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Tactical planning of forest harvesting under different scheduling restrictions

Planejamento tático da colheita florestal considerando diferentes restrições de programação

Linamara Smaniotto Ferrari[1], Julio Eduardo Arce[1], Allan Libanio Pelissari[1], Julio Peretti da Silva[2], Afonso Figueiredo Filho[3], Edilson Batista de Oliveira[4]

[1]Universidade Federal do Paraná – UFPR, Curitiba, PR, Brasil
[2]Universidade Estadual de Santa Catarina – UDESC, Lages, PR, Brasil
[3]Universidade Estadual do Centro-Oeste – UNICENTRO, Guarapuava, PR, Brasil
[4]Empresa Brasileira de Pesquisa Agropecuária – Embrapa Florestas – EMBRAPA, Colombo, PR, Brasil

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Abstract

Tactical and operational planning are steps that guide the sequence of operations and as they are implemented, impact on the final cost of the wood. Thus, the aim of this study was to carry out the optimized production planning of forest harvesting operations regarding the wood supply for pulpwood production, in order to minimize cutting and transportation costs, through Mixed Integer Linear Programming (MILP). *Pinus* spp. stand data of a pulp company located in Santa Catarina, Southern Brazil, were used. The forest area consists of 3,714.68 hectares divided into 74 management blocks based on place and age characteristics. The approach to solve this planning was based on the test of three scenarios to minimize costs by applying different constraints: Scenario A) volume balance; Scenario B) maximum scheduling distance between blocks; and Scenario C) volume balance and maximum scheduling distance between blocks. After processing the scenarios, the *Spanning tree* algorithm was used to define the timber production routes between the blocks and the factory. The scenario A resulted in lower operational cost; however, it presented 49% (142 km) more road network than Scenario C. In contrast, Scenario B presented greater economic risk than the other scenarios, since it presented discontinuous production along the planning horizon. In conclusion, Scenario C was the best cost and risk reduction alternative. This result highlights the importance of properly structuring a management problem, since areas related to the planned activity may present a significant share of the final costs, which can influence the selection of the best solutions.

Keywords: Cost minimization; Mixed Integer Linear Programming; Techniques and forest operations.

Resumo

O planejamento tático e operacional são etapas que direcionam a sequência de operações e, à medida que são implementados, impactam no custo final da madeira. Dessa forma, o objetivo deste estudo foi realizar o planejamento otimizado de produção das operações de colheita florestal quanto ao suprimento de madeira para produção de celulose, a fim de minimizar os custos de corte e transporte através da Programação Linear Inteira Mista (MILP). Foram utilizados dados de plantio de *Pinus* spp. de uma empresa localizada no estado de Santa Catarina, Sul do Brasil. A área florestal é composta por 3.714,68 hectares, dividida em 74 blocos de manejo em função das características de localidade e idade. A abordagem para resolver este planejamento baseou-se no teste de três cenários para minimizar os custos aplicando diferentes restrições: Cenário A) balanço de volume; Cenário B) distância máxima de escalonamento entre blocos; e, Cenário C) balanço de volume e distância máxima de programação entre

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Corresponding author: linamara_ferrari@hotmail.com
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blocos. Após o processamento dos cenários foi aplicado o algoritmo *Spanning tree* para a definição das rotas de escoamento da madeira entre blocos e indústria. O cenário A obteve menor custo operacional, porém, apresentou 49% (142 km) mais de malha viária do que o Cenário C. Em contrapartida, o Cenário B apresentou maior risco econômico do que os demais cenários, pois apresentou produção descontínua ao longo do horizonte de planejamento. Em conclusão, o Cenário C foi a melhor alternativa de redução de custos e riscos. Este resultado evidencia a importância de estruturar adequadamente um problema de gestão, uma vez que áreas relacionadas à atividade planejada podem apresentar uma parcela considerável dos custos finais, o que pode influenciar na seleção das melhores soluções.

Palavras-chave: Minimização de custos; Programação Linear Inteira Mista; Técnicas e operações florestais.

INTRODUCTION

Tactical and operational planning are key components in the timber supply chain since they impact on the final cost of the wood, as they are implemented, which makes them to be critical steps that need to be well planned (Marques et al., 2014). The tactical model reports operations on smaller units of space and time to enable the operational plan, which considers more detailed location decisions related to a shorter planning period (Church, 2007).

The tactical analysis in forest harvesting is related to the selection and sequencing cut of forest stands or blocks (D'Amours et al., 2011), which determines when, where, and how much timber needs to be harvested to meet the temporal demands of volume (Buongiorno & Gilles, 2003). The analysis of the road network is another important component to be addressed in this planning stage, since the industry needs efficient roads to provide access to harvesting areas (D'Amours et al., 2011).

However, formulating a model which describes a real condition in an adequate way and that can be solved within convenient time limits becomes a difficult issue. Forest operations entail activities that are limited by the relationship between productive and economic yields, logistics costs, and environmental issues (D'Amours et al., 2011), increasing the problem complexity.

There are some solution methods and computerized tools in the literature which were developed to address optimized cut sequencing problems, such as the ones presented by Bettinger et al. (2009), Smaltschinski et al. (2012), Marques et al. (2014), and Silva et al. (2016). After the model solution and the cut schedule approval, it is possible to set up a basis for negotiating outsourcing contracts for harvest services, road construction companies, wood suppliers and traders (Marques et al., 2014) in order to minimize operational uncertainties.

Thus, the aim of this study was to carry out the optimized tactical planning of forest harvesting, in order to minimize cutting and transportation costs, considering demand constraint and spatial dispersion of *Pinus* stand blocks to be harvested over a 5-year planning horizon.

MATERIAL AND METHODS

Description of area

In this study, data were collected from a pulp company located in Santa Catarina, Southern Brazil, which uses the timber from its own forests as raw material for pulpwood production. The region's climate is classified, according to Köppen, as Cfb humid mesothermal, with average annual temperature of 17ºC, frost in winter months, and reliefs of plateaus and mountainous surfaces.

The study area was composed of a *Pinus* spp. stand of 3.714,68 ha, with ages ranging from 10 to 15 years (Figure 1) and a management cycle of 15 years. It was divided into 74 management units (blocks), according to the location and the stands' age. The relief is characterized by having 90% of the area with a slope lower than 15% and it is adequate for mechanized harvesting.

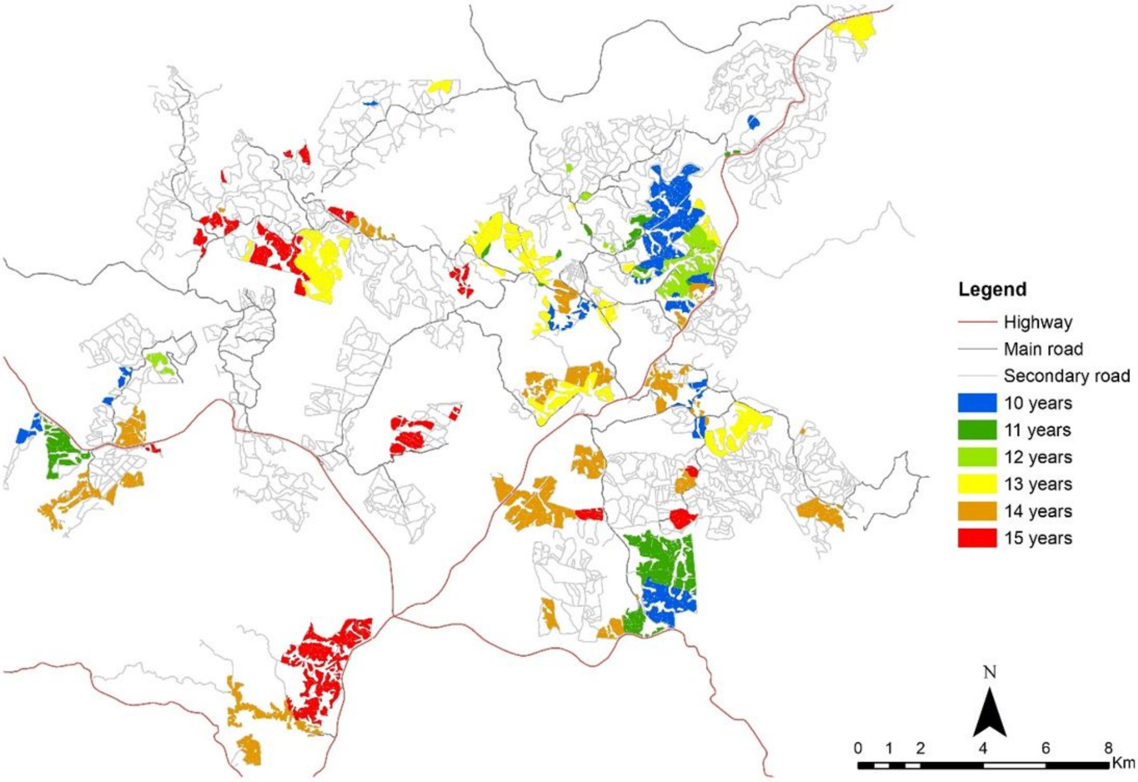

Figure 1. Initial structure of the *Pinus* spp. stand by age group.

Mathematical model

The mathematical model was formulated with the objective of minimizing costs in the forest harvesting operations, which are susceptible to production restrictions. In order to solve the problem, a Mixed Integer Linear Programming (MILP) model was used, based on the formulation of the Type I model (Johnson & Scheurmann, 1977), for the annual harvest scheduling as indicated in Equations 1 to 10, below.

$$\text{Min } Z = \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{s=1}^{S}\left[(1+t)^{-k} m_{kls}\, p_{kls}\right] + \sum_{r=1}^{R}\sum_{s=1}^{S} f_{rs} \sum_{r=1}^{R}\sum_{l=1}^{L}\left[(1+t)^{-k} w_{klrs}\right] + \sum_{i=1}^{I}\sum_{j=1}^{J} x_{ij} \sum_{k=1}^{K}\left[\left(g_{ijk} - c_{ijk}\right) * (1+t)^{-k}\right] \quad (1)$$

Subjected to:

$$h_{ks} = \sum_{l=1}^{L} q_{kls} * \left(\sum_{r=1}^{R} w_{klrs} + m_{kls}\right) \quad \forall k, \forall s \quad (2)$$

$$\sum_{s=1}^{S} w_{klrs} = \sum_{i}^{i \in r}\sum_{j}^{J}\left(x_{ij}\, v_{ijkl}\right) \quad \forall k \quad (3)$$

$$\sum_{k=1}^{K} y_{bk} \le 1 \quad \forall b \quad (4)$$

$$\sum_{i=1}^{i \in b}\sum_{j=1}^{j \in i} x_{ij} + o_{bk} = y_{bk} * a_{bk} \quad \forall b, \forall k \quad (5)$$

$$\sum_{s=1}^{S}\sum_{l=1}^{L} w_{klrs} \le \left(1+\left(\frac{u_{kr}}{100}\right)\right) * \sum_{s=1}^{S}\sum_{l=1}^{L} w_{(k-1)lrs} \quad \forall r, k \ge 2, \ldots, K \tag{6}$$

$$d_{b1b2} * \lambda_{b1b2k} < D \quad \forall k, \forall b1, \forall b2, \forall b2 \ne b1 \tag{7}$$

$$y_{b1k} * y_{b2k} - \lambda_{b1b2k} < 1 \quad \forall b2 \ne b1, \forall k \tag{8}$$

$$x_{ij} \ge 0 \quad \forall i, \forall j \tag{9}$$

$$y_{bk}, \lambda_{b1b2k} \in \{0,1\} \quad \forall b, \forall b1, \forall b2, \forall k \tag{10}$$

Where:
I : Number of stands in the forest;
B : Number of blocks in the forest;
J : Number of management regimes;
K : Number of years of the planning horizon;
L : Number of forest products;
S : Number of destinations;
R : Number of regions;
t : Annual interest rate;
m_{kls} : Wood volume (m^3) purchased from third-party suppliers, of product l, in the year k, and assigned to the destination s;
p_{kls} : Purchase cost (R$ per m^3) of the product l, in the year k, and allocated to destination s;
w_{klrs} : Wood volume generated (m^3) by region r, of product l, when harvested in the year k, and allocated in the destination s;
f_{rs} : Freight cost (R$ per m^3) regarding the region r for the destination s;
g_{ijk} : Present income (R$ per ha) obtained from sawn wood sales (minimum diameter of 28 cm and length of 2.60 m) to third-party suppliers regarding the stand i, year k, and management regime j;
c_{ijk} : Cost of wood production (R$ per ha) generated by stand i when harvested in the year k, and using the management regime j;
h_{ks} : Volume demanded (ton) in each period of the planning horizon k for the destination s;
q_{kls} : Conversion factor (m^3 in ton) applied in each product l, destination s, and period of the planning horizon k;
v_{ijkl} : Wood volume generated (ton/ha) by stand i, of product l when harvested in the year k, and using the management regime j;
u_{kr} : Maximum percentage of volume variation (%) in each period of the planning horizon k in the region r;
d_{b1b2} : Minimum path (km) between blocks $b1$ and $b2$;
D : Maximum dispersion between blocks;
x_{ij} : Cutting area of the stand i (ha) with application of management regime j;
o_{bk} : Idle cutting area (ha) of the block b in year k;
a_{bk} : Area (ha) of the block b in year k.
y_{bk} : Binary variable that assumes 1 in case block b is chosen to be part of the solution in the year k, or assumes 0 otherwise;
λ_{b1b2k} : Binary variable that assumes 1 in case the arc connecting blocks $b1$ and $b2$ is select for the solution in the year k or assumes 0 otherwise.

The objective function (1) aims at minimizing harvest costs taking into account the investments in wood purchase of the market, freight and cost of production. The constraint (2) guarantees the industry's wood demand is met along the planning horizon through the sum of the harvest volume and purchased wood from third-party suppliers. As the demand parameter was established in tons, a conversion factor between m^3 to tons was used in this restriction. Constraint (3) ensures the conservation of the annual volume flow between timber production and supply as the amount of volume produced in the regions must be the same as that received at the destinations. Constraint (4) requires each stand to be harvested only one time over the planning horizon. The constraint (5) requires that the area of each block must be composed of the sum of the cut areas and unscheduled cut areas. The restriction (6) represents the total volume production during the period k, which can range up to 10% of the volume of period k-1. The restrictions (7) and (8) limit the scheduling between production units to a maximum dispersion, in a same year. The constraint (9) ensures that the decision variable does not assume a negative value, and the constraint (10) imposes that the decision variables assume only binary values.

In this way, three cost minimization scenarios were evaluated under different constraints in the tactical forest scheduling of harvesting operations. The first scenario (scenario A) sought to balance the production volume in the planning horizon. Scenario B was limited to scheduling harvesting areas with up to 23 km of distance between blocks (distances of less than 23 Km resulted in unfeasible solutions). On the other hand, scenario C worked with all constraints imposed in scenarios A and B (Table 1). In addition, the scenarios were evaluated on a computer with an Intel® Core ™ Duo CPU 2.93 GHz and 4Mb RAM.

Table 1. Evaluated scenarios in the optimization process considering the objective function of present cost minimization.

Scenario	Name	Constraints
A	Volume balance	2 - 5, 8 - 9
B	Maximum scheduling distance between blocks	2 - 4, 6 - 9
C	Volume balance + Maximum scheduling distance between blocks	2 - 9

Planning parameters

The company's products are classified as pulpwood (minimum diameter of 8 to 28 cm and length of 2.4 m) and sawn wood (diameter above 28 cm with a length of 2.6 m). The pulpwood assortment is allocated exclusively to the industry's supply for pulp production, while the sawn wood assortment is marketed without the commitment to meet a specific demand. Thus, the sawn wood sales in the local market complement the company's income.

The annual production demand for the industry supply was established to be 337,500 tons of pulpwood assortment for the first year, and 450,000 tons for the other four years of the planning horizon. However, as the volume demanded by the industry uses tons as the measurement unit and the forest-volume projections use the unit m^3, a factor of 0.95 was used to convert the cubic meter into tons. Furthermore, the production estimates were set by using the *SisPinus*®software (Empresa Brasileira de Pesquisa Agropecuária, 2017), which is internally driven by the *OpTimber-LP* software (Optimber Otimização e Informática Ltda, 2017).

The forest cost data were obtained through the sum of production costs, timber purchase, and freight costs. They were submitted to a fixed interest rate of 10% per year. All prices and costs applied in this study correspond to the values practiced by the company in 2016, which were equivalent to R$ 19.74 per m^3 (US$ 1 ≈ R$ 4.05) and R$ 24.42 per m^3 of wood harvested in flat areas (below 15% slope) and undulating relief (above 15% slope), respectively. The factory's freight costs, which were limited to the pulpwood volumes, varied according to each block location. The market purchase price of the pulpwood was R$ 66.50 per m^3 and the sales price of sawn wood was R$ 125.88 per m^3.

Generation of the route planning for harvest access

Harvest planning considerably affects decisions related to the remaining operations of the supply chain, such as the transportation costs, the costs of transferring forest machines between sites, and the costs of producing and distributing the wood-based products (Marques et al., 2014). Moreover, according to Machado & Lopes (2014), harvesting and forest transportation represent at least 50% of the final costs of wood delivered to the industry. Both operations can affect the viability of management plans (D'Amours et al., 2011). This study also aimed at evaluating the total road distances to be used in each scenario, because of the importance of a joint analysis of these areas in the decision making process.

For this purpose, the *Spanning tree* algorithm was implemented in the *LINGO* software (Lindo Systems Inc., 2017) to create minimum path matrices for each period of the evaluated scenarios. Thus, the harvest scheduling solution generated by the *OpTimber-LP* (Optimber Otimização e Informática Ltda, 2017) was used as a basis to sequence the cutting order of the selected blocks in each year. The algorithm was applied considering that each block and the destination (the industry) were classified as a node, and the roads that connect the nodes were considered as edges. The *Spanning tree* algorithm involves choosing a set of paths with the shortest total length, given a connected network, but not directed to a specified destination (Clark et al., 2000).

RESULTS AND DISCUSSION

In this paper, different scenarios were assessed to optimize the forest harvesting tactical planning and to minimize the cutting and transportation costs, considering different constraints. Initially, different harvest scheduling scenarios were optimized and resulted in 36,263 decision variables, of which 27,380 corresponded to integer variables. After this stage, the shortest total distances between the selected blocks in each scenario to the industry were evaluated.

From the solutions of the scenarios, it can be observed that the company will need to buy pulpwood to supply the minimum demand required for pulp production in some years (Figure 2). In addition, all the evaluated scenarios used the total area available to meet the pulp demand along the planning horizon.

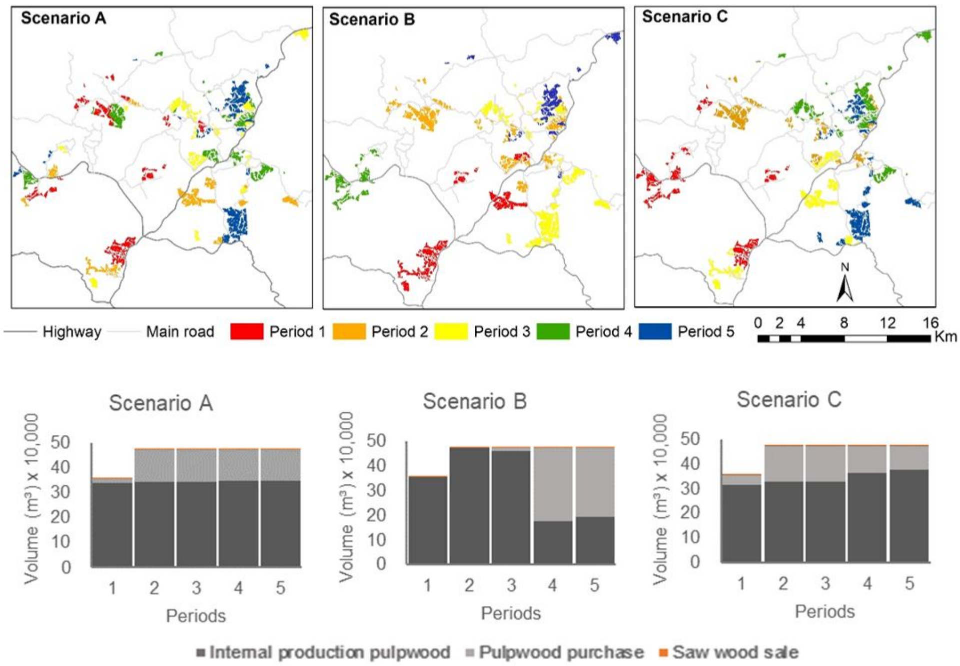

Figure 2. *Pinus* spp. stand harvesting tactical scheduling of scenarios A, B, and C. The upper part of the figure shows the spatialization of the cutting units in each year of the planning horizon. The lower part of the figure shows: the annual volume quantity of the internally produced pulpwood assortment (dark gray); the amount of pulpwood assortment that needs to be purchased from third-parties (light gray); and the production of the sawn wood assortment intended for sale (orange).

According to the spatial results presented in Figure 2, the scenarios tended to program older cutting areas to meet the demand and reduce part of the production costs by selecting areas with sawn wood. Even though scenario A was subjected to the volume balance constraint, it provided a larger search space for solving the problem, as it did not use the 23 km cut aggregation constraint. It also resulted in a geographically dispersed annual harvesting schedule (e.g., Period 1 and Period 3 shown in red and yellow on the map). Therefore, scenario A presented a pulpwood production larger than scenarios B and C (Table 2), reducing the company's need to buy wood from the market. It resulted in a lower current cost (Figure 3), as the sum of production and freight costs corresponded on average to 55.6% less than the purchase value from third-party suppliers.

Table 2. Optimization outcomes for 5 years of planning regarding the total volume obtained in each scenario.

	TOTAL VOLUME (m^3)		
Application	**Scenario A**	**Scenario B**	**Scenario C**
Internal production pulpwood	1,723,338.00	1,659,200.90	1,713,457.90
Pulpwood purchase	526,661.99	590,799.05	536,542.06
Sawn wood sale	1,857.11	6,257.57	5,618.45

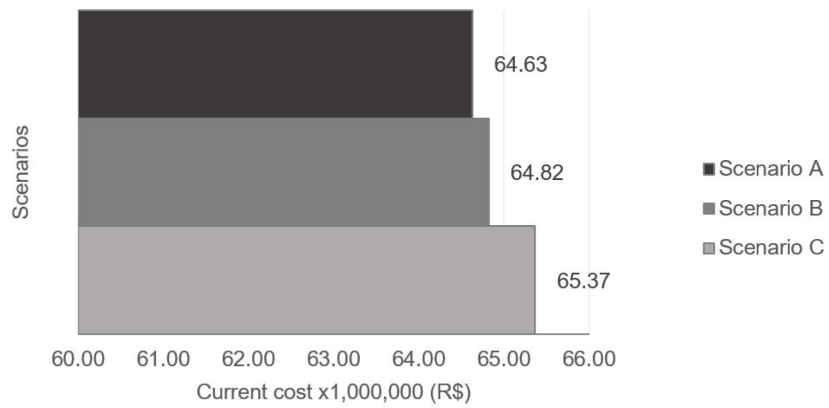

Figure 3. Current cost of the harvest scheduling optimization process of a *Pinus* spp. stand.

On the other hand, scenario B limited the harvest scheduling in up to 23 km and did not use the annual volume balance constraint by area. These limitations enabled the strategy to concentrate on more cutting volume at the beginning of the planning horizon in order to minimize the total costs (Figure 2). However, as scenario B was able to concentrate a higher cutting volume in the first periods, it resulted in a lower total pulpwood production. Furthermore, as scenario B restricted the maximum spatial dispersion between harvesting units, it limited the amount of cutting units available to be scheduled. In this way, these limitations agreed with the lower amount of pulpwood obtained, highlighting the need to purchase 12% more wood in scenario B than in A (Table 2).

Although scenario B showed a greater pulpwood purchase need than scenario A, it presented only 0.3% of difference in the current cost (Figure 3). This can be confirmed by assessing Figure 2, in which there is a higher need to buy wood in the last two years in scenario B. Thus, the decapitalization of the monetary value of the 4th and 5th periods become more evident than when the values are fractionated over the planning horizon, as they occur in scenarios A and C.

Scenario C, with the inclusion of the volume balance and scheduling distance limit constraints, provided a more restrictive strategy with low flexibility in scheduling harvesting operations. Thus, scenario C resulted in a lower amount of pulpwood than scenario A and, consequently, a higher purchase of wood is required.

Even though scenario C required only 2% (Table 2) more pulpwood purchase than scenario A (instead of 12% between scenarios B and A), it resulted in the costliest solution of this study (Figure 2). This is also related to the previously mentioned decapitalization. In scenario C there was a higher need to purchase wood from the market at the beginning of the planning horizon in contrast to scenario B, which postponed the purchase and limited it to only two years, resulting in a lower current cost.

Although scenario B was able to aggregate harvesting blocks and meet the company's supply-demand, it resulted in the scenario with the highest risk as the annual production was not sustainable. The discontinued production over the planning years makes it possible to face opportunity costs from the market and economic losses due to gaps in the production process (Augustynczik et al., 2015).

Thus, due to the more balanced variations in timber production between scenarios A and C, the shortest total road distances between the industry and the cutting blocks of each scenario were evaluated because as the forest is managed the transportation costs change. The results showed that although scenario A resulted in lower current cost, it presented 49% (142 km) more road network than scenario C (Figures 2 and 4). Nevertheless, Öhman & Eriksson (2010) emphasize that the benefits generated from an aggregate harvest, such as the reduction of road construction and maintenance, and the transport of harvesting machines between harvesting sites, are not capitalized. The economic impact generated from the aggregation of harvest blocks can be lower than the costs evaluated (Öhman & Eriksson 2010). In addition, the costs related to the aggregation of harvesting units occur only in the first rotation, but the economic benefits generated for the harvesting and maintenance of the roads are compensated by the subsequent rotations (Augustynczik et al., 2016).

Hence, it is fundamental to combine harvesting decisions and road investments because the forest industry is highly dependent on an efficient road network, which allows the access between harvesting areas and the targeted market (Marques et al., 2014). Therefore, scenario C presented the best cutting plan among the scenarios tested since it was able to group the harvesting blocks and work with the volume balance over the years, resulting in lower opportunity risk for the company.

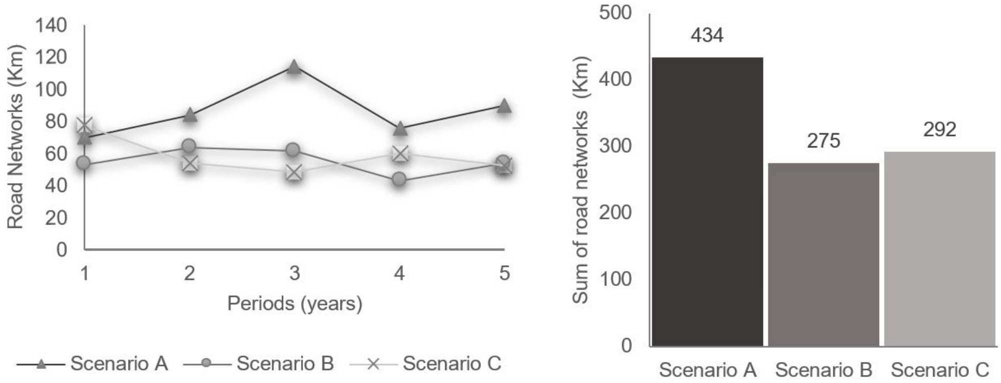

Figure 4. Recurrent sum of the road networks (km) used in *Pinus* spp. stand harvesting scenarios.

CONCLUSIONS

- The scenarios presented different opportunity risks related to the company's wood supply.
- The spatial scheduling of cutting scenarios affect the cost associated with the forest harvesting operation.
- Scenario C, which minimized costs and presented volume balance limitations over the planning horizon and harvest spatial dispersion, presented itself as the best remuneration alternative and showed a lower opportunity risk than the other scenarios.

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