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ARTICLE

Strategic planning in a forest supply chain: a multigoal and multiproduct approach

Diego Broz, Guillermo Durand, Daniel Rossit, Fernando Tohmé, and Mariano Frutos

Abstract: Supply chain management problems are widespread across all economic activities. We analyze here how to address these in the case of the forest industry, which in emerging economies such as Argentina is subject to high logistic costs and faces problems of biological and economic sustainability. In this work, we analyze a management model covering from the schedule of harvesting activities and the transportation of raw materials to the final transformation at several industrial plants. Since this involves more than one objective, single-criterion mathematical programming methods are not appropriate. Here, instead, we introduce an extended goal programming formulation of the problem, able to yield good solutions in a computationally efficient way. We consider four goals: the maximization of the net present value of the production, the minimization of interannual variations in harvests, the maximization of carbon capture in the form of forest biomass, and the minimization of variations in the mean annual distance covered in transportation to the industrial plants. We apply this theoretical model to derive solutions for an actual Argentinean company. We show that the model reaches the target levels of the different goals, except for carbon balance, which is negative in all of the scenarios under evaluation.

Key words: forest management, goal programming, industrial forest plantations, multiple criteria decision-making, supply chain management.

Résumé : Les problèmes de gestion de la chaîne logistique sont courants dans toutes les activités économiques. Nous étudions ici la façon de les aborder dans le cas de l'industrie forestière qui, dans les économies émergentes comme en Argentine, est sujette à des coûts logistiques élevés et rencontre des problèmes de durabilité biologique et économique. Dans cet article, nous analysons un modèle de gestion qui englobe le calendrier des activités de récolte et le transport de la matière première jusqu'à la transformation finales dans diverses installations industrielles. Étant donné que cela implique plus qu'un objectif, les méthodes de programmation mathématiques monocritère ne conviennent pas. Au lieu de cela, nous introduisons une formulation du problème fondée sur une variante de la programmation des objectifs, capable de produire de bonnes solutions tout en étant efficace sur le plan du traitement informatique. Nous avons retenu quatre objectifs : maximiser la valeur actualisée nette de la production, minimiser la variation interannuelle de la récolte, maximiser le captage du carbone sous forme de biomasse forestière et minimiser la variation de la distance annuelle parcourue pour le transport jusqu'aux installations industrielles. Nous avons appliqué ce modèle théorique pour générer des solutions dans le cas d'une compagnie argentine réelle. Nous montrons que le modèle atteint les différents objectifs cibles à l'exception du bilan de carbone qui est négatif dans tous les scénarios qui ont été évalués. [Traduit par la Rédaction]

Mots-clés : aménagement forestier, programmation des objectifs, plantations forestières industrielles, prise de décision multicritère, gestion de la chaîne logistique.

Introduction

Forests and forest industries have a very important role in the economic and social development of the northeast of Argentina. However, the management of their supply chains faces problems, i.e., the integration of forest harvesting scheduling, log transportation, and factory demands. The reach of this integration can be extended to encompass the larger problem of developing and managing efficient supply chains, which are known to promote the competitiveness of businesses in globalized markets (Boston 2014), but in Argentina, the costs of the export logistics of forest products account for 30% of the Free On Board value, three to five times higher than those of its main competitors in the region, i.e., Chile, Brazil, and Uruguay (AFOA 2015). In addition to these high costs, the persistence of inflation leads to a scenario of low competitiveness that must be addressed using sound management practices underpinned by robust decision support tools.

It is well known that the application of supply chain management techniques has become increasingly important for the forest industry (Carlsson and Rönnqvist 2005; D'Amours et al. 2008; Carlsson et al. 2009; Varas et al. 2014; Rönnqvist et al. 2015). This is especially relevant due to the high costs incurred during the transportation phase, covering up to 45% of the total costs (Weintraub et al. 1996; Broz 2015). To ensure the efficient management of these resources, techniques based on mathematical programming are customarily applied (Rönnqvist et al. 2015).

In this work, we introduce an extending goal programming (EGP) approach, integrating the maximization of certain objec-

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D. Broz. UNaM CONICET, Facultad de Ciencias Forestales – Bertoni 124, Misiones, Argentina.
G. Durand. PLAPIQUI UNS CONICET, Departamento de Ingeniería Química – Camino "La Carrindanga", Km 7. Bahía Blanca, Argentina.
D. Rossit. INMABB UNS CONICET, Departamento de Ingeniería – Av. Alem 1253, Bahía Blanca, Buenos Aires, Argentina.
F. Tohmé. INMABB UNS CONICET, Departamento de Economía – San Andrés 800, Bahía Blanca, Buenos Aires, Argentina.
M. Frutos. IIESS UNS CONICET, Departamento de Ingeniería – Av. Alem 1253. Bahía Blanca, Argentina.
Corresponding author: Diego Broz (email: diego.broz@uns.edu.ar).

tives and the attainment of balances in certain activities in time. The objectives and activities include the schedule of harvesting operations and the transportation of raw materials and their transformation in several industrial plants. The model treats aspects of tactic and strategic planning in a single mathematical structure. Unlike the models in Silva et al. (2010), Giménez et al. (2013), and Diaz-Balteiro et al. (2013), where the main issue is the amount and timing of forest treatments, we seek an optimal harvesting and provision policy. We disregard all aspects of forest management other than the number of turnover periods. This makes our approach similar to Troncoso et al. (2015), where a single framework covers all of the stages of this industry, although their choice of goals is not the same as ours. Models in this line tend to focus only on short, i.e., 5 year long, horizons (Paradis et al. 2013, 2015) and seek the maximization of the net present value of production (Shabani and Sowlati 2013; Shabani et al. 2014; Troncoso et al. 2015). Such approaches tend also to discard goals related to environmental, logistic, and sustainability aspects of the production process.

Our main contribution is the development of a planning approach for a long strategic horizon (18 years), addressing simultaneously various goals of the forest industry (of an economic, environmental, logistic, and silvicultural nature). It is intended as a model of decision making of a vertically integrated firm supplying several products (veneer log, sawlog, and pulpwood) to different production units (pulp mill, MDF factory, sawmill, and plywood mill).

The paper is structured as follows. The following section is a review of the relevant literature. The next section presents the main features of the model and a description of the application case. We describe both the analytical model and its interpretation from the point of view of the preferences of potential decision-makers. The next section presents the results of applying the model to the particular case at hand. The next section discusses the results and the last section summarizes the main conclusions derived from this research.

Literature review

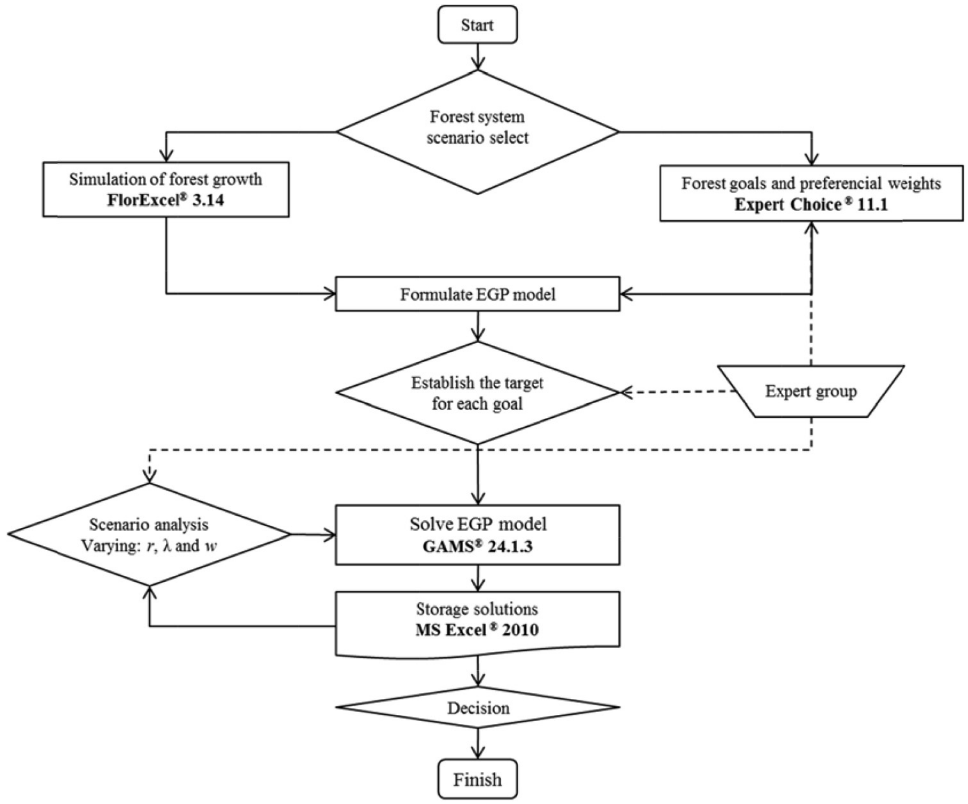
While supply chain models have been widely discussed in several strands of the literature on production processes, we will focus on the main contributions in the specific field of forest management. Gunnarsson et al. (2007), for instance, presented a mathematical model of the entire supply chain including a large number of continuous variables and a set of binary variables to reflect different combinations of products and order selections. The model yields optimal decisions on the transportation of raw materials from harvest areas to pulp mills, the production mix and contents at pulp mills, the distribution of pulp products from mills to customers, and finally the selection of potential orders and their levels. Chauhan et al. (2009) minimized a combination of harvesting and transportation costs in mixed-integer optimization models under demand satisfaction constraints. These authors considered two-echelon timber procurement systems in which the first echelon consists of multiple harvesting blocks and the second of multiple mills. Their results showed good performance of the branch-and-price approach (implanted by the CPLEX solver) for large-scale problems. Shabani and Sowlati (2013) and Shabani et al. (2014) have approached a similar problem in the case in which wood biomass is destined to the production of electricity. These authors developed a mixed integer nonlinear programming model of the optimization of the supply chain where the objective is improving cost competitiveness. The model is solved using the outer approximation algorithm provided by the AIMMS software package. This tool allows, additionally, finding the optimal scenario, assessing different configurations. Paradis et al. (2015) presented a two-level formulation, based on a classical wood supply optimization model, which explicitly anticipates the consumption of industrial fibers. This model is NP-hard, nonlinear, and nonconvex but can be decomposed into convex subproblems yielding a global optimum. The corresponding solution exhibits a low risk of wood supply failure (Paradis et al. 2013, 2015). Troncoso et al. (2015) presented a model of the supply chain of a vertically integrated firm. The goal is to determine which stand to cut and when and where to send each of its products. The analysis is carried out in the framework of two scenarios, one of independent management of the two sectors (forest and industry) and another integrating them. Both scenarios are evaluated using the mixed-integer linear programming model, where the maximization of net present value (NPV) determines the best practice. These authors showed that NPV can increase up to 5.0% when management is integrated.

Contemporary concerns with the protection of the environment together with the growing demand of natural resources are forcing the firms in the sector to change their business models. In particular, forest companies are focused on improving their supply chain management to ensure sustainability (Wu and Pagell 2011). At the same time, worries about the emission of greenhouse gases have led to policies of reduction of environmental impacts (Colombo et al. 2012; Dadhich et al. 2015). According to Martí et al. (2015), the greenhouse gas emissions come from direct and indirect sources at the different stages of the supply chain. This is relevant for our purposes, since it indicates that comprehensive supply chain approaches are essential to ensure the cost-effectiveness of carbon management strategies.

Goal programming (GP)

The use of multiple-criteria decision-making tools has been recommended to deal with the management problems of the forest industry (Buongiorno and Gilles 2003; Bettinger et al. 2009). Several of these methods have been implemented as specialized decision-making software: the analytic hierarchy process, the analytical network process, data envelopment analysis, multiattribute utility theory, evolutionary multiobjective optimization, multiple-objective mathematical programming, etc. One of the approaches most widely applied in the field is GP, based on Herbert Simon's "satisficing" alternative to optimization. This idea, contrary to the usual multiobjective approaches, is not to find optimal levels of the variables but to attain some prespecified target values. Each class of potentially conflicting goals is associated with an aspiration level. A weight is allocated to each goal, indicating its degree of priority. A solution would be an allocation of resources or a plan that "satisfies" the goals, i.e., that it get as closely as possible to their aspiration levels (see, for instance, Silva et al. 2010; Diaz-Balteiro et al. 2013; Giménez et al. 2013;). GP was initially proposed by Charnes et al. (1955) and Charnes and Cooper (1961) and later developed and extended within a "satisficing" logic by Lee (1972), Ignizio (1976), Romero (1991), and Jones and Tamiz (2010) among others. Pioneering applications of GP to forest management can be found, for instance, in Field (1973) and Diaz-Balteiro and Romero (1998). In particular, the EGP approach provides a flexible analytical framework for these applications (Romero 2004). This extension of GP is easy to postulate and facilitates the interaction between the model and actual decision-makers. Either priorities (lexicographical orderings) or preferences (weights) can be defined, striking a balance among the goals (Romero 2004; Broz 2015). While finding only "satisficing" solutions, instead of optimal ones, can be seen as a disadvantage, these make the approach closer to real-world decision-making processes. The steps towards the development of a EGP model involve finding the appropriate goals, defining their target values, and using as variables the *deviation* from the aspiration levels. The computational burden imposed by these extra variables can be, in most cases of interest, handled with relative ease by current software packages. An additional advantage of EGP stems from its origins as a variant of linear programming. Models based on this approach are easy to understand and their results can be interpreted in a natural way (Zeleny 1981; Broz 2015).

Fig. 1. Flowchart of the framework of analysis.



Materials and methods

In this section, the main elements in our framework will be presented. This includes the structure of the decision-making process, the case study, with its assumptions and parameters, and the ensuing EGP model.

The decision-making process

Figure 1 shows the sequence of steps leading to the decisions made according to our model. We apply it to a case study involving a vertically integrated firm in the forestry industry. To do that, we have to consider the fundamentals of our model, like the forest management goals, the preferential weights, and the physical, environmental, and silvicultural constraints faced by the firm. Data obtained from surveying the forest structure together with information about the industrial system provide the inputs for the simulation of the production process. Once the targets for the goals are formulated, the EGP model is solved, providing a plan and additional data for the decision-makers.

Selection of a forest system scenario

The province of Misiones has 85% of the forest plantations as well as 90% of the forest industries in the whole country (MAGyP 2013). It is thus highly relevant to optimize the supply chains in this economic sector. Any gains in efficiency may constitute a substantial contribution to the development of this region and of the entire Argentinean economy.

We focus on the case of vertically integrated forest firms. The relevant data (dasometric, silvicultural, and geographical information) were provided by Arauco S.A., the main firm in the region. In particular, dasometric data were obtained using field inventories and a geographic information system to determine spatial parameters. We consider a compound of 100 stands of *Pinus taeda* L. aged from 1 to 14 years, with densities ranging from 373 to 1325 trees/ha, a survival rate of 95%, and a site index from 20 to 22 m, with a base age index of 15 years. While in the past, some parts of the stands were trimmed, this is no longer done except for forest health considerations. Thus, the only relevant prescriptions are determined by the earliest harvest age and the length of the planning horizon. So, for instance, if the earliest harvest age were 13 years and the planning horizon 18 years, we would face a scenario of 470 prescriptions. The area covered by the harvest blocks ranges between 5.1 and 236.6 ha, being the system's total surface of 8319 ha. On the other hand, the industrial sector consists of a pulp mill, a sawmill, a MDF factory, and a plywood mill (Fig. 2) distributed all along Misiones. These production units consume logs of different lengths and diameters. The model should determine a harvest schedule satisfying in the best possible way all of the different goals in an 18 year period.

Simulation of forest growth

The production parameters were determined from the bucking requirements of the industry (Table 1). The plywood mill requires logs wider than 30 cm and lengths in the range of 1.75–2.25 m, i.e., veneer logs. On the other hand, the sawmill has two production lines for logs of 2.4 m length, one for diameters between 25 and 30 cm, i.e., sawlogs of large diameters, and the other for diameters ranging from 18 to 25 cm, i.e., sawlogs of small diameters. Finally, the pulp mill and the MDF factory consume logs of diameters between 8 and 18 cm with a length of 2.6 m, known as pulpwood. While it is possible to degrade the products, like using veener logs as sawlogs, we will assume here that each quality is only destined to its better use.

To project the volumes of production, we use the equations of the "Simulación Forestal" module of FlorExel® 3.14 (http://www.florexel.com.br) implemented in MS Excel® as a visual basic application. In this case, we applied a fifth-degree polynomial taper function fitted with data from 315 *P. taeda* trees from Paraná, Brazil. By means of these projections, a table is generated, providing the inputs for the model.

Fig. 2. An instance of the forest system constituted by a group of stands, an industrial complex, and roads connecting the components.

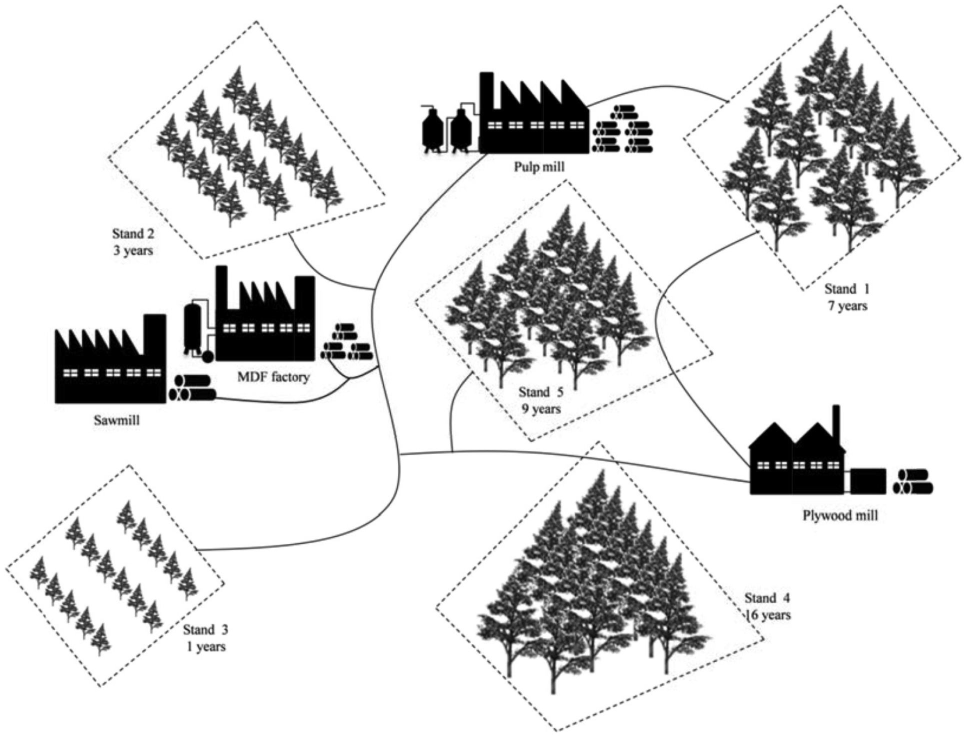


Table 1. Log bucking parameters.

Product	Min LD	Max LD	LongMin	LongMax
Veneer log	30	99	1.75	2.25
Sawlog, large diameter	25	30	2.4	2.4
Sawlog, small diameter	18	25	2.4	2.4
Pulpwood	8	18	2.6	2.6

Note: LD, log diameter (centimetre); LongMin, minimum length of log (metres); LongMax, maximum length of log (metres).

Goals and preferential weights

In our analysis, we also include classical aspects of forest management, related, on the one hand, to the sustainability and profitability of production as well as its carbon balance and on the other to supply chain concerns, e.g., transportation costs and balance, clients' demands, etc. A group of experts, constituting by a forest engineer, an industrial engineer, and an economist, under directives of the firm, established the goals. These experts were selected because of their strong background in management science and their familiarity with the forest sector in Misiones, Argentina. They carried out an analysis of both the firm's main objectives and the constraints imposed by its environment. The first goal proposed by them is the improvement of profitability measured by NPV. This implies that the discounted cash flow must be maximized (Clutter 1992; Bettinger et al. 2009; Kuuluvainen et al. 2012). Another goal is to reach a positive carbon balance to reduce the emission of greenhouse gases by maximizing the difference between the amount of carbon sequestered in the forest biomass and the quantity released by harvesting (Hoen and Solberg 1994; Masera et al. 2003; Diaz-Balteiro et al. 2013; Giménez et al. 2013; Mäkipää et al. 2014). Another goal is the usual balance of production, i.e., the minimization of interannual fluctuation of the volume of harvested wood. Ideally, each annual harvest should collect the same amount of wood (Clutter 1992; Buongiorno and Gilles 2003; Bettinger et al. 2009;). The experts suggested another goal, little considered in the literature but highly relevant for firms, namely the balance of transportation, that is, to minimize the interannual fluctuation of the distances covered by a given fleet of (a fixed number of) trucks of the company (Broz 2015). This allows a reduction in the cost of transportation. Logistic costs affect significantly the competitiveness of the forest sector in Argentina, Brazil, and Uruguay. Its losses are mostly attributed to the incidence of logistic costs in the final price of the products (Arvis et al. 2014; Schwab 2015).

Formulation of the EGP model

As said, we have four goals, set by the group of experts: (*a*) the maximization of the NPV of future flows, (*b*) the maximization of carbon fixation, (*c*) the minimization of interannual variations in production, and (*d*) the minimization of the interannual variations in the mean transportation length.

This problem combines classical aspects of forest management with features of the primary and industrial production, including its economic, logistic, and silvicultural aspects as well as its carbon balance. The latter two aspects have not, as far as we know, been analyzed previously in the literature on supply chain management. This integral approach, covering from the stands to the industrial plants, allows the determination of which stands to harvest, when to harvest, and where to send the subproducts, and, indirectly, in a postoptimization assessment, which roads should be built or reconstructed.

With these results at hand, the firm can make sound decisions relating the supply of timber, its transportation, and the satisfaction of demands. Furthermore, thanks to the multiobjective approach of the model, other aspects of an economic and environmental nature can be also addressed.

In Table 2, we list all of the variables and parameters of the model, which can be seen as a sparse transportation model for a time period (p) in which each stand (i) produces subproducts (k) that have preassigned destinations (j). Figure 3 represents a case for three stands, four subproducts, and four destinations. Notice that all of the subproducts of a stand must be simultaneously delivered at a given period p (we consider only 18 possible periods).

In this example, $i = 1$ generates all four subproducts destined to the four industries. Stand $i = 2$ does not generate subproduct $k = 4$

Table 2. Indexes, variables, and parameters of the model.

	Description
Index	
i	Stands, $i = 1, \ldots, I$
j	Destinations, $j = 1, \ldots, J$
k	Products, $k = 1, \ldots, K$
p	Years, $p = 1, \ldots, P$
q	Goals, $q = 1, \ldots, Q$
Variable	
x_{ip}	Binary variable: 1 if stand i is harvested (and replanted) at period p, 0 otherwise
pr_{ikp}	Amount of product k obtained from stand i at period p (t)
vd_{ijkp}	Amount of product k from stand i destined to industry j at p (t)
D	Maximal admissible deviation from the goals
nq	Negative deviation down from the optimal level when the goal q is to be maximized
pq	Positive deviation up from the optimal level when the goal q is to be minimized
Parameter	
vol_{ikp}	Amount of product k from stand i at period p (t/ha), determined from the simulation
γ	Carbon/biomass conversion rate (t/m³)
δ	Basic density
feb	Biomass expansion factor, from tree to final product
R	Root to tip relation between diameters
F	Fraction of biomass that is left in the forest for decomposition
fd	Dimensional factor (m³/t)
η_j	Yield at destination j
d_{ij}	Distance from stand i to destination j (km)
N_J	Length of the planning horizon
s_i	Surface of stand i (ha)
M_i	Minimum harvest age of stand i (years)
a_{ip}	Age of stand i at period p (years)
r	Discount rate, yielding the present value of future yields adjusted by risk
PV_{ikp}	Market price of product k from stand i at period p ($/t)
CTK	Average transportation cost, assuming 80% on asphalt roads and 20% on dirt roads ($/km)
CCC_{ikp}	Cost of elaborating and loading product k of stand i at p ($/t)
CC	Load capacity of a truck (30 t)
D_{jp}^{min}	Minimal demand of industry j at period p (t/year)
D_{jp}^{miax}	Maximal demand of industry j at p (t/year)
λ	Weight of the sum of deviation variables
PV	Present value ($); PV* is the ideal level, PV* is the anti-ideal
BC	Carbon balance (t); BC* is the ideal, BC* the anti-ideal
VOL	Volume control (t); VOL* is the ideal, VOL* is the anti-ideal
DIS	Equilibrium distance of interannual transport (km); DIS* is the ideal, DIS* is the anti-ideal
W_q	Weight of goal q
g_q	Aspiration level of goal q
A_{jk}	Binary: 1 if product k is sent to the destination j, 0 otherwise

and thus does not have to deliver to destination $j = 4$. Finally, $i = 3$ generates subproducts 1 and 2 that can be destined for industries 1, 2, and 3.

Goals

As said, the model has four goals, which can be formally presented as follows:

NPV

$$\left\{\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{p=1}^{P}\left[\frac{pr_{ikp}\times \mathrm{PV}_{ikp} - pr_{ikp}\times \mathrm{CCC}_{ikp} - \mathrm{CTK}\sum_{j=1}^{J}\frac{vd_{ijkp}}{\mathrm{CC}}\times d_{ij}}{(1+r)^{p}}\right]\right\} + n^{\mathrm{PV}} - p^{\mathrm{PV}} = g_{\mathrm{PV}} \tag{1}$$

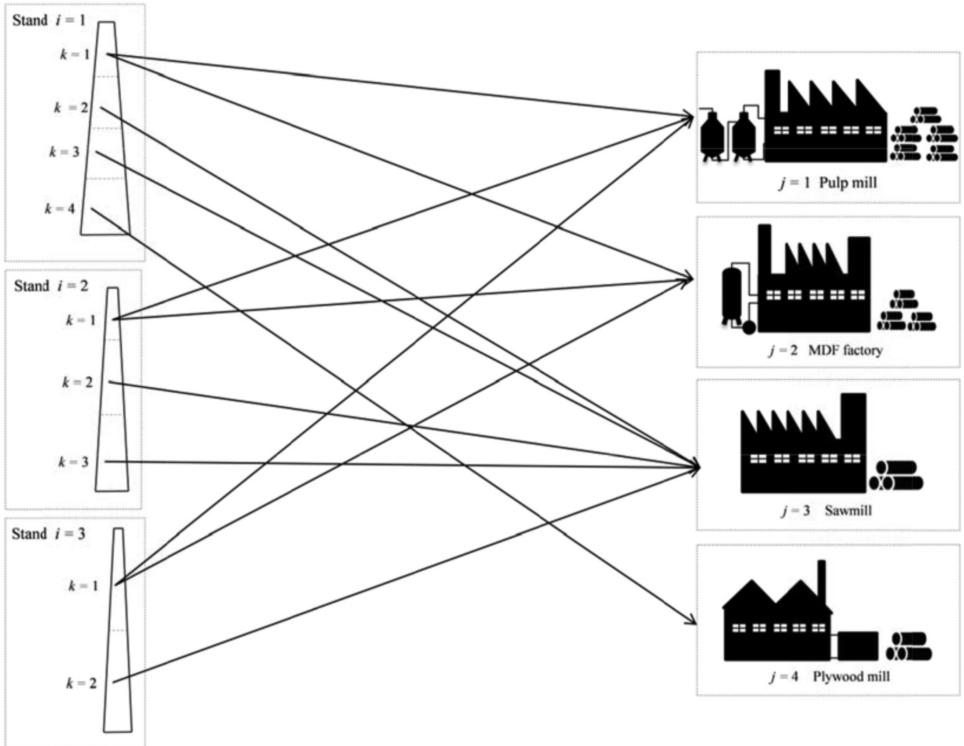
The condition given in eq. 1 indicates that the goal is the maximization of the NPV of production, that is, the (discounted) sale of final products minus harvesting and transportation costs. Notice that, as prescribed originally by Simon (1955), what is actually sought is a close approximation, satisficing a given goal or aspiration level g_{PV} minimizing the deviation n^{PV}. The aspiration level for this goal is fixed by the group of experts.

Carbon balance

$$\sum_{i=1}^{I}\left\{\begin{array}{l}\gamma\delta feb(1+R)\times fd\left[\sum_{k=1}^{K}(s_i\times vol_{ikp} - s_i\times vol_{ik(p-1)})\right] - \\ \gamma\delta feb(1+F)\times fd\sum_{k=1}^{K}pr_{ikp} - \gamma\delta\times fd\left[\sum_{j=1}^{J}\sum_{k=1}^{K}vd_{ijkp}(1-\eta_j)\right]\end{array}\right\} + n_p^{\mathrm{CAR}} - p_p^{\mathrm{CAR}} = g_{\mathrm{BC}} \quad \forall p > 1 \tag{2}$$

The second goal, represented by eq. 2, intends to maximize the capture of carbon in the form of forest biomass, which is obtained from the difference between the forest growth and the losses due to harvesting, evaluated according to the Kyoto protocol. This is a way of providing incentives for the sequestration of carbon as a way of reducing the emission of greenhouse gases (Manley and Maclaren 2012). In this case, therefore, we seek the closest possible value for n^{CAR}. Notice that we do not incorporate as possible causes of loss events like fire, plagues, and other natural sources, which have a minimal impact in the region on which we want to apply the model. The equations and parameters for this goal were determined according to Briggs (1994) and reports in Penman et al. (2003).

Fig. 3. Assignation rule at a given period p.



Harvest volume balance

$$(3)\qquad \sum_{i=1}^{I}\sum_{k=1}^{K} pr_{ikp} - \sum_{i=1}^{I}\sum_{k=1}^{K} pr_{ik(p+1)} + n_p^{\mathrm{VOL}} - p_p^{\mathrm{VOL}} = 0 \qquad p = 1, \ldots, P-1$$

In eq. 3, we intend to minimize the fluctuation in the harvested amounts from period p to period $p + 1$ for all relevant periods. The fluctuations are bounded by the aspiration level, and thus, we seek to make both n_p^{VOL} and p_p^{VOL} close to zero. The amount of production can reach a steady amount by planting immediately after harvesting, as to compensate for the extraction. Here, we follow closely Clutter (1992), Diaz-Balteiro and Romero (2003), and Giménez et al. (2013).

Transport balance

$$(4)\qquad \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} d_{ij} \times \frac{vd_{ijkp}}{CC} - \frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P} d_{ij} \times \frac{vd_{ijkp}}{CC}}{N_J} + n_p^{\mathrm{DIS}} - p_p^{\mathrm{DIS}} = 0 \quad \forall p$$

The goal in eq. 4 is the minimization of the interannual variation in the distances covered by transportation and thus to balance the annual transportation budget. We thus seek that the distance covered in any period be close to the average transportation length. Here again, n_p^{DIS} and p_p^{DIS} must be brought close to zero.

Minimax goals

Combining the goals, we obtain the MINMAX (Chebyshev function) of the goal programming model:

$$(5)\qquad \begin{aligned} &W_1\left(\frac{n^{\mathrm{PV}}}{\mathrm{PV}^* - \mathrm{PV}_*}\right) \le D \\ &W_2\left(\frac{n^{\mathrm{CAR}}}{\mathrm{BC}^* - \mathrm{BC}_*}\right) \le D \\ &W_3\left(\sum_{p=1}^{P-1} \frac{n_p^{\mathrm{VOL}} + p_p^{\mathrm{VOL}}}{\mathrm{VOL}_* - \mathrm{VOL}^*}\right) \le D \\ &W_4\left(\sum_{p=1}^{P} \frac{n_p^{\mathrm{DIS}} + p_p^{\mathrm{DIS}}}{\mathrm{DIS}_* - \mathrm{DIS}^*}\right) \le D \end{aligned}$$

Then, the largest deviation D between the achievement of each goal and its target value is minimized, i.e., we seek to equilibrate the different goals. Here, each W_q weights a goal $q = 1, \ldots, 4$. In our application, we determine them in a pairwise comparison process (Romero 1991; Jones and Tamiz 2010). The information to run this analysis was obtained again from the group of experts, who built a comparisons matrix, evaluating by pairs the criteria, giving relative importance to them. Then, the matrix was normalized, yielding the weights and assessing the consistency: the deviation variables n and p are scaled to the difference between ideal and antideal values and thus becoming pure numbers.

Achievement function

Then, the achievement function subject to constraints and goals can be written as

$$(6)\qquad Min(1-\lambda)D + \lambda \times \left[\left[W_1\left(\frac{n^{\mathrm{PV}}}{\mathrm{PV}^* - \mathrm{PV}_*}\right)\right] + \left[W_2\left(\frac{n^{\mathrm{CAR}}}{\mathrm{BC}^* - \mathrm{BC}_*}\right)\right] + \left[W_3\left(\sum_{p=1}^{P-1} \frac{n_p^{\mathrm{VOL}} + p_p^{\mathrm{VOL}}}{\mathrm{VOL}_* - \mathrm{VOL}^*}\right)\right] + \left[W_4\left(\sum_{p=1}^{P} \frac{n_p^{\mathrm{DIS}} + p_p^{\mathrm{DIS}}}{\mathrm{DIS}_* - \mathrm{DIS}^*}\right)\right] \right]$$

Table 3. Subproduct destination rule.

Destination		Product: Pulp logs, k_1	Fine-sawn logs, k_2	Thick-sawn logs, k_3	Veneer logs, k_4
Pulp mill	j_1	(×)			
MDF factory	j_2	(×)			
Sawmill	j_3		(×)	(×)	
Plywood mill	j_4				(×)

Note: (×) indicates that subproduct k is destined to j.

Expression 6 is intended to minimize the deviation of all four goals where λ is a control parameter that can take values within the closed interval [0,1]. In this case, λ weights the importance of the sum of the measures of the deviations described by eq. 5. Then, if λ = 1, we have a way to satisfy goals 1–4 but in an unbalanced fashion. On the other hand, if λ = 0, we get balanced solutions but perhaps not very close to the aspiration levels. For $\lambda \in (0,1)$, we have a compromise between satisficing and balancing the goals. This approach reflects better the preferences of the expert group than any isolated goal.

Constraints

The constraints of the problem are formulated as follows:

$$(7)\qquad pr_{ikp} = s_i \times vol_{ikp} \times x_{ip} \quad \forall i; \forall k; \forall p$$

$$(8)\qquad \sum_{j=1}^{J} vd_{ijkp} \times A_{kj} = pr_{ikp} \quad \forall k; \forall i; \forall p$$

In eq. 7, $x_{ip} \in \{0,1\}$ gets value 1 only at the period p at which stand i must be harvested. This expression also yields the partial volume of the harvest destined to become subproduct k. Equation 8 ensures that each subproduct k is sent to a destination j and constraints the delivery of subproducts to the industries as determined by Table 3.

$$(9)\qquad \sum_{p=1}^{P} x_{ip} = 1 \quad \forall i$$

$$(10)\qquad x_{ip} + x_{yp} \le 1 \quad \forall p; y \in \psi_i$$

$$(11)\qquad M_i x_{ip} \le a_{ip} \quad \forall i; \forall p$$

$$(12)\qquad \sum_{i=1}^{I}\sum_{k=1}^{K} vd_{ijkp} \ge D_{jp}^{\min} \quad \forall p, \forall j \qquad \sum_{i=1}^{I}\sum_{k=1}^{K} vd_{ijkp} \le D_{jp}^{\max} \quad \forall p, \forall j$$

$$(13)\qquad x_{ip} \in \{0,1\}, \mathrm{Pr}_{ikp} \in \mathbb{R}, vd_{ijkp} \in \mathbb{R}$$

Equation 9 ensures that the stands will be harvested once in the planning horizon. Expression 10 indicates that no adjacent stands must be harvested at the same period p. This reflects the so-called unit restriction model, which, given the set ψ_i of stands adjacent to i, no $l \in \psi_i$ can be harvested in the same period as i. Constraint 11 establishes a minimal age for a tree to be harvested, according to either technological or economic criterion established by the expert group. This indicates that stand i will be harvested when it has an age a_{ip} in the time interval $[M_i, \ldots, P]$. In the case of Misiones, the experts indicate that no tree younger than 13 years old should be harvested because it reaches its full potential within a few more years. Expression 12 establishes conditions on the demands from the industry, determined again by the experts. Finally, expression 13 indicates the types of the variables.

Table 4. Eighteen scenarios analyzed.

EGP approach (λ) and goal weight (w)	Discount rate (r) (%)	Scenario
$\lambda = 0$ and $w_1 = w_2 = w_3 = w_4 = 1$	15	scen1
$\lambda = 0$ and $w_1 = 0.166$, $w_2 = 0.151$, $w_3 = 0.621$, $w_4 = 0.062$	15	scen2
$\lambda = 0.5$ and $w_1 = w_2 = w_3 = w_4 = 1$	15	scen3
$\lambda = 0.5$ and $w_1 = 0.166$, $w_2 = 0.151$, $w_3 = 0.621$, $w_4 = 0.062$	15	scen4
$\lambda = 1$ and $w_1 = w_2 = w_3 = w_4 = 1$	15	scen5
$\lambda = 1$ and $w_1 = 0.166$, $w_2 = 0.151$, $w_3 = 0.621$, $w_4 = 0.062$	15	scen6
$\lambda = 0$ and $w_1 = w_2 = w_3 = w_4 = 1$	25	scen7
$\lambda = 0$ and $w_1 = 0.166$, $w_2 = 0.151$, $w_3 = 0.621$, $w_4 = 0.062$	25	scen8
$\lambda = 0.5$ and $w_1 = w_2 = w_3 = w_4 = 1$	25	scen9
$\lambda = 0.5$ and $w_1 = 0.166$, $w_2 = 0.151$, $w_3 = 0.621$, $w_4 = 0.062$	25	scen10
$\lambda = 1$ and $w_1 = w_2 = w_3 = w_4 = 1$	25	scen11
$\lambda = 1$ and $w_1 = 0.166$, $w_2 = 0.151$, $w_3 = 0.621$, $w_4 = 0.062$	25	scen12
$\lambda = 0$ and $w_1 = w_2 = w_3 = w_4 = 1$	35	scen13
$\lambda = 0$ and $w_1 = 0.166$, $w_2 = 0.151$, $w_3 = 0.621$, $w_4 = 0.062$	35	scen14
$\lambda = 0.5$ and $w_1 = w_2 = w_3 = w_4 = 1$	35	scen15
$\lambda = 0.5$ and $w_1 = 0.166$, $w_2 = 0.151$, $w_3 = 0.621$, $w_4 = 0.062$	35	scen16
$\lambda = 1$ and $w_1 = w_2 = w_3 = w_4 = 1$	35	scen17
$\lambda = 1$ and $w_1 = 0.166$, $w_2 = 0.151$, $w_3 = 0.621$, $w_4 = 0.062$	35	scen18

Analysis of scenarios

Table 4 summarizes the scenarios drawn from the Misiones data under different combinations of three parameters: the discount rate (r), the weighted preference model (λ), and the preferences for goals (W_q).

For each scenario, we analyze the behavior under the balanced goals setting (λ = 0), the aggregate goals (λ = 1), and a mixed setting (λ = 0.5). We also study the outcomes under heterogeneous weights given by the experts ($W_1 \neq \ldots \neq W_q \neq 1$) as well as the case in which they are given homogeneous weights ($W_1 = \ldots = W_q = 1$). Finally, we studied the typical behavior of the discount rate (r) for the forest sector in Argentina, according to previous results in Broz (2015) and the data drawn from the national statistics reported in INDEC (2015).

Solving the EGP problem

The overall model is implemented in GAMS® 24.1.4 with the optimization package CPLEX 12.1. The model was run on a PC with an Intel Core i3-2310M, CPU@ 2.10 GHz processor, 4 GB of RAM memory, and a 64 bit operating system. The input (volume, age, prices, etc.) and output data are summarized in two MS Excel spreadsheets connected through the exchange of GDX (GAMS Data Exchange) files. We obtain different outputs by varying the parameters of the model, yielding alternative harvest programs. The final decision on which plan to implement is made on the basis of the analysis of those alternative scenarios.

Results

This section presents the scenarios under analysis as well as the ensuing results from the trade-off matrix and the outcomes of the EGP model.

Table 5. Trade-off matrix for four goals with a discount rate of 25%.

	Max. PV (US$)	CO_2 balance (t)	Volume control (t)	Transport balance (km)
Max. PV	**6 968 698**	*–318 866*	*273 659*	*1 863 610*
CO_2 balance	*5 844 569*	**–131 047**	54 584	905 912
Volume control	6 557 085	–302 008	**11 053**	859 338
Transport balance	6 508 283	–310 380	52 581	**29 211**

Note: Bold, ideal values; italic, anti-ideal values.

Trade-offs between ideal and anti-ideal values

The trade-off matrix (Table 5) presents ideal and anti-ideal values for each of the goals analyzed in this paper. The ideal values are obtained solving the problem just for the corresponding goal. The anti-ideal values arise from the solution of the entire problem just for all of the other goals. In bold typeface, we represent the ideal values and in italics the anti-ideal ones. The volume control and the transport balance are captured by the sum of deviations, which ideally should be null.

An important conclusion can be drawn from these trade-off matrices: there are conflicts between all criteria involved in each model, i.e., the ideal values of different goals cannot be simultaneously achieved. Therefore, we can conclude that an acceptable harvest schedule depends critically on the weights given by the experts.

The EGP approach

Given the importance of trade-offs, we implemented a pairwise comparison method to find the weights of the different goals in both scenarios. For this, we used Expert Choice® version 11.1. Table 6 presents the results for 18 scenarios analyzed. The running times ranged between 12.2 and 151.5 s.

Example of a scenario

Just to clarify how the results of these exercises must be read, let us consider a particular instance. Here, the discount rate (r) is 15%, $\lambda = 0$, and $w = 1$ (scen1). Here, the NPV is US$ 16 331 298 and the CO_2 balance fell –278 160 t for the entire period. On average, 204 946 t of wood and 627 227 km are, respectively, harvested and covered per year. Figure 4 presents the yearly levels of provision for all of the scenarios. In some cases, kinks in the trajectories can be detected, which cannot be avoided to not generate infeasible solutions.

The effect of the discount rate

We can see that the discount rate has a significant effect on the PV. As expected, PV has an inverse relation with r: an increase of 15%–25% and 35% in the discount rate yields a decrease of PV between 60% and 80%, falling from 16 million for $r = 15\%$ to just slightly more than 3 million for $r = 35\%$. Besides, we found that a lower r improves the other goals, the balance of carbon, production, and transportation. This is because the ensuing increase in PV closes the gap with g_{PV}, allowing a better distribution among the other goals.

Behavior under the different settings

The average performance of the aggregate ($\lambda = 1$), mixed ($\lambda = 0.5$), and balanced ($\lambda = 0$) settings shows that the mixed one yields a PV (US$ 8 709 923) that is up to 3.6% larger than in the balanced one and a 1.3% larger than in the aggregate case. Even if in all the scenarios the carbon balance is negative, in the aggregate setting, it is improved over the other two cases: an average of –250 961 t, 5.6% and a 10.3% better than the mixed and the balanced setting, respectively. The balanced setting, in turn, led to a slightly larger mean annual production (204 898 t/year), up to 1.3% over the two others but with a larger deviation. The aggregate setting led to a more homogeneous production, with a standard deviation and variation coefficient up to 19.5% and 18.1% less than the other settings, respectively. It also yields a lower transportation length (615 821 km/year), 2.6% less than the balanced setting and 0.3% less than the mixed one. The standard deviation and the variation coefficient are, in the aggregate setting, lower at 68.6% and 64.2%, respectively, than in the balanced one, while the corresponding differences are not larger than 1.8% with the mixed setting.

The effect of the weights

Analyzing the weights of the different goals (w), we can see that there are no significant differences among the results in the cases of inhomogeneous ($w \neq 1$) and homogeneous ($w = 1$) weights with respect to PV, carbon sequestering, mean production, transportation length, and total production. Nevertheless, inhomogeneous weights increase up to 16.2% in the balance of production and 30.0% in the balance of transportation.

The joint effect of settings and preferences

The homogeneous mixed setting ($\lambda = 0.5$ and $w = 1$) yields a PV (US$ 8 736 615), up to 3.9% larger than the other cases, the balanced ones being the worst no matter the weights. In all scenarios, the aggregate approach with homogeneous preferences ($\lambda = 1$ and $w = 1$) leads to the best carbon balance (–249 515 t), on average 11.4% superior to the other combinations. For forest production, the balanced setting with homogeneous preferences ($\lambda = 0$ and $w = 1$) was slightly better by 1.5%, with a mean production of 204 893 t/year. Nevertheless, the aggregate setting with homogeneous preferences ($\lambda = 1$ and $w = 1$) balanced production better, since its standard deviation and the variation coefficient are 10.0% and 36.9%, respectively, lower than in the other cases. The case of $\lambda = 1$ and $w \neq 1$ yields the lowest mean transportation distance (612 228 km/year), while in the case of $\lambda = 0.5$ and $w = 1$, we have a large reduction of variation, 59.6% less than in the other cases. For this goal, as said, the worst cases were those of $\lambda = 0$ followed by the mixed setting with inhomogeneous weights ($\lambda = 0.5$ and $w \neq 1$). Production in the $\lambda = 0$ and $w \neq 1$ case was 1.5% larger than in the other cases, with a mean amount of 3 688 247 t.

Tables 7 and 8 summarize the behavior of forest production and transportation length, respectively, along the planning horizon, depending on the settings and the weights given by the experts. The lowest variation is obtained with the aggregate setting (43.4%) followed by the balanced and the mixed one, the latter departing up to 11.1% from the mean production. Inhomogeneous weights lead to an accumulated variation of 65.5%, while with homogeneities rises to 71.9%, up to 9.8% over the mean. The aggregate setting with homogeneous preferences leads to the lowest accumulated deviation (42.4%). It is followed by the mixed setting, also with homogeneous weights, which yields a deviation of 72.5%. In these latter cases, the extreme cases do not depart more than 6.3% from the mean value. The balanced setting, instead, leads to an accumulated deviation of 69.8%, with extreme variations of up to 12.2%.

Table 8 shows that the accumulated variations in transportation length are 69.4%, 76.1%, and 135.5% in the aggregate, mixed, and balanced setting, respectively. The latter case even yields a period with a 20% variation with respect to the mean length. Homogeneous preferences led to a lower variation of 77.8% as well as lower extreme annual variations. The combination of mixed setting and homogeneous weights yields the lowest accumulated variation (59.6%) followed by the aggregate setting, also with homogeneous preferences (66.7%). The extreme variations in these cases are lower than 11.4%. The worst performance is that of the balanced setting with both inhomogeneous and homogeneous preferences, yielding accumulated variations of 163.7% and 140.2%, respectively. The corresponding extreme cases were 17.3% and 22.9% with respect to the mean length.

With a scale of (increasing) shades of gray, we show in both tables cases of variations of 5%, 10%, and 20% with respect to the mean. We can see that forest production (Table 7) is significantly stable, since 77% of the annual variations are below 5%, while 21%

Table 6. EGP results for the 18 supply chain scenarios analyzed.

			Balance of forest production			Balance of forest transportation				
Scenario	PV	Carbon	A-F	SD-F	CV-F	A-T	SD-T	CV-T	TFH	CPU
scen1	16 331 299	–278 160	204 946	17 172	8.38%	627 227	88 373	14.09%	3 689 031	36.0
scen2	16 070 897	–276 062	204 526	13 032	6.37%	628 247	90 122	14.34%	3 681 460	17.5
scen3	16 257 451	–246 260	200 989	10 743	5.35%	619 883	32 538	5.25%	3 617 804	151.5
scen4	16 265 801	–257 549	202 569	12 482	6.16%	615 998	55 078	8.94%	3 646 247	18.7
scen5	15 858 316	–236 515	199 581	9877	4.95%	616 329	39 488	6.41%	3 592 455	38.2
scen6	16 011 428	–243 361	200 875	12 036	5.99%	606 070	56 054	9.25%	3 615 744	12.2
scen7	5 911 752	–264 334	202 997	14 498	7.14%	627 621	79 255	12.63%	3 653 942	26.4
scen8	6 089 906	–263 666	204 093	15 645	7.67%	629 828	81 829	12.99%	3 673 669	25.9
scen9	6 624 871	–268 819	204 097	13 681	6.70%	624 790	36 487	5.84%	3 673 744	26.2
scen10	6 534 475	–280 492	206 137	24 212	11.75%	609 977	90 571	14.85%	3 710 475	22.4
scen11	6 602 265	–256 026	202 488	12 549	6.20%	618 503	41 469	6.70%	3 644 793	37.8
scen12	6 556 248	–256 067	203 598	14 115	6.93%	616 575	52 139	8.46%	3 664 767	30.5
scen13	2 946 326	–291 551	206 735	15 178	7.34%	641 138	87 761	13.69%	3 721 234	36.7
scen14	3 030 932	–286 399	206 090	19 631	9.53%	636 387	94 510	14.85%	3 709 613	27.5
scen15	3 327 523	–271 738	204 678	14 940	7.30%	619 072	52 579	8.49%	3 684 211	21.2
scen16	3 249 418	–264 847	203 782	11 871	5.83%	614 892	47 928	7.79%	3 668 067	37.2
scen17	3 305 571	–256 005	203 445	12 869	6.33%	623 406	43 141	6.92%	3 662 012	30.5
scen18	3 227 959	–257 792	203 888	18 154	8.90%	614 040	77 179	12.57%	3 669 982	18.2

Note: PV, present value (US$); Carbon, CO_2 balance (t); A-F, average annual forest production (t/year); SD-F, standard deviation of forest production (t); CV-F, coefficient of variation of forest production (%); A-T, average transport distance (km/year); SD-T, standard deviation of transport distance (km/year); CV-T, coefficient of variation of transportation (%); TFH, total forest harvesting production (t); CPU, process time (seconds).

Fig. 4. Evolution of supply levels by industry (scen1).

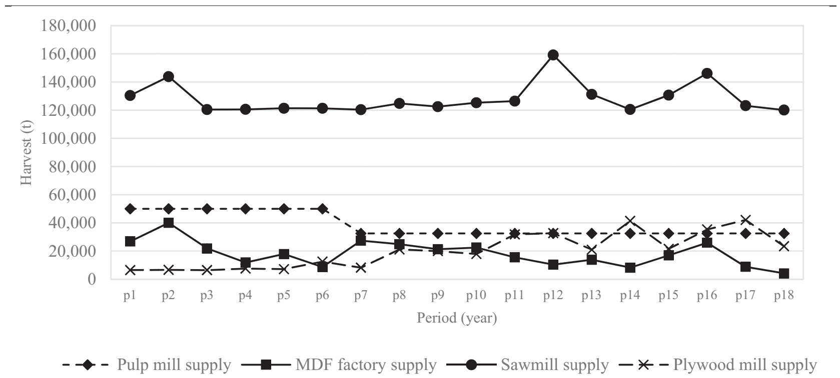


Table 7. Behavior (%) of production levels with respect to the mean.

	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}	p_{13}	p_{14}	p_{15}	p_{16}	p_{17}	p_{18}	Σ Cum.
$\lambda = 0$	4.3	7.4	–1.1	1.0	–4.1	–1.1	–9.1	0.9	4.6	1.1	–0.1	7.3	–2.0	–1.6	–4.6	4.7	2.4	–10.3	67.8
$\lambda = 0.5$	7.7	1.0	3.1	–5.3	–5.5	–0.7	–1.5	–3.3	3.7	11.1	2.4	–1.5	5.6	–1.5	–4.3	0.1	–2.4	–8.9	69.7
$\lambda = 1$	5.2	1.9	2.1	2.9	–4.9	0.5	–4.0	0.0	0.0	4.9	0.9	–1.7	–0.7	2.3	1.0	–3.1	–0.4	–6.9	43.4
$w = 1$	4.7	1.8	1.5	–3.2	–4.0	1.9	–3.4	1.4	4.8	–3.1	1.9	–3.7	0.1	9.8	–5.5	8.1	–5.2	–7.9	71.9
$w = 1$	9.3	1.0	–0.3	0.8	6.4	1.0	–1.3	8.1	0.9	0.0	–2.7	0.7	4.5	–4.1	–6.3	–5.1	–6.7	–6.2	65.5
$\lambda = 0$ and $w = 1$	12.2	4.7	0.0	–0.9	–5.5	2.4	–3.9	–0.2	0.5	4.7	1.3	–0.1	3.6	5.3	–8.2	–1.4	–5.6	–9.1	69.8
$\lambda = 0$ and $w = 1$	6.0	4.2	1.0	–2.2	–4.8	–0.9	–5.3	–1.2	4.2	6.1	1.2	2.9	1.8	–1.5	–4.4	2.4	0.0	–9.6	59.8
$\lambda = 0.5$ and $w = 1$	5.0	1.9	1.8	–0.1	–4.4	1.2	–3.7	0.7	2.4	0.9	1.4	–2.7	–0.3	6.1	–2.3	2.5	–2.8	–7.4	47.5
$\lambda = 0.5$ and $w = 1$	10.8	2.9	–0.1	0.0	0.5	1.7	–2.6	3.9	0.7	2.3	–0.7	0.3	4.1	0.6	–7.3	–3.3	–6.2	–7.6	55.7
$\lambda = 1$ and $w = 1$	6.3	3.5	0.2	1.6	–0.9	0.1	–4.8	3.0	1.8	2.0	–0.6	2.1	0.6	–1.1	–3.3	–1.1	–1.5	–7.8	42.4
$\lambda = 1$ and $w = 1$	8.2	2.5	1.5	–3.1	–5.0	1.2	–2.9	–0.7	3.0	4.3	1.9	–1.8	3.1	4.5	–6.0	2.3	–4.4	–8.6	65.1

of those values are in the range 5%–10% and only 2% has a variation over 10%. The mean length of transportation (Table 8) instead shows more dispersion, with 61% of the cases under 5%, 25% between 5% and 10%, 13% between 10% and 20%, and 2% larger than 20%. The more extreme cases are more frequent at the start and the end of the planning horizon. Both tables also show that the largest variations are obtained in the balanced setting.

Discussion

The resulting program covers at least one forest rotation, discarding the potential of settling on suboptimal solutions. We ran the model on information provided by the largest forest-industrial compound in northeastern Argentina.

Among the main findings of this paper, we must mention the negative impact of emphasizing the maximization of the present

Table 8. Behavior (%) of the average transport distance with respect to the mean.

	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}	p_{13}	p_{14}	p_{15}	p_{16}	p_{17}	p_{18}	Σ Cum.
$\lambda = 0$	14.4	17.1	15.0	2.9	−1.3	4.6	−1.0	−1.4	4.1	9.2	0.4	−0.2	−0.9	−9.4	−14.0	−9.4	−10.0	−20.1	135.5
$\lambda = 0{,}5$	8.4	6.6	7.1	0.8	0.4	3.3	−1.5	−6.2	3.6	−1.6	0.6	−7.4	−2.3	4.8	−5.6	2.4	−9.1	−4.4	76.1
$\lambda = 1$	13.6	8.6	5.5	0.8	0.3	1.3	−1.7	−1.3	0.6	4.0	−1.3	−1.5	−2.0	−0.4	−3.2	−7.3	−4.6	−11.5	69.4
$w = 1$	10.5	10.4	8.0	2.0	1.0	1.4	−0.9	−0.5	3.2	2.3	−0.2	−0.9	−3.4	−4.0	−6.6	−6.4	−4.9	−11.1	77.8
$w = 1$	13.8	11.3	10.4	1.0	−1.4	4.7	−1.8	−5.4	2.3	5.6	0.0	−5.2	−0.1	0.6	−8.8	−3.3	−10.9	−12.9	99.6
$\lambda = 0$ and $w = 1$	12.4	22.0	13.2	3.8	0.6	2.6	−3.5	3.2	6.0	0.4	0.8	5.1	−7.9	−7.4	−12.3	−9.5	−6.7	−22.9	140.2
$\lambda = 0$ and $w = 1$	16.4	12.3	16.7	2.0	−3.1	6.6	1.4	−6.0	2.1	18.1	0.1	−5.6	6.1	−11.3	−15.7	−9.4	−13.3	−17.3	163.7
$\lambda = 0.5$ and $w = 1$	7.8	4.2	6.3	2.6	−1.4	1.3	−0.9	−3.4	1.1	2.8	−1.7	−7.0	0.7	1.2	−5.0	1.8	−8.3	−2.0	59.6
$\lambda = 0.5$ and $w = 1$	9.1	9.0	8.0	−1.1	2.1	5.4	−2.0	−8.9	6.1	−6.0	3.0	−7.8	−5.3	8.5	−6.3	2.9	−10.0	−6.7	108.3
$\lambda = 1$ and $w = 1$	11.3	4.8	4.5	−0.5	3.7	0.5	1.6	−1.2	2.5	3.8	0.4	−0.8	−2.9	−5.8	−2.4	−11.4	0.2	−8.3	66.7
$\lambda = 1$ and $w = 1$	15.9	12.5	6.4	2.1	−3.1	2.2	−5.0	−1.3	−1.3	4.1	−3.0	−2.2	−1.1	5.0	−4.1	−3.0	−9.4	−14.7	96.5

value over the achievement of the other goals. In particular, in agreement with the results in Silva et al. (2010) and Diaz-Balteiro et al. (2014), carbon balance can be achieved only at the price of a lower present value. This shows that single-objective optimization may lead to poor satisfaction of other potential goals yielding a rigid and unsatisfactory model (Buongiorno and Gilles 2003).

We also found that the discount rate has a strong impact on the present value of the system, while the balance of carbon is negative in all scenarios, with a deficit over 14 000 t/year. Furthermore, the rather uncommon characteristics of the Argentinean economy make the discount rate the most sensitive parameter of the model, determining the main features of the supply chain. Future work involves, instead, using a stochastic model in which the effects of an erroneous assessment of the discount rate in a volatile economy are less detrimental for the firms in the sector.

On the other hand, comparing different scenarios, we see that aggregate settings have the best performances, while mixed settings have the worst behavior, that is, the focus on just the specific goals, instead of adding their balance as an extra objective, yields better results. In turn, homogeneous preferences had a slightly better performance but inhomogeneous ones contributed more to reducing fluctuations in forest production and the length of interannual transportation. The combination of a mixed setting with homogeneous preferences gave the best performances, that is, it seems that the setting is much more relevant than the information on the weights of the goals provided by the experts. Furthermore, this latter information seems to add rather little to the optimum, since equally weighted goals seem to yield better results than diversified weights, except for balancing each of the goals.

Conclusions

We can conclude that the EGP approach yields valuable solutions to the planning problem of an integrated firm in the forest industry when several (somewhat conflicting) goals are postulated. This method achieves an equilibrium between the different objectives, which becomes advantageous for a firm that has to balance so many and different components of its production activities.

We found that NPV runs contrary to the other goals. Its maximization worsens the others. This indicates that our multiobjective approach is better than single-objective ones, since it allows avoiding unintended consequences in other aspects of the activity of the firm.

The consideration of several products and processing units allows the incorporation of logistic goals, in particular the need to balance transportation and thus the resources devoted to the fleet of trucks of the company.

On the other hand, the economic and logistic goals impose environmentally negative solutions. In each scenario, carbon balance is negative, indicating the release of an amount of greenhouse gases that is not compensated for by sequestration.

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