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Research article

A modeling framework for the optimal forest supply chain design considering residues reuse

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ABSTRACT

In the forest industry, large volumes of residues are generated during the harvesting and lumber production, whose re-use can increase the economic opportunities in this industry. In this sense, they can be used as raw material for some products (pellets, wood panels, among others) or as fuels for energy production. Due to the great number of available production alternatives and involved elements, a supply chain approach is appropriate to address this problem. Then, taking into account the particular conditions of the forest industry in Argentina, a mixed integer linear programming formulation is proposed in order to obtain the optimal design of the forest supply chain emphasizing the appropriate use of forest and wood residues. The model determines the location and size of each production facility, the amounts of products and residues to be generated, and all the material flows between forest sites and plants, between plants, and between plants and customers, in order to maximize the total benefit. This approach is suggested as a tool to analyze the optimal configuration of the forest supply chain by assessing the viability of different production alternatives. Through the different considered scenarios, it can be concluded that a strategic design for the forest supply chain is required in order to achieve an efficient use of harvest and sawmill residues.

1. Introduction

In the forest activity two big matters can be distinguished: one focuses on forestry, particularly forest management, including planting, growing, harvesting, etc., and another one focuses on industrial production or the exploitation and transformation of forest resources. This article is concerned with the second issue, from a perspective of a supply chain (SC). The SC involves many different production stages, processes, flows and products, and it entails several aspects as logs and products transportation, energy generation, lumber, paper, medium density fiberboard (MDF) productions, among others. In particular, this SC has interesting opportunities for the production of second generation biofuels, options for process integration, utilization of harvest and sawmills residues as raw material for different final products, and many alternatives of connections and exchanges among the involved actors. Taking into account the global forest sector is becoming more complex, interlinked and cross-sectoral, a detailed analysis of the available alternatives, the involved tradeoffs and the expected results is justified (Heinimö et al., 2011; Hurmekosky and Hetemäki, 2013).

One aspect that characterizes the forest industry is the large quantity of residues generated in the mechanical transformation of wood, from harvesting to obtain final products. These residues have not received much attention until now despite having interesting applications (Uasuf and Becker, 2011). Several reasons, such as involved volumes, required facilities, distances and logistic costs, have affected their efficient employment.

During harvesting, residues like foliage, branches and leaves, are generate, which can be used for producing different products. Depending on forest supply chain design, they constitute non-commercial material left on site after harvesting, or, sometimes, are chipped for transporting and sent to a plant for a later use (Vance et al., 2018). In this work, they are referred as harvesting residues and considered as raw material for pellets and ethanol production. Sawmill (or wood) residuals are those material generated by the mechanical transformation of logs, like bark, wood chips, and dust. These materials are a key issue in this industry because the generated quantity and variety constitute a big percentage of the raw material. Fortunately, these residual materials can be useful as feedstock for other products, such as bioethanol, pellets and wood panels.

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Biofuels include a wide range of fuels which are derived from biomass. In particular, foresting and sawmill residues are an option which can be used as feedstock, benefiting the production of second generation biofuels, i.e. fuels produced from residues of crop and forest (Awudu and Zhang, 2012). Biofuels can be solid (pellets or residues used for burning) and liquid (ethanol). Even though nowadays fossil fuels dominate the market, the penetration of second-generation liquid biofuels is expected to take place by the year 2020 in favorable circumstances, not only by economical and availability reasons, but also by environmental conditions (Demirbas et al., 2011).

Different articles have analyzed proposals for the production of biofuels using forest resources. For example, Pirraglia et al. (2013) developed a techno-economic model for the production of torrefied wood pellets, considering critical production parameters, and evaluating sensitivity to changes in some key parameters as capital cost, biomass delivery costs, labor, and energy consumption of a facility. Uasuf and Becker (2011) proposed diverse scenarios by studying the production costs of pellets and energy consumption using sawmills residues in the Argentinean Northeast. Pettersson et al. (2015) proposed a geographically explicit optimization model by determining the location of the different biofuel production units from forest biomass in Sweden.

On the other hand, Whalley et al. (2017) presented an economic biomass SC model to estimate the costs of biomass delivery, harvesting and chipping of the logging residues, and transport of the biomass chips to a biorefinery for biofuel production. Sarkar et al. (2011) developed a detailed techno-economic model based on demonstrated technologies currently available for producing high quality syngas from forest biomass. Mirkouei et al. (2016) analyzed the use of mobile refineries in combination with large-scale non-mobile refineries to facilitate the production of biofuel near the source of underutilized forest harvesting residues.

Forest SC design and planning are crucial for integrating different actors and activities. An analysis framework is required, and mathematical modeling, mainly using mixed integer linear programming (MILP) is a useful tool to achieve these objectives allowing decision makers to have right insights about efficient SC designs (Mishra et al., 2017). In a recent work, Mirkouei et al. (2017) presented a literature review on techno-economic modeling and optimization efforts targeted on biofuel supply chain from forest biomass. They conclude that future biomass-to-bioenergy SC must resort to the development of efficient and effective forest biomass supply chain networks. They also highlight that, more investigation into modeling and optimization of pretreatment as a part of the upstream segment of biomass-to-bioenergy SCs is needed. In the same direction, Rönnqvist et al. (2015) addressed diverse open problems in the forest industry. In particular, for SC planning they states that even though plans for the different SC components can be set, the main effort must be done in coordinating these plans across units.

Some approaches have been proposed for forest SC optimization, including the use of forestry residues and the biofuel production from them. Mobini et al. (2013) presented a model for the pellet SC, analyzing different raw materials. Kong et al. (2012) considered an integrated market where all raw materials are taken into account, including forest and sawmill residues. Cambero et al. (2015) presented a mathematical model for the production of heat, electricity, pellets and pyrolysis biofuel from available forest harvesting and sawmills residues applied to a case study in Canada. An MILP model is formulated by Troncoso and Garrido (2005) for solving the facilities location, the freight distribution and the forest production problem. Dansereau et al. (2014) proposed a framework for forestry biorefineries to help decision-makers to identify different SC policies for a variety of market conditions. Troncoso et al. (2015) dealt with the SC planning problem, including different time horizons and emphasizing the integration among production facilities.

From the above it can be noted that, in order to achieve a sustainable and efficient design of the forest SC, it is necessary to consider all the actors involved and the different alternatives for the use of residues. Previous articles integrate some production facilities and, sometimes, residues are considered. However, to the best of our knowledge, there are few published articles that distinguish among residues types and its uses, and almost none analyze the integrated design including production of traditional products as well as biofuels in the context of forest SC optimization.

On the other hand, in Argentina exists 1,200,000 hectares of planted forests, being Pinus and Eucalyptus the main species (Ministry of Science, Technology and Productive Innovation of Argentina, MINCyT, 2013). This amount is expected to increase and there are many possibilities and advantages to improve this activity. In particular, the northeast region has suitable soils, high tree growth rates, and low production costs, among other beneficial characteristics, that make the forest industry attractive and promising. Reports from public agencies also informed that more than 70% of forest residual biomass has no use, and most of harvest residues are burnt, deteriorating the soil quality (Ministry of Science, Technology and Productive Innovation, 2013). Therefore, the study of the uses for the different harvest and sawmills residues for adding value to the forest SC represents a challenge for academic and industrial sectors.

In this context, this work proposes a mathematical model for the optimal design and strategic planning of the forest SC. Different production facilities, products and raw materials are considered, as well as integrated industrial sites conforming production clusters. These clusters are introduced in order to reduce the distances between feasible locations, favoring the use of residues among facilities. Forest industries are strongly related because a variety of residues obtained from the log and lumber processes can be used for manufacturing different products. The proposed approach considers in detail the processing of residues from harvest areas and sawmills. Usually, these elements are discarded, prioritizing the main components of the production system, but in this approach, all the resources are prioritized and integrated in order to improve the raw material consumption and ensure a sustainable production. Also, the distribution of the raw material (logs) among the different production facilities is a model decision. The proposed model takes into account all these elements for a suitable assessment of the total system contemplated in the forest SC, considering the tradeoffs that affect its design. In this way, the proposed approach can be used as a tool for analyzing and designing the forest SC from a strategic perspective, where a key element is the suitable utilization of the different generated residues. Finally, this study is based on geographic and technical parameters of the northeast region of Argentina, but this model can be easily adapted to other geographical locations.

The paper is organized as follow: the next section introduces the problem, analyzing the different production facilities involved. The optimization model is presented in Section 3. Section 4 describes the SC problems addressed in this article, whose results are shown in Section 5. Finally, Section 6 presents the conclusions of this work.

2. Problem statement

A centralized forest SC, which raw material is bought from diverse sites that do not belong to the SC firm, is considered. Several production options and uses for harvest and sawmills residues are taken into account from a strategic perspective.

The forest SC considered in this work involves three echelons: harvest areas, productions facilities and consumer regions. Harvest areas are sites that provide logs, belonging to *pinus taeda* species, of

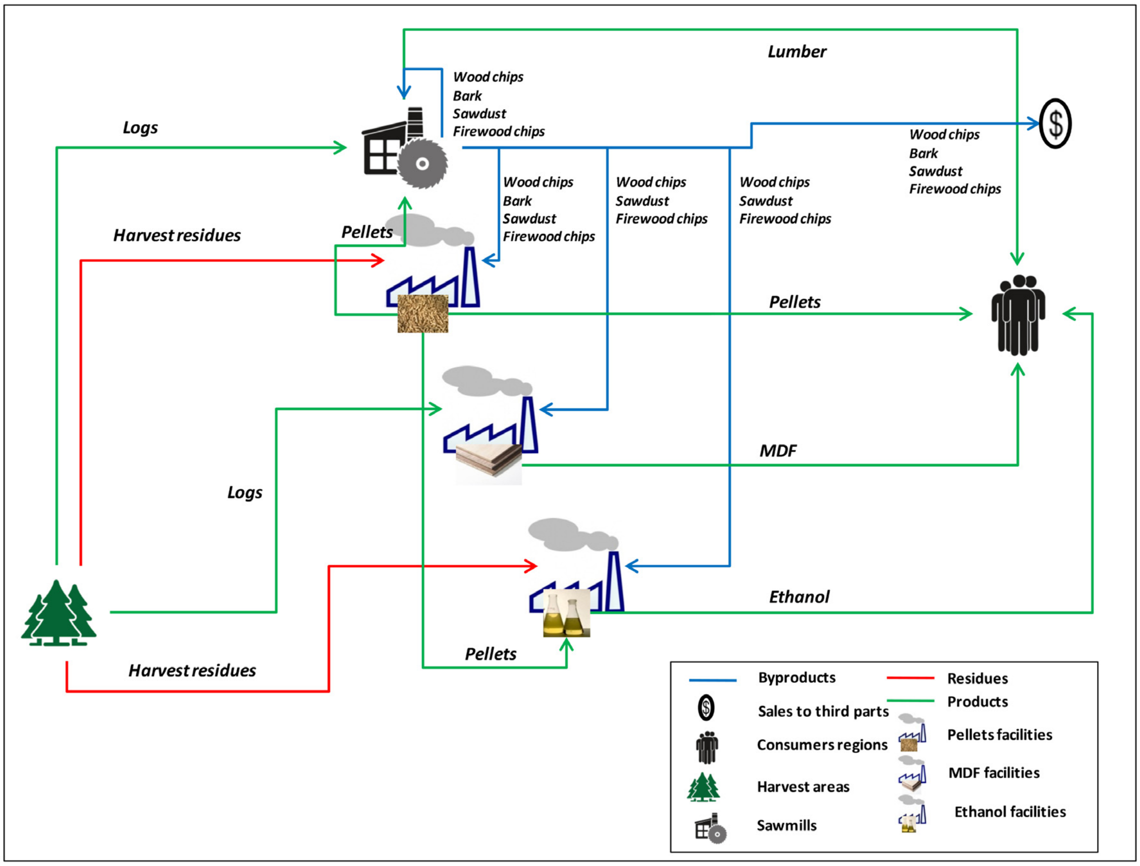


Fig. 1. Forest SC: feedstock, products and residues links among different network nodes.

different diameters. According to the Food and Agriculture Organization of the United Nations (FAO, 2006), from the trees cut down in these areas, 38% stays in the forest as harvest residues (branches, stump, sawdust and foliage). From the total harvest residues, it is assumed that 40% must stay in the forests in order to preserve the soil structure and quality. The remaining 60% can be used as raw material for pellets and ethanol production.

Four types of production facilities are considered in this work: sawmills, ethanol, medium-density fiberboard (MDF), and pellets plants. Different possible locations are proposed for each type of plant, such that, the model determines simultaneously plant installation, type, location, and size. Diverse flows exist among SC nodes, taking into account the raw materials, residues and products considered. The logs for sawmills production and those required as raw material for MDF plants are obtained from harvest areas, while the residues from these sites can be used for ethanol and pellets production. Raw material cost is considered as well as transportation cost from harvest areas to production plants. Sawmills generate different residues during their operation. Taking into account the usual productions conditions in the studied region, these residues represent the 55% of the logs that arrives to the sawmills: 8% is converted into bark, 18.5% into wood chips, 13% into firewood chips, 12% into sawdust and 3.5% are remains. These sawmills residues can be utilized as raw material for pellet, ethanol and MDF production, or, as fuel for the boiler in the same sawmill. Sawmills residuals can be also sold to third parts, but minimum or maximum demands are not considered for them.

For each residue considered in this work, the moisture content (MC) is adopted as an average amount because the approach refers to strategic design and planning of supply chain. From the tactical and operational points of view, MC must be considered in order to evaluate the product and cost quality (Acuna et al., 2012). Detailed studies regarding to MC impact on operation and transportation of wood biomass were presented by Sosa et al. (2015a) and Sosa et al. (2015b).

It is assumed that two lumber types are produced in sawmills: one of better quality with a specific level of moisture content used for construction or furniture production, and the other one, without humidity requirement, usually dried in outdoor weather conditions, employed, for example, for pallets.

MDF panels are produced through the agglomeration of lignocellulosic particles (wood chips, firewood chips, sawdust). On the other hand, hydrolysis fermentation is assumed for the ethanol production. All products are sent to consumer regions to fulfill maximum specific demands.

In this work, thermal energy for lumber and ethanol processes is generated through pellets, which can be used as solid fuel in the boilers. In the case of sawmills, their residues are also used as energy source, while for ethanol facilities, the potential energy sources are pellets and liquid fuels acquired from external suppliers.

Fig. 1 shows the possible relations among SC facilities, while the model elements and their links are resumed in Table 1. It can be noted that “sales to third parts” represent the sawmills residues sold when they are not utilized for energy or production.

3. Mathematical model

In this Section, the mathematical model for the optimal design of the forest SC is formulated. The objective function, the mass balances between the different SC echelons and among facilities, and the design equations are presented. The symbols used for sets, parameters and variables are described in the Nomenclature section.

Table 1
Relationships among facilities, raw materials, sources, fuels, and products.

Type of facility	Raw material	Source of raw material	Fuel	Product	Sawmills residues
Sawmill	Logs	Harvest areas	Sawmills residues, pellets	Lumber	Wood chips, firewood chips, bark, sawdust.
MDF	Logs, wood chips, firewood chips, sawdust	Harvest areas, sawmills	–	MDF	–
Pellets	Harvest residues, wood chips, firewood chips, bark and sawdust	Harvest areas, sawmills	–	Pellets	–
Ethanol	Harvest residues, wood chips, firewood chips and sawdust	Harvest areas, sawmills	Pellets, external fuels	Ethanol	–

It is assumed that there are different types of raw material r, for example diverse log diameters, at each harvest area s. Production facilities f ($f_1 = sawmills, f_2 = MDF, f_3 = pellets, f_4 = ethanol$) can be located at proposed locations l, to supply several products to the different consumer regions k. Each installed facility adopt a maximum capacity t. $C(f)$ defines the set of plants f that can use logs as raw material, i.e. sawmills and MDF facilities. As more than one product can be produced in certain plants, p is used for defining the product and $V(p,f)$ states the relation between the products p produced in each facility type f. In this work, $V(p,f)$ considers that lumbers of types p_1 and p_2 are produced in sawmills (f_1), while MDF p_3, pellets p_4 and ethanol p_5 are produced by facilities f_2, f_3 and f_4, respectively. $D(f)$ represents the set of plants f that can use residues as raw material, i.e. pellets and ethanol facilities in this model. $R(q,p)$ states that sawmill residue q can be used for product p as raw material. In this work, $R(q,p)$ considers that woodchips q_1, firewood chips q_2 and sawdust q_4 are raw materials for products p_3, p_4, and p_5, while bark q_3 can be only used for product p_4.

The objective function considers the profit (Pf) maximization given by the incomes from sales minus investment (Ic), production (Pc), energy (Ec), transportation (Tc) and raw material (Rc) costs considering a period of one year:

$$Pf = I - Rc - Tc - Ic - Ec - Pc \tag{1}$$

In Eq. (2) the income, I, is calculated multiplying the amounts of produced product p in plant f located in site l and sold to customer k (Qp_{lkpf}) and residues q generated at sawmill located in l (Bs_{lq}) delivered to consumers by its selling price (Sp_p for product p, Sb_q for sawmill residue q):

$$I = \sum_{\substack{l,k,p,f \\ (p,f)\in V(p,f)}} Qp_{lkpf} Sp_p + \sum_{l,q} Bs_{lq} Sb_q \tag{2}$$

Raw material cost corresponds to the amount of purchased logs for lumber and MDF productions multiplying by its unitary cost Crm_{rs}:

$$Rc = \sum_{\substack{s,l,r,f,p \\ (p,f)\in V(p,f) \\ f\in C(f)}} Crm_{rs} Ql_{slrfp} \tag{3}$$

Transportation cost includes the amount of logs (Ql_{slrfp}), products (Qp_{lkpf}), and sawmill ($Br_{ll'qfp}$) and forest (Qr_{slfp}) residues delivered between SC nodes, and pellets transported for energy production to ethanol plants ($Qpe_{ll'}$) and to sawmills ($Qb_{ll'}$). It is calculated multiplying the amount of these materials by the distance between the involved nodes (drf_{sl}: distance between raw material sites and facilities; $dff_{ll'}$: distance between facilities; dfc_{lk}: distance between facilities and consumer regions) and the relative cost ($Ctrm_r$, raw material transportation cost; $Ctrf$ and Ctr_q residues transportation cost for forest and sawmill residues q, respectively; Ctp_p product transportation cost) depending on the characteristics of the shipped material (volume, moisture, etc.):

$$\begin{aligned} Tc = {} & Ctrm \sum_{\substack{s,l,r,f,p \\ (p,f)\in V(f,p) \\ f\in C(f)}} Ql_{slrfp} drf_{sl} + \sum_{\substack{s,l,f \\ f\in D(f)}} Ctrf Qr_{slfp} drf_{sl} \\ & + \sum_{\substack{l,l',q,f,p \\ (p,f)\in V(p,f) \\ (q,p)\in R(q,p)}} Ctr_q Br_{ll'qfp} dff_{ll'} \\ & + \sum_{\substack{l,k,p,f \\ (p,f)\in V(p,f)}} Ctp_p Qp_{lkpf} dfc_{lk} \\ & + Ctp_{p4} \sum_{l,l'} (Qpe_{ll'} + Qb_{ll'}) dff_{ll'} \end{aligned} \tag{4}$$

The annualized investment cost is given by the power law expression on unit capacity (Ravermark and Rippin, 1998):

$$Ic = \sum_{\substack{l,t,f \\ t\in T_f}} CCF_{ft} \alpha_f \left(Plmax_{tf}\right)^{\beta_f} w_{ltf} \tag{5}$$

where CCF_{ft} represents the capital charge factor on the time horizon (one year), which includes amortization and maintenance terms of each facility type, and α_f and β_f are cost coefficients which depend on the type of plant. For each installed facility f, a maximum production capacity is selected, $Plmax_{tf}$, from a set of discrete sizes. Finally, w_{ltf} is a binary variable which indicates if facility f is located in site l with capacity t.

In the local context, the boilers of sawmills are fed with harvest and sawmills residues, as well as boilers for ethanol plants which also use liquid fuel if it is necessary. Then, the cost of the fuel bought from external sources to produce thermal energy in ethanol facilities, is calculated multiplying the quantity of necessary liquid fuel (lf_l) by its unit cost (cf) as it is expressed by Eq. (6).

$$Ec = cf \sum_{l} lf_l \tag{6}$$

Production cost involves the operation costs of the installed plants that depend on their production capacity t:

$$Pc = \sum_{\substack{l,p,t,f \\ t\in T_f \\ (p,f)\in V(p,f)}} P_{ltfp} Cp_{ptf} \tag{7}$$

where Cp_{ptf} represents the production cost for product p in a plant f of capacity t, and P_{ltfp} is the produced amount of each product.

Following, the different constraints included in the model are presented. Eq. (8) states that each raw material r, in each harvest area s, has a limited availability, $Maxrm_{sr}$. This value is a model parameter provided by the set of forest companies involved in the SC. Then, the logs utilized by production facilities (Ql_{slrfp}) cannot exceed the available capacity:

$$\sum_{\substack{l,f,p \\ f\in C(f) \\ (p,f)\in V(p,f)}} Ql_{slrfp} \leq Maxrm_{sr} \quad \forall s, r \tag{8}$$

It is assumed that the raw materials proceed from the same tree species that predominates in the studied region, varying only its diameter. Thus, r corresponds to the different considered sizes.

Residues generated in the harvest areas are assumed to be proportional to the quantity of consumed logs according to the parameter fr, following provided by the Food and Agriculture Organization of the United Nations (FAO). The total amount of harvest residues utilized by ethanol and pellets facilities as raw material, Qr_{slfp}, must not exceed the available quantity.

$$\sum_{\substack{l,r,f,p \\ f\in C(f) \\ (p,f)\in V(p,f)}} Ql_{slrfp} fr \geq \sum_{\substack{l,f,p \\ f\in D(f) \\ (p,f)\in V(p,f)}} Qr_{slfp} \quad \forall s \tag{9}$$

In order to represent the effect of production scale on the process, for each facility f, a size t must be selected from a set T_f of available capacities. Then, the capacities for sawmill, ethanol, pellets and MDF facilities are determined using discrete sizes, which are related with the equipment dimension employed at each plant.

Sawmills and MDF plants utilize logs from harvest areas as raw material, which are converted into final products according to a conversion factor c_{pr}. This parameter represents the process productivity.

Residues from sawmills can be used as raw material for MDF, pellets and/or ethanol, and converted into final products according to the conversion factor yb_{qp}. Besides, residues can be used as raw material for pellets and ethanol according to the conversion factor yr_p.

Therefore, the total production of each product p in each facility (P_{ltfp}) considers the total amount of raw material: logs (Ql_{slrfp}), forest residues (Qr_{slfp}) and sawmill residues ($Br_{ll'qfp}$) that arrives at facility f in location l multiplied by the appropriate conversion factors Eq. (10).

$$\sum_{t\in T_f} P_{ltfp} = \sum_{\substack{s,r \\ f\in C(f)}} c_{pr} Ql_{slrfp} + \sum_{\substack{l',q \\ (q,p)\in R(q,p)}} yb_{qp} Br_{ll'qfp} + \sum_{\substack{s \\ f\in D(f)}} yr_p Qr_{slfp} \quad \forall l, (p,f)\in V(p,f) \tag{10}$$

As was previously defined, the binary variable w_{ltf} is equal to 1 if facility f is installed with capacity t at site l:

$$w_{ltf} = \begin{cases} 1 \text{ if facility f with capacity t is installed at site l} \\ 0 \text{ otherwise} \end{cases}$$

If a plant f with size t is located, then the total production cannot exceed its maximum capacity, $Plmax_{tf}$:

$$\sum_{\substack{p \\ (p,f)\in V(p,f)}} \rho_p P_{ltfp} \leq Plmax_{tf} w_{ltf} \quad \forall l, f, t\in T_f \tag{11}$$

where ρ_p correspond to productivity factors that consider different production rates of the products. At most one size is selected for each production facility type at location l:

$$\sum_{t\in T_f} w_{ltf} \leq 1 \quad \forall l, f \tag{12}$$

Eq. (13) defines the quantity of each type of residue generated in sawmill located at site l. The total amount of logs used for lumber production is multiplied by a conversion factor (cb_q) to obtain the quantity of each type of sawmill residue (B_{lq}):

$$B_{lq} = cb_q \sum_{\substack{s,r,p \\ (p,f)\in V(p,f)}} Ql_{slrf_1p} \quad \forall l, q \tag{13}$$

The different sawmill residues can be used as raw materials for pellets, MDF and ethanol production ($Br_{ll'qfp}$), as fuels for boilers (Bb_{lq}) in the same sawmill or can be sold to third parties (Bs_{lq}). These amounts must not exceed the produced quantity in each sawmill:

$$B_{lq} \geq \sum_{\substack{l',f,p \\ (p,f)\in V(p,f) \\ (q,p)\in R(q,p)}} Br_{ll'qfp} + Bb_{lq} + Bs_{lq} \quad \forall l, q \tag{14}$$

As was mentioned in the previous section, the difference between both lumber types (p_1, p_2) considered in this model, is that p_1 requires drying by artificial heat and brushed, while p_2 is dried with natural air. Suppose that a portion fl of lumber type p_2 is also dried through heat from boilers taking advantage of the technical conditions of sawmills. Then, as thermal energy in sawmills is generated by boilers fed with sawmills residues (Bb_{lq}) and pellets ($pb_{l'l}$), the quantity of different fuels q and pellets, multiplied by their calorific capacities cc_q and ccp, respectively, must satisfy the total energy required for drying the lumber:

$$ed \sum_{\substack{t \\ t\in T_f}} (P_{ltf_1p_1} + P_{ltf_1p_2} fl) \leq \sum_q cc_q Bb_{lq} + ccp \sum_{l'} pb_{l'l} \quad \forall l \tag{15}$$

where (ed) is a model parameter that represents the energy required for the lumber drying process.

Pellets can be used as fuel in other facilities or be sold to satisfy market demands. The amount of pellets sent to ethanol facilities ($Qpe_{ll'}$), to sawmill boilers ($Qb_{ll'}$) and sold to customers (Qp_{lkp4f3}) must be less than the produced amount (P_{ltf3p4}), as states Eq. (16):

$$\sum_{l'} Qpe_{ll'} + \sum_{l'} Qb_{ll'} + \sum_k Qp_{lkp_4f_3} \leq \sum_{\substack{t \\ t\in T_f}} P_{ltf_3p_4} \quad \forall l \tag{16}$$

The required thermal energy in each ethanol facility is proportional to the ethanol production, and it can be fulfilled with two possible sources: pellets ($Qpe_{l'l}$)or external fuels (lf_l):

$$ef \sum_{\substack{t \\ t\in T_f}} P_{ltf_4p_5} = ccp \sum_{l'} Qpe_{l'l} + lf_l \quad \forall l \tag{17}$$

where the parameter ef represents the energy conversion factor.

Eq. (18) states that the product provided from the different facilities (Qp_{lkpf}) to each consumer region k cannot exceed their maximum demand ($Dmax_{kp}$)

$$\sum_{\substack{l,f \\ (p,f)\in V(p,f)}} Qp_{lkpf} \leq Dmax_{kp} \quad \forall k, p \tag{18}$$

The total amount of each product sent to consumers regions is limited by its production in each facility, as it is posed in Eq. (19).

$$\sum_{\substack{t \\ t\in T_f}} P_{ltfp} \geq \sum_k Qp_{lkpf} \quad \forall l, (p,f)\in V(p,f) \tag{19}$$

Finally, the mathematical model for the optimal forest SC design consists in the maximization of the net benefit, given by Eq.(1) subject to Eqs. (2)–(19).

Table 2
Maximum demands of each final product in the different consumer regions (*k1*–*k4*).

	Lumber [m^3 $year^{-1}$]		MDF [m^3 $year^{-1}$]	Pellets [t $year^{-1}$]	Ethanol [m^3 $year^{-1}$]
	Type 1	Type 2			
k1	9000	15000	90000	85000	90000
k2	20000	60000	200000	150000	100000
k3	38000	65000	380000	180000	320000
k4	75000	9000	550000	75000	550000

4. Case study

The proposed model is applied to the design of a forest SC in the northeast and center regions of Argentina. In the first region, large areas of forested land with commercial species are available, while, the principal consumer zones are located in the central region (IERAL, 2011). Model parameters and some assumptions are proper of the Argentine forest industry.

The model assumes eight available harvest areas, *s1*–*s8* with two types of raw materials ($r1$ and $r2$), which vary according to the log diameter. A total of nineteen possible locations for production facilities are assumed: in harvest areas (*l1*–*l4* next to *s1*–*s4* respectively, *l5*–*l7* next to *s6*–*s8* respectively, and *l8* close to *s5*), in consumer regions (*l12*–*l15)* or in sites located in medium distances between harvest and customer zones (*l9*–*l11, l16*–*l19)*. For each plant type, a set of three capacities are considered: *t1* (greater capacity*), t2*, and *t3* (smaller capacity). Therefore, the production and investment costs vary according to the selected size. Yields and conversion rates are assumed equal for all sites depending on the used raw material. Forest and sawmills residues conversion factors can be derived from Section 2, where the proportions were stated.

Four consumers regions are selected, located in the center of the country, namely *k1*, *k2*, *k3* and *k4,* located near to *l12*-*l15*, respectively. Fig. 2 shows the locations for each raw material sites and customer zones, which are also possible locations for facilities installation, as well as the remaining proposed sites fir facilities installation (*l9*-*l11* and *l16*-*l19*). Table 2 shows the maximum demands of lumber, MDF, pellets and ethanol for each region; these values were based on average data from the Ministry of Agriculture, Livestock and Fishing of Argentina (2013).

Ground transportation through trucks is assumed. Costs vary according to the material transported: 0.045 \$ $(t\ km)^{-1}$ for raw material, 0.118 \$ $(t\ km)^{-1}$ for harvest and sawmills residues, 0.055 \$ $(m^3 km)^{-1}$ for lumber and MDF, 0.11 \$ $(t\ km)^{-1}$ for pellets, and 0.126 \$ $(m^3\ km)^{-1}$ for ethanol. Costs and selling prices were determined considering values from the Argentinean forest industry (INTA, 2013; Ministry of Agriculture, Livestock Fishing, 2012; IERAL, 2011), except the ones related to ethanol production which were taken from the literature (Wei et al., 2009). It is assumed that raw material cost does not vary with the geographical location and is equal to 23 \$ t^{-1} and 29.23 \$ t^{-1} for $r1$ and $r2$ respectively. Sawmill residues selling prices are equal to 14.11\$ t^{-1} for wood chips, 7.06 \$ t^{-1} for firewood chips and 3.18 \$ t^{-1} for bark and for sawdust. The external fuel cost is equal to 1.096 10^{-6} \$ kj^{-1}, the adopted values for the calorific capacity are 1.92 10^4 kj kg^{-1} for pellets, 9.61 10^3 kj kg^{-1} for bark, 1.07 10^4 kj kg^{-1} for wood chips, 1.25 10^4 kj kg^{-1} for sawdust, and 10^4 kj $kg^{-1}$for firewood chips. The required energy in each case is 1.51 10^6 kj m^{-3} for lumber drying and 1.28 10^7 kj m^{-3} for ethanol production.

The proposed model is solved considering these parameters and those displayed in the Appendix Section. Results are analyzed in detail, emphasizing the distribution and employment of residues. Also, some model parameters are varied in order to highlight the capability of the proposed approach to solve different production–distribution scenarios and to represent the involved trade-offs.

The proposed model has been developed to analyze specific and realistic problems of the involved region, although these examples have been prepared only to show the model capabilities on simplified scenarios.

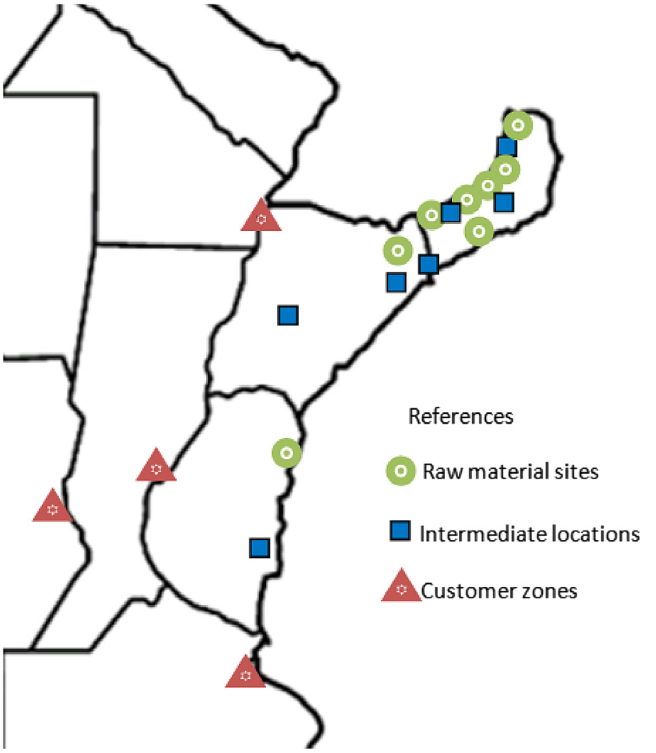


Fig. 2. Locations for harvesting areas, customer zones and plant locations.

5. Results and discussion

In order to analyze the impact of the different considered elements over the SC configuration and test the model performance, the results of the aforementioned case study are presented. This example and those corresponding to model parameters variations, were formulated and solved in GAMS (Brooke et al., 2012), version 24.1.3 with a 2.8 GHz Intel Core i7 processor. The CPLEX 12.5.1 solver was employed for solving the MILP formulations. The models involve 7770 continuous variables, 304 binary variables and 2095 constraints. In all cases, the optimal solution was obtained in around one minute.

5.1. Example

The optimal SC design for the model parameters presented in Section 4 is described in Fig. 3. As it can be noted from the figure, there is a trend to install different production facilities forming clusters, even though there is no location that includes the four types of facilities. Most facilities are located in harvest areas, avoiding the raw material transportation cost. The total benefit is \$ 156,900,000, and the detailed list of sales and costs is shown in Table 3. The available amount of logs is completely used by MDF facilities and sawmills, while the residues from harvest areas are totally consumed by the pellets and ethanol production (Table 4). Taking into account that these residues have no acquisition cost

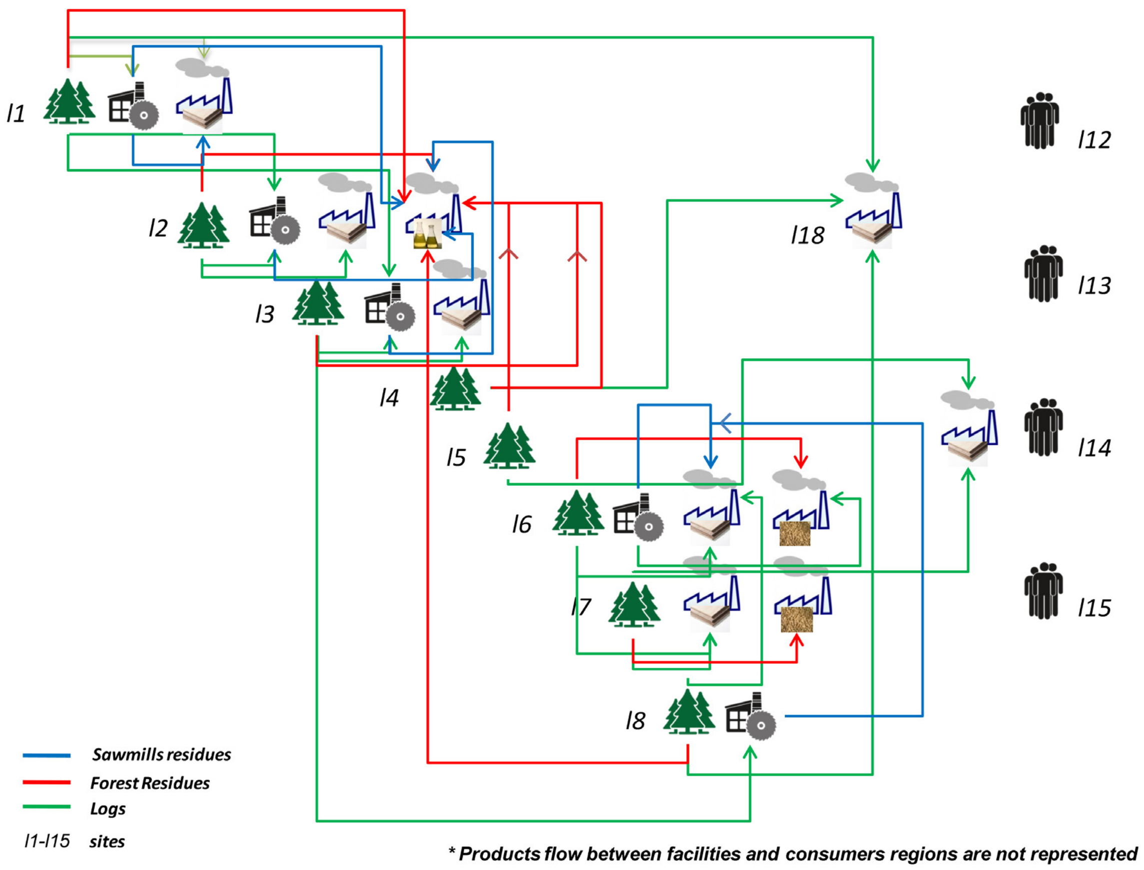


Fig. 3. Optimal SC configuration.

Table 3
Economic report for the different studied cases.

	Millions per year
Sales	
Lumber	50.88
MDF	418.57
Ethanol	58.98
Pellets	7.09
Sawmills residues	0.00
Investment cost	
Sawmills	0.89
MDF	56.25
Ethanol	10.10
Pellets	0.27
Production cost	
Sawmills	26.44
MDF	226.19
Ethanol	18.88
Pellets	2.39
Transportation costs	37.19
Net Benefit	156.91

Table 4
Demand satisfaction, production and feedstock use.

% of supplied demand	
Lumber	86%
MDF	98%
Pellets	6%
Ethanol	5%
% of used raw material	100%
% of used residues	100%
Production	
Lumber [m^3 year^{-1}]	250152
MDF [m^3 year^{-1}]	1180000
Pellets [t year^{-1}]	28963
Ethanol [m^3 year^{-1}]	50000

and only the transportation cost to production plants is considered, they are employed by facilities located near the place where they are generated. Therefore, their use is very attractive and represents a great opportunity to reduce the onsite burning of this material.

Table 5 shows the installed capacities for each facility and the site where they are located. It can be observed (Table 4) that a total of 250,152 m^3 of lumber, 1,180,000 m^3 of MDF, 28,963 t of pellets and 50,000 m^3 of ethanol are produced. The installed capacity is fully used in the case of MDF and ethanol facilities, while 99% and 72% of the total capacity are utilized for sawmills and pellets facilities respectively. In the later case, it is important to notice that, due to investment cost of pellets facilities, is most profitable install two plants in locations close to raw material than a bigger one and transporting the raw material to that plant.

The maximum demands for MDF is 98% satisfied, while 86% of lumber requirement is fulfilled, providing the total demand of type 1 and 72.6% of type 2 lumbers. Only 5% of the maximum demands of pellets and ethanol are fulfilled. MDF demand is not totally satisfied because the installation of an additional facility for covering the 2% of unsatisfied demand is not profitable. Ethanol facility is installed in a strategic point, close to different raw material sources, to reduce the transportation cost.

The residues generated in sawmills are distributed among the diverse facilities. Wood chips, firewood chips and sawdust are sent to nearby ethanol and MDF facilities (Fig. 4). The other sawmill residue, the bark, is used for generating the necessary thermal energy for the sawmill where it is produced, and the remaining material is utilized for pellet production. The total production of

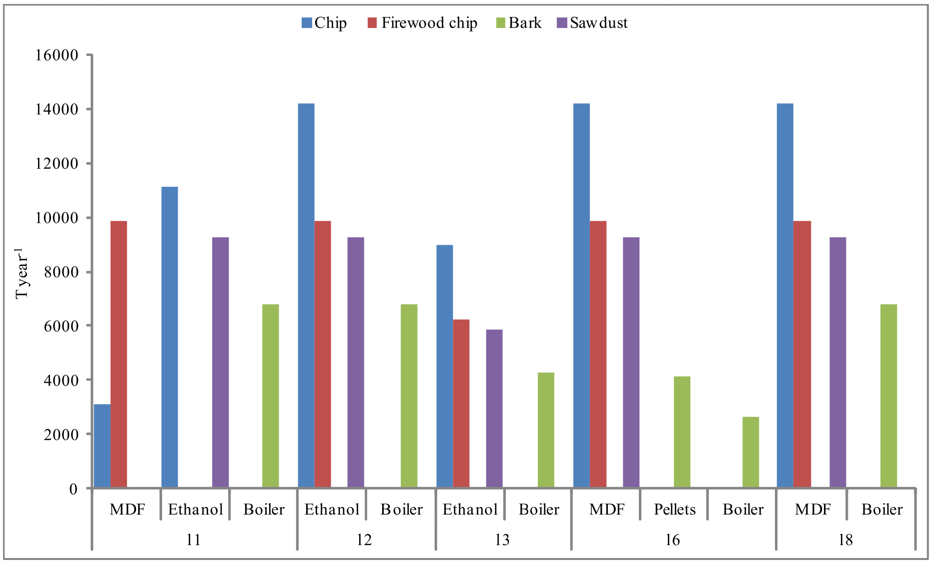


Fig. 4. Optimal distribution of sawmills residues to the different sites where they are utilized.

Table 5
Optimal facilities location and adopted sizes in the studied case.

	l1	l2	l3	l6	l7	l8	l14	l18
Sawmills	❶	❶	❷	❶		❶		
MDF	❸	❶	❸	❶	❷		❸	❶
Pellets				❷	❷			
Ethanol		❸						

Capacities: t1: ❶ t2: ❷ t3: ❸

green: raw material site; **blue**: consumer site**; black**: intermediate site

pellets is sold to consumers, i.e. they are not used as fuels for boilers.

Table 5 shows the facilities capacity and location. It worth to highlight that all sawmills are installed close to a harvest area in order to reduce the log transportation costs. Moreover, with the aim of taking advance on the use of sawmills residuals, the other plants are located in the sites where sawmill are installed. In case of site *l*8, a sawmill of the biggest capacity is installed for supplying its residues to MDF facility located at *l*6 which has also the biggest capacity production. MDF plants located in *l*14 and *l*18 use only logs for its production, which are transported from the nearest raw material sites. The use of these materials allows valorizing elements that previously were scarcely utilized or discarded, and now add value to the entire SC.

5.2. Model performance

The configuration and the operations of the optimal SC strongly depend on the values adopted by the different parameters. In order to evaluate how the model responds to model parameter changes, some problem data are modified from the previous example, one at a time. In this way, different solutions are obtained and the model capabilities are tested.

Scenario a: The lumber selling price is increased by 25% respect to the original value. Some characteristics of the optimal solution for this scenario are displayed in Table 6. The raw material and residues are completely utilized. The total benefit is equal to 169,000,000 \$ year^{-1}. The MDF production keeps the same, ethanol decreases to 45,380 m^3 year^{-1}, pellets production slightly increases to 29,582 t year^{-1} and lumber augments to 270,000 m^3 year^{-1}. Comparing to the previous example, the sites where facilities are located (Table 7) are not modified as well as the sizes of the different plants except for the sawmill located in the site *l* 3, which increases its production. Although the lumber price is better than before, the total demand is not fulfilled because to achieve this, it is necessary to install another sawmill that is not profitable due to the economy of scale. On the other hand, as MDF is the more profitable production, there is a tradeoff between both productions (lumber and MDF) for the use of logs. The ethanol production is reduced because a greater amount of sawmills residues are now sent to MDF facilities in order to replace the logs that are utilized for lumber production.

Scenario b: The raw material availability decreases 25%. As the more profitable production is MDF, its production amount remains the same, while lumber is reduced by 90%, ethanol by 38% and pellets by 30%. All the raw material and the residues are utilized. The total benefit is 124,000,000 \$ year^{-1}. Due to the reduction of logs availability, a lower amount of this raw material is sent to the only installed sawmill. This plant has a medium size. Ethanol and pellets facilities are located in the same places as before, the latter installed with less capacity (Table 7).

Scenario c: in order to analyze the possibility of a change in the price of MDF, its selling price is decreased by 25%. Again, all logs and residues are utilized. The benefit is equal to 61,000,000 \$ year^{-1} representing a reduction of 60% respect to the initial presented Example. The lumber demands is totally fulfilled, while MDF demands are 83% satisfied (Table 6). The pellets production does not vary considerably and the quantity of ethanol increases 33%, installing a facility with greater capacity in the same site that the previous cases (*l*2).

In this case, the lower selling price for the MDF turns the lumber production more economically attractive, and its maximum demand is fulfilled. Also, greater amounts of sawmills residues are generated and used for increasing ethanol production, instead of sending them to MDF facilities. This situation is reflected in the percentage of fulfilled MDF demand, which is reduced compared with the initial presented Example.

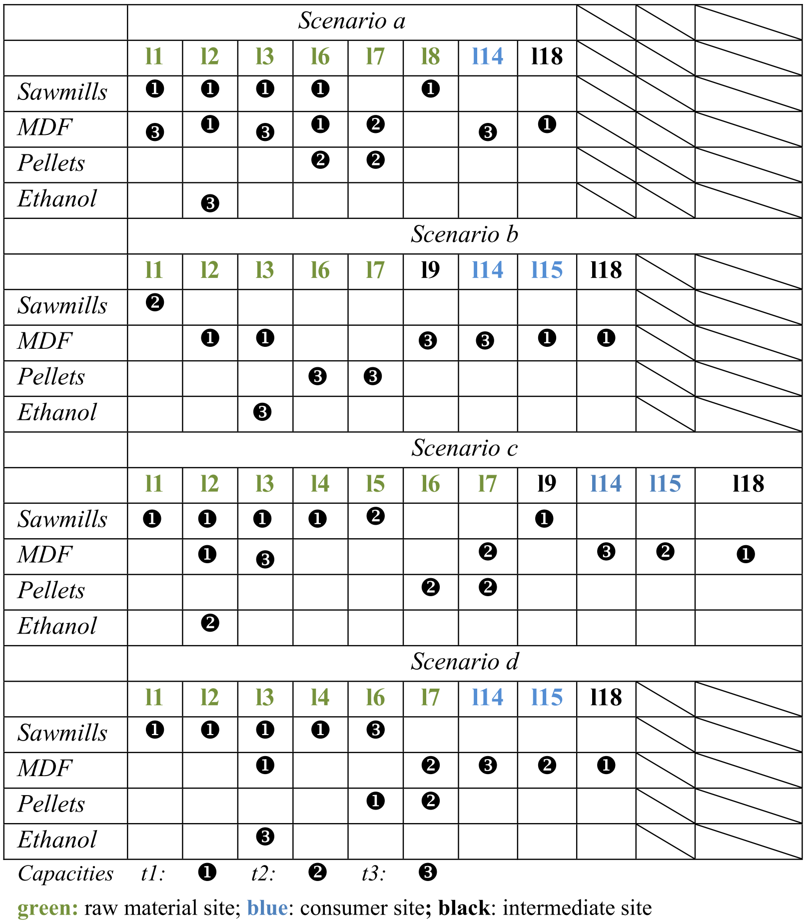
Scenario d: With the objective of analyzing SC changes when demands are modified, all product maximum demands are 25%

Table 6
Production and demand satisfaction of different studied scenarios (a–d).

	Scenario a	Scenario b	Scenario c	Scenario d
% of supplied demand				
Lumber	93%	10%	100%	100%
MDF	98%	98%	83%	100%
Pellets	6%	4%	6%	9%
Ethanol	4%	3%	6%	6%
% of used raw material	100%	100%	99%	83%
% of used residues	100%	100%	100%	100%
Production				
Lumber [m^3 $year^{-1}$]	270000	28250	291000	218250
MDF [m^3 $year^{-1}$]	1180000	1180000	1000000	900000
Pellets [t $year^{-1}$]	29582	20492	29136	34002
Ethanol [m^3 $year^{-1}$]	45387	30946	66556	50000
Benefit [Millions per year]	169.7	123.8	60.8	127.3

Scenario a: lumber price is increased. Scenario b: raw material availability is decreased. Scenario c: MDF selling price is decreased. Scenario d: demands are increased.

Table 7
Facilities location and adopted sizes for the different scenarios.



	Scenario a							
	l1	l2	l3	l6	l7	l8	l14	l18
Sawmills	❶	❶	❶	❶		❶		
MDF	❸	❶	❸	❶	❷		❸	❶
Pellets				❷	❷			
Ethanol		❸						

	Scenario b								
	l1	l2	l3	l6	l7	l9	l14	l15	l18
Sawmills	❷								
MDF		❶	❶			❸	❸	❶	❶
Pellets				❸	❸				
Ethanol			❸						

	Scenario c										
	l1	l2	l3	l4	l5	l6	l7	l9	l14	l15	l18
Sawmills	❶	❶	❶	❶	❷			❶			
MDF		❶	❸				❷		❸	❷	❶
Pellets						❷	❷				
Ethanol		❷									

	Scenario d								
	l1	l2	l3	l4	l6	l7	l14	l15	l18
Sawmills	❶	❶	❶	❶	❸				
MDF			❶			❷	❸	❷	❶
Pellets					❶	❷			
Ethanol			❸						

Capacities *t1:* ❶ *t2:* ❷ *t3:* ❸

green: raw material site; **blue**: consumer site**; black**: intermediate site

reduced. The optimal benefit is now equal to 127,000,000 \$ $year^{-1}$, 20% less than the Example presented in Section 5.1. The lumber production is enough to fulfill the total demand. Also, the maximum demand of MDF is satisfied. Ethanol production remains the same, while pellets production is equal to 34000 t $year^{-1}$. This last amount is increased due to the reduction of MDF production. Now, a greater amount of sawmills residues are available and used for pellets production. The raw material is not completely utilized (Table 6) and this situation generated changes in the SC configuration where some facilities locations are modified. The ethanol facility is installed in a place (l 2) where the total amount of logs is utilized by sawmills and MDF plant, facilitating residues transportation and reducing this cost. Pellets facilities are installed in the same sites but both of them with greater production capacity. Sawmills residues are totally utilized as raw material, but in this case, they are used for pellets and ethanol productions since MDF only utilizes logs. The generated harvest residues are also totally consumed.

The SC configuration varies according to the considered values for different parameters. The location of each facility is a critical

Table A.1
Model parameters for facilities.

	MDF			Pellets			Ethanol			Sawmills			
	t1	t2	t3	t1	t2	t3	t1	t2	t3		t1	t2	t3
Maximum installation capacity [m^3 $year^{-1}$]	250000	150000	100000	26000 [a]	20000 [a]	13000 [a]	100000	70000	50000		54000	36000	18000
Production cost [$ m^{-3}]	168.00	160.00	152.00	81.00 [b]	82.40 [b]	84.00 [b]	341.47	354.61	359.86	*Lumber type 1* *Lumber type 2*	52.09 43.57	52.62 43.85	53.65 44.70

[a] Unit: [T $year^{-1}$].

[b] Unit: [$ T^{-1}].

Table A.2
Available logs at each raw material site.

	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8
Logs of r_1	135000	117000	117000	117000	33750	33750	67500	67500
Logs of r_2	195000	169000	169000	169000	48750	48750	97500	97500

point in this type of industry, mainly due to the use of harvest and sawmills residues as raw material. Through the studied cases, it can be noticed that the use of these materials is a feasible alternative, but supply chain needs to be strategically designed. In this sense, the model represents a simply but useful tool for analyzing different production and distribution scenarios for planning the use of different raw material types and resources.

6. Conclusions

In this work, a MILP model for the optimal design of a forest SC is proposed. The approach highlights the employment of forest and sawmills residues and how this use affects to the processes integration, adding value to the overall SC. The approach was implemented taking into account the characteristics of the forest industry in the northeast region of Argentina. Different cases were analyzed in order to identify and show capabilities of the proposed framework.

Taking into account the objectives of the proposed formulation, the results were very encouraging. First of all, an appropriate representation of the forest supply chain from a strategic perspective was attained. Second, an adequate treatment of the problem of forest residues allowed taking advantage of these resources.

The presented formulation allows simultaneously assessing key elements and their tradeoffs for the development of this economical sector. The effects of different decisions about plant locations and cluster conformation, production scale, products profitability, etc., can be evaluated and the tradeoffs among them are appropriately considered. Thus, the proposed approach represents a useful tool for analyzing different forest SC scenarios in order to improve the efficiency and productivity of this industry and adding value to the entire system.

Taking into account that the residues employment is a key objective of this work, results show that their use is a profitable alternative. Also, the production of ethanol is a new encouraging option, but it largely relies on the considered context (for example, prices).

Obviously, all presented results strongly depend on model parameters, mainly costs, prices, availabilities, considered products, among other. However, this work is presented as a framework that allows the analysis of different scenarios and, therefore, results should be considered in relation to the adopted assumptions under specific contexts. The proposed formulation can be modified to easily consider new alternatives.

Table A.3
Yields and conversion rates.

	Lumber [m^3 T^{-1}]	MDF [m^3 T^{-1}]	Pellets [T T^{-1}]	Ethanol [m^3 T^{-1}]
Logs	0.262	0.972	–	–
Harvest residues	–	-	0.360	0.121
Wood chips	–	0.810	0.468	0.157
Firewood chips	–	1.053	0.410	0.138
Bark	–	-	0.468	0.157
Sawdust	–	1.296	0.576	0.194

Table A.4
Economic parameters for installation cost.

α_{f1}	2399.0000
α_{f2}	52780.3000
α_{f3}	3205.7000
α_{f4}	136100.0000
β_{f1}	0.6000
β_{f2}	0.6000
β_{f3}	0.6000
β_{f4}	0.6000
CCF_{ft}	0.1125

Acknowledgments

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Nomenclature

Sets	
$f \in F$	production facilities type
$k \in K$	consumers regions
$l \in L$	production facilities location
$p \in P$	final products
$q \in Q$	byproducts
$r \in R$	raw material type
$s \in S$	harvest areas
$t \in T_f$	production facilities capacities
Parameters	
cb_q	conversion factor logs-byproduct [t t^{-1}]
cc_q	calorific capacity of byproducts [kj t^{-1}]
CCF_{ft}	capital charge factor for facility f with capacity t
ccp	calorific capacity of pellets [kj T^{-1}]
cf	liquid fuel cost [$ kj^{-1}]
c_{pr}	conversion factor logs-products ([m^3 t^{-1}] or [t t^{-1}])

(*continued on next page*)

Table A.5
Distance from harvest area to potential facilities location [km].

	l1	*l2*	*l3*	*l4*	*l5*	*l6*	*l7*	*l8*	*l9*	*l10*	*l11*	*l12*	*l13*	*l14*	*l15*	*l16*	*l17*	*l18*	*l19*
s1	0	50	80	92	223	562	939	250	56	270	268	1577	1338	1177	857	1135	650	387	1100
s2	50	0	30	42	172	512	889	200	44	170	168	1477	1238	1077	757	1037	600	337	1050
s3	80	30	0	115	150	355	732	43	74	140	138	1447	1208	1047	727	997	580	317	1030
s4	92	42	115	0	126	430	807	118	86	128	126	1435	1196	1035	715	840	555	292	1005
s5	250	200	43	118	31	177	689	0	244	30	70	1277	1038	877	557	827	410	147	835
s6	223	172	150	126	0	343	720	170	140	98	177	1092	810	427	588	1020	472	251	972
s7	562	512	355	430	343	0	511	177	556	342	344	965	726	565	245	523	285	231	765
s8	939	889	732	807	720	511	0	750	933	719	721	588	349	188	132	725	391	718	256

Table A.6
Distance between facilities locations [km].

	l1	*l2*	*l3*	*l4*	*l5*	*l6*	*l7*	*l8*	*l9*	*l10*	*l11*	*l12*	*l13*	*l14*	*l15*	*l16*	*l17*	*l18*	*l19*
l1	0	50	80	92	185	562	939	250	7	118	247	1391	1273	1044	588	1136	650	387	1100
l2	50	0	30	42	135	512	889	200	47	68	197	1341	1226	994	538	1037	600	337	1050
l3	80	30	0	115	111	355	732	43	71	42	173	1317	1202	970	512	997	580	317	1030
l4	92	42	115	0	110	430	807	118	131	18	113	1257	1137	910	452	840	555	292	1005
l5	185	135	111	110	0	190	701	170	182	128	91	1262	1146	915	496	1020	472	251	972
l6	562	512	355	430	190	0	511	177	316	203	100	1072	956	725	351	523	285	231	765
l7	939	889	732	807	701	511	0	750	827	714	610	694	481	347	517	725	391	718	256
l8	250	200	43	118	170	177	750	0	288	175	75	1134	1018	787	395	868	320	120	820
l9	7	47	71	131	182	316	827	288	0	113	244	1384	1268	1037	583	1082	597	335	1097
l10	118	68	42	18	128	203	714	175	113	0	131	1271	1155	924	470	966	481	219	981
l11	247	197	173	113	91	100	610	75	244	131	0	1171	1055	824	417	1225	376	177	1055
l12	1391	1341	1317	1257	1262	1072	694	1134	1384	1271	1171	0	727	347	883	390	980	1140	660
l13	1273	1226	1202	1137	1146	956	481	1018	1268	1155	1055	727	0	350	962	636	741	1068	231
l14	1044	994	970	910	915	725	347	787	1037	924	824	347	350	0	536	181	723	804	404
l15	588	538	512	452	496	351	517	395	583	470	417	883	962	536	0	500	263	252	784
l16	1135	1037	997	840	1020	523	725	868	1082	966	1225	390	636	181	500	0	764	753	578
l17	650	600	580	555	472	285	391	320	597	481	376	980	741	723	263	764	0	285	552
l18	387	337	317	292	251	231	718	120	335	219	177	1140	1068	804	252	753	285	0	879
l19	1100	1050	1030	1005	972	765	256	820	1097	981	1055	660	231	404	784	578	552	879	0

(*continued*)

Cp_{ptf}	production cost of products with capacity t ($[\$\ \mathrm{m^{-3}}]$ or $[\$\ \mathrm{t^{-1}}]$)
Crm_{rs}	raw material r cost $[\$\ \mathrm{t^{-1}}]$
Ctp_p	products transportation cost $[\$\ (\mathrm{t\ km})^{-1}]$
Ctr	byproducts and residues transportation cost $[\$\ (\mathrm{t\ km})^{-1}]$
$Ctrm$	raw material transportation cost $[\$\ (\mathrm{t\ km})^{-1}]$
$Dmax_{kp}$	maximum demand of product p in region k ($[\mathrm{m^3\ year^{-1}}]$ or $[\mathrm{t\ year^{-1}}]$)
dfc_{lk}	distance between facility location l and consumer region k [km]
$dff_{ll'}$	distance between facility location l and facility location l' [km]
drf_{sl}	distance between harvest areas s and facility location l [km]
ed	energy needed for lumber drying process $[\mathrm{kj\ m^{-3}}]$
ef	ratio of thermal energy necessary for ethanol production $[\mathrm{kj\ m^{-3}}]$
fl	ratio of lumber drying by steam
fr	residues generated from harvested trees $[\mathrm{t\ t^{-1}}]$
$Maxrm_{sr}$	maximum raw material r in area s $[\mathrm{t\ year^{-1}}]$
$Plmax_{tf}$	maximum production in facility f with capacity t ($[\mathrm{m^3\ year^{-1}}]$ or $[\mathrm{t\ year^{-1}}]$)
Sb_q	byproducts selling price $[\$\ \mathrm{t^{-1}}]$
Sp_p	product selling price ($[\$\ \mathrm{t^{-1}}]$ or $[\$\ \mathrm{m^{-3}}]$)
yb_{qp}	conversion factor byproduct q in product p ($[\mathrm{m^3\ t^{-1}}]$ or $[\mathrm{t\ t^{-1}}]$)
yr_p	conversion factor residues-products $[\mathrm{m^3\ t^{-1}}]$
α_f, β_f	investment economic factors
Binary Variables	
w_{ltf}	indicates if facility f in location l is installed with capacity t
Continuous variables	
B_{lq}	byproducts generated in sawmill l $[\mathrm{t\ year^{-1}}]$

(*continued*)

$Br_{ll'qfp}$	flow of byproducts between sawmill in location l and facility f in location l' $[\mathrm{t\ year^{-1}}]$
Bb_{lq}	byproducts flow to boilers in sawmill in location l $[\mathrm{t\ year^{-1}}]$
Bs_{lq}	byproducts sold to third parties in sawmills in location l $[\mathrm{t\ year^{-1}}]$
Ec	energy cost of external fuels $[\$\ \mathrm{year^{-1}}]$
lf_l	necessary fuel in ethanol facility of location l $[\mathrm{kj\ year^{-1}}]$
I	incomes $[\$\ \mathrm{year^{-1}}]$
Ic	investment cost $[\$\ \mathrm{year^{-1}}]$
Pc	production cost $[\$\ \mathrm{year^{-1}}]$
P_{ltfp}	amount of product p produced in facility f in location l with capacity t ($[\mathrm{m^3\ year^{-1}}]$ or $[\mathrm{t\ year^{-1}}]$)
ρ_p	productivity factor for product p.
$Qb_{ll'}$	pellets flow between pellets facility in location l and sawmill in location l' $[\mathrm{t\ year^{-1}}]$
Ql_{slrfp}	flow of raw material r from site s to produce p in facility f in location l $[\mathrm{t\ year^{-1}}]$
Qp_{lkpf}	flow of products p from facility f in location l to region k ($[\mathrm{m^3\ year^{-1}}]$ or $[\mathrm{t\ year^{-1}}]$)
$Qpe_{ll'}$	flow of pellets from facility in location l to ethanol facility in location l' $[\mathrm{t\ year^{-1}}]$
Qr_{slfp}	flow of residues from site s to produce p in facility f in location l $[\mathrm{t\ year^{-1}}]$
Rc	raw material cost $[\$\ \mathrm{year^{-1}}]$
Tc	transportation cost $[\$\ \mathrm{year^{-1}}]$

Appendix. Model parameters

See Tables A.1–A.8

Table A.7
Distance between facilities location and consumer regions [km].

	k1	*k2*	*k3*	*k4*
l1	1391	1273	1044	588
l2	1341	1226	994	538
l3	1317	1202	970	512
l4	1257	1137	910	452
l5	1262	1146	915	496
l6	1072	956	725	351
l7	694	481	347	517
l8	1134	1018	787	395
l9	1384	1268	1037	583
l10	1271	1155	924	470
l11	1171	1055	824	417
l12	0	727	347	883
l13	727	0	350	962
l14	347	350	0	536
l15	883	962	536	0
l16	390	636	181	500
l17	980	741	723	263
l18	1140	1068	804	252
l19	660	231	404	784

Table A.8
Products selling prices.

		Consumers regions			
		k1	*k2*	*k3*	*k4*
Lumber [$ m^{-3}]	*Type 1*	229.2	223.4	215.2	218.0
	Type 2	194.5	188.7	180.5	183.0
MDF [$ m^{-3}]		359.2	353.4	345.2	348.1
Pellets [$ T^{-1}]		294.6	271.9	239.6	250.8
Ethanol [$ m^{-3}]		1213.5	1199.7	1179.6	1186.6

References

Acuna, M., Anttila, P., Sikanen, L., Prinz, R., Asikainen, A., 2012. Predicting and controlling moisture content to optimise forest biomass logistics. Croat. J. For. Eng. 33 (2), 225–238.

Awudu, I., Zhang, J., 2012. Renewable and sustainable energy. Review 16, 1359–1368.

Brooke, A., Kendrick, D., Meeraus, A., Raman, R., 2012. GAMS, A User's Guide. GAMS Development Corporation, Washington, DC.

Cambero, C., Sowlati, T., Marinescu, M., Röser, D., 2015. Strategic optimization of forest residues to bioenergy and biofuel supply chain. Intern. J. Energy Res. 39, 439–452.

Dansereau, L.P., El-Halwagi, M., Mansoornejad, B., Stuart, P., 2014. Framework for margins-based planning: forest biorefinery case study. Comput. Chem. Eng. 63, 34–50.

Demirbas, M.F., Balas, M., Balas, H., 2011. Biowastes-to-biofuels. Energy Convers. Manage. 52, 1815–1828.

FAO (Food and Agricultural Organization of the United Nations). 2006. Tendencias y perspectivas del sector forestal en América Latina y el Caribe. Estudio FAO Montes.

Heinimö, J., Malinen, H., Ranta, T., Faaij, A., 2011. Renewable energy targets, forest resources, and second-generation biofuels in finland. Biofuels Bioprod. Biorefining 5, 238–249.

Hurmekosky, E., Hetemäki, L., 2013. Studying the future of the forest sector: review and implications for long-term outlook studies. For. Policy Econ. 34, 17–29.

IERAL, 2011. de la Fundación Mediterránea, Una Argentina competitiva, productiva y federal: cadena foresto industrial. Año no 17-edición no 95 (http://www.ieral.org/images_db/noticias_archivos/2832-Cadena%20forestoindustrial.pdf).

INTA (National Institute of Agricultural Technology), 2013. Planilla de precios forestales. NEEA Concordia.

Kong, J., Rönnqvist, M., Frisk, M., 2012. Modeling an integrated market for sawlogs, pulpwood, and forest bioenergy. Can. J. Forest Res. 42, 315–332.

Ministry of Agriculture, Livestock Fishing, 2012. 2013 Industrias forestales Año 2012. (https://www.agroindustria.gob.ar/sitio/areas/ss_desarrollo_foresto_industrial/estadisticas/_archivos//000000_Industrias%20Forestales/120000_2012%20-%20Industrias%20forestales.pdf).

Ministry of Science, Technology and Productive Innovation, 2013. Argentina Innovadora 2020. Plan Nacional de Ciencia y Tecnología (http://www.mincyt.gob.ar/adjuntos/archivos/000/022/0000022576.pdf).

Mirkouei, A., Haapala, K., Sessions, J., Murthy, G., 2017. A review and future directions in techno-economic modeling and optimization of upstream forest biomass to bio-oil supply chains. Renew. Sustain. Energy Rev. 67, 15–35.

Mirkouei, A., Mirzaie, P., Haapala, K.R., Sessions, J., Murthy, G.S., 2016. Reducing the cost and environmental impact of integrated fixed and mobile bio-oil refinery supply chains. J. Clean. Prod. 113, 495–507.

Mishra, D., Gunasekaran, A., Papadopoulos, T., Hazen, B., 2017. Green supply chain performance measures: a review and bibliometric analysis. Sustain. Prod. Consum. 10, 85–99.

Mobini, M., Sowlati, T., Sokhansanj, S., 2013. A simulation model for the design and analysis of wood pellet supply chains. Appl. Energy 111, 1239–1249.

Pettersson, K., Wetterlund, E., Athanassiadis, D., Lundmark, R., Ehn, C., Lundgren, J., Berglin, N., 2015. Integration of next-generation biofuel production in the swedish forest industry –a geographically explicit approach. Appl. Energy 154, 317–332.

Pirraglia, A., Gonzalez, R., Saloni, D., Denig, J., 2013. Technical and economic assessment for the production of torrefied ligno-cellulosic biomass pellets in the US. Energy Convers. Manage. 66, 153–164.

Ravermark, D., Rippin, D., 1998. Optimal design of multiproduct batch plant. Comput. Chem. Eng. 22, 177–183.

Rönnqvist, M., D'Amours, S., Weintraub, A., 2015. Operations research challenges in forestry: 33 open problems. Ann. Oper. Res. 232, 11.

Sarkar, S., Kumar, A., Sultana, A., 2011. Biofuels and biochemicals production from forest biomass in Western Canada. Energy 36, 6251–6262.

Sosa, A., Acuna, M., MacDonell, K., Devlin, G., 2015a. Controlling moisture content and truck configuration to optimise biomass supply chains in Ireland. Appl. Energy 137, 338–351.

Sosa, A., Acuna, M., MacDonell, K., Devlin, G., 2015b. Managing the moisture content of wood biomass for the optimisation of Ireland's transport supply strategy to bioenergy markets and competing industries. Energy 86, 354–368.

Troncoso, J., D'Amours, S., Flisberg, P., Rönnqvist, M., Weintraub, A., 2015. A mixed integer programming model to evaluate integrating strategies in the forest value chain - a case study in the Chilean forest industry. Can. J. Forest Res. 45, 937–949.

Troncoso, J.J., Garrido, R., 2005. Forestry production and logistics planning: an analysis using mixed-integer programming. For. Policy Econ. 7, 625–633.

Uasuf, A., Becker, G., 2011. Wood pellets production costs and energy consumption under different framework conditions in Northeast Argentina. Biomass Bioenergy 35, 1357–1366.

Vance, E.D., Prisley, S.P., Schilling, E.B., Tatum, V.L., Wigley, T.B., Lucier, A.A., Van Deusen, P.C., 2018. Environmental implications of harvesting lower-value biomass in forests. Eric D. For. Ecol. Manage. 407, 47–56.

Wei, L., Pordesimo, L., Igathinathane, C., Batchelor, W., 2009. Process engineering evaluation of ethanol production from wood through bioprocessing and chemical catalysis. Biomass Bioenergy 33, 255–266.

Whalley, S., Klein, S.J.W., Benjamin, J., 2017. Economic analysis of woody biomass supply chain in Maine. Biomass Bioenergy 96, 38–49.