OPTIMAL DESIGN OF FOREST SUPPLY CHAIN CONSIDERING EFFICIENT RESIDUES AND BYPRODUCTS REUSE

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Abstract. Forest supply chain includes different actors which work together to obtain many products through a set of processes that must be efficiently integrated. Nevertheless, the great number of involved elements and the available production alternatives hinder to attain an optimal supply chain design. A key element to achieve this objective is the adequate utilization of residues and byproducts that abound in these industries. Nowadays, the production of bioethanol from forest raw materials is also a new option that must be addressed in the context of the supply chain. Taking into account the particular conditions of the forest industry in Argentina, a mixed integer linear programming formulation is proposed in order to attain the optimal design of the forest supply chain, emphasizing the appropriate use of residues and byproducts and the production of bioethanol from these raw materials.

Keywords: Forest residues and byproducts, biofuels, optimization.

1. Introduction

Forest Supply Chain (SC) involves many different production stages, processes, products, etc. covering a variety of aspects as harvesting, transportation, energy generation, lumber, paper, woodboards production, etc. 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 (Heinimö et al., 2011; Sipilä et al., 2009; Joelsson et al., 2009).

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, they represent an unexplored option with little competition with other uses, especially food like other sources of bioenergy.

It is important to initially clarify the difference between residues and byproducts in the context of this article. 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 those produced from the mechanical wood transformation of logs. Luckily, these residual materials can be useful as feedstock for other products.

Biofuels are fuels derived from renewable biological resources, like plants and animal matters. An option among these resources are forest residues and byproducts, which can be used as feedstock, benefiting the production of second generation biofuels. In this context, these materials can be used as fuels for producing energy or as raw material for pellets production, conforming solid biofuels. On the other hand liquid biofuels from forestry residues, a promising alternative in the near future, is gaining interest in the last years by governments, industries, and researchers. Even though nowadays conventional liquid fuels dominate the market, the penetration of second-generation liquid biofuels is expected to take place by 2020 in favorable circumstances, not only by economical and availability reasons, but also by environmental conditions (Hoefnagels et al., 2014). In this context, the forest industry takes an important position, being the principal producer and consumer of forest biomass.

Forest SC is generally composed of many interconnected facilities that produce different products, suppliers and customers, and its planning is crucial for integrating the different actors and activities (D'Amours et al., 2009). . Design and planning of the SC is a hard work, taking into account the variety of possible uses of different materials and the diverse involved industries, with several trade-offs. Many 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.

The main objective of this work is to generate a mathematical model for the optimal design and strategic planning of the forest supply chain in order to optimize its economical performance. Different production facilities, products and raw materials are considered, as well as integrated industrial installation sites conforming production clusters. Forest industries are strongly related since raw materials have different uses. From its processing, diverse byproducts are obtained that, at the same time, can be used to manufacture different 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 different 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.

This study is based on geographic and technical parameters of Argentina, but it can be easily adapted to other geographical locations. The proposed approach determines the productive structure of the forest SC. From a strategic point of view, the model determines the production facilities location and their capacities. Besides, the production flows are selected from the links among the adopted locations. Then, the types of raw material supplied for each product, the facilities selected for each production process, the transport among nodes, the demand fulfillment, etc. are defined from an economical perspective. In particular, this approach is focused on residues and byproducts treatment and biofuels energy alternatives from them, allowing an integrated study of this problem for the forest industry. In this way, the proposed model can be used as a tool for analyzing and designing the forest SC from a strategic perspective.

2. Problem statement

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 destination of different byproducts and residues. It involves strategic decisions of the forest SC in which three echelons are considered: harvest areas, productions facilities and consumer regions.

Harvest areas are sites where logs can be obtained. Trees with different diameter size can be harvested in each site. From the tree cut down in these areas, a percentage (38%) stays in the forest as harvest residues (branches, stump, sawdust and foliage) and the obtained logs are used as raw material for products requiring mechanical transformation. From the total of the harvest residues 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 destinations.

Four different 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 different 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 boiler in the same sawmill. The byproducts generated are wood chips, firewood chips, bark and sawdust in the percentage showed in Figure 2. "Remains" make reference to material that cannot be reutilized.

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. Fig. 1 shows the different possible relations between SC facilities.

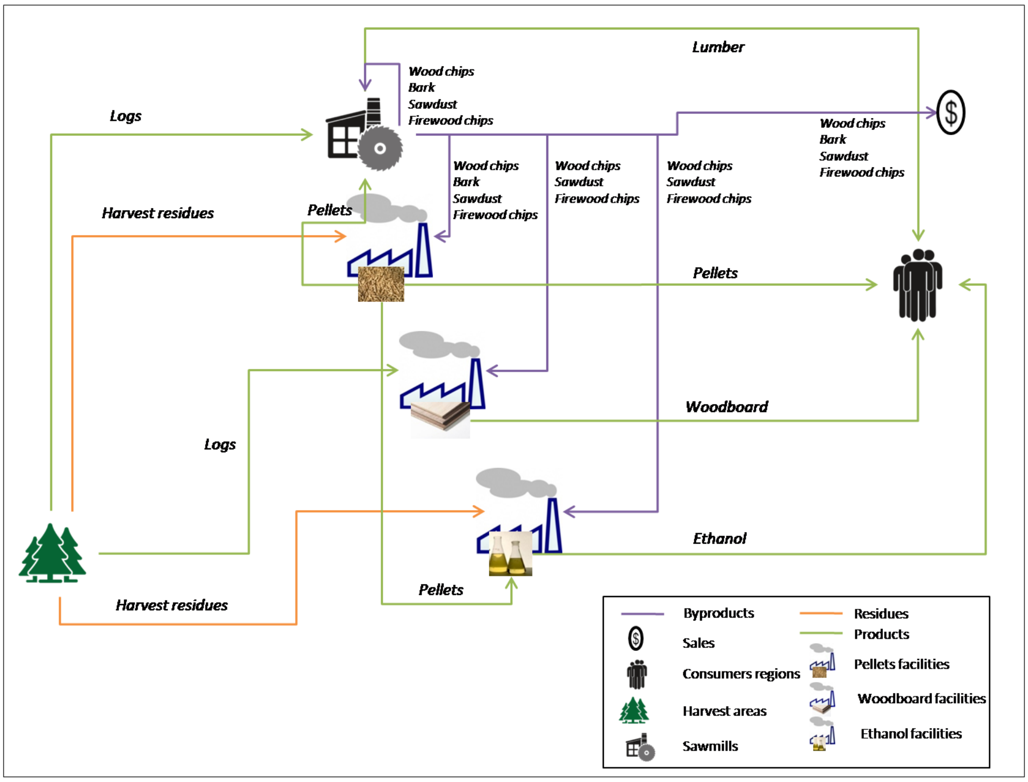

Fig. 1.Flows and interactions among SC nodes.

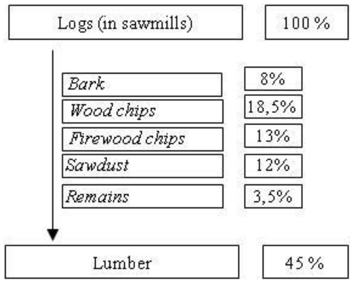

Fig. 2. Sawmills byproducts

3. Mathematical Model

In this section, the mathematical model for the optimal design of the forest SC considering the use of harvest residues and sawmill byproducts is formulated. The mass balances between the different SC echelons and among facilities, design equations, and the objective function are presented.

It is important to underline that, in some aspects, certain model elements refers to conditions related to the case study that is analyzed in the next section, but the model can be easily extended to a more general situation .

3.1 Harvest areas

Let r denote the raw material type, s the raw material site, and l the possible plant location, then inequality (1) states that each harvest area has a maximum capacity for each raw material ($Maxrm_{sr}$). Therefore, the total amount of logs utilized by sawmills (Qh_{slr}) and woodboard facilities ($Qhwb_{slr}$) must not exceed this capacity.

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

In this work, it is assumed that the used raw materials proceed from the same tree species, varying only its diameter. Then, r corresponds to the different sizes considered in the model. This assumption is based on only one tree species predominates in forests of the considered region.

Residues that are generated in harvest areas are assumed to be proportional to the quantity of consumed logs following a parameter $fres$. In inequality (2) the total amount of harvest residues utilized by ethanol ($Qrese_{sl}$) and pellets ($Qresp_{sl}$) facilities as raw material, must not exceed the generated quantity.

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

3.2 Facilities production

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

Sawmills. Sawmills utilize as raw material logs from harvest areas, which are converted into final products according to a conversion factor ($convl$). In this formulation, it is assumed that this factor does not depend on the index r. Taking into account the different raw materials r proceed of the same tree species differing only in the diameter size, the same proportion of final products is obtained using different raw materials. This assumption can be easily modified to introduce different productivities. Let i denote the different products that can be produced that differ in humidity and other technical aspects. The total lumber produced in each sawmill is equal to the total amount of raw material (Qh_{slr}) that arrives at the sawmill at location l multiplied by the conversion factor (Eq. 3). The produced lumber type does not vary with the raw material and the conversion factor, because the process is quite similar for them. In this general formulation, only the total production is required to design the SC.

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

In particular, in this initial version, it is assumed that only two lumber types (i_1, i_2) can be produced in sawmills. One requires being dried by artificial heat and to be brushed. The other one is of lower quality, and can be dried almost completely with natural air. It is assumed that to produce this product, the drying process implies taking out a fraction of lumber humidity by heat from boilers (fl) and the rest with natural air.

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, $ccch$, ccf, $ccsdt$, 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. (4).

$$endry\sum_t (Prodlumb_{li_1t} + Prodlumb_{li_2t}\,fl) \leq ccb\ Bboil_l + ccch\ Chboil_l + ccf\ \ Fchboil_l \\ +ccsdt\ Sdtboil_l + ccp\sum_{l'} Pellboil_{l'l} \qquad \forall l \tag{4}$$

Equation (5)-(8) states the generated quantity of each type of byproduct according to the amount of utilized raw material. The logs used for production are multiplied by a conversion factor of wood chips ($convchip$), firewood chips ($convchipf$), bark ($convbark$) and sawdust ($convsdt$) to obtain the quantity of each type of byproduct: wood chip ($Chip_l$), firewood chip ($Fchip_l$) , bark ($Bark_l$) and sawdust ($Sdust_l$).

$$Chip_l = convchip\sum_{sr} Qh_{slr} \qquad \forall l \tag{5}$$

$$Fchip_l = convchipf\sum_{sr} Qh_{slr} \qquad \forall l \tag{6}$$

$$Bark_l = convbark\sum_{sr} Qh_{slr} \qquad \forall l \tag{7}$$

$$Sdust_l = convsdt\sum_{sr} Qh_{slr} \qquad \forall l \tag{8}$$

A binary variable w_{lt} is defined in order to select a discrete size t when sawmill l is allocated. Then:

$$w_{lt} = \begin{cases} 1\ if\ \ a\ sawmill\ in\ site\ l\ with\ capacity\ t\ is\ installed \\ 0\ otherwise \end{cases}$$

Sawmills can be installed with different capacities, achieving different quantities of final products. If there is no sawmill installed at location l with operation capacity t ($w_{lt} = 0$), the lumber produced in that sawmill is zero. On the contrary, when it is installed, the production must not exceed its maximum capacity ($Pl_t^{\max}$). As it is mentioned before, the maximum production capacity does not depend on the type of produced lumber taking into account the basic equipment is shared by all of them.

$$\sum_i Prodlumb_{lit} \le Pl_t^{\max} w_{lt} \qquad \forall l,t \quad (9)$$

Moreover, at most one size is selected for the sawmill at each location:

$$\sum_t w_{lt} \le 1 \qquad \forall l \qquad (10)$$

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. (11)-(14).

$$Chip_l \ge \sum_{l'} chippell_{ll'} + \sum_{l'} chipet_{ll'} + \sum_{l'} chipwb_{ll'} + chipsle + chboil \qquad \forall l \quad (11)$$

$$Fchip_l \ge \sum_{l'} fchippell_{ll'} + \sum_{l'} fchipet_{ll'} + \sum_{l'} fchipwb_{ll'} + fchipsle + fchboil \qquad \forall l \quad (12)$$

$$Bark_l \ge \sum_{l'} barkpell_{ll'} + bboil_l + barksle_l \qquad \forall l \qquad (13)$$

$$Sdust_l \ge \sum_{l'} sdtpell_{ll'} + \sum_{l'} sdteth_{ll'} + \sum_{l'} sdtwb_{ll'} + sdtsle_l + sdtboil_l \qquad \forall l \qquad (14)$$

Woodboards facilities. Logs and sawmills byproducts can be used as raw materials for woodboards facilities. The produced amount of woodboards ($\sum_t Prodwb_{lt}$) is obtained multiplying the amount of the different employed raw materials ($Qhwb_{slr}$, $chipwb_{l'l}$, $fchipwb_{l'l}$, $sdtwb_{l'l}$) by the corresponding conversion factor ($ywb_{\log}$, ywb_{chip}, ywb_{fchip}, ywb_{sdt}) which establishes the quantity of woodboards produced per amount of each raw material type, as is expressed in Eq. (15).

$$\sum_t Prodwb_{lt} = ywb_{\log}\sum_{sr} Qhwb_{slr} + ywb_{chip}\sum_{l'} chipwb_{l'l} + ywb_{fchip}\sum_{l'} fchipwb_{l'l} + ywb_{sdt}\sum_{l'} sdtwb_{l'l} \quad \forall l \tag{15}$$

Woodboards facilities can be installed with different capacities depending on the maximum possible production allowed. The maximum capacity of each facility is selected from a set of available discrete sizes. Binary variable b_{lt} allows selecting the adopted size. Equation (16) establishes that if woodboard facility at location l with capacity t is not installed ($b_{lt} = 0$), its production is zero, and, on the contrary, if it is installed the production must not exceed its maximum capacity (Pwb_t^{max})

$$Prodwb_{lt} \leq Pwb_t^{max} b_{lt} \qquad \forall l,t \tag{16}$$

At most one maximum capacity is adopted at each site l:

$$\sum_t b_{lt} \leq 1 \qquad \forall l \tag{17}$$

Pellets facilities. Harvest residues and sawmills byproducts are used as raw materials to produce pellets. Eq. (18) states that pellets production in plant at location l ($\sum_t Prodpell_{lt}$) is proportional to the total raw material ($Qresp_{sl}$, $chippell_{l'l}$, $fchippell_{l'l}$, $barkpell_{l'l}$, $sdtpell_{l'l}$) supplied to that plant, multiplied by conversion factors related to each raw material type ($ypell_{res}$, $ypell_{chip}$, $ypell_{fchip}$, $ypell_{bark}$, $ypell_{sdt}$).

$$\sum_t Prodpell = ypell_{res}\sum_s Qresp_{sl} + ypell_{chip}\sum_{l'} chippell_{l'l} + ypell_{fchip}\sum_{l'} fchippell_{l'l} + ypell_{bark}\sum_{l'} barkpell_{l'l} + ypell_{sdt}\sum_{l'} sdtpell_{l'l} \quad \forall l \tag{18}$$

As it was mentioned before, the maximum capacity of each pellets facility is selected from a set of discrete size options through the binary variable v_{lt}. If capacity t is selected for pellet facility at location l, its production ($Prodpell_{lt}$) must not exceed a certain maximum quantity (Pp_t^{max}):

$$Prodepell_{lt} \leq Pp_t^{max} v_{lt} \qquad \forall l,t \tag{19}$$

At most one capacity must be selected for each location l:

$$\sum_t v_{lt} \le 1 \quad \forall l \qquad (20)$$

Pellets can be used as fuel in other facilities or be sold to satisfy market demands. The amount of pellets sent to ethanol facilities ($Qpellpe_{ll'}$), to sawmills boilers ($Pellboil_{ll'}$) and sold to customers (Qp_{lk}) must not exceed the produced amount ($\sum_t Prodpell_{lt}$). This constraint is given by:

$$\sum_{l'} Qpellpe_{ll'} + \sum_{l'} Pellboil_{ll'} + \sum_k Qp_{lk} \le \sum_t Prodpell_{lt} \quad \forall l \qquad (21)$$

Ethanol facilities. Harvest residues and sawmills byproducts are used as raw materials to produce ethanol. Ethanol production ($\sum_t Prodet_{lt}$) is equal to the total raw material coming from harvest areas and sawmills ($Qrese_{sl}$, $chipeth_{l'l}$, $fchipeth_{l'l}$, $sdteth_{l'l}$) multiplied by the conversion factors related to the raw material ($yeth_{res}$, $yeth_{chip}$, $yeth_{fchip}$, $yeth_{sdt}$).

$$\sum_l Prodet_{lt} = yeth_{res} \sum_s Qrese_{sl} + yeth_{chip} \sum_{l'} chipeth_{l'l} + yeth_{fchip} \sum_{l'} fchipeth_{l'l} + yeth_{sdt} \sum_{l'} sdteth_{l'l} \quad \forall l \qquad (22)$$

Binary variable u_{lt} allows selecting the plant size from a set of available discrete sizes and, thus, the maximum possible ethanol production is determined. Equation (23) establishes that if facility at location l is installed with size t, its production ($Prodet_{lt}$) is limited by its maximal capacity Pet_t^{max} .

$$Prodet_{lt} \le Pet_t^{max} u_{lt} \quad \forall l,t \qquad (23)$$

At most one ethanol capacity is selected for each location:

$$\sum_t u_{lt} \le 1 \quad \forall l \qquad (24)$$

The required thermal energy in each ethanol facility can be fulfilled with two possible sources: pellets or external fuels. Then, the quantity of thermal energy required at plant in location l is proportional to the ethanol production ($\sum_t Prodet_{lt}$) calculated through the parameter $enet$, and must be satisfied using fuels supplied to l by pellets ($Qpellpe_{l'l}$) and external fuels ($extfuel_l$) (Eq. 25).

$$enet \sum_t Prodet_{lt} = ccp \sum_{l'} Qpellpe_{l'l} + extfuel_l \qquad \forall l \qquad (25)$$

3.3 Demands constraints

Let k denote the different customers regions and Dl_{ki}^{max} , Dp_k^{max} , Dwb_k^{max} and De_k^{max} the maximum demand of lumber, pellets, woodboards, and ethanol respectively. The total amount of each product provided from facilities in location l (Ql_{lki} , Qp_{lk} , Qwb_{lk} , Qe_{lk}) to each consumer region k cannot exceed their maximum demand. These constraints are represented by

$$\sum_l Ql_{lki} \le Dl_{ki}^{max} \qquad \forall k,i \qquad (26)$$

$$\sum_l Qp_{lk} \le Dp_k^{max} \qquad \forall k \qquad (27)$$

$$\sum_l Qwb_{lk} \le Dwb_k^{max} \qquad \forall k \qquad (28)$$

$$\sum_l Qe_{lk} \le De_k^{max} \qquad \forall k \qquad (29)$$

Equations (30)-(33) state that the total amount of each type of product sent to consumers regions is limited by its production in each facility.

$$\sum_t Prodlum_{lit} \ge \sum_k Ql_{lki} \qquad \forall l,i \qquad (30)$$

$$\sum_t Prodwb_{lt} \ge \sum_k Qwb_{lk} \qquad \forall l \qquad (31)$$

$$\sum_t Prodpell_{lt} \ge \sum_k Qp_{lk} \qquad \forall l \qquad (32)$$

$$\sum_t Prodet_{lt} \ge \sum_k Qe_{lk} \qquad \forall l \qquad (33)$$

(33)

3.4 Objective function

The adopted objective function represents the profit maximization given by the incomes from sales minus installation, production, transportation and raw material costs considering a time period of one year:

$$Max\ profit = Incomes - Rmatcost - Transpcost - Instcost - Enercost - Prodcost \qquad (34)$$

The incomes, $Incomes$, includes products and byproducts sales, as it is presented in Equation (35). Products are lumber, woodboard, pellets and ethanol. Byproducts are sawdust, wood chips, firewood chips and bark generated in sawmills. Incomes from products sales are obtained multiplying the amounts of products delivered to consumers by its selling price, where $Slelum_i$, $Slewb$, $Slepell$, and $Sleeth$ correspond to lumber, woodboard, pellets and ethanol selling prices, respectively. Byproducts that are not used as raw materials for other products can be sold to third parts. Incomes from these sales are obtained multiplying the respective amounts of sawdust ($sdtsle_l$) , chips ($chipsle_l$), firewood chips ($fchipsle_l$), and bark ($barksle_l$) by its selling price ($sdtprice$, $chipprice$, $fchipprice$ and $barkprice$ respectively).

$$\begin{aligned} Incomes = {} & \sum_{lki} Ql_{lki} Slelum_i + Slepell \sum_{lk} Qp_{lk} + Sleeth \sum_{lk} Qe_{lk} + Slewb \sum_{lk} Qwb_{lk} \\ & + \sum_{l} (chipsle_l chipprice + fchipsle_l fchipprice + barksle_l barkprice + sdtsle_l sdtprice) \end{aligned} \qquad (35)$$

Raw material cost ($Rmatcost$) corresponds to the procurement of the raw materials (logs) required for production. Therefore, $Rmatcost$ is calculated from the cost of raw materials (Crm_{rs}) and the amounts of logs supplied to sawmills (Qh_{slr}) and woodboards facilities ($Qhwb_{slr}$).

$$Rmatcost = \sum_{slr} Qh_{slr} Crm_{rs} + \sum_{slr} Qhwb_{slr} Crm_{rs} \qquad (36)$$

Transportation cost ($Transpcost$) includes the raw material transportation from harvest area to sawmills and woodboard facilities ($Qh_{slr}, Qhwb_{slr}$), products (Ql_{lki} , $Qwb_{lk}, Qp_{lk}, Qe_{lk}$), byproducts ($Qbypwb_{ll'}$, $Qbype_{ll'}$, $Qbypp_{ll'}$) and residues ($Qresp_{sl}$, $Qrese_{sl}$) delivery between the different SC nodes, and pellets transfer for energy production ($Qpellpe_{l'l}, Pellboil_{l'l}$). It is calculated multiplying the amount of transported material by the distance among the involved nodes and its relative cost depending on the shipped material.

$$Transpcost = \sum_{slr} Qh_{slr} disthl_{sl} Ctrm + \sum_{slr} Qhwb_{slr} disthwb_{sl} Ctrm + \sum_{sl} Qresp_{sl} disthp_{sl} Ctres$$
$$+ \sum_{sl} Qrese_{sl} disthe_{sl} Ctres + \sum_{ll'} Qbypwb_{ll'} distswb_{ll'} Ctres + \sum_{ll'} Qbype_{ll'} distse_{ll'} Ctres$$
$$+ \sum_{ll'} Qbypp_{ll'} distsp_{ll'} Ctres + \sum_{l'l} Qpellpe_{l'l} distpe_{l'l} Ctpell + \sum_{l'l} Pellboil_{l'l} distsp_{l'l} Ctpell$$
$$+ \sum_{lki} Ql_{lki} distsk_{lk} Ctlum + \sum_{lk} Qwb_{lk} distwbk_{lk} Ctwb + \sum_{lk} Qp_{lk} distpk_{lk} Ctpell + \sum_{lk} Qe_{lk} distek_{lk} Cteth$$
(37)

Installation cost ($Instcost$) is determined for each type of production facility in each possible location by the capacity of the allocated plant. It is given by the general expression (38), where A corresponds to maximum installed capacity for the different facilities included in this formulation:

$$Installation = CCF \ \alpha A^{\beta} \qquad (38)$$

CCF represents the capital charge factor on the time horizon, which includes amortization and maintenance terms, and α and β are cost coefficients defined for each facility type. The adopted amortization time is twenty years. Therefore, the installation cost for sawmills, pellets, ethanol and woodboards facilities is stated as:

$$Instcost = CCF(\sum_{lt} \alpha_{saw} \left(Pl_t^{max}\right)^{\beta_{saw}} w_{lt} + \sum_{lt} \alpha_{pel} \left(Pl_t^{max}\right)^{\beta_{pel}} v_{lt} + \sum_{lt} \alpha_{et} \left(Pl_t^{max}\right)^{\beta_{et}} u_{lt}$$
$$+ \sum_{lt} \alpha_{wb} \left(Pl_t^{max}\right)^{\beta_{wb}} b_{lt} \qquad (39)$$

The variable $Enercost$ is the cost of the fuel bought from external sources of the SC to produce thermal energy in ethanol facilities. This cost is calculated multiplying the quantity of the liquid fuel necessary ($Extfuel_l$) by its price ($cfuel$) as it is expressed in Eq. (40).

$$Enercost = cfuel \sum_{l} Extfuel_l \qquad (40)$$

Production cost ($Prodcost$) involves the labor and supplies costs required to obtain the lumber, woodboards, pellets and ethanol. This cost depends on production capacity t

of each facility and it is obtained multiplying in each case the total production by its production cost ($Cprodlum_{it}, Cprodwb_t, Cprodpell_t, Cprodet_t$):

$$Prodcost = \sum_{lit} Prodlumb_{lit} Cprodlum_{it} + \sum_{lt} Prodwb_{lt} Cprodwb_t + \sum_{lt} Prodpell_{lt} Cprodpell_t + \sum_{lt} Prodet_{lt} Cprodet_t$$

(41)

4. Case study

The proposed model is applied for designing a forest SC in the northeast and center regions of Argentina.

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. Byproducts and residues conversion factors can be deduced from section 2, where the different proportions were stated. As it was previously mentioned, in this work, two different types of lumber are produced which basically differ in the brushing and the final humidity from different drying alternatives. It is reflected in its operation cost and heat consumption. Four consumers regions are selected, located in the center of the country: Buenos Aires, Chaco, Córdoba y Santa Fe.

The different model parameters were mainly determined considering values from the Argentinean forest industry, except the ones related to ethanol production which were taken from literature. . These elements are not shown in this document due to space reasons, but readers can request them to the authors

5. Results

The proposed mathematical formulation is solved for the model parameters presented in the case study. The attained configuration of the optimal SC is described in Fig. 3 and it consists in 5 sawmills, 7 woodboards facilities, 1 ethanol facility, and 2 pellets facilities. As can be observed from the Figure 3, in the optimal supply chain exists a trend to install the different facilities production configuring clusters, even though there is no location that includes the four facilities types. Most production plants tend to be located in harvest areas, avoiding high raw material transportation cost. Only two woodboards facilities are not installed near these areas: *l18* which is located in an intermediate point and *l14* in a consumer region. The total benefit is $ 156.9 MM, sales are equal to $535.5 MM, investments costs are $ 67.5 MM and production costs are $ 311.1 MM. Raw materials are completely utilized, distributing the available quantity between woodboards facilities and sawmills, while the residues from harvest areas are totally consumed by pellets and ethanol production. The capacities installed for each facility and the production of the different products varies in each site, producing a total of 250152 m^3 of lumber, 1200000 m^3 of woodboards, 28963 T of pellets and 50000 m^3 of ethanol (Table 1). The installed capacity is totally utilized in the case of woodboards and ethanol facilities, sawmills are utilized in a 99% and pellets facilities in a 72%. In the latest case, it is important to notice that, due to the installation cost of pellets facilities, is more profitable install two plants in locations near to the raw material sites than one bigger plant and transporting the raw material.

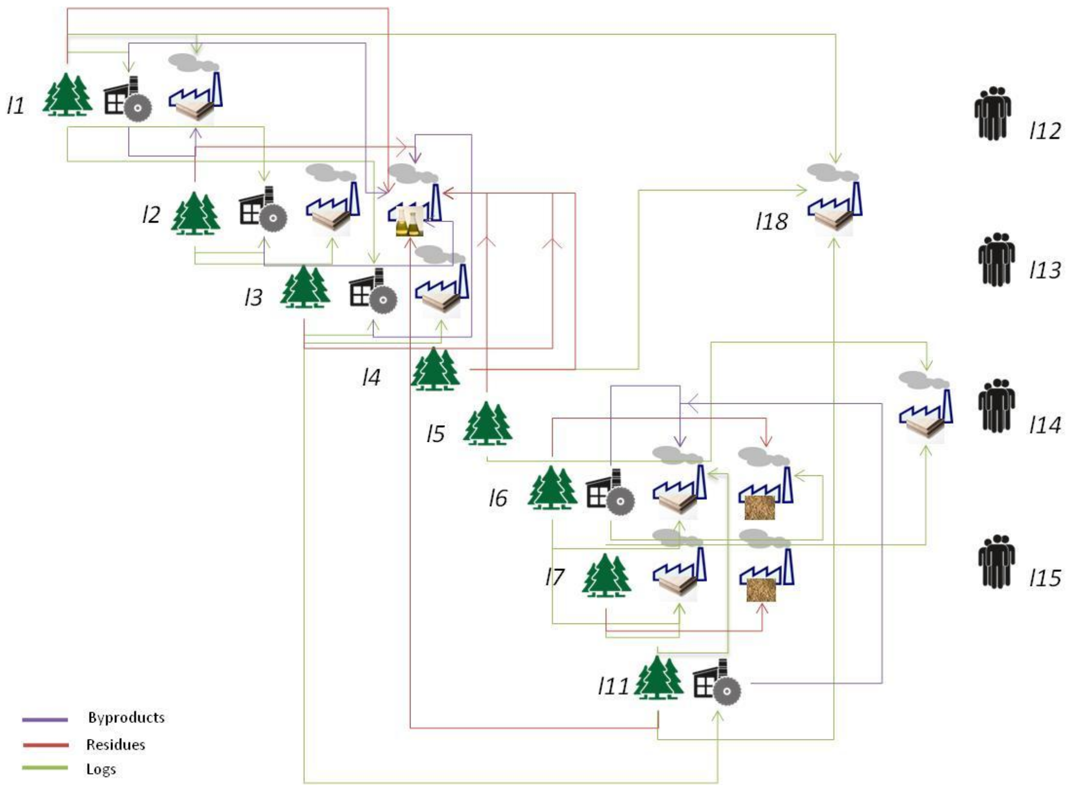

Fig. 3. Optimal SC configuration.

The maximum demand for woodboards is satisfied in a 98.4%, while lumber requirement is fulfilled in 86%, providing the total maximum demand of lumber type 1 and the 72.6% of type 2. Only 5% of the maximum demand of pellets and ethanol is fulfilled. Woodboards demand is not totally satisfied because of the installation of additional facilities for covering the remaining demand is not profitable. Regarding location of ethanol facility, it is installed in a strategic point, near the different sources, in order to reduce the transportation cost.

The byproducts generated in sawmills are totally distributed between the different facilities. It can be seen from Fig. 4 and 5 that these materials are distributed in the facilities located in the same or in near locations. Bark can only be used as fuels or as raw material for pellets as is stated in section 2. So, in this case, it is utilized for generating the necessary thermal energy for supplying the same sawmill where it is produced, while the leftovers are utilized for pellet production (Fig. 4). The distribution of residues is influenced by the distance to the production facilities. The total production of pellets is sold to consumers since they are not used as fuels for boilers.

Table 1. Production in each facility.

	Sawmills [m^3 year^{-1}]			Woodboards [m^3 year^{-1}]		Pellets [T year^{-1}]		Ethanol [m^3 year^{-1}]	
	Production		IC	Production	IC	Production	IC	Production	IC
Location	**Type 1**	**Type 2**							
l1	38793	15207	54000	100000	100000				
l2	38793	15207	54000	250000	250000			50000	50000
l3	24534	9617	36000	100000	100000				
l6	1086	52913	54000	250000	250000	15300	20000		
l7				150000	150000	13662	20000		
l11	38793	15207	54000						
l14				100000	100000				
l18				250000	250000				
Poduction	**250152**			**1200000**		**28962**		**50000**	

IC: installed capacity

In order to analyze residue and byproducts use, the same example is performed avoiding the use of harvest residues and sawmills byproducts in the ethanol and pellets production processes. The first one has no an economic value so cannot be sold, whereas sawmills byproducts can be sold to customers.

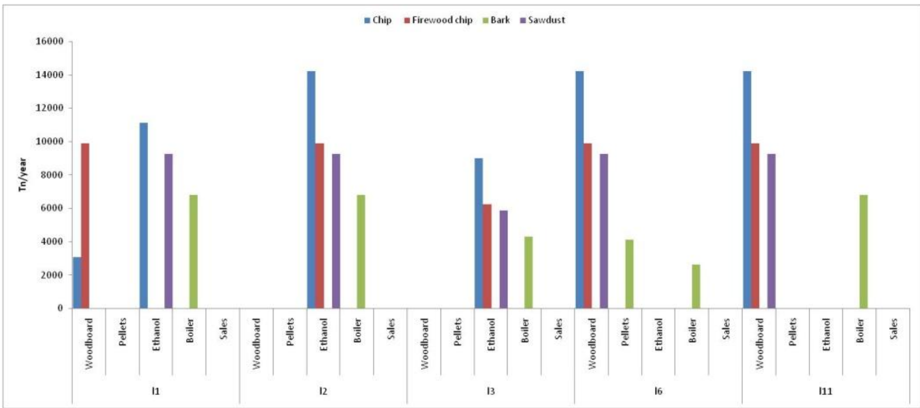

Fig. 4. Sawmills byproduct distribution.

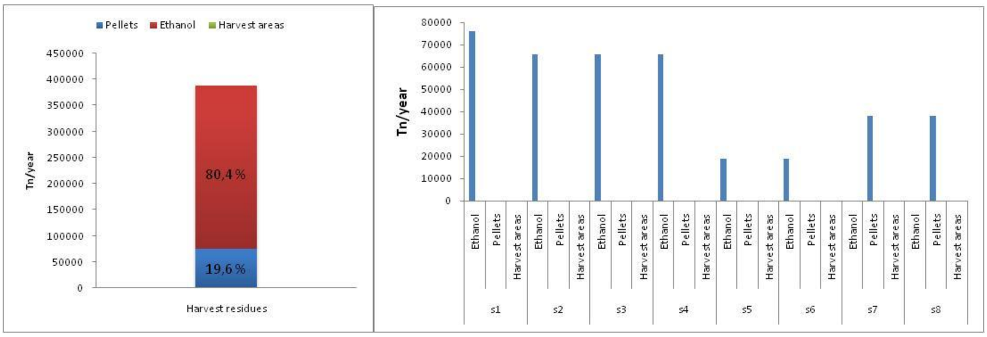

Fig. 5. Distribution of available harvest residues.

In this case, taking into account the added constraints, lumber and woodboard are only produced in the optimal solution. The woodboard demand is fulfilled with the installation of 6 woodboard facilities, while 4 sawmills are installed supplying the maximum demand of lumber type 1 and a 47% of type 2, being a 72,8% of total lumber demand. The raw material is fully utilized, and the total production of woodboards and lumber is equal to 1200000 m^3 and 212118 m^3 respectively. Therefore, since no byproduct sawmills are utilized for woodboards production and this production is more profitable than lumber, logs are first used for fulfilling woodboard demand and lumber is produced in a smaller amount. There is no ethanol and pellet production because no source of raw material is considered in this case.

The total benefit is equal to $ 126 MM, 20 % less than the first case. Sawmills byproducts are sold and its sale is equal to $1200131.26. The transportation cost is also reduced because only logs are transported.

Other cases can be easily studied and analyzed, but due to space reasons these are not presented in this work.

6. Conclusions

In this work, a 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.

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.

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 alternative. However, all the results should be evaluated under a judicious perspective. Obviously, they strongly depend on model parameters, mainly costs, prices, availabilities, products considered, etc. This work is presented as a tool for facilitating the analysis of different scenarios and, therefore, results should be considered in relation to adopted assumptions.

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