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Sustainability in the forest supply chain considering the efficient use of residues and byproducts

Sustentabilidad de la cadena suministro forestal considerando el uso adecuado de subproductos y residuos

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Resumen

La cadena de suministro (CS) integra globalmente las unidades productivas con sus fuentes de suministros y sus clientes, y coordina todos los flujos de entrada y salida (materiales, información, finanzas, etc.) de tal manera que los productos sean producidos y distribuidos en las cantidades correctas, en las localizaciones apropiadas y en el tiempo adecuado. Estas tareas implican actividades complejas que presentan diferentes compromisos entre los actores involucrados y requieren de un esfuerzo significativo para coordinar las acciones conjuntas. En particular, la CS forestal, tiene un gran número de participantes que por su heterogeneidad plantean interesantes desafíos de integración. Uno de los aspectos que caracteriza a la industria forestal es la gran cantidad de residuos y subproductos generados en la transformación mecánica de la madera, desde la plantación hasta la obtención de productos finales. El uso de estos residuos no ha recibido demasiada atención, y son muchos los factores que afectan su uso adecuado y eficiente, como los grandes volúmenes involucrados, lo cual encarece su transporte, agravado por las largas distancias que deben recorrer y las instalaciones necesarias para su procesamiento. En la actualidad, estos residuos suelen quemarse para evitar su acumulación. Esto genera humo, cenizas y gases que impactan en el ambiente de manera perjudicial, provocan el incremento del efecto invernadero y modifican el paisaje de la zona en la que se encuentran. Para evitar todos estos inconvenientes y desventajas, en este trabajo se propone desarrollar un modelo de programación matemática mixto entero lineal (MILP, por sus siglas en inglés, Mixed Integer Linear Programming), para el diseño y planeamiento óptimo de la CS forestal. El modelo plantea las diferentes alternativas de producción, con el objetivo de maximizar el beneficio neto, generando el diseño y el planeamiento de la producción, en un marco sustentable mediante la utilización de residuos y subproductos. Este trabajo se desarrolla considerando las características de la industria forestal de Argentina, pero puede ser fácilmente adaptado a otras regiones geográficas. El enfoque propuesto representa una herramienta útil para la toma de decisiones y el análisis de distintos escenarios de producción y distribución de la CS forestal sustentable.

Abstract

Supply chain (SC) globally integrates production units with raw material sources and customers, and coordinates all input and output flows (materials, information, finance, etc.) so that the products are produced and distributed in the right amounts, in appropriate locations and at the right time. These activities involve complex tasks that have different tradeoffs between the involved actors and require significant effort to coordinate the common actions. In particular, the forest SC has many heterogeneous participants, therefore, its integration is a challenging issue. One of the main aspects in the forest industry is the huge amount of generated residues and by-products generating through the wood mechanical transformation, from the harvest to the final product production. The residues use has not receive much attention, and its appropriate and efficient use is affected by many factors, as big involved volume, which increases the transportation cost. Nowadays, residues are burned in order to avoid its accumulation. This generates smoke, ash and gases impacting the environment, increasing the greenhouse effect and modifying the landscape. With the aim of avoiding these drawbacks, in this work a mixed integer linear programming (MILP) model for the optimal design and planning of the forest SC is proposed. The formulation considers different production alternatives, with the objective of maximizing the net benefit, generating the sustainable design of the overall network. This work is developed considering the particular characteristics of the Argentinean forest industry, but it can be easily adapted for other geographical regions. The

proposed approach represents a useful tool for decision making and analysis of different production-distribution scenarios of sustainable SCs.

Introduction

The forest industry involves many industries type, products, processes, etc. which needs to interact in order to obtain different final products. To achieve an integrated analysis of these interactions, it is necessary to contemplate all the aspects involved in the forest supply chain (SC). On the other hand, these industries play an important role in the social and economic development of many countries. In particular, this SC has interesting opportunities for the production of second generation biofuels, options for process integration, utilization of byproducts and residues as raw material for different final products, and the possibility of connections and exchanges between the involved actors. All these elements justify a detailed analysis of the available alternatives, the trade-offs involved and the expected results [1-3].

One aspect that characterizes the forest industry is the quantity of residues and byproducts generated in the mechanical transformation of wood, from plantation up to obtaining final products. These residues have not received much attention until now despite having interesting applications. Several reasons, as involved volumes, long distances, required facilities, etc., have affected their efficient employment. From the biofuels perspective, these forest residues represent an unexplored option of little competition with other uses, especially with food.

It is important to initially clarify the difference between residues and byproducts in the context of this work. The first one is material that is inevitably produced and has not a priori economic value; the second one has an economic value, although it is not the core production of that industry. So, onwards on this study, residues refer to material generated in harvest areas, and byproducts to those produced from the mechanical wood transformation of logs.

Forest SC is generally composed of many interconnected facilities that produce diverse products, suppliers and customers, and its planning is crucial for integrating the different actors and activities [4]. Design and planning of the SC is a hard work, taking into account the variety of possible uses of many materials and the distinct involved industries, with several trade-offs. Diverse elements can severely affect supply chain performance. Its configuration requires a decision and analysis framework with strategic, tactic and operative considerations, which leads to represent this problem resorting to a supply chain approach, where the operations can be studied integrating different nodes and links.

Mathematical modeling is a useful tool for designing and planning optimal SC operations. Taking into account these particular characteristics, many approaches have been proposed for forest SC optimization, including the use and production of biofuels from forestry residues. Mobini et al. [5] present a model for the pellet supply chain analyzing production costs and different raw material types. The model includes uncertainties, interdependencies between stages of the supply chain, and resource constraints which, according to the authors, were usually simplified or ignored in previous studies. The outputs of the model include the amount of energy consumed in each process, the associated CO_2 emissions and the cost components of wood pellets delivered to the customers. Gunnarson et al. [6] study the supply chain of forest fuel. Residues from harvest areas and byproducts from sawmills are transported and stored for satisfying demands for heating plants. The supply chain problem is formulated as a large mixed integer linear programming model (MILP). Beaudoin et al. [7] propose a MILP model with the aim of supporting tactical decisions in the forest industry. In the model, different available sources of raw material are considered to produce lumber in a set of possible mills, analyzing the option of selling wood chips, extracting higher value from the logs processed in the mill. Scott et al. [8] propose a decision-making framework for many alternatives in operations of lignocellulosic ethanol using Eucalyptus Globulus as raw material. MILP and mixed integer non linear programming (MINLP) optimization models are used as tools. Cambero et al. [9] present a mathematical model for the production of heat, electricity, pellets and pyrolysis biofuel from available forest harvesting residues and sawmills byproducts applied to a case study in British Columbia, Canada. Troncoso and Garrido [10] formulate a MILP model for solving the facilities location problem, the freight distribution problem and the forest production problem. The model decides the rotation age for each one of the stands selected to be harvested in

a time period, being a useful tool to decide on harvest scheduling. Dansereau et al. [11] propose a framework for forestry biorefineries based on optimizing a superstructure to help decision makers to identify different supply chain policies for a variety of market conditions.
Taking into account previous articles, the main objective of this work is to formulate a mathematical model for the optimal design and strategic planning of the forest supply chain considering the use of forest residues for producing added value products. Different production facilities, products and raw materials are considered, as well as integrated industrial installation sites conforming production clusters. These clusters are introduced in order to assess the involved trade-offs among the considered production facilities, the distances between feasible locations and scale requirements. Forest industries are strongly related since raw materials have diverse uses. From its processing, a variety of byproducts are obtained that, at the same time, can be used to manufacture many products. The proximity between facilities can encourage these integration approaches but affect severely transportation costs, for example.
Also, the proposed approach considers in detail the processing of residues and byproducts. Many times, these elements are discarded, giving priority to the main components of the production system. The presented model considers that all these elements are critical for a correct assessment of the total system contemplated in the forest SC. Taking into account that the viability of many options depends on the appropriate byproducts processing, this work includes a detailed analysis of the different generated residues, their characteristics and the diverse possible production alternatives. Finally, the possibility of biofuels production from forest resources is incorporated considering that, nowadays, it is a basic option for the efficient performance of the forest sector.

Problem statement

Harvested areas, production facilities and consumer regions are the three echelons considered in this study. The possible relations between SC facilities, the model elements and their links are shown in Figure 1.
Trees with different diameter size can be harvested in each site. From the tree cut down in these areas, 38% stays in the forest as harvest residues (branches, stump, sawdust and foliage) while the obtained logs are used as raw material for products requiring mechanical transformation. From the total of the harvest residues, it is assumed that 40% may stay in the forests in order to preserve the soil structure and quality maintaining certain natural conditions, therefore the remaining 60% can be used for different uses.
Four production facilities are considered: sawmills, ethanol, woodboard and pellet plants. Diverse connections exist among them, such as flows of different types of products, residues and byproducts used as raw material for other products or as fuel for producing the necessary thermal energy for some processes, etc. The logs for sawmills production and those required as raw material for woodboards plants are obtained from harvest areas, while the residues from these sites can be used for ethanol and pellets production. Sawmills can also generate byproducts along the process to obtain lumber. These can be utilized by ethanol, woodboards and pellets facilities as raw material, or, as fuel for the boiler in the same sawmill.
Thermal energy is required in lumber and ethanol processes, and pellets can be used as solid fuel for generating this energy in boilers. In case of sawmills, the possible sources of solid fuel are pellets and byproducts. In the case of ethanol facilities, the possible energy sources are pellets and liquid fuels acquired from external suppliers.
The products are sent to consumers regions, which have a maximum demand of the different products.
Diverse material flows can interconnect the facilities included in the considered SC. The industries involved in forest SC can exchange materials and fuels reducing waste generation and making the overall network more efficient. Obviously, the distance among them is a key factor to encourage their integration. Several location alternatives are contemplated: near harvest areas, near consumer regions or in intermediate points. Facilities can be allocated in different sites or in the same place conforming clusters, affecting the configuration of the entire SC and influencing its economical performance. Facilities near harvest areas reduce raw materials transport costs but favor small plants increasing scale penalties. If factories are located near consumer areas, the raw material transportation cost is increased, the scale production is also affected depending on the specific demands of each area but products delivery is more efficient. Intermediate cluster where

productions are integrated can increase its performance, taking advantage of production scale, but transport costs are severely affected depending on distances from harvest and consumer areas.

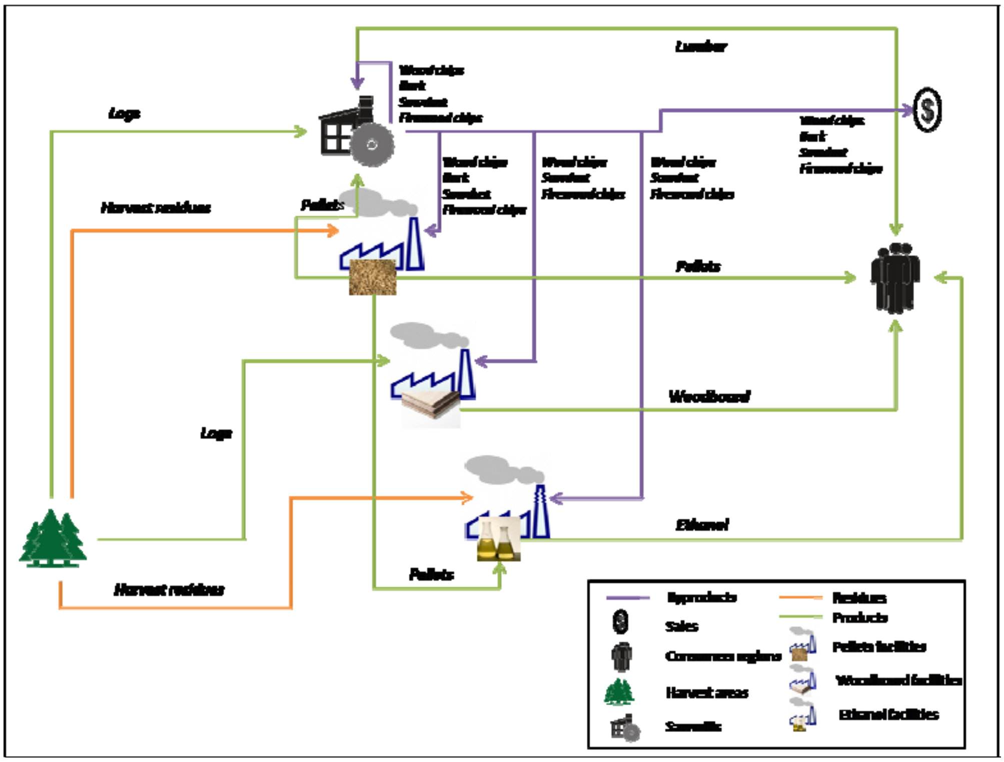

Fig. 1. Flows and interactions among SC nodes.

Methodology

A mixed integer linear programming (MILP) is developed in order to maximize the profitability of the total forest supply chain given by products and byproducts sales minus the cost of raw material procurement, transportation, production and facilities installation. The assumed forest SC considers several production options. Nevertheless, new alternatives, nodes, links, etc. can be easily added taking into account specific contexts. The model is focused on different wood transformation processes and in the analysis and uses of byproducts and residues. It involves strategic decisions of the forest SC in which three echelons are considered.
In order to have a brief overview of the mathematical formulation, some of the model constraints and the objective function is presented. For space reasons the completed version is not formulated, but it is available for interested readers. The model obtains the production of each product, facilities locations and their capacities, the material flows between the harvest areas and the facilities, and among the facilities, and the products transportation to customers in order to maximize the net benefit given by the incomes for sales minus the installation, production, transportation and raw material costs. The MILP was implemented and solved in General Algebraic Modeling System (GAMS).

Mass balances equations between harvest areas and sawmills and woodboard facilities:

$$\sum_{l} Qh_{slr} + \sum_{l} Qhwb_{slr} \le Maxrm_{sr} \qquad \forall s,r \qquad (1)$$

$$\Big(\sum_{lr} Qh_{slr} + \sum_{lr} Qhwb_{slr}\Big)\, fres \ge \sum_{l} Qrese_{sl} + \sum_{l} Qresp_{sl} \qquad \forall s \qquad (2)$$

Eq. (1) states that the amount of logs of diameter r transported from harvest area s to sawmill located in place l (Qh_{slr}) plus the amount of logs of diameter r from harvest area s to woodboard facility located in l ($Qhwb_{slr}$), is less than the available amount of logs of diameter r at harvest area s. Eq. (2) define that the amount of produced residues at harvest area s is greater than the residues utilized for ethanol ($Qrese_{sl}$) and pellets productions ($Qresp_{sl}$). $fres$ represents the log-residue conversion factor.

Mass balances and design equations for sawmills:

Eq. (3) defines the lumber production of type i at location l ($Prodlumb_{lit}$), where $convl$ is the log-lumber conversion factor.

$$\sum_{it} Prodlumb_{lit} = convl \sum_{sr} Qh_{slr} \qquad \forall l \qquad (3)$$

For sizing the facility, a set of different maximum capacities t are considered. Then, w_{lt} is a binary variable that takes value 1 if the total production of lumber at location l is less that the maximum capacity $Pl_t^{\max}$. Eq. (5) states that at most one maximum capacity is selected.

$$\sum_{i} Prodlumb_{lit} \le Pl_t^{\max} w_{lt} \qquad \forall l,t \qquad (4)$$

$$\sum_{t} w_{lt} \le 1 \qquad \forall l \qquad (5)$$

The byproducts productions at each sawmill is modeled according to the following constraints:

$$Chip_l = convchip \sum_{sr} Qh_{slr} \qquad \forall l \qquad (6)$$

$$Fchip_l = convchipf \sum_{sr} Qh_{slr} \qquad \forall l \qquad (7)$$

$$Bark_l = convbark \sum_{sr} Qh_{slr} \qquad \forall l \qquad (8)$$

$$Sdust_l = convsdt \sum_{sr} Qh_{slr} \qquad \forall l \qquad (9)$$

where $Chip_l$, $Fchip_l$, $Bark_l$, $Sdust_l$ are the chip, the firewood chip, bark and sawdust, respectively, produced at sawmill l, while $convchip$, $convchipf$, $convbark$ and $convsdt$ are the corresponding conversion factors.

The total amount of different byproducts ($Chip_l$, $Fchip_l$, $Bark_l$, $Sdust_l$) are sent to other facilities as raw material: wood chips for pellets ($chippell_{ll'}$), for ethanol ($chipeth_{ll'}$), for woodboards ($chipwb_{ll'}$), firewood chips for pellets ($fchippell_{ll'}$), for ethanol ($fchipeth_{ll'}$), for woodboards ($fchipwb_{ll'}$), bark for pellets ($barkpell_{ll'}$), sawdust for pellets ($sdtpell_{ll'}$), for ethanol ($sdteth_{ll'}$), for woodboards ($sdtwb_{ll'}$), sold to thirds ($chipsle_l$, $fchipsle_l$, $barksle_l$, $sdtsle_l$) and used in boilers ($Chboil_l$, $Fchboil_l$, $Bboil_l$, $Sdtboil_l$). This amounts must not exceed the produced quantity in each sawmill as present Eq. (10)-(13).

$$Chip_l \ge \sum_{l'} chippell_{ll'} + \sum_{l'} chipeth_{ll'} + \sum_{l'} chipwb_{ll'} + chipsle_l + Chboil_l \qquad \forall l \qquad (10)$$

$$Fchip_l \ge \sum_{l'} fchippell_{ll'} + \sum_{l'} fchipeth_{ll'} + \sum_{l'} fchipwb_{ll'} + fchipsle_l + Fchboil_l \qquad \forall l \qquad (11)$$

$$Bark_l \ge \sum_{l'} barkpell_{ll'} + Bboil_l + barksle_l \qquad \forall l \qquad (12)$$

$$Sdust_l \ge \sum_{l'} sdtpell_{ll'} + \sum_{l'} sdteth_{ll'} + \sum_{l'} sdtwb_{ll'} + sdtsle_l + Sdtboil_l \qquad \forall l \qquad (13)$$

Finally, the thermal energy in sawmills is obtained through boilers. The used fuels can be sawmills byproducts: bark, wood chips, firewood chips, sawdust ($Bboil_l$, $Chboil_l$, $Fchboil_l$, $Sdtboil_l$) and/or pellets from pellets facilities($pellboil_{l'l}$). The quantity of different fuels, multiplied by its calorific capacity ccb, $ccch$, $ccfc$, $ccsdt$, ccp, respectively, must satisfy the requirements of both type of lumber ($Prodlumb_{li_1t}$, $Prodlumb_{li_2t}$) taking into account the energy required ($endry$) to dry them, as it is expressed by Eq. (14).

$$
\begin{aligned}
&endry\sum_{t}(Prodlumb_{li_1t} + Prodlumb_{li_2t}\,fl) \leq \\
&ccb\;Bboil_l + ccch\;Chboil_l + ccfc\;Fchboil_l + ccsdt\;Sdtboil_l + ccp\sum_{l'} pellboil_{l'l} \qquad \forall l
\end{aligned}
\tag{14}
$$

Similar mass balances and energy equations are stated for woodboard, ethanol, and pellets plants. These formulations are omitted for space reasons in this work.
As was previously mentioned, the objective function maximizes the net benefit given by the Eq. (15):

$$Max\;profit = Incomes - Rmatcost - Transpcost - Instcost - Enercost - Prodcost \tag{15}$$

$Incomes$ represents the products and byproduct sales, while $Rmatcost$, $Transpcost$, $Enercost$ and $Prodcost$ are raw material, transportation, energy and production costs. All these variables are calculated proportionally to the involved amount in each case. On the other hand, the *Instcost* is the facilities installations cost and it is calculated as

$$Instcost = CCF(\sum_{lt}\alpha_{saw}\left(Pl_t^{max}\right)^{\beta_{saw}} w_{lt} + \sum_{lt}\alpha_{pell}\left(Pp_t^{max}\right)^{\beta_{pell}} v_{lt} + \sum_{lt}\alpha_{et}\left(Pet_t^{max}\right)^{\beta_{et}} u_{lt} + \sum_{lt}\alpha_{wb}\left(Pwb_t^{max}\right)^{\beta_{wb}} b_{lt} \tag{16}$$

where CCF represents the capital charge factor on the time horizon, which includes amortization and maintenance terms, Pl_t^{max}, Pp_t^{max}, Pet_t^{max}, Pwb_t^{max} are maximum option size t for each selected sawmill, pellets, ethanol and woodboard plants respectively, and α and β are cost coefficients defined for each facility type.
w_{lt}, v_{lt}, u_{lt}, and b_{lt} are binary variables for sawmills, pellets, ethanol and woodboard plant selection at site l with maximum production capacity t, respectively.

Case study

The proposed model is applied for designing a forest SC in the northeast and center regions of Argentina. The first region is characterized for having the largest amount of afforested areas in the country; meanwhile, the principal consumers are located in the central zone.
The model assumes eight available harvest areas with two types of raw materials, which varies according to the log diameter. A great quantity of residues is produced by forest pruning. Actually, these materials are burnt and, therefore, no profitable use is achieved. The use of these residues as raw material for other products is considered in this case, in order to attain a more efficient SC. Residues must not be entirely collected, since some of them are necessary to mitigate soil erosion and remove soil nutrients. It is assumed that just only a 60% of the total generated amount can be removed.
A total of nineteen possible locations for production facilities are assumed: in harvest areas, in consumer regions or in intermediate sites. Facilities can be grouped generating productive clusters located in the same site or they can be installed as isolated facilities in different places. The first option facilitates the integration among productive installations and the second one reduces transport costs allocating small facilities near harvest areas or consumer regions. Obviously, the production scale is a critical factor in the involved trade-offs. The facilities can be installed with many capacities and the production cost varies according to this condition.
Four consumers regions are selected, located in the center of the country: Córdoba, Buenos Aires, Santa Fe and Chaco, with a maximum demand of lumber, woodboards, pellets and ethanol for each region.
Ground transportation through trucks is assumed. Costs and selling prices were determined considering values from the Argentinean forest industry. Two types of lumber are can be produced in each sawmill. The model parameters are not provided because space reasons, but they can be asked to the authors.

Results

Table 1 shows the facilities locations and its production as well as the installed capacity. The raw material and harvest residues are completely utilized, distributing the former in woodboards and lumber, while the second ones in ethanol and pellet production as it is shown in Figure 2 and Figure 3. The net benefit is equal to $ 181.9 MM.

Table 1. Facilities allocation, production and capacity for the study case.

	Sawmills [m^3 year^{-1}]			Woodboards [m^3 year^{-1}]		Pellets [T year^{-1}]		Ethanol [m^3 year^{-1}]	
	Pdction		IC	Pdction	IC	Pdction	IC	Pdction	IC
Location	**Type 1**	**Type 2**							
I1	38793	15207	54000						
I2	38793	15207	54000	250000	250000			66793	70000
I3	38793	15207	54000	250000	250000				
I4	8127	11082	36000						
I6						15957	20000		
I7				150000	150000	15711	20000		
I8				150000	150000				
I9	38793	15207	54000						
I14				100000	100000				
I15				250000	250000				
I18				250000	250000				
Pdction	**235210**			**1400000**		**31669**		**66793**	

IC: installed capacity, Pdction: production

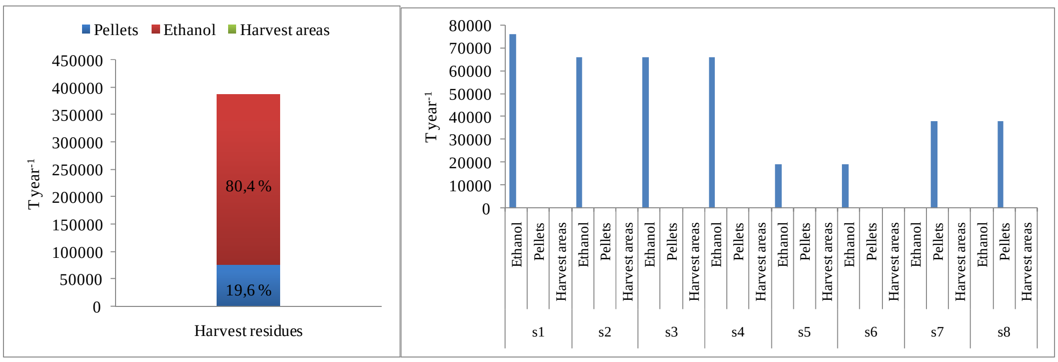

Fig.2. Available harvest residues distribution.

In the optimal solution, 5 sawmills are installed, 4 located in harvest areas in order to reduce raw material transport cost and 1 in an intermediate location, 7 woodboards facilities, 3 located in harvest areas, 2 in intermediate locations and 2 in consumers regions. Sawmills byproducts are principally sent to ethanol production. Woodboards maximum demand is 99.8% satisfied, as well as 66% of lumber, fulfilling the maximum demand of type 1 while 48.2% of type 2 lumber. Ethanol and pellet maximum demands are nearly 6.4% satisfied. Pellets are not used as fuel for boilers, they are sold to consumers regions. It worth mentioning that woodboard facilities produce the total installed capacity. Therefore, for covering the remaining demand (0.2% of the total demand), a bigger plant must be installed which is not profitable because of economic scale.
As it was previously mentioned, the total produced residues and byproducts are utilized for the production of pellets, ethanol and woodboards. In this way, the disposals are avoided. Besides obtaining a sustainable SC, the product diversification adds value to the overall production network.

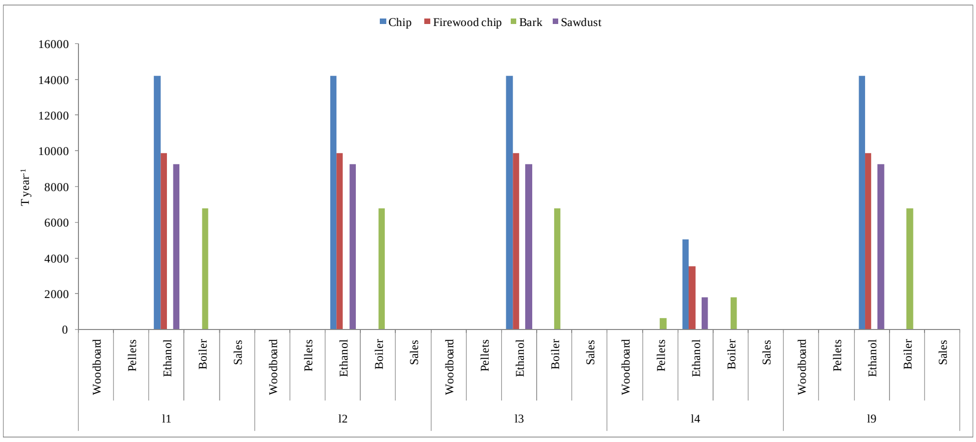

Fig. 3. Sawmills byproducts distribution.

Conclusions

In this work, a mathematical modeling framework for optimizing the forest supply chain design is proposed. A MILP model was formulated and applied for a SC of wood transformation in Argentina, where different residues and byproducts are reutilized with the objective of adding value to the overall SC and achieve a more sustainable production.

The proposed formulation allows simultaneously assessing key elements for the development of this economical area. The effect of different decisions about plant locations, production scale, products profitability, etc. can be evaluated and the trade-offs among them are assessed. Therefore, the presented approach represents a useful tool for analyzing different forest SC scenarios where the use of diverse residues and byproducts is specially considered in order to improve the efficiency and adding value to the entire system, re using resources in order to minimize environmental impacts.

Taking into account the analysis of the residues and byproducts use was a key objective of this work, results show that their employment is a profitable and sustainable alternative. However, all the results should be evaluated under a judicious perspective. Obviously, they strongly depend on model parameters, mainly costs, prices, availabilities, considered products, etc. This work is presented as a tool to ease the analysis of different scenarios and, therefore, results should be considered in relation to adopted assumptions.

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