

Design and optimization of a supply chain for cogeneration of electrical and thermal energy from forest biomass

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Abstract. A forestry-industrial company from the north of Misiones province buys electricity for covering its energy demand. The installation of a cogeneration plant for producing thermal and electrical energy from biomass in order to satisfy the company demand and upload the surplus to the electricity grid is researched in this work. Several options for supplying the cogeneration plant exist and different alternatives; namely pulp chip, industrial waste, forest waste and industrial residues from sawmills; must be taken into account and selected. In this framework, the calorific value, costs and market of different biomass fuels are necessary data for the optimal setting of the company supply chain. This study develops a mathematical model for optimizing it with a global perspective in order to identify the best decisions and supply-flows. The objective function aims at setting the supply chain configuration that maximizes profits and selects the best biomass supply-sources and products-destinations. Optimal flows within the supply chain are also fixed. The MILP model is solved with GAMS and its optimal configuration on four realistic scenarios is analyzed.

Keywords: forestry biomass, cogeneration, optimal supply chain.

1 Introduction

Given the dependence of the global economy on fossil fuels, the oil price volatility, the long-term forecasted decline in worldwide petroleum reserves and the growing energy consumption, considerable research efforts have been focused on finding new and sustainable alternatives with less environmental impact. Alternative energy-sources should ideally be renewable and sustainable. Biomasses include biodegradable products, waste and residues of biological origin from agriculture, forestry and aquaculture. Biomass comes from a wide range of raw materials like wood, agricultural crops, byproducts of wood processing, manure and the organic processing of waste. Biomass, as a form of renewable energy, has the advantage of being easily stored, transported and used. This makes biomass unique among other renewable energy options [1]. Although the consumption of biomass for generating energy presents several advantages [2], some difficulties as availability, cost, quality, conversion performance,

transport-cost and the performance of the logistics system must be overcome for its efficient use as fossil-fuels replacement. This leads to high managing costs of a biomass supply chain which in turn constitutes a strong incentive for the optimal design and optimization of such a supply chain. The main forest biomass (wood used directly as fuel) originates by waste derived from the harvest and represents in Argentina, 264,000 t per year. It arises mainly from implanted forests. The biomass generated from forest harvests is basically composed of branches, canopies and sections of stem outside commercial standards. Calorific capacity of industrial and forest biomass vary very little, even between different species because its chemical composition is almost invariant. Although the calorific capacity on a dry basis does not vary substantially, an important aspect to take into account, due to drying time, is the wet content. The use of forest biomass reduces the costs of land preparation, planting and maintenance, which may imply a saving of 10% of the total preparation cost prior to planting [3]. In addition, the use of forest biomass reduces the likelihood of forest fires and the environmental impact produced by the emission of CO₂ into the atmosphere due to the lower amount of fuel present in the field. In the other hand, the negative ecological impact of forest waste extraction must be considered. The total extraction of this material can stimulate the loss of nutrients and, in some cases, the erosion of the soil caused by letting it naked. Although there are very few studies evaluating the optimal amount of organic material that should be left on the soil to compensate for the loss of essential nutrients by the extraction of forest biomass; Borjesson [4] suggests that the minimum amount of waste required to maintain soil fertility may vary between 0.8 and 2.2 t/ha per rotational period, depending on the particular conditions of the area. A study carried out by Fassola et al., [5] allows estimating the biomass of *Pinus taeda* L, which, in turn, allows evaluating the potential to produce energy from this biomass. Gómez and Vergara [6] classify the biomass of the industrial type considering the waste generated in sawmills, which include:

Bark: outer layer of round wood. It is obtained in sawmills that have bark betterers, leaving the bark as wood residue.

Mops: Lateral sections of the log obtained in the sawing process.

Chips: Thin tape of variable thickness, obtained by means of the brushing of pieces of wood.

Pinching: Residues from terminal sections of wood pieces originated from the process of dimensioning the length of the wood.

Chips without bark: small pieces of wood of square or rectangular section, chopped by a chipper.

Slash: log lateral sections, characterized by having two clean faces, which are re-processed and incorporated into the volume of sawn wood or sold to barracks for use.

This study develops a mathematical model for optimizing the supply chain of a forestry industrial company located in the north of Misiones (Argentina). The feasibility of operating a 4,5 MW cogeneration plant with different biomass alternatives as raw materials is included in the developed model. The objective function aims at setting the supply chain configuration that maximizes profits and selects the best biomass supply-sources and products-destinations. Optimal flows within the chain are also fixed. The MILP model of the supply-chain is solved with GAMS and its optimal configuration in four different scenarios is illustrated.

2 Problem description

The forestry-industrial company is located in the north of Misiones province and is vertically integrated, i.e., it owns forest, sawmill, and a cogeneration plant that produce logs, lumber, plywood, pulp, paper and bioenergy by using biomass as fuel. The cogeneration plant (Demand₁) produces 3.5 MW from a consumption of 70,080 t/years of biomass. The raw material feed to the cogeneration plant are chip produced by the own chippers (CH₁ and CH₂) currently in operation in sawmill. Besides, sawmill waste (R) as bark, sawdust and bark chip are used. In addition to this, two potential machines are considered to obtain more raw materials. A chipper machine (CH₃) able to process pulp logs (PU₁, PU₂,... PU_n) from forest (Stand₁, Stand₂, Stand_n) is considered in order to obtain pulp chip for supplying different customers (Demand₁, Demand₂, ... Demand_n). Besides this, biomass from forest harvesting (thinning and clear cut) is a potential raw material source if a chipper (CH₄) is acquired to process branches, leaves and fine stem. Finally, sawmills of the region (Sawmill₁, Sawmill₂, Sawmill_n) are potential suppliers of raw material (sawdust, waste, bark). The surplus of raw material not destined to the cogeneration plant (Demand₁) can be sold to different customers (Demand₁, Demand₂, ..., Demand_n). The firm seeks to find the optimal use of different biomass sources in such a way that profits are maximized while the demand of the cogeneration plant is satisfied (See Figure 1).

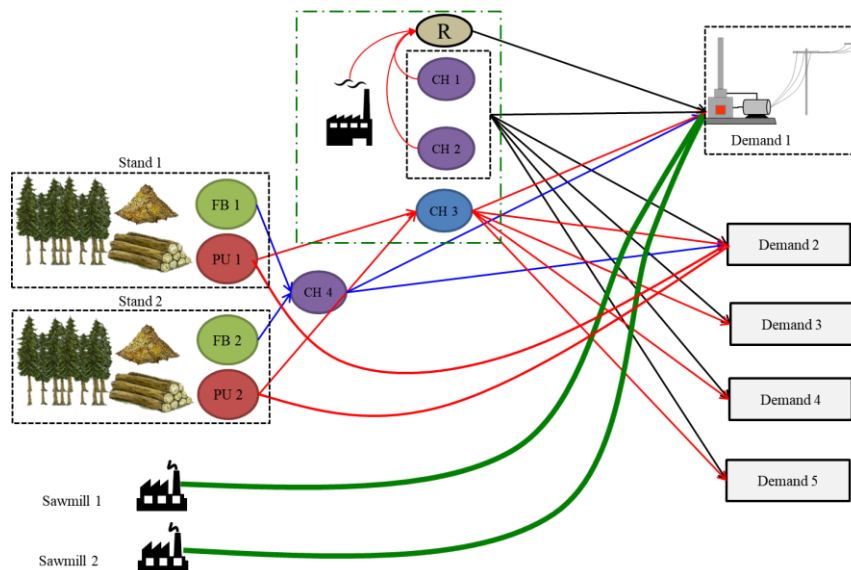


Fig. 1. Supply chain options of the case study.

3 Mathematical model of the supply chain

In this section sets, parameters, variables and equations of the model developed to optimize the company supply chain are presented.

Sets

I	Chip machines
J	Destinations
A	Sawmills
K	Products
R	Stands

Variables

$ChAsP_{ij}$	Amount of wood chip to transport from actually working chip-machine $i = 1, 2$ to destination j (t/year).
$TrPulp_{ri=3}$	Quantity of pulp logs to send from stand $r = 1, 2$ to the potential chip machine $i = 3$ that will be installed in sawmills property (t/year).
$ChTr_{i=3j}$	Amount of wood chip to transport from chip machine $i = 3$ to destination j (t/year).
$TrPulp_{rj}$	Amount of pulp logs to send from stand r to destination j (t/year).
$YTrPulp$	Binary variable defining the investment decision for buying the chip machine for pulp logs in the sawmill land.
$BioPosCos_{ri}$	Amount of after-harvest biomass going from stand r to the chip machine $i = 4$ (t/year).
$ChBio_{rj}$	Amount of chip biomass going from chip machine $i = 4$ to the energy plant $j = 1$ and destination $j = 2$.
$YInvBio$	Binary variable that define draw upon whether biomass active the set and investment.
$YBiom_r$	Binary variable defining if draw upon the biomass from the stand $r = 1, 2, \dots, R$ (t/year).
$ChAsTer_{aj}$	Amount of products to send from sawmills a to the plant $j = 1$ (t/year).
$YAsTer_{aj}$	Binary variable that takes the value 1 when sawmill a sells all k sub-products; otherwise it takes value 0.
$EconChip_i$	Define the economic benefit from currently working chip machines $i = 1$ and $i = 2$ (\$/year).
$EconChip_{i=3}$	Economic benefit from chip machine $i = 3$ regarding its potential installation (\$/year).
$EconChip_{i=4}$	Economic benefit from potential chip machine $i = 4$ for processing after-harvest biomass (\$/year).
$CosAsTer$	The total cost of buying biomass from other sawmills (\$/year).
OF	Objective variable (\$/year).

$DistTransTrChip_{i=3j}$	Total traveled distance from chip machine $i = 1, 2$ to destination $j = 1$ (km).
$DistTransTrPul_{ri=3}$	Total travelled distance from the stand r to the chip machine $i = 3$ (km).
$DistTransTrChip_{i=3j}$	Total traveled distance from chip machine $i = 3$ to destination $j = 2$ (km).
$DisTransChipBio_{i=4j}$	Total travelled distance between the biomass chip machine $i = 4$ and destination $j = 1, 2$ (km).
$DistTransAsTer_{aj=1}$	Total travelled distance for transporting sub-products from sawmill a to destination $j = 1$ (km).
$CostTransProp$	Cost to transport inside waste (\$).
$DistChipBiom_{r=1j}$	Total distance for transporting chip biomass from stand $r = 1, 2, \dots, R$ to destination $j = 1, 2$ (km).
$EconTrCliente$	Economic benefit from selling pulp logs to clients (\$/t).
$PrResAsP_k$	Amount of inside waste to send to destination $j = 1$ (t/year).

Parameters

$PMinCh_i$	Minimum chip production by machine $i = 1, 2$.
$PMaxCh_i$	Maximum chip production by machine $i = 1, 2$.
r	Yield of chips obtained from pulp logs (%).
$DemTr_{j=2}$	Demand of pulp logs by destination $j = 2$ (t/year).
$OMaxTP_r$	Offer of pulp logs by stand r (t).
r'	Yield of chip biomass obtained from post-harvesting biomass (%).
$OMinBF$	Minimum amount of biomass available in stand r (t/year).
$OMaxBF$	Maximum amount of biomass available in stand r (t/year).
$OffChAsTer_{ak}$	Offer of product k by sawmills a (t/year).
$DemE$	Demand of the plant that can be satisfied with wood chip, brush wood chip, biomass chip and waste (t/year).
$DemChP_j$	Wood chip demand of destination j (t/year).
$CosTraTPul_{ri=3}$	Pulp logs transportation cost from stand r to the potential chip machine $i = 3$ (\$/t).
$CosVCh_{i=1,2}$	Variable production-cost for chip machine i (\$/t).
$CosFCh_{i=1,2}$	Fixed production-cost for chip machine i (\$/t).
$CosVPrChTr_{i=3}$	Variable production-cost for the potential chip machine $i = 3$ (\$/t).
$CosFPrChTr_{i=3}$	Fixed production-cost for the potential chip machine $i = 3$ (\$/t).
$InvChTr$	Investment amortization (\$).
$CosTrChBio_{i=4j}$	Transportation-cost from (potential) chip machine $i = 4$ to destination j .
$CosVPrChBio_{i=4}$	Variable production-cost for (potential) biomass chip machine $i = 4$ (\$/t).
$CosFPrChBio_{i=4}$	Fixed production-cost for potential biomass chip machine $i = 4$ (\$/t).
$InvBio$	Investment cost for potential biomass chip machine $i = 4$ (\$)

$CosTrAsTer_{aj=1}$	Transportation-cost from sawmills a to destination $j = 1$ (\$/km)
$\$PAsTer_{ak}$	Market price of sawmills a products k (\$/t).
$\$ChPulp$	Market price of the wood chip (\$/t).
$\$Bio$	Market price of biomass chip (\$/t).
$CostCh_{ij}$	Chip transportation-cost from i to destination j (\$/km).
$CosTrP_{ri=3}$	Transportation cost from the stand r to (potential) chip machine $i = 3$ (\$/km).
q	Truck transportation-capacity (t/travel).
dCh_{ij}	Distance from chip machine i to destination j (km)
$dTrP_{ri=3}$	Distance from stand r to chip machine $i = 3$ (km).
$dAs_{aj=1}$	Distance from sawmills a to destination j (km).
$CostTransp_{ij=1}$	Internal transportation-cost of own chip from the chip machine i to the energy plant. (\$/t).
$PrResAsP_k^{Min}$	Minimum production-waste k .
$PrResAsP_k^{Max}$	Maximum production-waste k .
$CostTranspInt_{ij=1}$	Transportation-cost of chip from chip machine i to the energy plant (\$/t).
$CosBiom_{rj=1,2}$	Transportation-cost of biomass chip from stand r to destination $j = 1, 2$ (\$/km).
dR_{rj}	Distance from stand r to destination $j = 1, 2$.
$CosTranTr_{rj=2}$	Transportation cost of pulp logs from stand r to destination $j = 2$ (\$/km).
$\$TrPulp$	Market price of pulp logs (\$/t).

In order to model the topology of the supply chain, a brief description of constraints and the objective function is next presented.

Model constraints

Eq. (1) imposes upper and lower bounds to the waste production in the sawmill of the company owning the cogeneration plant.

$$PrResAsP_k^{Min} \leq PrResAsP_k \leq PrResAsP_k^{Max} \quad k \in K \quad (1)$$

Eq. (2) states that the total amount of wood chips produced by machine i must be bounded by the interval defined by the minimum and maximum production capacity of machine i .

$$PMinCh_i \leq \sum_{j \in J} ChipAsP_{ij} \leq PMaxCh_i \quad i \in I : i \leq 2 \quad (2)$$

Eq. (3) defines the amount of wood chips that will be produced from pulp log with the potential chip machine $i = 3$, just in case this machine is installed.

$$r \sum_{r \in R} TrPulp_{ri} = ChTr_{ij} \quad i \in I : i = 3 \quad (3)$$

Eq. (4) defines the amount of pulp logs that will be directly sent to destination $j = 2$. This quantity must not exceed the customer demand predefined by a contract.

$$\sum_{r \in R} TrPulp_{rj} \geq DemTr \quad j \in J : j = 2 \quad (4)$$

Eq. (5) states that the amount of pulp logs to send from stands $r = 1, 2, \dots, R$ to destination $j = 2$ and chipper $i = 3$ cannot overcome the logs offer available on such stands.

$$TrPulp_{rj} + TrPulp_{ri} \leq OMaxTp_r \quad \forall r, i, j : r \in R, i = 3, j = 2 \quad (5)$$

Eq. (6) states that variables $TrPulp_{ri}$ can only be positive just in case chip machine $i = 3$ is installed. Otherwise, these variables must value zero.

$$\sum_{r \in R} TrPulp_{ri} \leq B_M YTrPulp \quad i \in I : i = 3 \quad (6)$$

Eq. (7) computes the biomass quantity as the product between the transformation coefficient r' and the quantity of after-harvest biomass.

$$r' BioPosCos_{r4} = ChBio_{r4} \quad r \in R \quad (7)$$

Eq. (8) is an auxiliary constraint used to define the biomass flow from stands $r = 1, \dots, R$, to chipper $i = 4$ and to destination $j = 1, 2$.

$$ChBio_{ri} = ChB_{rij} \quad r \in R, i = 4, j = 1, 2 \quad (8)$$

Eqs. (9) imposes upper and lower bounds to the biomass flow from stands $r = 1, \dots, R$ to chipper $i = 4$ just in case the decision variable $YInvBio$ is activated.

$$YInvBio \times OMinBF_r \leq BioPOsCos_{ri} \quad (9.a)$$

$$i \in I : i = 4$$

$$YInvBio \times OMaxBF_r \geq BioPOsCos_{ri} \quad (9.b)$$

Eq. (10) states that quantities of products to send from sawmills $a = 1, \dots, A$ to the cogeneration plant $j = 1$ must not exceed the available offer from sawmills, just in case decision variable $YAsTer$ is activated.

$$ChAsTer_{aj} \leq YAsTer \sum_{k \in K} OfferChAsTer_{ak} \quad a \in A, j \in J : j = 1 \quad (10)$$

Eq. (11) defines the demand $DemE$ of plant energy $j = 1$ as the summation of the waste production in the own sawmill; the amount of wood chips produced by the working chipper; the potential chip produced by installing a chipper to process pulp logs; the potential biomass produced by the use of forest harvest residues; and the purchase of waste from sawmills of the region.

$$\sum_{k \in K} PrResAsP_k + \sum_{\substack{i \in I: \\ i \leq 2}} ChAsP_{ij} + ChTr_{i=3j} + \sum_{r \in R} ChB_{ri=4j} + \sum_{a \in A} ChAsTer_{aj} \geq DemE \quad j \in J : j=1 \quad (11)$$

Eq. (12) defines the amount of wood chip that a client j can receive from chipper $i = 1, 2$ and from the potential chipper $i = 3$.

$$r \sum_{\substack{i \in I: \\ i \leq 2}} ChipAsP_{ij} + ChTr_{i=3j} \leq DemChP_j \quad j \in J : j \geq 1 \quad (12)$$

Eq. (13) defines the internal cost incurred by transporting the own chips.

$$CostTransp \sum_{k \in K} PrResAsP_k = CostTranspP \quad (13)$$

Eq. (14) defines the economic benefit originated from the chip production with currently working machines i_1 and i_2 .

$$\sum_{\substack{i \in I: \\ i \leq 2}} EconCh_i = \$ChPulp \sum_{\substack{i \in I: \\ i \leq 2}} \sum_{\substack{j \in J: \\ j \leq 2}} ChAsP_{ij} - \sum_{\substack{i \in I: \\ i \leq 2}} ChAsP_{ij=1} CostTranspInt_{ij=1} - \sum_{\substack{i \in I: \\ i \leq 2}} \sum_{\substack{j \in J: \\ j \leq 2}} \frac{ChAsP_{ij} dCh_{ij}}{q} CostCh_{ij} - \sum_{\substack{i \in I: \\ i \leq 2}} \sum_{\substack{j \in J: \\ j \leq 2}} ChAsP_{ij} CostVCh_{ij} - \sum_{\substack{i \in I: \\ i \leq 2}} CostFCh_i \quad (14)$$

Eq. (15) define the economic benefit of a potential chip machine i_3 installed to process pulp logs from the own forest.

$$EconCh_{i=3} = \$ChPulp \sum_{\substack{j \in J: \\ j \leq 2}} ChTr_{i=3j} - \sum_{\substack{i \in I: \\ i=3}} \sum_{\substack{j \in J: \\ j \leq 2}} ChTr_{ij} CostVCh_{ij} - \sum_{\substack{i \in I: \\ i=3}} \sum_{\substack{j \in J: \\ j \leq 2}} \frac{TrPulp_{ri} dTrP_{ri}}{q} CostTrP_{ri} - ChTr_{i=3j=1} CostTranspInt_{i=3j=1} - \sum_{\substack{i \in I: \\ i=3}} (CostFCh_i + InvChTr) YTrPulp - \sum_{\substack{i \in I: \\ i=3}} \sum_{\substack{j \in J: \\ j \leq 2}} \frac{ChTr_{i=3j} dCh_{ij}}{q} CostCh_{ij} \quad (15)$$

Eq. (15) defines the economic benefit of a potential chipper machine i_4 installed to process after-harvest biomass.

$$\begin{aligned}
 EconCh_{i=4} = & \$Bio \sum_{r \in R} \sum_{\substack{j \leq 2 \\ i=4}} ChBio_{rij} - \sum_{r \in R} \sum_{\substack{j \leq 2 \\ i=4}} ChBio_{rij} CostVCh_j - \\
 & - \sum_{\substack{r \in R \\ i=4}} \sum_{j \leq 2} \frac{ChBio_{rij} dR_{rj}}{q} CostBiom_{rj=1} - (CostFCh_{i=4} + InvBio)YInvBio
 \end{aligned} \tag{16}$$

Eq. (17) define the total cost of buying waste (bark, sawdust and bark chip) from other sawmills in the region. When binary variable $YAsTer = 1$, all waste must be purchased but if $YAsTer = 0$ buying waste is not allowed at all.

$$\begin{aligned}
 CosAsTer = & \sum_{\substack{a \in A \\ j=1}} CosTransAsTer_{aj} \frac{dAs_{aj} ChAsTer_{aj}}{q} \\
 & + YAsTer \sum_{\substack{k \in K \\ a \in A}} OfferChAsTer_{ak} \$PAsTer_{ak}
 \end{aligned} \tag{17}$$

Eq. (18) defines the economic benefit generated from selling pulp logs from the own forest to client j_2 .

$$EconTrCliente = \$TrPulp \sum_{\substack{r=1 \\ j=2}} TrPulp_{rj} - \sum_{\substack{r \in R \\ j=2}} \frac{TrPulp_{ij} dR_{rj}}{q} CostTranTr_{rj} \tag{18}$$

Objective function

The objective function seeks to maximize profits of the supply chain. It is written as the difference between benefits and operative costs. Total benefits are defined by the sum of benefits from currently working chipper machines (i_1, i_2), potential chipper machines (i_3, i_4) and sales of pulp logs. Operative costs are computed as the sum of transport costs and costs of buying waste from other sawmills.

$$OF = \sum_{i \in I} EconCh_i + EconTrCl - (CostTranspP + CosAsTer) \tag{19}$$

In order to test the above developed model, a realistic instance defined as a base scenario as well as three scenarios deviating from the base-one were solved and analyzed in the next section.

4 Results and discussion

Base scenario

To meet the demand of 70,080 t per year of the thermal plant (Demand 1), the optimal solution indicates that 63% of the fuel arises from by-products (shavings, sawdust, bark) of the company's own sawmill. This corresponds to the total volume of by-products generated by the sawmill. This is due to two main reasons: the low price of byproducts (they can just be used as fuel) and the low cost of transporting them to the thermal plant. A 30% of the fuel arises from by-products of third-party sawmills. Although the logistic cost increases, due to the low market price, it is still a good supply alternative. Finally, the remaining fuel (7%) is chip pulp from the own sawmill. Although this fuel has a high market value, the transportation cost to the thermal plant is low. In the base scenario, the model does not activate investment the decision variables for both the equipment for the transformation of pulpable trunk (Ch_3) and for the use of forest biomass (Ch_4). A surplus of 170,086 t per year of raw material is obtained. A 73% of this raw material is sold as pulpable stock and a 27% as pulp chip. This last raw material arises as the surplus pulp-chip obtained from the own sawmill. The benefit obtained is \$ 6,526,761. The instance was coded in GAMS 23.6 and solved in just 13.1 s. It involves 12 binary variables, 643 continuous variables and 538 constraints.

Table 1. Results for tested scenarios

	<i>Scenarios</i>			
	Initial	Of.AsTer × 5	Of.AsTer = 0	DemPE ↑12t/hs
<i>Thermal plant demand (t/year)</i>	70.080	70.080	70.080	105.120
<i>By-products from the own sawmill(t/year)</i>	44.400	44.400	44.400	44.400
<i>Chip aserradero propio (t/year)</i>	4.679	0	8.641	0
<i>Chip trunk (t/year)</i>	0	0	0	22.679
<i>Chip biomass (t/year)</i>	0	16.342	17.039	17.039
<i>By-products from third party sawmills(t/year)</i>	21.001	9.338	0	21.001
<i>Total</i>	70.080	70.080	70.080	105.120
<i>Offer to clients</i>				
<i>Pulpable trunk (t/year)</i>	124.365	124.365	124.365	99.166
<i>Chip from own sawmill (t/year)</i>	45.721	50.400	41.759	50.400
<i>Chip biomass (t/year)</i>	0	0	0	0
<i>Chip trunk (t/year)</i>	0	0	0	0
<i>Total (t/year)</i>	170.086	174.765	166.124	149.566
<i>Total supply cost (\$/year)</i>	11.312.327	13.776.223	15.145.577	28.150.567
<i>GLOBAL PROFIT (\$/year)</i>	6.526.761	4.636.002	2.208.156	-9.380.814

Alternative scenarios

In order to evaluate the performance of the model, three variants deviating from the base scenario are defined and solved.

The first alternative scenario considers that the number of by-products from sawmills ($Of.AsTer \times 5$) decreases from 10 to 5. In this scenario, 63% of the raw material comes from the by-products of the own sawmill. Like in the base scenario, this percentage corresponds to the total quantity of raw materials offered by the sawmill. A 13% corresponds to byproducts from third-parties sawmills and represents all the raw material available in these industries. Finally, 13% of the remaining fuel is obtained by using post-harvest biomass of the company. So, the investment on a machine for processing the remaining products of the forest harvest is required. From this supply scheme there is a surplus of 174,765 t per year of biomass; 71% of this biomass corresponds to pulpable trunk and 29% to pulp chip coming from the company's sawmill. This percentage is sold to a third party (Demand 2) due to its high market value. The benefit obtained is \$ 4,636,002.

In the second alternative scenario, a supply scheme without offers by third-party sawmills ($Of.AsTer = 0$) is evaluated. For this scenario, the plant is 63% supplied with the own sawmill by-products. The remaining 27% is supplied with biomass chip, considering the investment on the corresponding equipment for the use and transformation of raw materials in biomass chip. A 13% is supplied from the own sawmill products. Although these products have a high market value, since there is no offer from sawmills in the area, the model-solution suggests to consume them in a minimum quantity. The surplus of biomass for this scenario is 166,124 t per year; a 75% corresponds to pulpable trunk and a 25% to own sawmill's chip which are marketed. In this scenario, an annual benefit of \$ 2,208,156 is obtained.

In the third alternative scenario, an increase on the demand of the power plant in 105,120 t per year (Demand 1) was studied. The model solution indicates that a 42% of the plant consumption is satisfied with byproducts generated by the own sawmill. This quantity corresponds to the totality of the by-products generated in the sawmill. A 22% corresponds to trunk chip, which implies the investment on the corresponding equipment to process and transform pulpable trunk. A 14% of consumption corresponds to biomass chip; triggering the investment on the corresponding equipment. A 20% of the demand is supplied with by-products from sawmills in the area, which corresponds to the total quantity offered by them. For this scenario the remaining biomass corresponds to 66% of pulpable trunk and 34% of chip generated by the own sawmill. The latter represents the total pulp chip produced. The annual benefit is \$ -9,380,814, which means that the total cost of supplying plant exceeds the benefits of selling the biomass surplus.

5 Conclusions

In this work, a MILP model developed to define the supply flows of raw materials from different origins (sawmill by-products, post-harvest biomass, pulp chip and pulpable trunks) to a cogeneration plant producing electrical and thermal energy was pre-

sented. The objective of the model is to maximize the profit obtained by commercializing the remaining biomass while prioritizing the supply toward the thermal plant. In order to study the performance of the model four scenarios were presented and solved. For these scenarios, the model solutions implied that the greatest benefit was obtained by supplying the plant with the available raw material of lower market value, followed by a remnant of higher value raw material but with low logistic costs. For scenarios where the equipment investment decision was activated for processing raw materials, the commercialization of the pulp chip was prioritized. Although the raw material present a very low transportation cost, its market value positions it as a product to be marketed in order to maximize the annual net profit.

The next research step involves a systematic sensibility study on raw material costs, on products values and on the quantity of available alternative biomasses. In the long term the most critical variables should be considered as stochastic variables.

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