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Integrated approach for the bucking and production planning problems in forest industry

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ABSTRACT

The appropriate integration among production activities is a key factor for the development of the forest industry in the northeast of Argentina. Sawmills are one of the main logs consumers. However, production planning of sawmills has been managed independently of the forest production. In this work, a mixed integer linear programming formulation is proposed in order to achieve an adequate logs supply that allows carrying out an efficient lumber production plan. Bucking decisions, as the number of stems to be harvested and the employed bucking patterns, are jointly solved with sawmill planning decisions, like the number and type of processed logs and the used cutting patterns, in order to fulfill the boards demands maximizing the net profit along the time horizon composed by several time periods (days). Through examples, the capabilities of the proposed approach are highlighted and the computational results are analyzed.

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1. Introduction

The conversion of wood into final lumber products involves important operations that must be coordinated in order to obtain the desired products with the available resources in an optimal way. Sawmills are one of the larger log consumers, and inappropriate bucking decisions can lead to poor performance or, even, infeasible lumber production planning. In other words, the bucking is an irreversible operation that directly impacts the sawmill production. Therefore, bucking and sawmill production planning decisions must be appropriately integrated in order to achieve the goals of the complete production system.

The tree bucking problem consists of deciding the amount and type of stems to be cut from different stands or providers, and how to convert stems into logs according to bucking patterns (BP). A BP determines the number of logs of different diameters and lengths that can be obtained from stems of a certain length. Bucking optimization problems were addressed during the past years. Laroze (1999) classified the decisions of this problem at stem, stand, and forest levels. At stem level, the decision is regarding to the BPs selection with the objective of maximizing the stem value. At stand level the objective is to maximize the aggregate production value selecting the suitable BPs for each class of stem in a single stand, where stand characteristics and market demands have to be taken into account. Finally, at the forest level, the aim is to make the whole system efficient and profitable. There are a variety of works addressing the different bucking levels. Pnevmaticos and Mann (1972) and Geerts and Twaddle (1984), in pioneering works, proposed mathematical models for the bucking problem as an independent operation, while Kivenen and Uusitalo (2002) presented a control system for combining the bucking operation with the demand price list through dynamic programming. Epstein et al. (1999) formulated a linear programming approach for short term harvesting considering a column generation algorithm for the BPs design. Arce et al. (2002) solved a forest level bucking optimization problem using mixed integer linear programming (MILP) and simple heuristic rules for the BP selection, considering demands and transportation costs.

On the other hand, sawmill production planning problem involves determining the amount and type (diameter and length) of logs to be processed in order to fulfill the board demands in a profitable manner. Logs are converted into boards using cutting patterns (CP). A CP is an arrangement of rectangles (thickness and width of the boards produced by the sawmill) within a circle that can be applied to logs of different lengths, if available. Different approaches were presented in the literature from the operational

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Nomenclature

Subscripts

a	Providers
b	Bucking patterns
d	Diameters of logs
f	Stems
i	Cross sectional area of boards
l	Length of logs and boards
p	Cutting pattern
t	Time period

Parameters

BM	Big constant
DM_{il}	Maximum demand of product with cross sectional area i and length l (units)
$CapF_{il}$	Stock capacity for board with cross sectional area i and length l (units)
$CapS_{af}$	Stems of high f available of supplier a (units)
$cprd_{dlp}$	Production cost for CP p applied to logs of diameter d and length l ($/unit)
$Crmp_{dl}$	Cost for stored old logs of diameter d and length l ($/unit)
$cset_p$	Unit setup cost for CP p ($)
CSt_{afbt}	Cost of stem of high f from provider a and cut by BP b in t ($/unit)
PV_{il}	Selling price of board of cross sectional area i and length l ($/unit)
t_{dlp}	Operating time for processing a log of diameter d and length l using CP p (h)
ts_p	Setup time for using CP p (h)
$Tmax_t$	Maximum daily operation time for sawmill (h)
δ_{bfdl}	Number of logs of diameter d and length l obtained when BP b is applied to a stem f
ρ_{dpi}	Conversion factor: number of boards of cross sectional area i produced when CP p is applied to logs of diameter d

Binary variables

x_{pt}	Indicates whether the primary CP p is used in period t

Integer variables

Q_{dlt}	Logs of diameter d and length l used in period t (units)
Qb_{dlat}	Logs of diameter d and length l delivered from supplier a in period t (units)
Qp_{dlpt}	Logs of diameter d and length l processed in period t (units)
Qt_{dlt}	Old logs of diameter d and length l processed in period t (units)
St_{afbt}	Stems of length f from supplier a, cut using BP b in period t (units)

Continues variables

CPr	Production cost ($)
CR	Raw material cost ($)
CSt	Setup cost ($)
In	Income for sales ($)
Ib_{dlt}	Logs of diameter d and length l stored in period t (units)
If_{il}	Final stock of board of cross sectional area i and length l at the end of planning horizon (units)
Ip_{ilt}	Boards of cross sectional area i and length l stored in period t (units)
IS_{aft}	Stems of height f of provider a available on t (units)
It_{dlt}	Old logs of diameter d and length l stored in period t (units)
Pi_{ilt}	Number of boards of cross sectional area i and length l produced in period t (units)
VF_{il}	Sold boards of cross sectional area i and length l (units)

and tactical points of view, with many alternatives according to the considered assumptions (cutting pattern generation, logs availability, yields, demand nature, etc.) and time horizon (weekly, annual, etc.).

Zanjani et al. (2010) proposed a robust optimization model for solving sawmill planning during a month with random raw material properties and yields. They also evaluate the customer service level through backorders, inventory size and costs. In Maturana et al. (2010), a mathematical formulation is presented with the aim of determining the volume and type of logs to be processed. They consider the production over six weeks, where the log supply is then adjusted. An annual planning period was considered by Alvarez and Vera (2014) for solving the uncertainties through robust optimization, while a decomposition approach was developed by Lobos and Vera (2016) for considering two different time scales: monthly and weekly. An integer programming (IP) model for determining the number of logs to be cut over a period of several days was presented by Pradenas et al. (2013). They proposed two approaches: a metaheuristic algorithm to solve the sawmill planning and a heuristic algorithm to generate the CPs for each log.

Usually, from an operational perspective, the problems of harvesting and bucking, on the one hand, and production planning in sawmills, a key sector of the forest industry, on the other hand, have been addressed as two separate topics. There are few works dealing with the simultaneous optimization of forest harvesting and sawmill operations (Troncoso et al., 2015). In a first approach, Maness and Adams (1991) proposed three individual models for carrying out bucking and sawing activities. The three models involve: a cutting pattern optimizer for the sawmill, a stem bucking model for bucking policies, and log allocation model which determines the production of the sawmill using the CPs generated by the first model for a given log obtained from the second one. Some works integrate the bucking and log supply planning problems, without details on involved processes at sawmills. Dems et al. (2015, 2017) presented a MILP model for the optimal wood-procurement planning problem considering bucking decisions through single and multiperiod approaches, respectively. The model integrates bucking, harvesting, transportation, and inventories decisions for a given amount of logs previously calculated. Recently, Fuentealba et al. (2019) proposed a heuristic method based on the column generation approach for solving the integrated tactical planning of harvesting and production in a sawmill. They presented a MILP model that involves a set of predefined cutting patterns in the sawmills and bucking rules.

In this context, this work proposes an approach that allows to integrate the planning of bucking and harvesting in the forest, and production in the sawmill. On one hand, there are different stands with available amounts of stems with their characteristics (length and diameter at breast height) that can be cut in different ways to produce logs, using BPs. In addition, the price of each log depends, among other things, on the dimensions of the stem from which it has been obtained, beyond other factors such as distance from the stand to the sawmill, etc. On the other hand, a log can be cut to produce boards in many different ways according to the CP that is selected. Additionally, a board can be obtained from different logs taking into account the selected CP. Therefore, the economic value of a board can vary significantly from the decisions that have been made both in the forest and in the sawmill.

Besides, once resources are available, they must be completely consumed, otherwise they generate inventories that are difficult to manage. This applies to logs obtained from the bucking operation, as well as to boards produced once a log is cut in the sawmill. In particular, considering the climatic conditions of the northeast of Argentina where this formulation is going to be applied, if the logs are not quickly processed, within several days, they suffer the attack of fungi, which deteriorates their quality and market value.

Therefore, there is a very combinatorial problem, with an important number of alternatives to be explored, which significantly increases when the problems of the harvesting and bucking in the forest are integrated with the production planning in the sawmill.

In this work, a MILP formulation that allows solving both problems in reasonable computational times and reaching highly efficient and competitive solutions is proposed. Through the examples it can be highlighted that the simultaneous optimization of both problems achieves important improvements in the economy and productivity of this industry.

The remainder of this paper is organized as follow. Section 2 presents a description of the addressed problem. The mathematical formulation is stated in Section 3 while numerical examples are presented in Section 4. Finally, the conclusions of this work are drawn in Section 5. With the aim of avoiding large table configurations, some problem data are shown as supplementary information.

2. Problem description

Every day, a sawmill receives logs of different diameters $d \in D$ and lengths $l \in L$, from diverse suppliers a, $a \in A$. Each supplier has an available amount of stems of length $f \in F$, $CapS_{af}$, at the beginning of the planning horizon, which are to be bucked according to bucking patterns (BP) b, $b \in B_f$. Although each type f of stem has been identified taking into account its length to simplify this introduction, each class f can be described by characteristics such as: thickness at the base and tip, conical form, etc. Let δ_{bfdl} be the number of logs of length l and diameter d obtained when the bucking pattern b is applied to a stem of length f. Therefore, the logs capacity for each supplier depends on, not only the available stems, but also on the bucking patterns used when stems are harvested in the stand. Fig. 1 shows two different bucking patterns for a stem of length f_1. In this work it is assumed that the total of logs obtained from a stem are bought by the sawmill and cf_{af} is the unitary cost of stem f provided by supplier a. In this way, the operations of the firm that owns the stands are simplified because log inventories are avoided. These stocks are difficult to manage, not only from the logistic point of view but also by fungal attacks, taking into account the climatic conditions of the region. Therefore, the benefit is very significant if customers can withdraw the complete stem once it is appropriately cut.

When logs arrive at sawmill from the different suppliers, they are classified according to length and diameter, and transferred to the sawing sector as is described in Fig. 2. There, they are processed using cutting patterns (CPs) for the corresponding useful diameter, i.e. the diameter of the larger cylinder that can be obtained from the log. Each CP is associated to a determined diameter, but it can be used for all the different log lengths with that diameter. When a CP is applied, different boards characterized by its width and thickness are obtained, while length coincides with the log length (Fig. 3). In this work, the final product is a board of cross sectional area i (width and thickness of a board) and length l. Therefore, the conversion from logs to boards is given by the parameter ρ_{dpi}, which determines the number of boards of cross sectional area i obtained when the CP p is applied to a log of diameter d. The processing time depends on the applied CP and the log length, while the sawmill has a limited operation time for the working day.

Taking into account the sawmill layout, more than 70% of sawmills in the Northeastern region of Argentina use the generic CP type *Cant Sawing*, according to the classification proposed by Todoroki and Rönnqvist (2002). The units involved in the cutting process are three types of saws: a main saw from which a cant and two flitches are obtained, a secondary saw where boards of different sizes and two flitches are obtained from the cant, and a re-sawing unit where flitches are processed (Fig. 2). Thus, this processing divides the log into five sections: a central block, two equal lateral flitches, and an upper and lower one, which are equal to each other. From each of these sections, the different boards will be obtained. This cutting process involves production and setup costs, where the last one corresponds to the CPs changeover, which generates periods without production.

CPs are obtained from an exhaustive search algorithm and used in the planning approach as model data (Fig. 3). According to log diameters, demanded boards, and yields for each pattern, the CP generator algorithm systematically arranges rectangles, which represents the cross sectional area of the board, in circles of diameter d, in order to fulfill the imposed yield. The required yield of each CP is fixed by the firm and represents the percentage of wood converted into boards (in volume). The cuts in the design of the CPs are made simulating the way in which the sawmill operates taking into account the available technology. This algorithm works separately on pieces of the log: the central block, two equal lateral flitches, and an upper and lower one, which are equal to each other. The different alternatives for cutting these parts for a certain diameter are determined. For each of these alternatives, taking

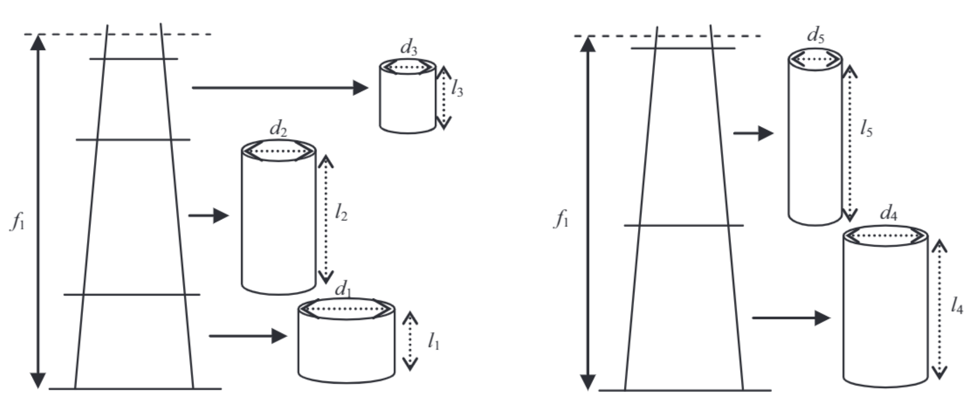

Fig. 1. Alternatives for the bucking operation.

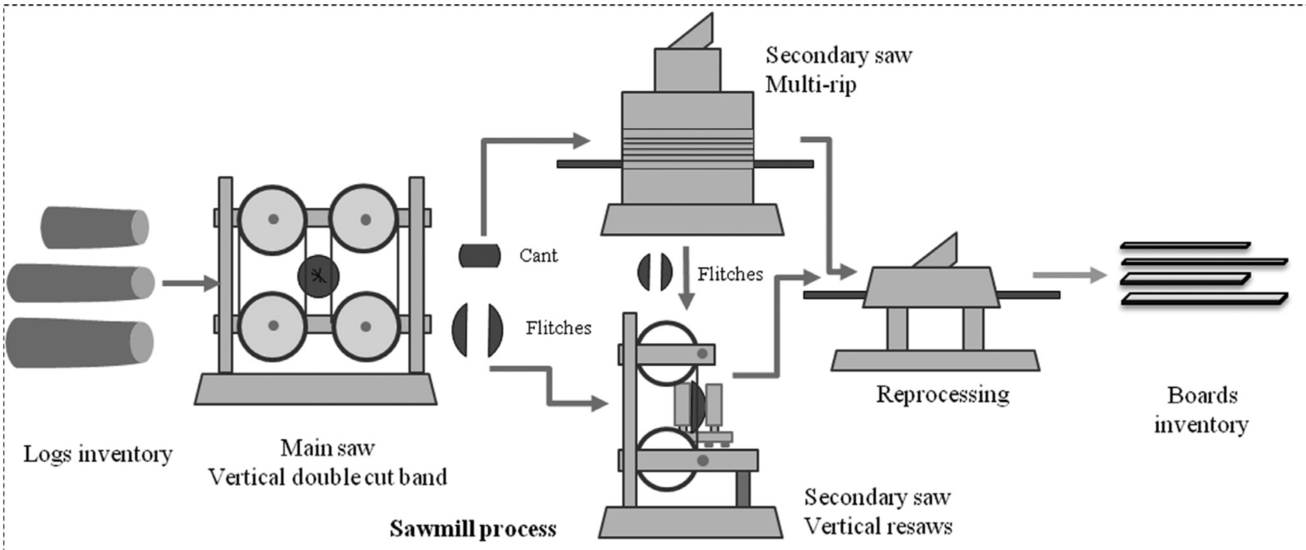

Fig. 2. Sawmill process for board production.

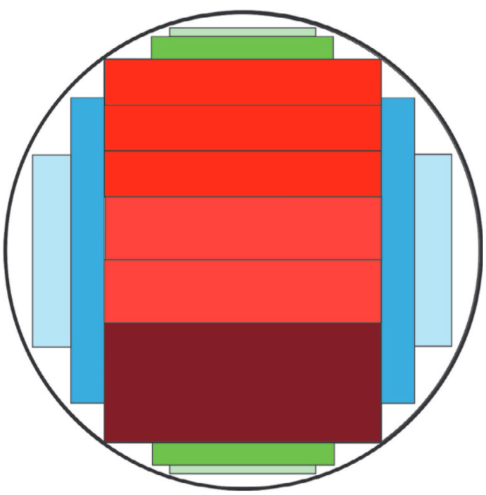

Fig. 3. Cutting pattern for a log.

into account the widths and thicknesses of the boards produced in the firm, an in-depth search is carried out to identify the feasible combinations of boards that can be obtained from each log piece. Then, the different combinations for the log pieces are jointed to generate the CP of the corresponding diameter. Similar procedures can be developed for different sawmill configurations. The appropriate selection of CPs is critical for sawmill objectives taking into account that several performance measures strongly depend on the chosen CPs: operations yield and cost, satisfied demand, stock levels, etc.

At the beginning of the planning horizon, there is an initial logs stock at the sawmill, namely old logs, and daily, new logs are bought from different suppliers. Always logs are incorporated through the purchase of complete stems. In this work, it is assumed that stems are cut when they are required, and no stock of stems is considered. For this reason, no old logs are bought. Taking into account a multiperiod approach is adopted, a stock of logs between consecutive days is considered. For each type of board, a maximum demand is stated which must be fulfilled at the end of the planning horizon. This maximum demand represents an upper bound for sales.

The objective is to determine the bucking operation and the detailed production planning of the considered period, i.e. daily decisions about bucking operation of each supplier, raw material purchases, amount of logs of each type (diameter and length) to be cut with each CP, logs stock level, finished product stock and demands fulfillment in order to maximize the net benefit given by sales income minus raw material, operation, and setup costs.

3. Model formulation

In this section, the mathematical modeling for the optimal bucking and lumber production planning is presented. The used symbols are described in Nomenclature section.

3.1. Bucking operation

As was previously described, each supplier a has a limited amount of available stems of length f, $CapS_{af}$, at the beginning of the planning horizon. This horizon is divided into periods t, usually days. Let St_{afbt} be the amount of stems from supplier a, of length f, cut using BP b in period t. Then, in each time period, the remaining amount of stems of length f from each supplier a, IS_{aft}, is given by the following equations:

$$IS_{aft} = CapS_{af} - \sum_{b} St_{afbt} \qquad \forall a, f, t = 1 \tag{1}$$

$$IS_{aft} = IS_{af,t-1} - \sum_{b} St_{afbt} \qquad \forall a, f, t > 1 \tag{2}$$

In this way, the final stock of stems f from supplier a at the end of the planning horizon is given by the variable $IS_{af,t_{final}}$. It is worth to mention that these stems remain available in the forest stand, without be cut, for the following planning horizons.

The conversion from stems to logs is stated according to the used cutting pattern $b \in B_f$. Let Qb_{dlat} be the variable that represents the amount of logs of diameter d and length l supplied from provider a to the sawmill in the period t, then:

$$Qb_{dlat} = \sum_{b,f} \delta_{bfdl}\, St_{afbt} \qquad \forall a, d, l, t \tag{3}$$

3.2. Log inventory at sawmill

When stems are cut in the forest, all the obtained pieces are transported to the sawmill. There are also an initial stock of logs of diameter d and length l from the previous planning periods, named It_{dl0}. These logs are handled separately from the logs purchased during the planning period because they have different conditions. Taking into account that they are affected by the appearance of spots due to fungi, its processing is a priority. Besides, they have been bought and paid in the previous period. To encourage its processing and simultaneously consider their cost in order to assess the profitability of the production plan, the old logs are assigned a lower cost than the cost of new purchased logs. This value is a parameter that is proposed by the planners, emphasizing that they should be consumed as soon as possible and considering the adopted multiperiod time horizon and the prevailing climatic conditions. Then, the balance for this type of logs is stated as follows:

$$It_{dl,t-1} = Qt_{dlt} + It_{dlt} \qquad \forall d, l, t \tag{4}$$

where Qt_{dlt} is the amount of old logs, i.e. raw material not provided by suppliers, of diameter d and length l used in the process at day t, and It_{dlt} the amount of old stored logs of diameter d and length l in period t.

On the other hand, for the purchased logs, the inventory balance is:

$$\sum_a Qb_{dlat} + Ib_{dl,t-1} = Q_{dlt} + Ib_{dlt} \qquad \forall d, l, t \tag{5}$$

where Ib_{dlt} is the amount of logs of diameter d and length l stored at the end of period t and Q_{dlt} are the processed logs in period t of diameter d and length l. It is assumed that at the first planning day ($t=1$), the amount of stored bought logs, Ib_{dl0}, is equal to zero.

3.3. Logs processing and lumber production

As was previously mentioned, the mathematical model considers the information about the CPs generated through an exhaustive search procedure.

After being applied the CP generator, for each identified CP p ($p \in P$), the conversion factors ρ_{dpi} are determined, which represent the number of products of cross sectional area i generated when the CP p has been used in a log of diameter d. Also, the time involved when p is applied to a log of diameter d and length l, t_{dlp}, are provided by the firm and introduced in the model.

The variable Pi_{ilt} defines the number of boards of cross sectional area i and length l, produced in period t, which is calculated according to the number of processed logs, Qp_{dlpt}, and the used CP p:

$$\sum_{p,d} Qp_{dlpt}\ \rho_{dpi} = Pi_{ilt} \qquad \forall l, t, i \tag{6}$$

$$\sum_p Qp_{dlpt} = Qt_{dlt} + Q_{dlt} \qquad \forall d, l, t \tag{7}$$

Eq. (7) states that processed logs come from purchased (Q_{dlt}) and old (Qt_{dlt}) logs.

The processing time is composed by a variable time that depends on the number of processed logs and a fixed time related to the employed CP and the corresponding setup time. Therefore, it is necessary to define a binary variable in order to determine the use of the CP p. Let x_{pt} be equal to 1 if CP p is used in period t, then Eq. (8) establishes that the maximum available time limit for each period t, $Tmax_t$, cannot be exceeded, while Eq. (9) states that no logs are processed using CP p in period t if x_{pt} is equal to zero:

$$\sum_{d,l,p} Qp_{dlpt}\ t_{dlp} + \sum_{p \in P} ts_p x_{pt} \le Tmax_t \qquad \forall t \tag{8}$$

$$\sum_{d,l} Qp_{dlpt} \le BM\ x_{pt} \qquad \forall p, t \tag{9}$$

BM is an upper bound for the number of logs of different diameters and lengths that can be cut according to CP p.

3.4. Boards inventory and demand fulfillment

In this approach, the maximum demands of products are global over the considered time horizon and, therefore, they limit the production of each product, as long as production is profitable, at the end of the planning horizon. Therefore, the produced boards in each period t are stored in order to satisfy the maximum demands in the last time period. Let Ip_{ilt} be number of boards of cross sectional area i and length l stored at day t. Eq. (10) states the inventory product balance:

$$Ip_{ilt} = Ip_{il,t-1} + Pi_{ilt} \qquad \forall i, l, t \tag{10}$$

It is worth noting that the initial product stock, Ip_{il0}, is a model parameter, which can be adopted equal to zero if no stock is available from previous planning periods.

The parameter DM_{il} describe the maximum demands of boards of cross sectional area i and length l at the end of the planning horizon, t_{final}, and VF_{il} is the variable that defines the total sales of the product of cross sectional area i and length l, therefore:

$$VF_{il} \le DM_{il} \qquad \forall i, l \tag{11}$$

Taking into account that stems must be completely processed and logs completely cut, the production can exceed the maximum demand proposed. Then, when production excess is generated, these boards must remain in inventory. In this case, a final stock of boards of type i and length l, If_{il}, can be achieved. Then, the following balance defines this stock:

$$Ip_{ilt_{final}} = VF_{il} + If_{il} \qquad \forall i, l \tag{12}$$

This final stock If_{il} can be bounded by limited store capacity or firm policies, $CapF_{il}$:

$$If_{il} \le CapF_{il} \qquad \forall i, l \tag{13}$$

3.5. Objective function

The objectives in production planning of sawmills can vary. According to the selected performance measure, different solutions can be attained and therefore, different production plans. For example, when benefit is maximized the solution prioritizes products with high profitability. And when the yield is maximized, the production plan emphasizes the use of raw material, without considering the profitability of the obtained boards. On the other hand, when the yield is maximized, inventory costs, demand fulfillment, and profit get worse. Recently, Broz et al. (2019) analyze in detail different performance measures through the use of an approach based on Goal Programming.

In this work, the proposed objective function maximizes the net benefit, given by the difference between the income from product sales (In) and costs of the raw material (CR), production (CPr), and setup (CSt).

The sales income is calculated as:

$$In = \sum_{i,l} VF_{il}\ PV_{il} \tag{14}$$

where PV_{il} represents the selling price of board of cross sectional area i and length l.

Raw material cost, CR, is given by the cost of the stems of length f from provider a, with unit cost CSt_{afbt}, and the cost of the use of stored old logs, where $Crmp_{dl}$ is its unit cost, as expresses Eq. (15):

$$CR = \sum_{a,f,b,t} St_{afbt}\ CSt_{afbt} + \sum_{d,l,t} Qt_{dlt} Crmp_{dl} \tag{15}$$

The production cost is shown in Eq. (16), where $cprd_{dlp}$ is the unit production cost, that takes into account cost such as energy consumption, labor, etc., when CP p is applied to logs of diameter d and length l,

$$CPr = \sum_{d,l,p,t} Qp_{dlpt}\ cprd_{dlp} \quad (16)$$

while the setup cost is given by Eq. (17):

$$CSt = \sum_{p,t} cset_p x_{pt} \quad (17)$$

where the unit setup cost, $cset_p$, depends on the used CPs.

Finally, the objective function is:

$$Max\ In - (CR + CPr + CSt) \quad (18)$$

Thus, the optimization model for the simultaneous bucking and production planning in a sawmill, involves the maximization of the net benefit given by Eq. (18), and involves the Eqs. (1)–(17).

4. Numerical examples

With the aim of highlight the benefits of the integration of bucking and production tasks, two examples are presented in this section. The first one considers the simultaneous bucking and production planning in a sawmill during five working days. Then, the same example is performed without considering the coordination with the bucking activity. In this last case, this task is decoupled and solved after knowing the amount of needed logs. In this way, it is shown how the economic profit, the sawmill process performance, and raw material use get worse when the both activities are separately carried out.

For both study cases, 5 different stem lengths (f_1,..., f_5) from 3 suppliers (a_1, a_2, a_3) are considered. For each type of stem, 10 different bucking patterns, b_1–b_{10}, are provided. Logs of 4 different diameters (d_1–d_4) and lengths (l_1–l_4) can be obtained through the bucking.

Maximum demands of 18 cross sectional area (i_1–i_{18}) boards and 4 lengths (l_1–l_4, the same lengths of logs) are known, with a total of 34,526 boards. With these parameters, the CP generator is executed and a total of 2903 cutting patterns are obtained for the different diameters. For space reasons, the configuration of these CPs as well as setup and production costs and times ($cset_p$ and $cprd_{dlp}$, and ts_p and t_{dlp} respectively) are not provided, but this information is available for interested readers. In Supplementary Information section, data about BP, demands, and selling prices are displayed. Stems availability and costs for each supplier, and initial stock of logs at sawmill, are shown in Tables 1, 2 and 3, respectively.

The planning horizon is equal to 5 periods (t_1–t_5) and 8 h per period are considered; therefore $Tmax_t$ is equal to 8 for each t and each period represents a working day. The data provided for this example represent a usual scenario for a medium size firm in the northeast region of Argentina.

Both examples are implemented and solved in GAMS (Rosenthal, 2017) using CPLEX solver in an Intel(R) Core(TM) i7-3770, 3.40 GHz. The computational time limit is fixed to 1200 CPU s.

Table 1
Stems availability for each supplier.

	f_1	f_2	f_3	f_4	f_5
a_1	150	150	0	0	100
a_2	100	120	0	50	120
a_3	80	0	200	200	80

Table 2
Stems costs for each supplier.

	f_1	f_2	f_3	f_4	f_5
a_1	337.39	625.5	1078.2	836.6	480.42
a_2	371.13	687.5	1186.1	920.26	528.46
a_3	387	719.33	1239.9	962.1	552.5

Table 3
Initial stock of logs at sawmill.

	d_1	d_2	d_3	d_4
l_1	10	0	0	0
l_2	10	10	0	0
l_3	12	15	0	0
l_4	15	15	0	0

4.1. Example 1

In this section, the optimal solution considering the data previously presented for the formulation stated in Section 3, is described. The model involves 201,392 equations, 192,536 continuous variables and 44,625 binary variables, and the optimality gap in the time limit is equal to 2%. The net benefit is equal to $369,846.5 as can be observed in Table 4, where in the first column the detailed costs and sales are presented for this case. Raw material, production and setup costs represent 52.3%, 30.3% and 17.4% respectively of the total cost.

In Table 5, the amount of stems provided by each supplier per period are shown. It is worth to note that, no stems are bought on t_4 and t_5. In the table, the number of BP applied by each provider in each period is also reported. Since no storage cost for logs are imposed and all the cut stems are transferred to the sawmill, the logs required for lumber production at the last planning period can arrive in any previous period. In other words, the stems cut in a period can be used in that period or in any subsequent one. These stems are converted into logs of different sizes (diameters and lengths).

Table 4
Economic results.

	Example 1	Example 2
Income for sales	1,163,695.5	1,215,773.4
Raw material cost	414,975.1	472,040
Production cost	240,369	257,345
Setup cost	138,504.9	142,698.3
Net benefits	369,846.5	343,690.1

Table 5
Bucking operation: supplied stems by providers and used BP.

	t_1	t_2	t_3
Supplier a_1:			
Length f_1	13	14	123
Length f_2	2	132	16
Length f_5	89	11	0
BP used by a_1	8	4	3
Supplier a_2:			
Length f_2	42	0	
Length f_4	36	14	
Length f_5	1	0	96
BP used by a_2	4	1	1
Supplier a_3:			
Length f_2	5	2	
Length f_4	91		
BP used by a_3	6	1	

Table 6
Amount and type of logs that arrives at sawmill in each period.

Diameter	Length	t_1	t_2	t_3
d_1	l_1	100	39	296
	l_2	97	125	112
	l_3	76	64	0
	l_4	72	0	23
d_2	l_1	107	14	100
	l_2	100	136	208
	l_3	108	0	23
	l_4	161	234	32
d_3	l_1	100	0	0
	l_2	32	28	0
	l_3	60	0	0
	l_4	46	34	0
d_4	l_1	50	0	0
	l_2	63	28	0
	l_3	74	6	0
	l_4	88	2	0

Table 7
Planning results for each period for Example 1.

	Period				
	t_1	t_2	t_3	t_4	t_5
Purchased logs [unit]	1334	710	794	0	0
Used logs [unit]	598	513	551	565	698
Production time [h]	8	8	6.3	6.5	8
Produced boards [unit]	8344	8004	4910	5142	6468

At the end of the planning horizon, the remaining amount of stems for each supplier represents 0% (all stems are cut), 51.5% and 82.5%, respectively, of their initial availabilities. The major provider is a_1, which supplies 400 stems converted into 1386 logs of different sizes. This provider offers the lowest cost of raw material, probably because of its proximity to the sawmill. Suppliers a_2 and a_3 provide 904 and 548 logs, respectively. Table 6 describes the amount of logs of each type that arrives at sawmill in each period. Besides the logs provided by the different suppliers, the sawmill processes all the logs included in the initial stock (Table 3). Table 7 summarizes the production planning for lumber production. From the available and used logs, the log inventory can be calculated in each period. From the provided logs, 780, 977, 1247, and 690 units are stored for period t_1–t_4 respectively, while the stored logs corresponding to the initial stock of old logs is 43, 43, 16, 8 units for the same periods. That means that, at the end of planning horizon (t_5), no logs are stored. Therefore, the proposed approach coordinates the bucking and production activities in an accurate manner, avoiding log inventory and reducing raw material costs. Except for periods t_3 and t_4, the processing time takes the entire working day, and the produced boards satisfy 90.5% of the maximum demand. The number of stored boards that are not destined to satisfy the demand is equal to 1629 units, 4.9% of the total production. Table 8 shows the amount of produced board for each cross sectional area i and length l. From that table and maximum demand parameters (Table A.3), the unsatisfied demand and storage for each type of board can be calculated.

Along the planning horizon, 16 CPs are used, and some of them, as p_{21}, are repeatedly utilized. For each period, 7, 4, 3, 4, and 5 CPs are employed. Table 9 shows the number of logs processed per CP and period, where CPs p are numbered from 1 to 2903, the total of generated cutting patterns.

It is worth to mention that the model allows following the traceability of products, and justifying why some board maximum demands are not fulfilled even when there are available production time and raw material. For example, product i_{15} has the highest selling price but it demand is not fully completed. This board can be only obtained from logs of diameter d_4. Taking into account the defined BPs, these logs come from stems f_3 and f_4, which are the most expensive. On the other hand, considering the generated CPs, when different CPs are applied to logs of diameter d_4 for obtaining i_{15}, products i_{10}, i_{12} and i_{14} can be also generated depending on the selected CP. For these products, the total demands of i_{12} and i_{14} are reached (i_{12} can be obtained from logs of other diameters). Therefore, due to raw material and processing costs, it is not convenient to produce more units of i_{15} and generate boards that cannot be sold.

Nevertheless, a detailed analysis of the results of the production planning is really complicated. For example, a determined log can be obtained not only from different suppliers but also different stems and BPs. Then, the cost of a specified log is not a direct calculation. On the other hand, a certain board can be produced from different logs. Therefore, determining the cost of a certain board is not simple either. In addition, it must be considered that, for both logs and boards, when a stem is cut to obtain logs, as well as when a log is cut to obtain boards, the entire unit is processed and a set of products is generated that, either they are destined to satisfy the demand or, inevitably they must be stored in inventory. This intricate system justifies the availability of tools that allow planning considering the combinatorial amount of available alternatives, beyond the efficient use of production resources.

The model provides a lot of information about bucking and planning activities, which can be used according to the firm interests. For example, the details of the BP applied to each stem and the resulting amounts of different logs, and the conversion of logs into boards according to the applied CPs, among others. Also, different objective functions can be used for reaching the pursued performance considering the firm policy. All this elements can be easily implemented in the proposed approach.

4.2. Example 2

In order to highlight the capabilities and advantages of the simultaneous optimization of bucking and production planning in the forest industry, in this example, both activities are separately approached. First, the production planning model of the sawmill is performed, without considering logs maximum capacity and cost. Then, a bucking model is executed according to the optimal required logs determined in the planning solution with the aim of obtaining the amount of stems that the sawmill has to buy. In the first model, the objective function is to maximize the net profit given by the difference between the sales income and the production and setup costs, while for the bucking approach the raw material costs for stems purchase is minimized. The sawmill planning model has 185,995 equations, 177,239 continuous variables and 43,875 integer variables, and the optimality gap is equal to 1.7% in 1200 CPU s. The bucking model has 3099 equations, 3064 continuous variables, 150 integer variables and it was solved in 0.07 CPU s with 0% gap optimality.

The optimal solution of the production planning for the sawmill gives the program shown in Table 10. The net benefit is equal to $ 815,730.1 without considering raw material cost. This cost is added after the bucking model is executed. In the second column of Table 4, the detailed costs are depicted and the net benefit is recalculated taking into account the stems cost.

In this case, the available production time is totally used and the maximum demand is 96.9% fulfilled, which represents a greater amount than that obtained in Example 1. This is due to no raw material cost is computed in the first model, and therefore more logs are used in order to increase the benefit. The processed logs are 3166 units, more than 8% greater than the previous case. Also, 19 different CPs are used in the planning horizon, and, in each period,

Table 8
Production amounts of each type of board.

	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	i_{13}	i_{14}	i_{15}	i_{16}	i_{17}	i_{18}
l_1	2104	1132	814	1493	798	200	200	200	200	50	64	176	0	100	100	1800	0	0
l_2	1596	1400	714	1548	800	150	150	120	64	91	36	182	0	182	182	1800	1000	84
l_3	1013	0	198	1561	0	418	192	120	120	1497	0	160	0	160	160	100	0	0
l_4	1284	572	320	1202	250	160	200	160	60	194	48	180	0	180	180	1499	1000	150

Table 9
Number of used logs per CP in each time period.

Diameter	CP	t_1	t_2	t_3	t_4	t_5
d_1	p_1	15		53		
d_1	p_6					
d_1	p_{13}	38		298		
d_1	p_{21}	95	35			
d_1	p_{23}				212	
d_1	p_{85}					212
d_2	p_{122}		96			
d_2	p_{131}	116				
d_2	p_{142}				159	
d_2	p_{302}	37				159
d_2	p_{335}	148		200		
d_2	p_{361}		71		121	
d_3	p_{456}	149				121
d_3	p_{464}				73	
d_3	p_{528}					73
d_4	p_{1314}		311	53		
Total logs		598	513	551	565	698

Table 10
Planning results for each period for Example 2.

	Period				
	t_1	t_2	t_3	t_4	t_5
Used logs [unit]	592	538	634	696	706
Production time [h]	8	8	8	8	8
Produced boards [unit]	7963	7822	6605	6551	7100

Table 11
Bucking operation: supplied stems by providers.

	a_1	a_2	a_3
Length f_1	150	0	0
Length f_2	150	75	0
Length f_3	0	0	39
Length f_4	0	50	27
Length f_5	100	120	80
BP used	10	6	6

8, 2, 5, 6, and 4 CPs are utilized, some of them are repeated in the considered periods. When CPs are applied, some products that are not required are produced increasing the boards inventory. The amount of stored products is 60% greater than the previous case (from 1629 units in Example 1 to 2616 boards in Example 2). Although inventory cost is not considered, it is neither a good practice nor firm policy to produce boards that are not demanded.

According to the optimal planning solution, the amount of each type of required log is fixed in the bucking approach and it is solved to obtain the stems to be cut for satisfying the log demand of the sawmill. In this case, the model is not multiperiod since it is necessary to obtain the amount of stems from each provider. Table 11 shows results of the bucking plan, as the amount of stems by length and supplier, and the number of applied BPs. As can be observed, the total of needed stems is increased from 687 (Example 1) to 791, and consequently, raw material cost is 13.75% higher. It is worth to highlight that log inventory is not increased a lot. Only 5 units of logs remain in stock, but as was previously mentioned, a lot of not demanded boards are produced.

Adding the raw material cost to the costs of the production planning solution, the net benefit in this example is $ 1,215,773.4, which represents 7% less than the first example.

In conclusion, the solution of bucking and planning operation with a two stage model approach worse the solution not only from the economic point of view, but also from the operational context: raw material use and inventory of final products are increased as well as sales. Higher incomes are attained but the net benefit is worsen due to raw material and production costs increase.

5. Conclusions

In this work, a MILP model for the simultaneous optimization of bucking and production planning in the forest industry was presented. Usually, from an operational perspective, these problems have been addressed as two separate topics. Taking into account that at this level this industry produces commodities, the different involved actors must work in a coordinate way to achieve efficient results.

Sawmill is a key sector of the forest industry because is an important source of logs demand. The proposed formulation combines operative decisions at forest and at facility level with the objective of maximizing the net profit. The cost of a stem depends on dimensions and supplier (distance from the harvest site to the sawmill), while the cost of a board depends on the log and the way (CP) used to obtain it. Therefore, the value that a board has at the moment it is commercialized varies significantly from the decisions that have been made both in the forest and in the sawmill.

Besides, once resources are available, they must be completely consumed, otherwise they generate inventories that are difficult to manage. This applies to the case of the logs that are obtained when cutting a stem in the forest and, also, of the boards that are produced once a log is cut in the sawmill. In particular, considering the climatic conditions of the northeast of Argentina, if the logs are not processed in a reasonable time, they suffer the attack of fungi, which deteriorates their quality and market value. Thus, it is important to fit the boards production to the provided logs in order to avoid inventories. Therefore, there is a very combinatorial problem, with an important number of alternatives to be explored, which increase significantly when the problems of the harvesting and bucking in the forest are integrated with the production planning in the sawmill.

The proposed formulation allows solving the integrated problem in reasonable computational times and reaching highly efficient and competitive solutions. Also, the model solution gives detailed and valuable information about the bucking and production planning in such way that these activities can be successfully performed. Through the examples, the comparison with a sequential methodology was stated and the capabilities and the improvements of the proposed approach were established.

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Supplementary material

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