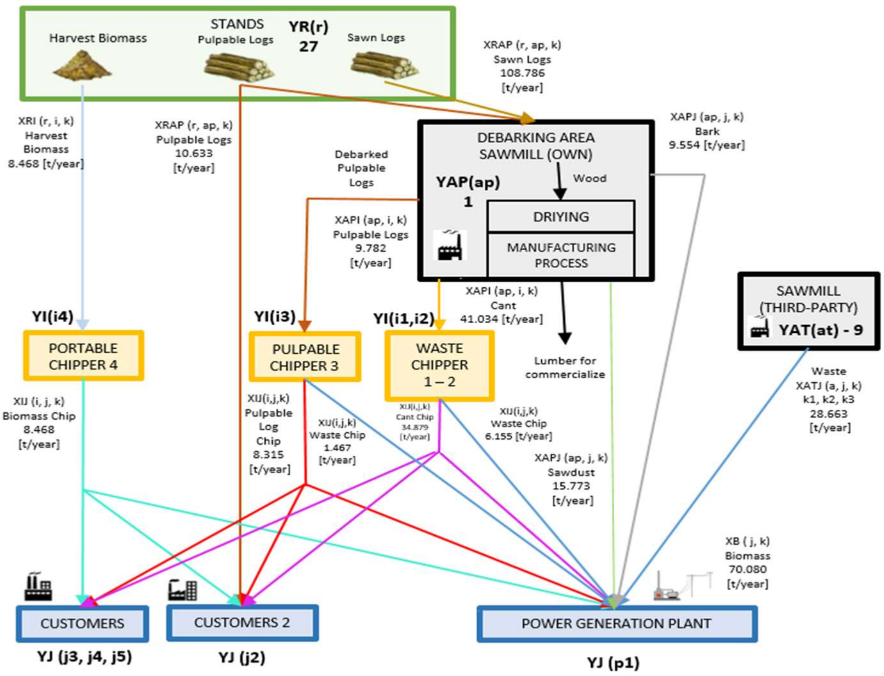

Fig. 5. Optimal network structure obtained for S4.

4.2 Results for scenarios with perturbed parameters ($S_{5.1}$ to $S_{7.4}$)

In this section, the results for cases $S_{5.1}$ to $S_{7.4}$ are shown (see Table 3). From the analysis of the results obtained for $S_{5.1}$ to $S_{5.4}$, it is highlighted that most of the increase in the production of the power generation plant is carried out with residues from external sawmills without intervening more stands than in S_4. This is due to the capacity of the company, with the proposed network topology and taking into account the maximum use of its own resources, is insufficient to cover the increased plant demand. In all the variations of the S_5 scenarios, the income from energy sales, the costs of buying residues in third-party sawmills and the costs of transporting them increase. In addition, in all scenarios, the revenues increase more than costs. In case $S_{5.4}$, in which 140.160 tons per year of waste are required for the operation of the plant, the economic benefit continues to be positive. In this case, only 98.743 tons of third-party waste are used, which represents 55% of the total waste that can be purchased to third-party sawmills (179.914 tons). Therefore, it is observed that, if required, it is feasible to increase the production of the plant without making major changes in the supply chain, since there is still an external supply of waste, at a reasonable market price, that can be used.

On the other hand, the results obtained considering the decrease in the amount of waste from external sawmills ($S_{6.1}$ to $S_{6.4}$) show that it can be easily managed, with a minimum variation in benefit, due to the great availability of external sawmills in the region where the company is located. The analysis of the results shows that in scenarios $S_{6.1}$ to $S_{6.3}$, the amount of waste required from external sawmills is the same, but the number of sawmills supplying waste increases. In these cases, the economic benefit of the company decreases by less than 1%. In scenario $S_{6.4}$ (in which there is an 85% decrease in the amount of waste available), the economic benefit is reduced by 3%. This is due to the fact that more stands have to be intervened and all the residues from third-party sawmills are used.

Table 3. Results for scenarios $S_{5.1}$ to $S_{7.4}$.

Case Scenarios	Stands	Pulpable Logs [t/year]	Saws Logs [t/year]	Harvest Biomass [t/year]	Pulpable Log Chip [t/year]	Cant Chip [t/year]	Biomass Chip [t/year]	Third-party sawmills	Waste third party sawmills [t/year]
$S_{5.1}$	27	15.633	108.786	8.468	8.315	34.879	8.468	11	46.183
$S_{5.2}$	27	15.633	108.786	8.468	8.315	34.879	8.468	13	63.703
$S_{5.3}$	27	15.633	108.786	8.468	8.315	34.879	8.468	15	81.223
$S_{5.4}$	27	15.633	108.786	8.468	8.315	34.879	8.468	17	98.743
$S_{6.1}$	27	15.633	108.786	8.468	8.315	34.879	8.468	11	28.663
$S_{6.2}$	27	15.633	108.786	8.468	8.315	34.879	8.468	13	28.663
$S_{6.3}$	27	15.633	108.786	8.468	8.315	34.879	8.468	17	28.663
$S_{6.4}$	30	18.943	109.545	8.860	10.903	35.122	8.860	20	26.987
$S_{7.1}$	27	15.633	108.786	8.468	8.315	34.879	8.468	9	28.663
$S_{7.2}$	27	15.633	108.786	8.468	8.315	34.879	8.468	8	28.663
$S_{7.3}$	30	18.943	109.545	8.860	10.903	35.122	8.860	3	12.881
$S_{7.4}$	30	18.943	109.545	8.860	10.903	35.122	8.860	0	0

Finally, in scenarios $S_{7.1}$ to $S_{7.4}$, the price increase of waste forces the company to reduce the purchase from external sawmills and replace it with its own products, which implies a decrease in profit. Given that the company must allocate more of its own products to be used as fuel in the power plant, the revenue decreases due to the reduction in sales of products to customers. This situation is clearly evidenced in scenarios $S_{7.3}$ and $S_{7.4}$ where the prices of waste increases between 75% and 100% with respect to S_4.

5 Conclusions

This work presents a MILP model for optimizing the structure and product flows of a forestry-industry company, taking into account the use of forestry resources to meet the needs of different customers and to satisfy the demand of a power generation plant. In the approach, several raw materials from stands and byproducts that flow through the network are accuracy considered, mainly those related to biomass and residues of the activity due to the importance of being used as fuel for the power generation plant.

The objective function of the model is the profit maximization. The proposed model was evaluated considering several operational conditions of a forestry-industrial company. In all cases, in few CPU time, optimal solutions were obtained. From the solutions can be seen the importance of considering a new network structure in order to increase the company profit. The solution obtained for the most general case (S_4) indicates the benefits of including new chippers for the treatment of forest biomass and pulpable logs. In this case, the company is able to increase the profit by intensifying the production of several products, taking advantage of the biomass and waste of all the company activity and decreasing the purchase of waste to third party sawmills. The results show the advantages of using the proposed approach as a decision-making tool.

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