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A comparison between individual factories and industrial clusters location in the forest supply chain

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ABSTRACT

A mathematical model for optimal supply chain design and planning is presented in this work. The concept of cluster, where several facilities producing different products are closely located, is introduced and specially considered. In order to analyze facilities integration, discounts on investment and production costs are assumed. In addition, tradeoffs between clusters and individual facilities configurations are assessed. The proposed approach is applied to a forest supply chain, where some production plants use the same raw materials while others compete for the use of byproducts and residuals. Results allow for costs reduction when resources and services are shared by plants within a cluster, where, besides, the effect of production scale on the overall SC is also taken into account.

1. Introduction

A supply chain (SC) is composed of a large number of participants, including production units, suppliers, and customers. In order to satisfy customer needs, products must be produced and distributed on time and in the required quality and quantity. Therefore, several decisions must be addressed in order to achieve an efficient SC coordination.

In particular, the forest SC consists of various members covering various activities such as harvest, transportation, production of several products, and power generation, among others (D'Amours et al., 2009). The heterogeneity of the different involved parts poses interesting challenges for design and planning.

Forest SC is addressed by many works in the literature to propose different contributions towards its efficient operation. Beaudoin et al. (2007) propose mixed integer linear programming (MILP) considering different sources of raw material for lumber production among a set of feasible sawmills with the possibility of selling wood chips to increase mills' profits. Bajgiran et al. (2016) formulate a MILP model and a heuristic algorithm for integrating tactical planning decisions in lumber SC.

The forest industry is characterized by a high byproduct and waste production at different stages. For various reasons, these have not been efficiently used despite having interesting applications. An attractive option for their use is the production of second-generation biofuels, thereby obtaining an environmentally friendly source of energy.

A possible option is to generate pellets. Pellet production has been studied from different perspectives. Economic analyses of its production in different countries were carried out by proposing changes in costs (Trømborg et al., 2013) (Uasuf & Becker, 2011) or different sources of raw materials to determine optimal production scales (Shahrukh et al., 2016). Ethanol is another possible biofuel using forest residues. Several raw materials (Lu et al., 2015) and different processes for their production have been studied (Wei et al., 2009). Costs have been also analyzed to determine the optimal size of biorefineries (Jenkins & Sutherland, 2014).

Several reviews have been conducted on different approaches to biofuel generation in the forest supply chain, including the optimization of economic, social, and environmental aspects (Shabani et al., 2013) (Cambero & Sowlati, 2014).

Alternative approaches and objectives to consider forest supply chain optimization can be found in the literature. Feng et al. (2010)) present a mathematical programming model to design an integrated biorefinery and a forest product supply chain network. Dansereau et al. (2014)) propose a framework for forest biorefineries by optimizing a superstructure to help decision makers identify different supply chain policies for different market conditions. Pettersson et al. (Pettersson et al., 2015) present a model for integrating biofuel production to an existing forest supply chain in Sweden. Rodríguez et al. (Rodríguez et al., 2016) propose a model using disjunctive programming for a case study of Argentine forest industry aimed at determining the optimal SC configuration and considering two different technologies for biofuel production.

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A significant aspect to be considered is integration among involved plants. In the forest industry, there is a strong cooperation and competition relationship among facilities in the use of raw materials, residuals, and byproducts. The same raw material can be used to elaborate several products and different plants can compete for residues and byproducts utilization. In this sense, forming clusters of different plants may be a good option to both optimize resources use and distribution and reduce costs. As regards the forest industry, cluster formation is worth being studied because it supports different integration alternatives among SC members.

There are many factors that favor industrial clusters formation. Porter (1998), in his development of clusters theory, postulates that the benefits are based on economies of scale, availability of human capital, and technology transfer. According to the sources of productivity, benefits and costs of the cluster may be related to: access to inputs and infrastructure, labor and human resources, access to information and performance measures, and complementary products.

There are some published works dealing with industrial clusters formation from different perspectives: SC performance improvement (Yan & Wang, 2008), the economic and industrial development of a region (Zhao et al., 2009), knowledge transfer (Purwaningrum & Evers, 2012), and avoidance of risks in knowledge exchange (Fang et al., 2011).

Tolossa et al. (2013)) present a review of works that integrate the concepts of supply chain management and industrial cluster. Qu et al. (2015)) discuss general operations and configuration policies of cluster supply chains. Nananukul (2013)) proposes a clustering model, where customers are grouped so as not to violate transport capacity restrictions and delivery times, and whose objective is to minimize transport costs. Hackl and Harvey (2013)) propose a framework methodology integrating renewable raw materials into industrial clusters to improve energy efficiency and resource utilization.

Other works deal with the importance of cluster formation to improve competitiveness of members from a conceptual point of view. By means of an empirical study, Canello (2016)) emphasizes that including migrant enterprises within local networks benefits economy and knowledge transfer. Cohen & Marrison (2008)) suggest that clustering of firms improves their performance and cost minimization. In order to minimize total costs, these authors and Rosenthal & Strange (2004)) present a production function affected by agglomeration factors. These factors take into account location and type of those industries that make up a cluster. Kadam et al. (2000)) suggest that the integration of a new ethanol plant with an already existing plant can reduce production costs and minimize capital expenditures by sharing equipment. They include a detailed analysis of cost reductions.

Taking into account the previous analysis found in the literature, it is possible to assert that the different advantages of forming a cluster were studied in depth, in spite of the lack of a systematic approach to determine where and how to compose these clusters. Besides, the advantages of forming a cluster are very varied and depend on each particular case (Kadam et al., 2000, for example).

Forest SC design and planning involve several decisions and coordination requirements due to the various uses of raw materials and the generation of diverse products and byproducts. Taking into account its characteristics, a forest SC is a clear candidate for taking advantage of a cluster configuration. However, specific approaches are required to appropriately evaluate the involved tradeoffs. As previously stated, there are no tools to solve this problem from a quantitative perspective.

Mathematical programming is a useful approach to optimize the operations included in the SC, since it allows simultaneously assessing different integration alternatives while considering all related elements (Corsano & Montagna, 2011; Corsano et al., 2011). The aim of this work is to evaluate the different tradeoffs between the allocation of individual installations and the formation of clusters for the forest industry. Cost reduction is considered according to the quantity and size of grouped plants. In this way, services and resources can be shared by plants in a cluster and, therefore, the production scale and structure of the overall SC can be modified.

The aforementioned problem is addressed by formulating a MILP model for the optimal design and planning of a forest SC to optimize economic performance. The SC involves different facilities that produce various products and byproducts. In addition, several raw material sites are considered, where logs with different characteristics are available and residues are obtained. The model determines location and size of each plant as well as material flows between SC nodes. Although the proposed model includes a detailed formulation considering many production options, the main contribution of this article is the special treatment of the benefits provided by cluster conformation. Specific tradeoffs are assessed using a quantitative perspective. As previously mentioned, the advantages gained by forming clusters have not been explicitly included in similar formulations. Therefore, the proposed approach allows for the correct assessment of its implementation in the forest industry, whose characteristics favor its adoption.

The paper is organized as follows: in the following section, the problem is presented with a description of the involved facilities. In section 3, the mathematical model is formulated. Section 4 shows results and presents the analysis and discussion of the different alternatives and, finally, conclusions are drawn in Section 5.

2. Problem statement

2.1. SC description

A three-echelon SC is considered: forests, which correspond to raw material sites where logs and residues are provided for production; different plants which produce wood, woodboards, pellets, and ethanol; and customer zones whose demands must be fulfilled. Fig. 1 schematizes SC nodes and connections. As well as the remaining elements of the problem, the SC structure can be modified to introduce new alternatives.

At each raw material site, different tree species of various diameters are considered. The harvest produces residues in the forest which are calculated as 38% of cut trees. Sixty per cent of this amount can be used for ethanol and pellet production, while the rest remains in the forest to preserve soil structure and quality.

As previously mentioned, the production facilities considered in this work are: sawmills and woodboard, pellet, and ethanol industries. There are several connections between facilities since some byproducts are used for manufacturing other products, thus generating flows among them. Also, each plant, except for ethanol facilities, generates byproducts that can be used in the same or another plant as a thermal energy source. Pellets can be used for generating thermal energy in all facilities, while ethanol plants can use pellets or acquire liquid fuel from external suppliers to satisfy fuel requirements. Finally, products are distributed to different consumption centers, which have maximum demands for each type of product.

The model poses the optimal allocation of production facilities in order to satisfy customers' requirements using the available forest raw materials. The objective is to maximize the net profit given by incomes from sales minus total SC costs, including investment, operation, raw materials procurement and transport.

Facilities must be located by selecting among a set of locations with different characteristics: close to supply areas, near consumption regions, or intermediate places. The proper allocation of these plants will influence the economic performance of the SC, taking into account that several critical aspects are significantly affected: production scale, distance among nodes, flows among facilities, etc. Plant installation near harvest areas can reduce raw material transportation costs. Small plants in each raw material site usually favor this criterion. If factories are installed in customer areas, raw material transportation cost is increased. The production scale will be influenced by each customer zone's demand, but final products transportation cost is reduced. If plants

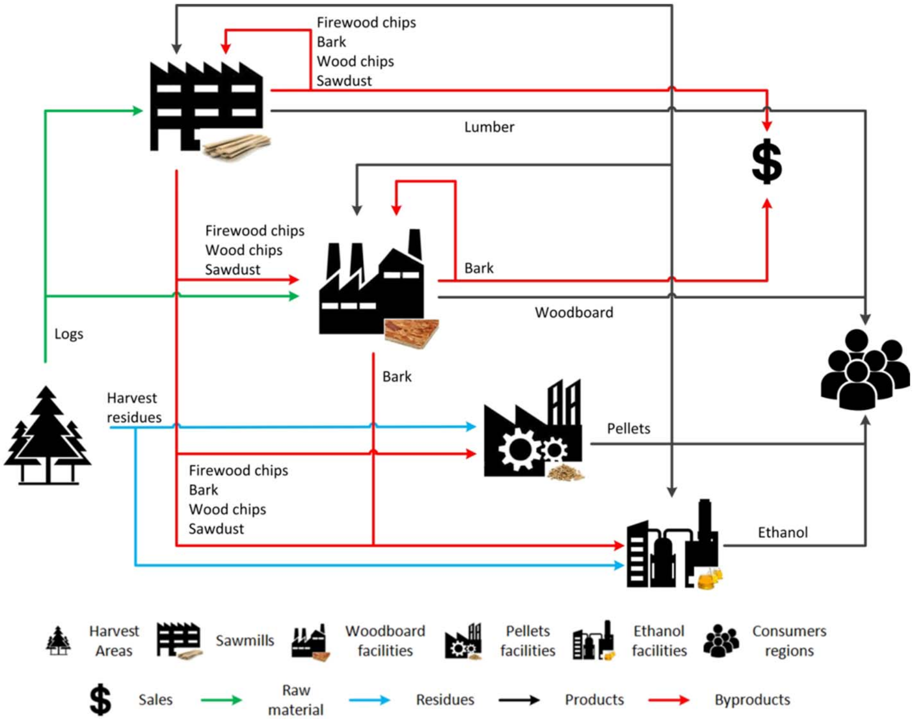

Fig. 1. Flows and interactions among SC nodes.

are installed in intermediate regions, issues such as the amount of processed products, distances to raw material sites and customer zones, among others, should be simultaneously evaluated.

At each location, several plants to produce different products can be installed. It is assumed that the same location cannot be allocated to plants of the same type. For each installed plant, a production capacity is selected from a discrete set of available maximum sizes. In this way, location and size are simultaneously optimized.

Until now, regardless of both the detail level of the SC model and the considered types of production facilities, previous models do not consider the advantages of several plants working jointly. Obviously, transport cost is reduced if plants exchange products and byproducts. However, new benefits can be added when taking into account the quantity and size of plants included in the cluster: shared technology, improvements brought about by a larger scale, improved access to utilities, reduced cost of general services, etc. Therefore, a formulation is required where specific savings favored by these links are specifically taken into account. The analysis will be focused on cluster formation and a proper assessment of its benefits by a mathematical formulation.

Following, a brief description of each production facility considered in this article is presented.

2.2. Plants description

2.2.1. Sawmills

Along mechanical wood processing, logs are transformed into pieces of different sizes and qualities, generating a lot of byproducts. These are classified into chip, chip wood, bark, and sawdust. The difference between chips and wood chip is that traces of bark remain in the latter. The produced wood is classified into different qualities to be sold. Meanwhile, byproducts may be used as a thermal energy source in the same factory, as raw material for woodboard, pellets, and ethanol production, or may be sold to third parties. Another source of thermal energy for these facilities is the acquisition of pellets.

2.2.2. Woodboard facility

Woodboards are produced using logs from harvest areas, and chips, wood chips, and sawdust from sawmills. Different types of boards can be made. Through log processing, also, bark is obtained, which can be sent to pellets and ethanol industries, sold to third parties, or used with pellets as a thermal energy source in this plant.

2.2.3. Pellet facility

Wood pellets are produced by compacting raw materials. Residues from harvest areas, byproducts from sawmills, and barks from board plants are used as raw materials. Once pellets are produced, they are distributed to the various plants as a thermal energy source or shipped to consumption centers.

2.2.4. Ethanol facility

Through physicochemical transformations, raw materials are transformed into ethanol, which is produced using residues from harvest areas and byproducts from sawmills. To satisfy energy requirements, ethanol facilities can use pellets or buy fuel from external suppliers.

3. Model formulation

In this section, balances among the different SC nodes, design equations, and the objective function are presented.

3.1. Raw material sites

Eq. (1) states that each raw material site s has a maximum capacity for each tree species z ($Maxrm_{zs}$). Therefore, the total raw material flow from these sites s to the different plants p installed at site l (Qh_{zspl}) cannot exceed this capacity.

$$\sum_{p \in ZP_z} \sum_{l} Qh_{zspl} \leq Maxrm_{zs} \quad \forall\, s, z \tag{1}$$

ZP_z is defined as the set of plants p that use tree species z for production.

At each raw materials site, produced residues are determined through parameter fhr_z that establishes the relationship between logs species and residues. Therefore, the amount of residues transported from each raw material site to all production plants that consume them

(Qhr_{spl}) is given by Eq. (2).

$$\sum_{p\in RP}\sum_{l} Qhr_{spl} \le \left(\sum_{p}\sum_{l}\sum_{z} fhr_z\, Qh_{zspl}\right) \quad \forall\, s \tag{2}$$

where RP represent the set of plants that consume residues from the forest. In this formulation, it is assumed that p includes the options of sawmill, woodboards, pellets, and ethanol; but new alternatives can be easily added.

3.2. Production facilities

Each plant p can be installed on a given site l, and it adopts a size from a set T_p, according to the equipment to be used. Thus, taking into account costs, productivities, etc. in relation to different sizes, the effect of the production scale is represented.

Let w_{ptl} be the binary variable for plant allocation and size selection:

$$w_{ptl} = \begin{cases} 1 & \text{if a plant } p \text{ in site l with capacity } t \text{ is installed} \\ 0 & \text{otherwise} \end{cases}$$

If plant p is installed at location l, only one size t is selected for it (Eq. 3).

$$\sum_{t} w_{ptl} \le 1 \quad \forall\, p,\, l \tag{3}$$

Eq. (4) indicates that the total input material for producing products at each plant of type p on site l (RM_{pl}) is equal to the amount of raw materials ($fl_z\ Qh_{zspl}$) and residues ($fr\ Qhr_{spl}$) coming from raw material sites s, plus byproducts ($fe_b\ Qr_{bp'pl'l}$) from production plants:

$$RM_{pl} = \sum_{z/p\in ZP_z}\sum_{s} fl_z\ Qh_{zspl} + \sum_{p'l'}\ \sum_{\substack{b/\\ b\in BP_{p'}\\ p\in PBy_b}} fe_b\, Qr_{bp'pl'l} + \sum_{s/p\in RP} fr\ Qhr_{spl} \quad \forall\, p,\, l \tag{4}$$

where fl_z, fe_b, and f_r represent the efficiency of each material in the process.

In this work, byproducts are obtained from sawmills (chip, chip wood, bark, and sawdust) and from woodboard plants (bark). Thus, BP_p represents the set of byproducts b produced in plant p, while PBy_b represents the set of plants p that use byproducts b as raw materials. When a plant does not use residues as a source of raw material, RP set is empty. Then, the last term of Eq. (4) is null. Analogously, if a plant does not consume a byproduct, this element is not included in the set PBy_b, and there is no contribution of this byproduct within the sum of the second term.

At each plant p, raw material RM_{pl} is converted into final products i. It is worth mentioning that some plants produce more than one product. Raw material consumption for each product is calculated using a conversion factor f_{ip}. Variable Pm_{iptl} represents the amount of product i produced at plant p with size t in location l. Therefore, Eq. (5) represents total production at plant p on site l.

$$\sum_{t,i/i\in IP_p} f_{ip} Pm_{iptl} = RM_{pl} \quad \forall\, p,\, l \tag{5}$$

where IP_p represents the set of products that are generated in plant p.

Taking into account that ${Pc_{pt}}^{max}$ represents the maximum capacities for sizes $t \in T_p$, for plant p, plant production is limited by this capacity. This is shown in Eq. (6).

$$\sum_{i\in IP_p} Pm_{iptl} \le w_{ptl} Pc_{pt}^{max} \quad \forall\, p,\, l,\, t \tag{6}$$

The following equation (Eq. 7) provides the amount of each type of byproducts b generated in each industry, depending on the amount of raw material input.

$$Qrt_{bpl} = fc_b \sum_{z,s} Qh_{zspl} \quad \forall\, p,\, l,\, b \in BP_p \tag{7}$$

where fc_b is a conversion factor for byproducts type b. If a byproduct b is not generated in a plant, it is not included in set BP_p.

The generated byproducts may be used as raw materials for other industries ($Qr_{bpp'll'}$), sold to third parties (Qs_{bpl}), or used as an energy source (Qb_{bpl}) in the same plant. This is posed in Eq. (8).

$$Qrt_{bpl} = \sum_{\substack{p',l'/\\ p'\in PBy_b}} Qr_{bpp'll'} + Qb_{bpl} + Qs_{bpl} \quad \forall\, b \in BP_p,\, p,\, l \tag{8}$$

Byproducts destination depends on supply chain needs and will be used to increase overall benefits.

3.3. Demand constraints

Let k be the different customer regions and ${D_{ik}}^{max}$ the maximum demand for each product type i. Eq. (9) determines that the amount of each product provided from facilities to each region k (Qp_{iplk}) cannot exceed the maximum demand of that region.

$$\sum_{p,l} Qp_{iplk} \le D_{ik}^{max} \quad \forall\, p,\, i \in IP_p,\, k \tag{9}$$

Also, the product flow to each region should not exceed the production of each plant (Eq. 10):

$$\sum_{t} Pm_{iptl} \ge \sum_{k} Qp_{iplk} \quad \forall\, p,\, p \ne pellet,\, i \in IP_p,\, l \tag{10}$$

Besides, pellets can be also used as a fuel source in other plants for power generation ($Qpellet_{p\,=\,pellet\ p'll'}$).This option is represented in Eq. (11).

$$\sum_{t} Pm_{ip=pellet\ tl} \ge \sum_{k} Qp_{ip=pellet\ lk} + \sum_{p'.l'} Qpellet_{p=pellet\ p'll'} \quad \forall\, i \in IP_p,\, l \tag{11}$$

3.4. Energy balance

For efficiency purposes, plants must meet their energy requirements. To meet these energy needs, plants can use the byproducts generated at the plant (Qb_{bpl}), acquiring pellets ($Qpellet_{p'\,=\,pellet\ pl'l}$) or external fuel ($Eext_{pl}$). Eq. 12 shows the energy balance for each plant, where the left side term represents the energy requirement of that plant, which is proportional to its production; and the right term stands for the energy obtained by using the various materials.

$$\sum_{\substack{t,i/\\ i\in IP_p}} Pm_{iptl} ed_p = \sum_{b\in BP_p} Qb_{bpl} cr_b + \sum_{l'} Qpellet_{p'=pellet\ pl'l} cp + Eext_{pl} \quad \forall\, p,\, l \tag{12}$$

where ed_p is energy required for the process, and cr_b and cp are the calorific capacities of residues and pellets, respectively.

3.5. Objective function

The adopted objective function represents profit maximization given by the difference between incomes from product and byproduct sales and raw materials, transportation, investment, production, and energy costs (Eq. 13).

$$G = Is - RMc - Tc - Ic - Pc - Ec \tag{13}$$

Considering that S_i and Sr_b are the selling prices for product i supplied by plant p and byproducts b respectively, the income from sales (Is) is represented by Eq. (14).

$$Is = \sum_{\substack{i,p,l,k/\\ i \in IP_p}} S_i Qp_{iplk} + \sum_{\substack{b,p,l/\\ b \in BP_p}} Sr_b Qs_{bpl} \tag{14}$$

Raw material costs (*RMc*) are related to the acquisition of the raw materials and residues needed for production. Therefore, they are calculated from material unit cost (Crm_z for logs and *Chr* for residues) and quantities supplied to each plant (Eq. 15).

$$RMc = \sum_{\substack{z,p,l/\\ p \in ZP_z}} Crm_z\, Qh_{zspl} + Chr \sum_{\substack{s,p,l/\\ p \in RP}} Qhr_{spl} \tag{15}$$

Transportation cost (*Tc*) includes transportation of raw materials and residues from supply areas to production plants, transportation of byproducts among plants, and shipping products to customer regions. As shown in Eq. (16), it is calculated by multiplying the amount of transported material by the distance between the involved nodes (Dhp_{sl} for distance between raw material site *s* and production site *l*, $Dpp_{ll'}$ for the distance between plants located at sites *l* and *l′*, respectively, and Dpk_{lk} for the distance between site *l*, and customer zone *k*) and their relative costs (*Ctrm* for raw materials, *Cthr* for residues, Ctr_b for byproducts, and Ctp_{ip} for product *i* from plant *p*), depending on the delivered material:

$$\begin{aligned} Tc = {} & Ctrm \sum_{\substack{z,s,p,l/\\ p \in ZP_z}} Dhp_{sl}\, Qh_{zspl} + Cthr \sum_{\substack{s,p,l/\\ p \in RP}} Dhp_{sl}\, Qhr_{spl} \\ & + Ctr \sum_{\substack{b,p,p',l,l'/\\ b \in BP_p\\ p' \in PBy_b}} Ctr_b\, Dpp_{ll'}\, Qr_{bpp'll'} \\ & + Ctp_{i=pellet,p=pellet} \sum_{p=pellet,p',l,l'} Dpp_{ll'}\, Qpellet_{p=pellet\, p'll'} \\ & + \sum_{\substack{i,p,l,k/\\ i \in IP_p}} Ctp_{ip}\, Dpk_{lk}\, Qp_{iplk} \end{aligned} \tag{16}$$

Investment cost (*Ic*) is determined for each type of production plant in every possible location taking into account its selected capacity (Eq. 17).

$$Ic = fam \sum_{p,t,l} \alpha_p (PC_{pt}^{max})^{\beta_p}\, w_{ptl} \tag{17}$$

where *fam* represents the capital charges factor on the time horizon, including amortization and maintenance; and α_p and β_p are cost coefficients defined for each type of facility.

Production cost (*Pc*) involves labor cost, services cost, etc., required for production. This cost is calculated in Eq. (18) and depends on capacity *t* of each facility *p* and is obtained by multiplying in each case the total production by its production cost, CP_{ipt}:

$$Pc = \sum_{\substack{i,p,t,l\\ i \in IP_p}} CP_{ipt}\, Pm_{iptl} \tag{18}$$

Energy costs (*Ec*) are related to the purchase of liquid fuel to meet energy requirements. Therefore, it is calculated from the unit cost of fuel (*Ce*) and the quantities used by each plant (Eq. 19).

$$Ec = \sum_{p,l} Ce\, Eext_{pl} \tag{19}$$

Investment and production costs will be affected when the clustering discount is applied. Its implementation is explained in the following section.

3.6. Cluster formation

In order to encourage the formation of industrial clusters, discounts on investment and production costs are proposed. Advantages are achieved if several plants are closely located, taking into account they can share infrastructure, machinery, labor, services, and supplies. The magnitude of benefits depends on the number of plants to be installed in a particular location, their relative production sizes, and the types of involved activities. For example, when several plants are jointly installed, large plants will have a lower discount than smaller facilities; i.e. smaller plants are more benefited, taking into account that they will take advantage of large scale resources and better technology provided by larger facilities.

Let *n* be the number of installed plants at a given site. This value is determined by binary variable y_{ln} using Eqs. (20) and (21).

$$\sum_{n=1}^{N_{plant}} n y_{ln} = \sum_{p,t} w_{ptl} \quad \forall\, l \tag{20}$$

$$\sum_{n=1}^{N_{plant}} y_{ln} \le 1 \quad \forall\, l \tag{21}$$

where

$$y_{ln} = \begin{cases} 1 & \text{if } n \text{ plants are installed on the site } l \\ 0 & \text{otherwise} \end{cases}$$

Note that, in the present work, only one plant of each type can be installed at each site *l*, and therefore the maximum number of plants at each site, N_{plant}, is equal to 4. In order to establish the relation among the sizes of installed factories at site *l*, binary variables $aux1_{ptl}$, $aux2_{pp'tt'l}$, $aux3_{pp'p''tt't''l}$, and $aux4_{pp'p''p'''tt't''t'''l}$, are defined for stating if the number of plants installed at site *l* is equal to one, two, three, or four respectively, in each case, with its corresponding type of plant *p*, and size *t*. In other words, these variables are defined as:

$$aux1_{ptl} = \begin{cases} 1 & \text{if only one plant } p \text{ of size } t \text{ is installed at site } l \\ 0 & \text{otherwise} \end{cases}$$

$$aux2_{pp'tt'l} = \begin{cases} 1 & \text{if plants } p \text{ and } p' \text{ with size } t \text{ and } t'\text{, respectively} \\ & \text{, are installed at site } l \\ 0 & \text{otherwise} \end{cases}$$

$$aux3_{pp'p''t\,t't''l} = \begin{cases} 1 & \text{if plants } p,\ p' \text{and } p'' \text{ with size } t,\ t' \text{ and } t''\text{, respectively} \\ & \text{, are installed at site } l \\ 0 & \text{otherwise} \end{cases}$$

$$aux4_{pp'p''p'''t\,t't''t'''l} = \begin{cases} 1 & \text{if plants } p,\ p',\ p'' \text{ and } p'''\text{with size } t,\ t',\ t''\text{and } t''' \\ & \text{, respectively, are installed at site } l \\ 0 & \text{otherwise} \end{cases}$$

In order to determine the value of each "*aux*" variable taking into account plant allocation, the following constraints are used (Eqs. 22–29):

$$aux1_{ptl} \ge w_{ptl} + y_{ln1} - 1 \quad \forall\, p, l, t \tag{22}$$

$$aux2_{pp'tt'l} \ge w_{ptl} + w_{p't'l} + y_{ln2} - 2 \quad \forall\, p, p', l, t, t', p \ne p' \tag{23}$$

$$aux3_{pp'p''tt't''l} \ge w_{ptl} + w_{p't'l} + w_{p''t''l} + y_{ln3} - 3 \quad \forall\, p, p', p'', l, t, t', t'', p \ne p' \ne p'' \tag{24}$$

$$aux4_{pp'p''p'''tt't''t'''l} \ge w_{ptl} + w_{p't'l} + w_{p''t''l} + w_{p'''t'''l} + y_{ln4} - 4 \quad \forall\, p, p', p'', l, t, t', t'', t''' p \ne p' \ne p'' \ne p''' \tag{25}$$

$$aux1_{ptl} \le y_{ln1} \quad \forall\, p, l, t \tag{26}$$

$$aux2_{pp'tt'l} \le y_{ln2} \quad \forall\, p, p', l, t, t', p \ne p' \tag{27}$$

$$aux3_{pp'p''tt't''l} \le y_{ln3} \quad \forall\, p, p', p'', l, t, t', t'', p \ne p' \ne p'' \tag{28}$$

$$aux4_{pp'p''p'''tt't''t'''l} \le y_{ln4} \quad \forall\, p, p', p'', l, t, t', t'', t''', p \ne p' \ne p'' \ne p''' \tag{29}$$

where subscripts $n1$, $n2$, $n3$, and $n4$, elements of set N, represent the number of plants to be installed in l; for example, if $y_{ln3} = 1$, three factories are installed in location l.

Thus, if two plants, p and p', with capacity t and t' are installed at site l, then $y_{ln2} = 1$, $w_{ptl} = 1$ and $w_{p't'l} = 1$, and therefore, by Eqs. (23) and (27), $aux2_{pp'tt'l} = 1$, while $aux1_{ptl} = 0$, $aux3_{pp'pp''tt't''l} = 0$, and $aux4_{pp'pp''p''tt't''t''l} = 0$ by Eqs. (21), (26), (28) and (29).

Investment and production costs are calculated by using these binary variables.

3.6.1. Investment cost

The investment cost for clusters in location l involving one, two, three, or four plants ($ICC_{l\,n}$) is presented. For each site l, at most one of these expressions is positive (Eqs. 30–33):

$$ICC_{ln1} = \sum_{p,t} ICPaux1_{ptl} \quad \forall\, l \tag{30}$$

$$ICC_{ln2} = \sum_{\substack{p,p',t,t'\\ p\ne p'}} parI2_{tt'} ICPaux2_{pp'tt'l} \quad \forall\, l \tag{31}$$

$$ICC_{ln3} = \sum_{\substack{p,p',p'',t,t',t''\\ p\ne p'<p''}} parI3_{tt't''} ICPaux3_{pp'p''tt't''l} \quad \forall\, l \tag{32}$$

$$ICC_{ln4} = \sum_{\substack{p,p',p'',t,t',t''\\ p\ne p'<p''<p'''}} parI4_{tt't''t'''} ICPaux\,4_{pp'p''p'''tt't''t'''l} \quad \forall\, l \tag{33}$$

$parI2_{tt'}$, $parI3_{tt't''}$ and $parI4_{tt't''t'''}$ are the discount parameters by clustering taking into account the adopted sizes by the allocated facilities. They are proposed by the designer considering specific sizes, proposed scales, involved technologies, corresponding production activities and all shared elements among plants. If only one plant is installed, no discount is applied. Note that the summation is over all involved plants in an ordered set of plants, and therefore, relations as $p' < p_{''}$ are stated to avoid duplicated combinations of plants.

$ICPaux1_{ptl}$, $ICPaux2_{pp'tt'l}$, $ICPaux3_{pp'pp''tt't''l}$, and $ICPaux4_{pp'pp''p'''\ tt't''t'''\ l}$ are the investment costs of each plant in a cluster of one, two, three, or four plants respectively. The subscript represents type and size of the involved plants. This allows applying a correct clustering discount parameter for each facility according to the quantity and size of plants installed in the same cluster. This is calculated according to Eqs. (34)–(36):

$$ICPaux\ 1_{ptl} \le ICP_{ptl} \quad \forall\, p, l, t \tag{34}$$

$$ICPaux\ 1_{ptl} \le ICP^{UP} aux\ 1_{ptl} \quad \forall\, p, l, t \tag{35}$$

$$ICPaux\ 1_{ptl} \ge ICP_{plt} - ICP^{UP}(1 - aux\ 1_{ptl}) \quad \forall\, p, l, t \tag{36}$$

for a cluster of a single plant, where ICP^{UP} is an upper bound for the investment cost, and IPC_{ptl} is the investment cost of each plant given by Eq. (37):

$$ICP_{ptl} = fam \quad \alpha_p (PC_{pt}^{max})^{\beta} w_{ptl} \quad \forall\, p, l, t \tag{37}$$

Previously, Eq. (17) corresponds to the total investment cost without discount. For a cluster of two plants, Eqs. (38)–(40)

$$ICPaux2_{pp'\,tt'l} \le ICP_{ptl} \quad \forall\, p, p', l, t, t', p \ne p' \tag{38}$$

$$ICPaux2_{pp'\,tt'l} \le ICP^{UP} aux2_{pp'tt'l} \quad \forall\, p, p', l, t, t', p \ne p' \tag{39}$$

$$ICPaux2_{pp'\,tt'l} \ge ICP_{ptl} - ICP^{UP}(1 - aux2_{pp'tt'l}) \quad \forall\, p, p', l, t, t', p \ne p' \tag{40}$$

Analogously, for $ICPaux3_{pp'pp''tt't''l}$, and $ICPaux4_{pp'pp''p'''tt't''t'''l}$, Eqs. (38)–(40) are formulated for calculating the investment cost of a cluster composed by 3 and 4 plants respectively.

Finally, the total investment cost is calculated according to Eq. (41).

$$Ic = \sum_{l,n} ICC_{ln} \tag{41}$$

3.6.2. Production cost

Discounts applied to production costs have a similar formulation to that for investment costs. Production cost of each cluster ($PCC_{l\ n}$) is calculated as shown in Eqs. (42)–(45). For each site l, at most one of these expressions is positive:

$$PCC_{ln1} = \sum_{p,t} PCPaux1_{ptl} \quad \forall\, l \tag{42}$$

$$PCC_{ln2} = \sum_{\substack{p,p',t,t'\\ p\ne p'}} parP2_{tt'} PCPaux2_{pp'tt'l} \quad \forall\, l \tag{43}$$

$$PCC_{ln3} = \sum_{\substack{p,p',p'',t,t',t''\\ p\ne p'<p''}} parP3_{tt't''} PCPaux3_{pp'p''tt't''l} \quad \forall\, l \tag{44}$$

$$PCC_{ln4} = \sum_{\substack{p,p',p'',t,t',t''\\ p\ne p'<p''<p'''}} parP4_{tt't''t'''} PCPaux4_{pp'p''p'''tt't''t'''l} \quad \forall\, l \tag{45}$$

$PCPaux1_{ptl}$, $PCPaux2_{pp'tt'l}$, $PCPaux3_{pp'pp''tt't''l}$, and $PCPaux4_{pp'pp''p'''tt't''t'''l}$s are production costs of each plant in a cluster conformed by one, two, three, or four plants respectively, and $parP2_{tt'}$, $parP3_{tt't''}$ and $parP4_{tt't''t'''}$ are the clustering discount parameters for each site l taking into account the sizes adopted by allocated facilities.

In order to determine the value of these costs, Eqs. (46)–(48) are used for $PCPaux1_{ptl}$:

$$PCPaux\ 1_{ptl} \le PCP \quad \forall\, p, t, l \tag{46}$$

$$PCPaux\ 1_{ptl} \le PCP^{UP} aux\ 1_{ptl} \quad \forall\, p, t, l \tag{47}$$

$$PCPaux\ 1_{ptl} \ge PCP_{ptl} - PCP^{UP}(1 - aux\ 1_{ptl}) \quad \forall\, p, t, l \tag{48}$$

where PCP^{UP} is the upper bound of production cost.

Similar constraints are stated for $PCPaux2_{pp'tt'l}$, $PCPaux3_{pp'p''tt't''l}$, and $PCPaux4_{pp'p''p'''tt't''t'''l}$ as formulated in Eqs. (38)–(40).

PCP_{plt} is production cost of each plant, calculated with Eq. (49).

$$PCP_{ptl} = \sum_{i\in IP_{ip}} CP_{ipt} Pm_{iptl} \quad \forall\, p, l, t \tag{49}$$

Therefore, total production cost is given by Eq. (50).

$$Pc = \sum_{ln} PCC_{ln} \tag{50}$$

4. Results

In order to highlight the capabilities of the proposed approach, two models are performed and compared: one model in which no discount is introduced for plants that are jointly installed in a site (considering Ic and Pc as Eqs. (17) and (18) respectively), and another model where discounts are applied through the equations presented in Section 3.5.

The case study is located in the Northwestern region of Argentina, which contain 80% of the country's forests. The models consider six sites of raw materials and fifteen possible locations for the installation of plants, being distributed as follows: six plants nearby raw material sources, four plants close to consumer regions, and the remaining plants

Table 1
Input and output flows of industries

		Sawmills	Woodboard	Pellets	Ethanol
Input	Raw materials	Log	Log	Residues	Residues
	Byproducts		Woodchips Firewood chips Sawdust	Woodchips Firewood chips Sawdust Bark	Woodchips Firewood chips Sawdust Bark
Output	Products	Lumber 1 Lumber 2	Board 1 Board 2	Pellets	Ethanol
	Byproducts	Woodchips Firewood chips Sawdust Bark	Bark		
Energy source		Byproducts Pellets	Byproducts Pellets	Pellets	Pellets External energy

at intermediate sites.

Table 1 describes the various input and output flows of industries. For example, sawmills use logs for producing two different types of lumber, while woodboards can produce two types of boards using logs, woodchips, firewood chips, and sawdust. As regards energy sources, it is assumed that only ethanol plants can receive external liquid fuel for generating energy in the plant.

There are four consumer regions with a maximum demand for each type of product. It is assumed that raw material cost does not vary with geographical location.

In order to simplify the result analysis and subsequent discussion, it is assumed that the same discounts are used for investment and production costs. Besides, instead of proposing specific values, a general mathematical expression is adopted as follows:

$$parI2_{tt'} = parP2_{tt'} = 0.9 + 0.1\frac{ord(t') - ord(t)}{|T_p| - 1}$$

$$parI3_{tt't''} = parP3_{tt't''} = 0.8 + 0.1\frac{[ord(t') - ord(t)] + [ord(t'') - ord(t)]}{|T_p| - 1}$$

$$\begin{aligned} parI4_{tt't''t'''} &= parP4_{tt't''t'''} \\ &= 0.8 + 0.1\frac{[ord(t') - ord(t)] + [ord(t'') - ord(t)] + [ord(t''') - ord(t)]}{|T_p| - 1} \end{aligned}$$

where $|T_p|$ represents the cardinality of the set of discrete sizes for facilities, i.e. the number of different sizes considered for each plant; and “ord(t)” represents the position in which size t is in the set. These parameters vary according to the size adopted by the plants included in the cluster and they are in the ranges depicted in Table 2.

It is important to emphasize that these clustering discounts are closely related to the types of plants that integrate the clusters and the technologies involved in their productive processes. In this work, a simplification of these values is made in order to facilitate the presentation. In real cases, a detailed analysis must be carried out to determine the discounts from the specific technologies and resources to be shared.

Both examples were implemented and solved in GAMS (Rosenthal, 2013) using CPLEX solver in an Intel(R) Core(TM) i7-3770, 3.40 GHz. Some model statistics are shown in Table 3.

Table 2
Range of parameters.

	Range
$parP2_{tt'}$	0.8–1
$parP3_{tt'}t''$	0.6–1
$parP4_{tt'}t''t'''$	0.4–1

4.1. *Without discounts*

The optimal attained SC configuration consists of 7 sawmills, 3 woodboard facilities, and 6 pellet factories. Ethanol plants are not installed. The plants are located in 9 different locations: six sites nearby raw material sources, two intermediate sites, and one site in consumer areas. Factories are installed to form 2 clusters of three plants, 3 clusters of two plants, and 4 of individual factories as shown Fig. 2.

In addition, Fig. 2 shows the size adopted by each factory, where t1 is the largest and t5 is the smallest one.

The total benefit is $ 204,414,266. Table 4 presents a detailed list of revenues and costs of each industry.

Table 5 shows the use of raw materials (logs) and harvest residues, while Table 6 depicts total production of each plant and demand satisfaction percentage. Table 7 shows total production capacity and percentage of facilities' use. For this example, at least 75% of the plant capacity is required to be used.

Byproducts generated in sawmills are sent to woodboard plants (95.5%) and the rest is either shipped to the pellet plants (0.6%) or used as an energy source in the same factory (3.9%). The bark from the woodboards industry is burned in the same plants (Table 8).

Pellets are mainly used as energy source for various plants (60.6% woodboards, 13.7% sawmills, and 7.8% pellets) and the rest is sent to consumer regions.

4.2. *With discounts*

When discounts are considered in the model, the optimal SC design consists of 3 clusters of four facilities and 1 cluster of two facilities. The attained SC configuration involves 4 sawmills, 4 woodboard facilities, 4 pellets facilities, and 3 ethanol facilities, making up a total of 15 industries, one less than in the previous case. The four clusters are installed near the harvest area as it can be noted in Fig. 3.

The total benefit is 18.3% greater than in the previous case (Table 4). Although the benefits of sawmills are reduced, the global result shows that a cooperative work among supply chain members allows for a greater overall benefit. Cost reduction is clearly noted in the costs of woodboard plants. In this case, the quantity and production of plants is increased; while production and investment costs decrease by 12% and 33% respectively.

Table 3
Model statistics.

	Equations	Continuous variables	Discrete variables	CPU time (*sec.*)
Without discounts	3733	22,324	420	4.8
With discounts	15,470,954	572,045	2,526,720	90,596.3

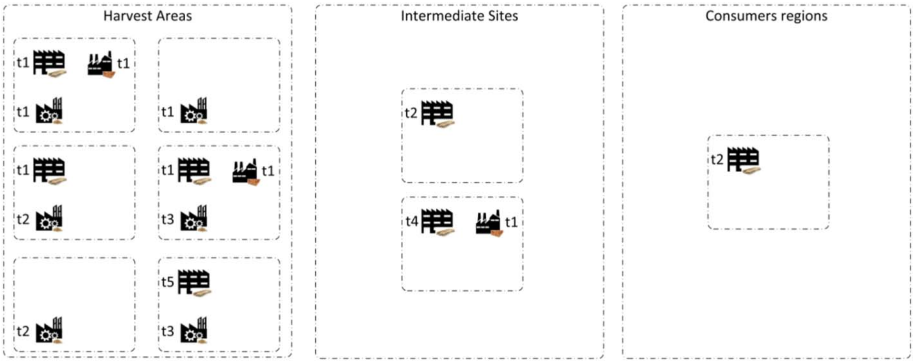

Fig. 2. Facilities location for no discount model.

Table 4
Economic report [million $/year]

		Without discounts	With discounts
Sawmills	Incomes	93.55	76.36
	Raw materials costs	18.73	15.39
	Investment cost	1.06	0.67
	Production cost	7.47	4.13
Woodboard	Incomes	295.31	306.49
	Raw materials costs	19.18	22.52
	Investment cost	34.44	30.31
	Production cost	73.11	49.19
Pellet	Incomes	4.97	0.00
	Raw materials costs	1.58	1.11
	Investment cost	0.87	0.48
	Production cost	4.61	2.03
Ethanol	Incomes	–	19.90
	Raw materials costs	–	0.47
	Investment cost	–	3.96
	Production cost	–	1.05
Transportation cost	Raw materials	6.17	4.63
	Between industries	2.29	0.27
	Product	19.90	23.56
Energy cost		–	1.20
Net benefit		204.41	241.78

Table 5
Use of raw materials.

		Without discounts	With discounts
Use of raw materials	Sawmills	49%	39%
	Woodboards	51%	61%
Use of residues	Pellets	100%	70%
	Ethanol	–	30%

Table 6
Production and demand satisfaction.

	Without discounts		With discounts	
	Production	Demand satisfaction	Production	Demand satisfaction
Lumber	294,263 m^3	49.9%	233,197 m^3	39.5%
Woodboards	900,000 m^3	72.6%	937,500 m^3	75.6%
Pellets	114,312 t	4.2%	80,000 t	0.0%
Ethanol	–	–	16,875 m3	15.9%

In this case, all clusters are installed close to harvest areas, which lead to a 25% reduction in raw material transportation costs. In addition, this concentration of all plants in 4 sites allows for an 88% reduction in transport costs among the various centers. On the other hand, the distance to consumption regions undergoes an 18% increase in product transportation. Globally, transportation cost remained almost constant.

Table 7
Total capacity of production

	Without discounts		With discounts	
	Production capacity	Use of installed capacity	Production capacity	Use of installed capacity
Lumber	301,500 m^3	97.6%	252,000 m^3	92.5%
Woodboards	900,000 m^3	100.0%	937,500 m^3	100.0%
Pellets	140,000 t	81.7%	105,000 t	76.2%
Ethanol	–	–	22,500 m3	75.0%

Table 8
Destination of byproducts.

		Raw materials	Energy	Sold
Without discounts	Sawmills	96.1%	3.9%	0.0%
	Woodboards	0.0%	100.0%	0.0%
With discounts	Sawmills	78.8%	21.2%	0.0%
	Woodboards	0.0%	100.0%	0.0%

As in those cases “without discounts”, raw materials and harvest residues are totally used. The percentage of use in each industry is presented in Table 5.

In the case “without discounts”, 45.1% of the raw material and 92.7 of the residues are used in the same harvest area, while the rest is sent to another site. Meanwhile, in the case “with discounts”, raw material and residues are used in the extraction area by 60.1% and 58.4%, respectively.

From Table 6, and in comparison with the previous case, it can be observed that woodboards remain as the main product of the SC, increasing production by 4.2%, while lumber and pellet production decreased by 20.8% and 30.0% respectively. This increase in board production is due to the discounts that turn production more profitable. In contrast to the previous case, ethanol production became profitable due to the discounts for clusters formation, generating a total of 16,875 m^3.

The byproducts produced in sawmills are sent to woodboard (56.7%) and ethanol plants (22.1%). The remaining amount is used as an energy source in the same plant. In the case of woodboard facilities, total byproducts are used as energy source (Table 8). In both cases, without and with discounts, the use of byproducts for generating products and energy is prioritized, and these are not sold to third parts.

It is worth mentioning that pellets are totally used for thermal energy in woodboard facilities (90.2), sawmills (1.9%), and in the same plant (7.9%). Therefore, customer demand satisfaction for this product is 0% (Table 6). For ethanol production, external liquid fuel is bought.

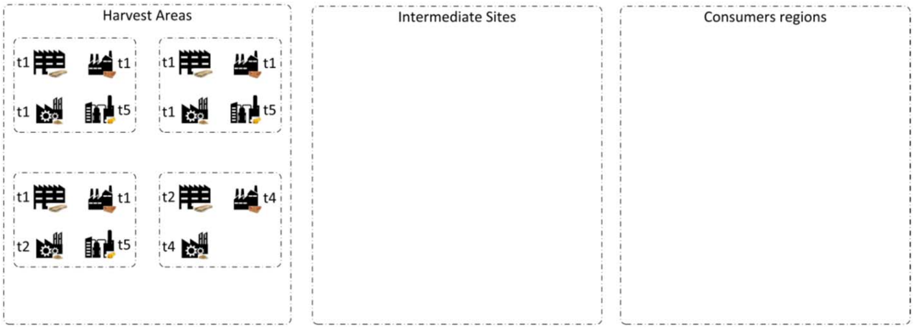

Fig. 3. Optimal SC design for discount mode l.

4.3. Discussion

It is worth mentioning that all results here presented are significantly affected by the adopted values for discounts. Anyway, the capability of the proposed formulation to explicitly include the effect of collaboration through a cluster conformation must be highlighted. In order to emphasize the model capabilities, general expressions to represent discounts have been employed in the solved examples to assess the proposed formulation from a general and independent point of view. However, it is very difficult to generalize the obtained discounts. In real cases, discounts should be discussed and calculated for each particular context, taking into account the available resources (Kadam et al., 2000). Several issues should be considered that cannot be generalized a priori. For instance:

- Can a common logs reception be installed in a specific site?
- Can a boiler be shared among the allocated plants taking advantage of a favorable scale factor?
- Can plants be nearby installed with a common surveillance system?

These topics and a long list of similar questions must be analyzed and discussed in a final and real implementation of the proposed formulation.

After this clarification, first, the great difference between both solutions must be emphasized. Even though tables and analyses are hardly affected by the weight of cluster conformation discounts, their favorable effect must be underlined. It is critical to detect the origin of the main changes attained with the concept of cluster.

Several costs, mainly transport-related ones, are increased; but production and investment costs are substantially reduced.

Tables 9 and 10 compare the relationship between global production and operation and investment costs respectively. Since ethanol is produced only in the case with discounts, these costs are not presented for the case without discounts. Clearly, a significant reduction in both tables has been attained. The provided tables show different variations whose magnitude is determined by several causes: the number of involved plants, their relative sizes, and the specific production being considered (affecting technology, resources, etc.).

An important result is the installation of ethanol plants in the case with discounts. Cost discounts turn ethanol production profitable. For this purpose, however, sawmills byproducts are used to produce ethanol instead of woodboards. Therefore, a larger amount of logs is used in woodboard production, decreasing these raw materials for sawmills and consequently reducing lumber production. Also, pellet production is decreased since ethanol production consumes forest residues. Woodboard production is evidently preferred, but the installation of ethanol plants in the clusters allows for a tight distribution of byproducts among clusters members to reach a better production mix.

As regards the production scale, woodboard plants are large (size t_1) in the case without discounts as well as in the case with discounts, adding a small plant (size t_4) in the case with discounts, which is favored by the (clustering) discount parameter. Since lumber production is reduced, fewer sawmills are installed in the case with discounts but all of them have a big size (3 of size t_1 and 1 of size t_2) in order to favor the installation of small ethanol plants which use sawmills byproducts. Finally, in the case with discounts, pellet plants are also fewer than in the case without discounts due to the reduction of its production. Even though the tables do not allow for comparison because no ethanol plants are installed in the case without discounts, the discounts applied to investment and production costs for small plants benefit the installation of these plants in the last case.

Table 9
Production cost/total production relation.

	Without discounts	With discounts	
Lumber [$/m3]	25.40	17.72	− 30.25%
Woodboards [$/m3]	81.24	52.47	− 35.41%
Pellets [$/T]	40.30	25.39	− 36.99%
Ethanol [$/m3]	–	62.24	–

Table 10
Investment cost/total production relation.

	Without discounts	With discounts	
Lumber [$/m3]	3.61	2.87	− 20.58%
Woodboards [$/m3]	38.26	32.33	− 15.51%
Pellets [$/T]	7.63	5.97	− 21.78%
Ethanol [$/m3]	–	234.93	–

5. Conclusions

In this work, a new formulation is presented for the optimal design of the forest supply chain. The main contribution is the special treatment of production clusters conformation. Taking into account the characteristics of the forest industry, this alternative is highly profitable. The shared use of logs and byproducts allows taking advantage of raw materials among related plants. Besides, sharing several resources and technologies brings about new benefits from production scale.

Although these advantages are widely recognized, they have not been included in previous models. Therefore, a formulation is proposed where cluster installation in a forest SC is assessed, considering discounts on investment and operation costs for facilities involved in the cluster. A MILP model for the optimal forest SC design and planning is presented. The different tradeoffs between clusters and individual facilities configurations are evaluated.

The results obtained from the example show that the introduction of discounts into cluster installation improves both the structure and profits of forest SC design. Cluster formation near harvest areas reduces raw material transportation costs and improves production diversification, including new products with better profitability. Placing facilities in a smaller number of sites reduces costs of transport between plants. Forming clusters to share plant resources and services increases their profitability. However, it should not be overlooked that all results and their magnitude will depend on the parameters adopted for the specific model, including considerations about the type of industry, the particular environment, local regulations, etc.

The approach addressed in this work represents a useful tool for analyzing production, resources, and services integration in forest SC, involving different facilities in the diversification of this industry.

Using the proposed formulation, a systematic and quantitative tool is available to compare different alternatives in order to achieve better productive and economic results. However, in order to successfully develop and implement these collaborative solutions, several additional conditions must be satisfied. Following Porter's analysis (1998), not only economical aspects must be taken into account, but also organizational, political, etc. issues must be considered. Evidently, they depend on particular contexts, and local aspects must be specially analyzed. Concluding, these collaborative and interorganizational proposals like supply chain, in general, and cluster, in particular, pose major challenges that quite often cannot be strictly included in a mathematical model. These concepts are very promising, but its correct application takes time and demands a new way of managing the involved firms. Besides, this is a general problem that exceeds forest industry, but strongly affects it when considering the tight links among its partners and actors. For example, some questions remain unanswered: how the overall net benefit increases are distributed in presence of industrial clusters, how to convince individual partners that major benefits will be achieved. These are critical questions. Undoubtedly, this collaboration will generate more efficient operations, but many times these benefits are not equally distributed among partners. This is a very interesting question that must be studied but is considered out of the scope of this work.

Nomenclature

Sets

$b \in B$	Type of by product
$i \in I$	Type of product
$k \in K$	Consumers regions
$l \in L$	Production facilities location
$n \in N$	Number of installed plants at a given site
$p \in P$	Type of plant
$s \in S$	Harvest areas
$t \in T_p$	Production facilities capacities
$z \in Z$	Raw material species
BP_p	Byproducts b produced in plant p
IP_p	Products i that are generated in plant p
PBy_b	Plants p that use byproducts b as raw material
RP	Plants p that consume residues from the forest
ZP_P	Plants p that use tree type z for their production

Parameters

α_p, β_p	Investment economic factors
Ce	Liquid fuel cost
Chr	Harvest residues cost
cp	Calorific capacity of pellets
CP_{ipt}	Production cost of product i in plant p with capacity t
cr_b	Calorific capacity of byproducts b
Crm_z	Raw material z cost
$Cthr$	Transportation cost of harvest residues transportation cost
Ctp_{ip}	Transportation cost of product i produced in p
Ctr	Transportation cost of byproducts
$Ctrm$	Transportation cost of raw materials
$D_{ik}{}^{max}$	Maximum demand of product i in region k
Dhp_{sl}	Distance between harvest area s and facility p installed on site l
Dpk_{lk}	Distance between facility p installed on site l and consumer regions k
$Dpp_{ll'}$	Distance between facility p and p' installed on site l and l'
ed_p	Energy needed for drying process
f_{ip}	Conversion factor of raw materials into product i produced in p
fam	Capital charge factor on the time horizon, which includes amortization and maintenance
fc_b	Conversion factor of raw materials into byproducts b
fe_b	Efficiency factor byproducts b
fhr_z	Factor of generation of residues from harvested trees species
fl_z	Efficiency factor raw materials z
fr	Efficiency factor residues harvest areas
ICP^{UP}	Upper bound for investment cost
$Maxrm_{zs}$	Maximum raw materials z in area s
$parI2_{tt'}$	Discount factors for production costs for each facility in relation to the size adopted when two factories are installed in one place
$parI3_{tt't''}$	Discount factors for production costs for each facility in relation to the size adopted when three factories are installed in one place
$parI4_{tt't''t'''}$	Discount factors for production costs for each facility in relation to the size adopted when four factories are installed in one place
$parP2_{tt'}$	Discount factors for production costs for each facility in relation to the size adopted when two factories are installed in one place
$parP3_{tt't''}$	Discount factors for production costs for each facility in relation to the size adopted when three factories are installed in one place
$parP4_{tt't''t'''}$	Discount factors for production costs for each facility in relation to the size adopted when four factories are installed in one place
$Pc_{pt}{}^{max}$	Maximum production in facility p with capacity t
PCP^{UP}	Upper bound for production cost
S_i	Sale price of product i
Sr_b	Sale price of byproducts b

Binary variables

w_{ptl}	Indicates if facility p is in location l with capacity t
y_{ln}	Indicates if n plants are installed in the locality l
$aux1_{ptl}$	Indicates if one plant is installed at a site l with its corresponding type of plant p and size t.
$aux2_{pp'tt'l}$	Indicates if two plants are installed at a site l with their corresponding type of plant p and size t.
$aux3_{pp'p''tt't''l}$	Indicates if three plants are installed at a site l with their corresponding type of plant p and size t.
$aux4_{pp'p''p'''tt't''t'''}$	Indicates if four plants are installed at a site l with their corresponding type of plant p and size t.

Continue variables

Ec	Energy cost of external fuels
$Eext_l$	Necessary fuel in ethanol facility in location l
G	Benefits
Ic	Investment cost
ICC_{ln}	Investment cost for clusters in location l involving n plants
ICP_{ptl}	Investment costs of plant p located in l with size t
$ICPaux1_{ptl}$	Investment costs of plant p with size t in a cluster of one plants located in l
$ICPaux2_{pp'tt'l}$	Investment costs of plant p with size t in a cluster of two plants located in l
$ICPaux3_{pp'p''tt't''l}$	Investment costs of plant p with size t in a cluster of three plants located in l
$ICPaux4_{pp'p''p'''tt't''t'''l}$	Investment costs of plant p with size t in a cluster of four plants located in l

Is	Incomes
Pc	Production cost
PCC_{ln}	Production for clusters in location l involving n plants
PCP_{ptl}	Production costs of plant p located in l with size t
$PCPaux1_{ptl}$	Production investment costs of plant p with size t in a cluster of one plant located in l
$PCPaux2_{pp'tt'l}$	Production costs of plant p with size t in a cluster of two plants located in l
$PCPaux3_{pp'p''tt't''l}$	Production costs of plant p with size t in a cluster of three plants located in l
$PCPaux4_{pp'p''p'''tt't''t'''l}$	Production costs of plant p with size t in a cluster of four plants located in l
Pm_{iptl}	Amount of product i produced in plant p located in l with size t
Qb_{bpl}	Flow of byproducts to boilers in plant p in location l
Qh_{zspl}	Flow of raw materials z from site s to facility p in location l
Qhr_{spl}	Flow of harvest residues from site s to facility p in location l
Qp_{iplk}	Flow of product i provided from facilities p to each region k
$Qpellet_{pp'll'}$	Flow of pellets from facility p at site l to facility p' at site l'
$Qr_{bpp'll'}$	Flow of byproducts from facility p at site l to facility p' at site l'
Qrt_{bpl}	Total of byproducts b generated at plant p installed at site l
Qs_{bpl}	Flow of byproducts b generated in plant p installed on site l sold to third parties
RM_{pl}	Total raw materials to be processed in plant p at site l
RMc	Raw material cost
Tc	Transportation cost

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References

Bajgiran, O., Kazemi Zanjani, M., Nourelfath, M., 2016. The value of integrated tactical planning optimization in the lumber supply chain. Int. J. Prod. Econ. 171, 22–33.

Beaudoin, D., LeBel, L., Frayret, J.-M., 2007. Tactical supply chain planning in the forest products industry through optimization and scenario-based analysis. Can. J. For. Res. 37, 128–140.

Cambero, C., Sowlati, T., 2014. Assessment and optimization of forest biomass supply chains from economic, social and environmental perspectives – a review of literature. Renew. Sust. Energ. Rev. 36, 62–73.

Canello, J., 2016. Migrant entrepreneurs and local networks in industrial districts. Res. Policy 45, 1953–1964.

Cohen, J., Marrison, Paul C., 2008. Agglomeration and cost economies for Washington State Hospital Services. Reg. Sci. Urban Econ. 38, 553–564.

Corsano, G., Montagna, J., 2011. Mathematical modeling for simultaneous design of plants and supply chain in the batch process industry. Comput. Chem. Eng. 35, 149–164.

Corsano, G., Vecchietti, A., Montagna, J., 2011. Optimal design for sustainable bioethanol supply chain considering detailed plant performance model. Comput. Chem. Eng. 35, 1384–1398.

D'Amours, S., Rönnqvist, M., Weintraub, A., 2009. Using operational research for supply chain planning in the forest products industry. Infor 46, 265–281.

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

Fang, Y., Liang, Q., Jia, Z., 2011. Knowledge sharing risk warning of industry cluster: an engineering perspective. Systems Engineering Procedia 2, 412–421.

Feng, Y., D'Amours, S., LeBel, L., Nourelfath, M., 2010. Integrated forest biorefinery supply chain network design using mathematical programming approach. CIRRELT 50.

Hackl, R., Harvey, S., 2013. Framework methodology for increased energy efficiency and renewable feedstock integration in industrial clusters. Appl. Energy 112, 1500–1509.

Jenkins, T., Sutherland, J., 2014. A cost model for forest-based biofuel production and its application to optimal facility size determination. Forest Policy Econ. 38, 32–39.

Kadam, K., Wooley, R., Aden, A., Nguyen, Q., Yancey, M., Ferraro, F., 2000. Softwood forest thinnings as a biomass source for ethanol production: a feasibility study for California. Biotechnology 16, 947–957.

Lu, X., Withers, M., Seifkar, N., Field, R., Barrett, S., Herzog, H., 2015. Biomass logistics analysis for large scale biofuel production: case study of loblolly pine and switchgrass. Bioresour. Technol. 183, 1–9.

Nananukul, N., 2013. Clustering model and algorithm for production inventory and distribution problem. Appl. Math. Model. 37, 9846–9857.

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.

Porter, M.E., 1998. Clusters and the new economics of competition. Harv. Bus. Rev. 76, 77–90.

Purwaningrum F, Evers H, Yaniasih. Knowledge flow in the academia-industry collaboration or supply chain linkage? Case study of the automotive industries in the Jababeka Cluster. Procedia - Social and Behavioral Sciences, 2012; 52: 62–71.

Qu T, Nie D, Chen X, Chen X.D, Dai Q, Huang G. Optimal configuration of cluster supply chains with augmented Lagrange coordination. Comput. Ind. Eng., 2015: 84: 43–55.

Rodríguez, M., Alasino, N., Vecchietti, A., 2016. Forest supply chain Optimization applying generalized disjunctive programming. In: Proceedings of the 26th European Symposium on Computer Aided Process Engineering – ESCAPE 26, pp. 709–714.

Rosenthal, R., 2013. GAMS|A User's Guide. GAMS Development Corporation, Washington, DC, USA.

Rosenthal, S., Strange, W., 2004. Evidence on the nature and sources of agglomeration economies. Handb. Reg. Urban Econ. 4, 2019–2171.

Shabani, N., Akhtari, S., Sowlati, T., 2013. Value chain optimization of forest biomass for bioenergy production: a review. Renew. Sust. Energ. Rev. 23, 299–311.

Shahrukh, H., Oyedun, A., Kumar, A., Ghiasi, B., Kumar, L., Sokhansanj, S., 2016. Techno-economic assessment of pellets produced from steam pretreated biomass feedstock. Biomass Bioenergy 87, 131–143.

Tolossa, N., Beshah, B., Kitaw, D., Mangano, G., De Marco, A., 2013. A review on the integration of supply chain management and industrial cluster. Int. J. Mark. Stud. 5, 164–174.

Trømborg, E., Ranta, T., Schweinle, J., Solberg, B., Skjevrak, G., Tiffany, D., 2013. Economic sustainability for wood pellets production – a comparative study between Finland, Germany, Norway, Sweden and the US. Biomass Bioenergy 57, 68–77.

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

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.

Yan, B., Wang, L., 2008. Supply chain management and clusters ——a case study on Guangdong automobile clusters. In: International Seminar on Business and Information Management, pp. 364–367.

Zhao, W., Watanabe, C., Griffy-Brown, C., 2009. Competitive advantage in an industry cluster: the case of Dalian Software Park in China. Technol. Soc. 31, 139–149.