Alternatives for optimal integration of forest supply chain operations

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Abstract. The market dynamics and requirements prompt the competition among individual companies included in a supply chain (SC). It is well-known that all the SC members search to improve its efficiency and increase its competitiveness, and in most cases, the results do not correspond to an equitable distribution among all the members of the achieved benefits. However, SC approaches generally address as a performance measure the profits of the entire system. In this way, a counterpoint arises between the optimality of the overall results and the benefit perceived by each of the participants. In this work, a mixed integer programming model is presented to assess the impact of a solution on the performance of the different SC members. Specifically, the proposed approach evaluates the tactical operations in a forest SC comprising bucking planning at the forest sites and production planning of lumber, electric power and two kinds of boards, each one at its production plant. Besides, through the examples, integration versus individual concerns is appraised for an industry that has increasing conflicts of interest.

1 Introduction

Forest supply chain (SC) includes various activities such as obtaining logs and residues from the bucking operation in the forest areas, transportation of materials among the involved members and obtaining product and energy in the production plants. In recent years, the forest industry has gained increasing interest, not only because of the variety of products that can be obtained from wood, but also because of the use of forest biomass for the biofuel industry. Its use as energy reduces the consumption of fossil fuels, replacing gas and oil in a sustainable way (it is considered carbon neutral [1]). On the other hand, a variety of products can be produced from harvest residues and by-products from factories (bark, sawdust, chips, etc.). Therefore, facilities in the SC are also competing for these materials. In this way, logs, harvest residues and by-products from lumber processing are feedstocks demanded by different facilities in the forest SC, and their successful utilization depends on the appropriate SC integration.

There are a lot of published works about forest SC. An extensive review was recently presented by Santos [2], who analysed 188 papers and classified them according to different characteristics like applied research methodology and sustainable dimension addressed (economic, environmental and social). From that review, it can be concluded that economic objective is the metric most considered in assessment studies, while the environmental and environmental together with economic are in the second place, being social metrics the least treated. According to the review of Barbosa-Póvoa [3], the most used approach to address SC decision making on SC considering the three dimensions of sustainability is optimization through mathematical programming.

Beyond the selection of single or multiple objectives to measure the SC performance, the real assessment for the SC development depends on each of its members and the relationships among them to empower total performance of the SC. In most of real-world supply chains, the members are not under the control of one single decision maker, and the benefits locally reached for some members could be against the global profit. Conversely, any decision made to optimize the performance of the SC does not impact all its members in the same way and may even cause losses to some of them. Moreover, in SC like in the forest industry, where different members compete for the same raw materials and resources and have their own objectives, it is difficult to state a SC measure performance that reconciles particular concerns with the global SC interest. In a previous work, Vanzetti [4] evaluated geographical cluster formation among wood-based plants with the objective of take advance of the sharing resources.

When forest SC value is evaluated, generally the chain is decoupled into two parts: the forest activities where the maximum expected value of the timber is pursued, and the industry activities where the objective is to obtain the maximum profit for the produced final products according to the log availability [5]. It is clear that the appropriate coordination of harvesting and production activities can reach higher benefits and a suitable use of raw materials, increasing the profitability of the overall SC. But there are no published works, to our knowledge, about how each member in the SC is benefited or not from this integration.

In order to tackle this drawback, in this work, a MILP model, comprising integrated decisions of bucking, distribution of materials, and production in a forest SC, is proposed. The SC involves different harvest areas and production plants consuming logs, harvesting residues and by-products from plants, for different products and energy demands. Usually, the overall SC profit is considered to measure the performance of the global production system. This evaluation hides the impact that this solution has on the operations of each of the participants in the SC. Therefore, this work tries to assess the difference between the optimal operation of the global system and the best performance of each of the members. On this basis, an alternative solution is proposed that equally distributes the effort among all participants, evaluating the deviation from the optimal operations of the global system and individual members, using goal programming (GP) concepts. This is a suitable approach to achieve a balanced solution considering the objectives of all members of the CS. Thus, the effort and benefits that each participant obtains from the SC operation can be assessed, becoming an appropriate tool for the proper management of SC. GP is based on the "satisfactory" logic of Herbert Simon [6] and has been implemented in logistics, environmental studies, economic evaluation, among others [7]. In the forest industry, this approach has been used for problems in forest management [8], forest logistics [9], biomass supply chain [10] and sawmill production [11].

The forest SC is presented as a very interesting example for this study considering the high level of integration of the involved operations and the tight commitment among all participants. Thus, through the example, integration versus individual concerns is appraised for an industry that has increasing conflicts of interest.

2 Problem description

In this work, a SC composed of the forest and productive sectors is considered. The first consists of a set of harvest areas located in different regions, and the second, by different production plants located in the same industrial zone. Each harvest area has a certain number of stems that can be divided to obtain logs of a certain diameter and length. Specifically, the bucking operation consists of cutting the stems to obtain logs. For this activity, a set of bucking patterns (BP) is available. Each BP is characterized by the amount of logs, of different dimensions, and harvest residues that is obtained from stems of certain size. Each type of stem has a set of BP associated with it. The obtained materials may be sent to the different production plants included in the SC or to clients outside the SC.

The plants included in this SC are: electric power generation plant, fibreboard facility, sawmill and plywood board facility. Each plant produces a set of products, and the production process of some of them can generate by-products that can be used as raw material in other plants, sold to customers or to obtain the energy required for the production process in that or other plants. In addition, all plants can purchase logs or by-products from external suppliers of the SC for the production or the generation of energy for the production process.

Below is a brief description of each production facility considered in this work:

- *Electric power generation plant:* this plant generates energy from biomass, in particular it uses small diameter logs, harvest residues and all the by-products generated in the other plants.
- *Fibreboard facility:* this plant uses logs of small or medium diameter, and by-products (chip, sawdust or peeler core) generated in other plants to obtain different types of boards, and bark as a by-product. By-products and harvest residues can be used to obtain the energy required by the process.
- *Sawmills:* this facility uses medium to large size logs for the production of boards of different sizes. For the production, cutting patterns (CP) are used to determine the amount and type of boards and by-products (bark, chip and sawdust) that are generated per log. The energy required to dry the boards is obtained from by-products and harvest residues.
- *Plywood facility:* uses large diameter logs to produce a set of products. The by-products generated in the process are bark, chip, sawdust and peeler core. The energy requirements of the process are covered with by-products of the processes or harvest residues. Peeler core is the centre of the log and is obtained after the peeling process.

The proposed model determines the maximum benefit obtained by the global SC, on the one hand, and of each SC member working independently, on the other. In this way, the effect and consequences that being part of the SC has for each member can be evidenced and assessed. As a result, some members may be broadly benefited and others may not. Taking into account the different possible scenarios, a new approach is proposed that allows an equitable distribution profit among the members of the SC, or, at least, weigh and appropriately adjust the impact of the solution for each of the participants..

2 Mathematical model

In this section, the mass, energy and economic balances of each sector involved in SC and the objective functions are presented.

2.1 Forest sector

Each harvest area *r* has a maximum number of stems *s* ($CMax_{rs}$) that can be cut with the BP *e*. Eq. 1 establishes that the number of stems *s* from harvest area *r* that will be cut with the BP *e* (Qs_{rse}) must not exceed the maximum quantity available at that location.

$$\sum_e Qs_{rse} \leq CMax_{rs} \qquad \forall\, r, s \tag{1}$$

Eq. 2 shows the number of logs *l* (Pl_{rl}) that is obtained after cutting the stem *s* with the BP *e*, where BP_{sel} is the number of logs *l* obtained from a stem *s* when the BP *e* is applied. Each log *l* is characterized by its length and diameter.

$$\sum_s \sum_e BP_{sel}\, Qs_{rse} \ = Pl_{rl} \qquad \forall\, r, l \tag{2}$$

These logs *l* can be sent to facility *f* ($Qlrf_{rfl}$) to transform them into products, be sold to third parties ($Qlrs_{srl}$) or remain as log inventory (Irl_{rl}) (Eq. 3).

$$Pl_{rl} = \sum_{f\, \in\, RFL_{fl}} Qlrf_{rfl} + Qlrs_{rl} + Irl_{rl} \qquad \forall\, r, l \tag{3}$$

where RFL_{fl} is the set of facilities *f* that use logs *l* in their production process.

After bucking operation, harvest residues (Plb_r) are generated. The available quantity will depend on the BP used and the number of cut stems (fr_{se}) (Eq. 4). These residues may be sent to facility *f* to generate products ($Qlbrp_{rf}$) or energy ($Qlbre_{rf}$), sold to external customers ($Qlbrs_{sr}$) or remain in inventory (Irb_r) (Eq. 5).

$$Plb_r = \sum_s \sum_e fr_{se}\, Qs_{rse} \qquad \forall\, r \tag{4}$$

$$Plb_r = \sum_{f\, \in\, RRF_f} Qlbrp_{rf} + \sum_f Qlbre_{rf} + Qlbrs_r + Irb_r \qquad \forall\, r \tag{5}$$

where RRF_f are the facilities that use harvest residues in their production process.

2.2 External suppliers

In addition to the raw material delivered by the harvest areas, each plant can obtain logs l and by-products b from external suppliers. Eq. 6 represents the quantity of logs l that are delivered to facility f ($Qlef_{fl}$), considering a stock of logs from suppliers (El_l). Similarly, Eq. 7 establishes the quantity of by-products b sent for production ($Qbefp_{fb}$) and for energy generation ($Qbefe_{fb}$). EB_b is the maximum amount available of each by-product.

$$\sum\nolimits_{f \in RFL_{fl}} Qlef_{fl} \le EL_l \qquad \forall\, l \tag{6}$$

$$\sum\nolimits_{f \in RFBp_{fb}} Qbefp_{fb} + \sum\nolimits_{f} Qbefe_{fb} \le EB_b \qquad \forall\, b \tag{7}$$

2.3 Facilities sector

Each facility f has a quantity of logs l ($Plfp_{fl}$) purchased from the harvest areas r and external suppliers (Eq 8). These logs may be assigned for the production of product i ($Qlfp_{fli}$) or remain in inventory Ifl_{fl} (Eq. 9). This equation does not consider the sawmills that will be treated differently in Eq. 14 and 15.

$$\sum\nolimits_{r} Qlrf_{rfl} + Qlef_{fl} = Plfp_{fl} \qquad \forall\, f, l \; \in RFL_{fl} \tag{8}$$

$$Plfp_{fl} = \sum\nolimits_{i \in RFI_{fi}} Qlfp_{fli} + Ilf_{fl} \qquad \forall\, f, f \neq saw\,, l \; \in RFL_{fl} \tag{9}$$

where RFL_{fi} represent the products i that are produced in the facility f.

Eq. 10 shows the quantity of by-products b destined for the production of product i ($Pbfp_{fbi}$). This availability considers the by-products obtained from external suppliers ($Qbef_{pfb}$) or acquired from other plants ($Qbffp_{f'fb}$). $RFBg_{fb}$ is the set of by-products generated in the facility f.

$$\sum\nolimits_{f' \in RFBg_{f'b}} Qbffp_{f'fb} + Qbefp_{fb} = \sum\nolimits_{i \in RFI_{fi}} Pbfp_{fbi} \;\; \forall f, b \in RFBp_{fb} \tag{10}$$

Eq. 11 establishes the amount of harvest residues destined to the production of product i ($Plbrp_{rfi}$)

$$Qlbrp_{rf} = \sum\nolimits_{i \in RFI_{fi}} Plbrp_{rfi} \qquad \forall\, r, f \tag{11}$$

Then, the quantity of product i obtained in each plant f (Pi_{fi}) is given by Eq.12, where fp_{fli}, fpb_{fbi} and fr_{bfi} are, respectively, the conversion factor of logs, by-products and harvest residues to product i of the facility f.

$$\sum_{l \in RFL_{fl}} fp_{fli}\, Qlfp_{fli} + \sum_{b \in RFBp_{fb}} fpb_{fbi}\, Pbfp_{fbi} + \sum_{f \in RRF_{rf}} frb_{fi}\, Plbrp_{rfi} = Pi_{fi} \qquad \forall f, f \neq saw, i \in RFI_{fi} \tag{12}$$

Considering that $Pmax_f$ represents the maximum production capacities of each facility f, the production of each plant is limited by this capacity. This is shown in Eq. 13

$$\sum_i Pi_{fi} \leq Pmax_f \qquad \forall f \tag{13}$$

At the sawmill, the available logs can be assigned to a CP p to obtain products ($Qlsaw_{lp}$) or remain in the log stock (Eq. 14). When a cutting pattern p is applied to a log l, the number of the different tables i that is obtained is determined. Considering all the logs and cutting patterns used, the quantity of products i obtained is represented by Eq. 15, where CP_{lpi} indicates the number of products i obtained when CP p is applied.

$$Plfp_{f=saw,l} = \sum_p Qlsaw_{lp} + Ilf_{f=saw,l} \qquad \forall l \in RFL_{f=saw,l} \tag{14}$$

$$\sum_l \sum_p CP_{lpi}\, Qlsaw_{lp} = Pi_{f=saw,i} \qquad \forall i \in RFI_{f=saw,i} \tag{15}$$

The products obtained in each facility f can be used to satisfy demand (Qi_{fi}) or remain in inventory (Ifi_{fi}) (Eq. 16). Eq. 17 states that only a percentage ($fper_{fi}$) of the quantity of products can be part of the inventory

$$Pi_{fi} = Qi_{fi} - Ifi_{fi} \qquad \forall f, i \tag{16}$$

$$Ifi_{fi} \leq fper_{fi}\, Pi_{fi} \qquad \forall f, i \tag{17}$$

The generation of by-products in the facility f (Pbf_{fb}) is proportional to the number of logs processed (Eq. 18), and, in the case of the sawmill, to the CP used (Eq. 19), where fb_{flb} and $fsaw_{lpb}$ are conversion factors for the by-product b. If a by-product b is not generated in a plant, it is not included in the $RFBg_{fb}$ set.

$$\sum_l fb_{flb}\, Plfp_{fl} = Pbf_{fb} \qquad \forall f, f \neq saw, b \in RFBg_{fb} \tag{18}$$

$$\sum_l \sum_p fsaw_{lpb}\, Qlsaw_{lp} = Pb_{f=saw,b} \qquad \forall b \in RFBg_{fb} \tag{19}$$

Eq. 20 shows the possible destinations of the by-products. These can be: used as an energy source in the same plant ($Qbfe_{fb}$), sent to other facilities for production ($Qbffp_{ff'b}$) or energy generation ($Qbffe_{ff'b}$), sold to customers ($Qbfs_{fb}$) or be part of the inventory for future use (Ifb_{fb}).

$$Pb_{fb} \geq Qbfe_{fb} + \sum_{f' \in RFBp_{f'b}} Qbffp_{ff'b} + \sum_{f'} Qbffe_{ff'b} + Qbfs_{fb} + Ifb_{fb} \qquad \forall b \tag{20}$$

To meet energy requirements, facilities can use by-products generated there, acquired from other plants or suppliers, and harvest residues. The Eq. 21 shows the energy balance for each installation. The term on the left represents the energy required by the plant, and the one on the right is the energy obtained from using the resources considered.

$$\sum_i Pi_{fi}\, ed_{fi} \le \sum_b cp_b\big(Qbfe_{fb} + Qbefe_{fb} + \sum_{f`} Qbffe_{f`fb}\big) + \sum_r cr\, Qlbre_{rf} \quad \forall\, f, f \neq ene \tag{21}$$

where ed_{fi} is the energy required for the process to produce i, and cp_b and cr are the heat capacities of the by-products and harvest residues, respectively.

2.3 Demand

The following restrictions determine that the quantity of logs (Eq. 22), harvest residues (Eq. 23), products (Eq. 24) and by-products (Eq. 25) destined for customers cannot exceed the maximum demand of each one of them. In addition, the quantity of product i must exceed a minimum demand (Di_{fi}^{min}).

$$\sum_r Qls_{rl} \le Dl_l \quad \forall\, l \tag{22}$$

$$\sum_r Qlbrs_r \le Drb \tag{23}$$

$$Di_{fi}^{min} \le Qi_{fi} \le Di_{fi} \quad \forall\, f, i \tag{24}$$

$$\sum_f Qbfs_{fb} \le Db_b \quad \forall\, b \tag{25}$$

where Dl_l, Drb, Di_{fi}, Db_b are the maximum demand for logs, harvest residues, products and by-products, respectively.

2.3 Economic Balances

Forest sector

Income (Ir_r): is proportional to the number of logs and harvest residues obtained (Eq. 26).

$$Ir_r = \sum_f \sum_l slf_{lf}\, Qlrf_{rfl} + \sum_l sls_l\, Qlrs_{rl} + \sum_f sbr_f\,\big(Qlbrp_{rf} + Qlbre_{rf}\big) + sbrs\, Qlbrs \quad \forall\, r \tag{26}$$

where slf_{lf} and sls_l represent the sale price of logs l to facility f and external customers, respectively, and sbr_f and $sbrs$ are the sale prices of harvest residues to facility f and external customers, respectively.

Operating costs (*Pcr_r*): depend on the number of stems *s* cut with the BP *e*. *CPr_{se}* is the unit cost for cutting a stem s with the PB e (Eq. 27).

$$Pcr_r = \sum_s \sum_e CPr_{se}\, Qs_{rse} \qquad \forall\, r \tag{27}$$

Profit (*Br*)*:* obtained by the difference between sales income and operating costs (Eq. 28)

$$Br = \sum_r (Ir_r - Pcr_r) \tag{28}$$

Facilities sector

Income (*If_f*): considers the quantity of products and by-products sold and their sale prices (Eq. 29).

$$If_f = \sum_i si_{fi}\, Qi_{fi} + \sum_b \sum_{f'} sb_b \left(Qbffp_{ff'b} + Qbffe_{ff'b}\right) + \sum_b sbs_b\, Qbfs_{fb} \qquad \forall\, f \tag{29}$$

where *si_{fi}* is the sale price of the products and *sb_b* and *sbs_b* are the sale price of the by-products to the different facilities or customers, respectively.

Raw Material Cost (*RMc_f*): is given by the unit cost of buying logs from the forest sector (*slf_{lf}*) and suppliers (*CRM_l*), of by-products from other facilities (*sb_b*) and suppliers (*Cb_b*), and harvest residues (*sbr_f*), as expressed Eq. (30):

$$RMc_f = \sum_r \sum_l slf_{lf}\, Qlrf_{rfl} + \sum_l CRM_l\, Qlef_{fl} + \sum_{f'} \sum_b sb_b \left(Qbffp_{f'fb} + Qbffe_{f'fb}\right) + \sum_b Cb_b \left(Qbefp_{fb} + Qbefe_{fb}\right) + \sum_f sbr_f \left(Qlbrp_{rf} + Qlbre_{rf}\right) \qquad \forall\, f \tag{30}$$

Operating costs (*PCf_f*): consider the amount of product generated and its unit cost per production (*CPf_{fi}*) (Eq. 31). In the case of the sawmill, this cost will depend on the number of times the CP *p* is applied to the log *l* (*Cpc_{lp}*) (Eq. 32)

$$Pcf_f = \sum_i CPf_{fi}\, Pi_{fi} \qquad \forall\, f, f \neq saw \tag{31}$$

$$Pcf_{f=saw} = \sum_l \sum_p Cpc_{lp}\, Qlsaw_{lp} \tag{32}$$

Transportation costs (*Tcr_f*): takes into account the transportation of logs and harvest residues from the harvest areas to the production plants, and the transport of by-products between facilities. As Eq. 33, it is calculated by multiplying the amount transported by the unit cost of the transported material (*CTl_l* for logs, *CTbr* for harvest residues and *CTb_b* for by-products) and the distance between the harvesting areas and the industries (*Drf_r*). The distance between the different plants is considered negligible since they are part of the same industrial complex.

$$Tcr_f = \left(\sum_r \sum_l CTl_l\, Qlrf_{rfl} + \sum_r CTbr \left(Qlbrp_{rf} + Qlbre_{rf}\right)\right) Drf_r + \sum_{f'} \sum_b CTb_b \left(Qbffp_{ff'b} + Qbffe_{ff'b}\right) \qquad \forall f \tag{33}$$

Profit (*Bf_f*): given by the difference between income and costs considered

$$Bf_f = If_f - RMc_f - Pcf_f - Tc_f \qquad \forall f \tag{34}$$

2.4 Objective function

In order to compare the global performance and of each facility independently, the following restrictions were established, with the aim of maximizing the income individually from the forest sector (Eq. 35), electric power generation plant (Eq. 36), fibreboard facility (Eq. 37), sawmills (Eq. 38) and plywood facility (Eq. 39), and the total income of the SC (Eq. 40).

$$\max Br \tag{35}$$

$$\max Bf_{f=ene} \tag{36}$$

$$\max Bf_{f=FB} \tag{37}$$

$$\max Bf_{f=saw} \tag{38}$$

$$\max Bf_{f=PW} \tag{39}$$

$$\max Br + \sum_f Bf_f \tag{40}$$

2.5 Goal programming

In order to have an equitable distribution of profit among SC members, a GP approach is proposed. The GP method is a tool that allows the objectives of each sector to be met simultaneously. In this method, an objective function is established for each goal (or objective), as well as an aspiration level for each one. Taking into account that all objectives cannot be optimized at the same time, these aspiration levels determine a minimum threshold that must be met in order to reach solutions that satisfy the criteria of decision makers. Then, the weighted sum of the deviations with respect to these aspiration levels is minimized and a solution adjusted to the preferences of the decision makers is obtained.

Eq. 41 and 42 show the evaluation of each goal.

$$Br + Nr = \psi r \tag{41}$$

$$Bf_f + N_f = \psi_f \qquad \forall f \tag{42}$$

where ψr and ψ_f are the aspiration level for the forest sector and for each facility, respectively, Nr and N_f are the deviation variables for aspiration for the forest sector and for each facility, respectively, and represents the level by which the value target does not reach aspiration level.

The variable ϕ determines the maximum deviation between all targets and is calculated using Eq. 43 and 44:

$$\frac{Wr(Nr+Pr)}{kr} \leq \phi \tag{43}$$

$$\frac{W_f(N_f+P_f)}{k_f} \leq \phi \qquad \forall f \tag{44}$$

where Wr and W_f are the preferences or weights set by the decision makers for the forest sector and the different facilities, respectively, and kr and k_f are the normalization constants associated with each goal.

Eq. 45 represents the achievement function of a GP model

$$\min(1-\lambda)\phi + \lambda\left(\frac{Wr(Nr+Pr)}{Kr} + \sum_f \frac{W_f(N_f+P_f)}{K_f}\right) \tag{45}$$

This expression minimizes the deviation of the five objectives where λ is a control parameter that can take a value between 0 and 1. When $\lambda = 0$ a maximum equilibrium is obtained and the maximum deviation is minimized, while, if $\lambda = 1$, the maximum efficiency following the preferences of the decision makers is achieved. Intermediate values of λ allow combining both criteria according to the wishes of the decision maker.

3 Case study

For this analysis, a SC composed of four harvesting areas is proposed, where each area has an only type of stem. There are 3 types of stems, and for each type there is five possible BP to obtain logs and harvest residues.

The bucking of the stems generates six types of logs that can be sent to the different facilities. For production, each facility can use logs and, in some cases, by-products of other facilities. In addition, logs and by-products can be purchased from suppliers who have a limited availibility of them. Each plant produces a number of products and by-products to be sold, or in the case of the latter, they can be used as an energy source in that facility or be sent to others. In the case of sawmills, there are five CP for each type of log to obtain their products.

Table 1 shows the materials that each plant can use as raw material, the products and by-products generated and the materials that can be used as a source of energy for its process. As can be seen, facilities not only compete for the raw material of the forest sector, but also for the by-products that they generate.

For the implementation of the proposal, the model will be first solved considering the plants working independently (Eq. 34-39) and then the CS in group form (Eq. 40). Finally, the GP approach will be used to find equitable solutions among members of the SC. The example was implemented and solved in GAMS using CPLEX solver in an Intel (R) Core (TM) i7-3770, 3.40 GHz.

Table 1. Facility materials and products.

Facility	raw material	products	by-products	Material for energy
Electric power	Log *l*1 Bark Chip Sawdust Peeler core Harvest residues	Electric	-	-
Fibreboard	Log *l*1 Log *l*2 Chip Sawdust Peeler core	Fibreboard 1 Fibreboard 2	Bark	Bark Chip Sawdust Peeler core Harvest residues
Sawmill	Log *l*2 Log *l*3 Log *l*4 Log *l*5	Board 1 Board 2 Board 3 Board 4 Board 5	Bark Chip Sawdust	
Plywood	Log *l*5 Log *l*6	Plywood 1 Plywood2	Bark Peeler core	

Table 2 shows the values obtained by using the objective functions Eq. 34-40, where each column corresponds to an optimization problem. The highlighted value presents the optimized target while the other values of the column are the remaining objectives. The last column corresponds to the losses of each facility within the SC with respect to its best result. For reasons of space, only the results related to the FO are shown. The model also allows knowing the flow of materials between the different members of the chain, quantity of products and by-products generated, energy requirements, incomes and costs of each plant, etc. In addition, for all cases, a fulfilment of at least 50% of the demand for each product is required.

Table 2. Economic benefits (k$).

	Max Forest	Max Ene	Max FB	Max Ase	Max Pw	Max SC	Loos (%)
Forest	**19544.7**	15579.0	17913.2	7174.1	10650.0	19146.8	2.0
Electric power	-1797.7	**1802.5**	-2267.7	-3466.9	-475.9	1471.5	18.4
Fibreboard	-610.1	-155.6	**11228.2**	-1339.7	-899.8	9331.1	16.9
Sawmill	-5184.1	-5613.7	-7135.7	**7968.9**	-2178.1	4245.8	49.7
Plywood	-12156.3	-16406.4	-7844.2	-5754.5	**6163.4**	2620.6	57.5
Total benefit	-203.6	-4794.2	11893.9	4581.9	13259.5	**36815.9**	

While optimizing the SC achieved a significantly higher total profit than the other objective functions, the behaviour of individual profits is not similar. When the profit obtained operating independently and integrated to the SC are compared, it can be seen that the forest sector would have a loss of 2% while in the plywood facility income would be 57.5% lower than if it operates independently from the rest of the SC participants, aiming only to optimize its profit. This shows the existence of conflicting interests between individual and global objectives, and very dissimilar behaviors for the participants which could lead to the estrangement of one of the members of the SC by not benefiting in the same way as the rest. These great differences justify the implementation of a GP approach that allows to properly evaluate the efforts and results for all participants in order to achieve a better distribution of the profit.

To carry it out, the aspiration levels and normalization constants shown in table 3 were used, and the preferences or weights will be the same for all members (W = 1). First values correspond to the optimal solutions of each problem of Table 2. It is important to note that the parameters should be chosen by the decision makers. Therefore, the following analysis is illustrative to show the possibilities of the proposed methodology.

Table 3. Aspiration levels and normalization constants

	Forest	Electric power	Fibreboard	Sawmill	Plywood
Aspiration levels (ψ)	19544.7	1802.5	11228.2	7968.9	6163.4
Normalization constants (k)	195.5	18.0	112.3	79.7	61.6

To assess the proposed approach, three scenarios were analysed with λ = 0, λ = 0.5 and λ = 1. Table 4 shows the benefit obtained by each sector in each scenario, the maximums obtained by each individual FO and the values attained in the FO global. The values in parentheses correspond to the percentage of loss compared to the best result obtained.

Table 4. GP results

	Individual max	Max SC	$\lambda = 0$	$\lambda = 0.5$	$\lambda = 1$
Forest	19544.7	19147.0 (2.0)	13614.9 (30.3)	13447.6 (31.2)	14890.4 (23.8)
Electric power	1802.5	1471.5 (18.4)	1255.6 (30.3)	1468.0 (18.6)	1729.3 (4.1)
Fibreboard	11228.2	9331.1 (16.9)	7821.6 (30.3)	9194.6 (18.1)	9423.9 (16.1)
Sawmill	7968.9	4245.8 (46.7)	5551.2 (30.3)	5482.9 (31.2)	4948.8 (37.9)
Plywood	6163.4	2620.6 (57.5)	4293.4 (30.3)	4240.7 (31.2)	3827.6 (37.9)
Total benefit	36815.9	36816.0 (0.0)	32536.7 (11.6)	33833.8 (8.1)	34820.1 (5.4)

When $\lambda = 0$, the losses obtained are equal for each sector (30.3%) but the global loss is only 11.6%, compared to the best value obtained. In this case, the sawmill and the plywood are the most favoured plants since they reduce their losses.

By increasing the value of λ, the overall benefit of the SC increases until obtaining a loss of 5.4% in the case of $\lambda = 1$. In this scenario, with the exception of the forestry sector, the profits of each industry increase compared to what was obtained by maximizing the SC.

The forest sector is the most disadvantaged of this approach. Starting from the basis that it had a very advantageous result in the global solution, with a benefit very similar to that obtained when its operation is optimized independently of the rest of the SC, it now has a 24% reduction in its profit, a very significant value compared to the initial case, but not so important when compared to the results of the rest of the participants. A possible way to reduce this increase would be by assigning a higher preference value (wr) to the forestry sector, a scenario not studied in this work.

In some way, this approach makes it possible to evaluate the impact that each solution has on the participants and it is the responsibility of those managing the SC to negotiate with all participants to achieve a win-win outcome for all parties. The results obtained in this approach are very sensitive to the values assigned to each parameter. Therefore, decision makers must work emphasizing the particular conditions of each sector to find a solution that meets their needs.

3 Conclusions

A MILP model was presented to analyse the behaviour of the economic benefits of different sectors of the forest industry working independently or doing it jointly conforming a SC. When an imbalance is observed between the profits obtained by each participant when forming part of the SC, the implementation of a GP approach allows these asymmetries to be properly assessed in order to generate balanced solutions for the results of the different participants. In this way, alternative solutions were obtained that allow a more equitable distribution of the efforts of the participants. These results are very sensitive to the parameters used (preferences w, control parameter λ, aspiration level ψ and normalization constant k) and decision-makers will have to analyse different scenarios to find a solution that can best satisfy the interests of each firm.

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