SCIENTIA
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Strategies for regulating timber volume in forest stands

Estratégias para regular o volume de madeira em povoamentos florestais

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Resumo

Os objetivos desta pesquisa foram: 1) avaliar duas estratégias de otimização para minimizar a diferença entre a máxima e mínima produção anual e minimizar os desvios de produção entre anos consecutivos; 2) comparar a sua performance com dois modelos tradicionais para regular o fluxo de volume de madeira. O problema deste estudo representou a situação real de uma empresa localizada no estado de Santa Catarina, Brasil, onde a estrutura da floresta estava altamente irregular, devido ao predomínio de povoamentos em idades avançadas. Alternativas de manejo foram propostas para cada povoamento e a programação linear foi usada para otimizar a estrutura da floresta. As estratégias alcançaram a demanda industrial de madeira em todos os períodos do horizonte de planejamento. O modelo que maximizou a produção (Estratégia 1) e o valor presente líquido (Estratégia 2) resultou na maior produção de volume e no maior retorno financeiro, respectivamente. No entanto, produção homogêneas de madeira foram obtidas usando as funções objetivo que minimiza a oscilação entre a máxima e mínima produção anual (Estratégia 3) e o desvio da produção entre anos consecutivos (Estratégia 4), quando comparadas com modelos tradicionais (Estratégia 1 e 2). A Estratégia 4 foi a mais apropriada, pois proporcionou retorno financeiro e volume de sortimentos satisfatório a longo prazo, reduzindo possíveis problemas operacionais que podem ocorrer.

Palavras-chave: Planejamento florestal; Regulação florestal; Pesquisa operacional; Manejo otimizado.

Abstract

The objectives of this research were: 1) evaluating two optimization strategies for minimizing the difference between maximum and minimum annual production and minimizing the production deviation between consecutive years; 2) comparing their performance with two traditional models to regulate the flow of timber volume. The problem given in this study represented a real situation of a forest company located in the state of Santa Catarina, Brazil, where the forest structure had become highly irregular due to predominance of trees with advanced ages. We proposed management alternatives for each stand, and linear programming was used to optimize the forest structure. The strategies achieved the industrial timber demand in all periods of the planning horizon. The models that maximized the production (Strategy 1) and the net present value (Strategy 2) resulted in the highest timber volume production and the highest financial return, respectively. However, we obtained homogeneous timber production by using the objective functions that minimize the maximum and minimum annual production oscillation (Strategy 3) and deviation production between consecutive years (Strategy 4), when we compared to traditional models (Strategy 1 and 2). The Strategy 4 was the most appropriate for providing satisfactory financial return and timber volume in the long-term, reducing possible operational problems that could occur.

Keywords: Forest planning; Forest regulation; Operational research; Optimized management.

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INTRODUCTION

Forest operational planning is a fundamental task for any company in a competitive environment, as it allows establishing priorities and defining actual strategies to achieve satisfactory results in the future (CAMPOS et al., 2013). The efficient production planning has great potential to reduce uncertainties involved in the decision-making process and to increase possibilities of achieving objectives and goals established by the company (REBOUÇAS, 2002).

In general, forest companies have the outstanding feature of requiring a detailed and efficient planning of all forest operations, which is the reason of long forest rotation. Planning requires that mathematical, statistical and computational tools are daily essentials for the planner, since they help to identify problems related from silvicultural activities to log processing systems.

However, forest planning was only boosted in 1940s, when George Dantzig developed a procedure of matrix calculation related to linear programming. The simplex algorithm creator caused a revolution by developing a mathematical procedure able to solve quite complex and large-scale problems (GOMIDE, 2009) in a relatively short-term.

From the appearance of the linear programming and its success in solving planning problems, forest managers could simulate many combinations of silvicultural activities and select the one most appropriate for a particular stand. Thus, decision-making about timber and non-timber forest production has been based on more sophisticated and consistent information, which are results of technical-scientific analysis, and not only based on the planner's empirical knowledge (FIORENTIN, 2016).

The balanced planning of forestry operations is often supported by mathematical techniques based on linear programming modes (RODRIGUEZ; BORGES, 1999). Linear programming is a mathematical procedure largely applied to solve long-term forest management problems (JOHSON; SCHEURMANN, 1977). According to Öhman and Eriksson (2002), the computational efficiency is one reason to use this method, aside from its versatility in formulating constraint matrices, which can be made by practically any growth projection model.

Other more modern and robust solution methods may also be found in forest literature, such as the heuristics applied by Bettinger and Zhu (2006), Ghaemi and Feizi-Derakhshi (2014); Gomide et al. (2013); Nascimento et al. (2012), Pukkala and Heinonen (2006), Silva et al. (2009). Non-spatial optimization problems are formulated efficiently by linear programming (HEINONEN, 2007). Furthermore, it also allows to achieve the global optimal value of the system (FALCÃO; BORGES, 2003), but cannot be obtained using heuristic techniques in many cases.

Even with the assistance of optimization techniques, it is fundamental to formulate different optimization strategies for regulating the stand volume structure. The analysis of different optimization sceneries is a powerful tool that can be used to predict in the long-term the effects of the forest management systems (NORDSTRÖM et al., 2013). Thus forest companies can avoid possible deficits of timber assortments in the long-term as well, being less susceptible to forest market fluctuations.

Nowadays, companies are including the regulation of forest production in their planning. This fact is directly associated with the uneven-flow timber production, caused mainly by the fast expansion of the forest companies over recent years. Still operational research techniques play an important role in the forest sector in decision-making processes (SILVA, 2001). The forest volume regulation is still a laborious and time-consuming procedure, due to the large quantity of decision variables and constraints that must be considered in the planning, requiring thus high time consumption for data processing and analysis of the results.

Due to the importance of the long-term planning in the forest company sustainability, this paper aimed at: (1) evaluating two optimization strategies in order to minimize the difference between the maximum and minimum annual production and minimize the production deviations between consecutive years; (2) compare their performance for regulating the forest stand volume structure with production and net present value maximization in traditional models. Therefore, we considered the hypothesis that the optimization models proposed in order to minimize the oscillation and production deviations are more efficient to regulate the annual flow of timber assortments, when compared to maximization models.

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MATERIAL AND METHODS

Problem description

The problem solved in this research is a real situation found in a forest company located in Santa Catarina State, southern Brazil. The proposal consisted of regulating the forest production in the pine stands (*Pinus* spp.) caused by existing uneven planted areas in some ages (Figure 1).

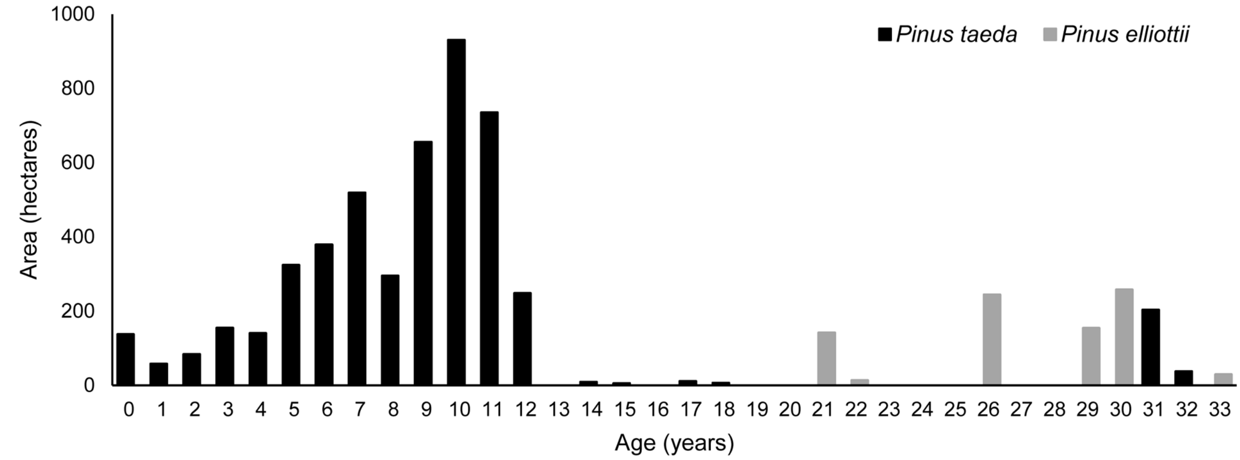

Figure 1. Forested area by age for both pine species.
Figura 1. Área de floresta por idade para ambas as espécies de pinus.

The total forested area corresponds to 5,786.75 ha with pine species distributed in 165 stands, with sizes ranging from 0.83 to 179.87 ha and a mean equal to 35.07 ha. From the total forested area, around 80% is under 12 years and 16% is above 26 years old. The total area by species is 4,942.53 ha (85.41%) for *Pinus taeda* L., and 844.22 ha (14.59%) for *Pinus elliottii* Engelm.

Management systems

Forest planning is often formulated by selecting the optimal combination of silvicultural treatments in many management alternatives (KURTTILA, 2001). Thus, we simulated different management alternatives aiming to regulate the volume structures in each of the stands. The first step in regulation consisted of developing three management systems through which the stands were classified into each one, according to pre-regulated conditions of thinning and clear-cutting periods (Figure 2).

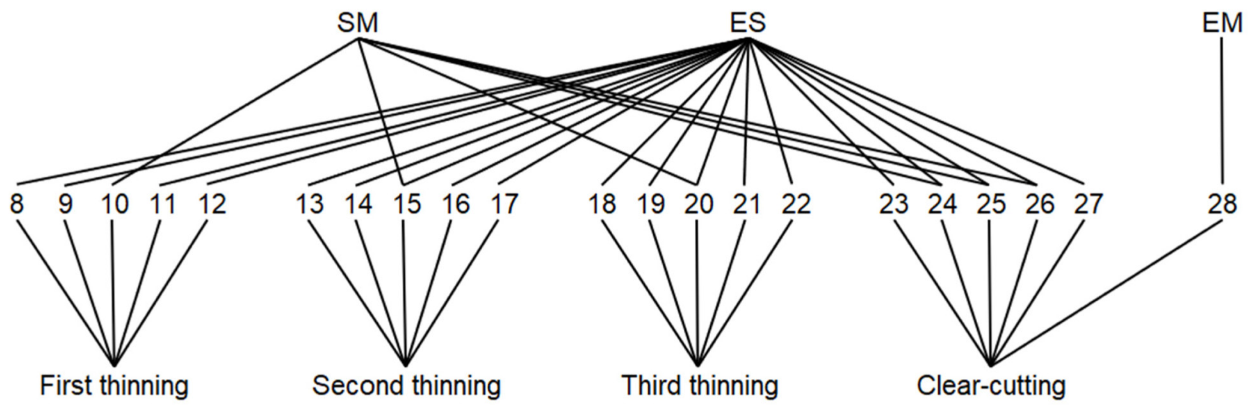

Figure 2. Standard management (SM), established stand management (ES) and exception management (EM) systems simulated by age for the pine stands.
Figura 2. Sistemas de manejo padrão (MP), manejo de povoamentos estabelecidos (ME) e manejo de exceção (ME) simulados por idade para os povoamentos de pinus.

We considered as standard management system (SM) the pine stand management that is considered ideal by the forest company. In this system, three pre-commercial thinning occurred at stand ages of 10, 15, and 20 years, respectively. The clear-cutting age ranged from 24 to 26 years.

To compose the alternative management systems we enlarged the thinning and clear-cutting periods from the standard one. We formulated a management system of established stands (ES), proposing the first rotation age to be more flexible than the SM. Stands belonging to this system had the first thinning applied between 8-12 years; the second between 13-17 years; the third between 18-22 years; and clear-cutting between 23-27 years.

The exception management system (EM) was the last alternative system studied, and it integrated stands older than 28 years. Clear-cutting was planned to occur up to 12 years of the planning horizon in order to avoid that all the older stands were harvested in the first year of the planning horizon. A further constraint was imposed so that thinning and clear-cutting would occur only three years after the last forest activity.

For all simulated management systems the thinning regime was determined as the first thinning from below, with 50% density removal, plus a systematic thinning to each seven lines; the second and third ones were thinning from below with 40% and 30% density removal, respectively.

Economic evaluation

We used average values of costs involved in the establishment and maintenance of the forest stands, thinning, and clear-cutting provided by the forest company (Table 1). The average costs for establishing and maintaining the forest stands are related with the herbicide manual application, ant control before and after planting, and seedlings replanting. We didn't consider the mechanized loading timber expenditures on the thinning and clear-cutting costs. The dollar quotation used was 3.14.

Table 1. Mean costs of the forest operations at each age of intervention in the pine stands.
Tabela 1. Custos médios das operações florestais em cada idade de intervenção dos povoamentos de pinus.

Forest operation	Age (years)	Cost
Planting and maintenance	0	636.94 $\$.ha^{-1}$
1st Thinning	8 a 12	12.10 $\$.ton^{-1}$
2nd Thinning	13 a 17	11.15 $\$.ton^{-1}$
3rd Thinning	18 a 22	10.51 $\$.ton^{-1}$
Clear-cutting	≥ 23	9.55 $\$.ton^{-1}$

The timber assortments (Table 2) into sawn, special sawn and veneer were configured for own consumption by the forest company, while the pulpwood class was intended exclusively for sale on the forest market. The timber class for energy was disregarded in the modeling, because this kind of product remained in the forest after thinning and clear-cutting operations.

Table 2. Dimensions of the timber assortments and market values.
Tabela 2. Dimensões dos sortimentos de madeira e valores de mercado.

Assortments	Diameter limits (cm)	Log length (m)	Price ($\$.m^{-3}$)
Firewood	< 8 cm	-	-
Pulpwood	≥ 8 < 18	1.60	6.47
Saw-log	≥ 18 < 25	2.50	15.03
Special saw-log	≥ 25 < 35	2.50	25.03
Veneer	≥ 35	2.20	42.45

Mathematical models

We solved the forest regulation based on the Type I model, as proposed by Johnson and Scheurmann (1977), and using four optimization strategies, which provided different decision-makings according to the forest stand. The performances of the strategies were compared in the regulation process. Two new minimization objective functions were proposed in this study aiming to compare them with two traditional maximization objective functions. The same basic and specific constraints for the minimization models were applied in all mathematical formulations.

Objective functions

The first objective function (Strategy 1) was modeled to maximize the production of timber assortments (01).

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$$MaxVOL = \sum_{i=1}^{M} \sum_{j=1}^{N} (X_{ij} \sum_{k=1}^{PH} VOL_{ijk}) \quad (01)$$

The second objective function (Strategy 2) was modeled to maximize the general net present value (NPV) from the timber assortments (02). This economic criterion is frequently used in forest optimization models, as can be observed in Hahn et al. (2014); Gomide et al. (2010; 2013); Silva et al. (2006).

$$MaxNPV = \sum_{i=1}^{M} \sum_{j=1}^{N} (NPV_{ij} X_{ij}) \quad (02)$$

The third objective function (Strategy 3) was modeled to minimize the difference between the maximum and minimum annual production of timber assortments (03).

$$MinDIF = Min(MinMax - MaxMin) \quad (03)$$

Lastly, the fourth objective function (Strategy 4) was modeled to minimize the absolute deviations of timber assortment productions between consecutive years (04).

$$MinDEV = VOLDEV \quad (04)$$

Constraints

The basic constraints (05) were used to indicate the availability of maximum area of each stand and to ensure the sum of the area of a same stand be equal to its total, under different management alternatives.

$$\sum_{j=1}^{N} X_{ij} \le A_i; \forall i \quad (05)$$

The basic constraint of timber demand (06) to supply the industrial consumption was used to ensure the average production flow was obtained in all periods of the planning horizon, which was defined as being 96,000 $m^3.year^{-1}$ for all optimization models. The timber overproduction of sawn, special sawn and veneer were configured to be destined to the forest market.

$$\sum_{i=1}^{M} \sum_{j=1}^{N} VOL_{ijk} X_{ij} = 96{,}000; \forall k \quad (06)$$

Besides these constraints, the optimization model (03) requires the constraints (07) and (08) together with its objective function, in order to minimize the difference between the maximum and minimum annual production of timber assortments.

$$\sum_{i=1}^{M} \sum_{j=1}^{N} (VOL_{ijk} X_{ij}) \le MinMax; \forall k \quad (07)$$

$$\sum_{i=1}^{M} \sum_{j=1}^{N} (VOL_{ijk} X_{ij}) \ge MaxMin; \forall k \quad (08)$$

The constraints (09) and (10) were applied to the optimization model (04) with its objective function, in order to minimize the absolute deviations of assortment production.

$$VOL_k - VOL_{k-1} < VOLDEV; \forall k > 1 \quad (09)$$

$$VOL_{k-1} - VOL_k < VOLDEV; \forall k > 1 \quad (10)$$

Where: PH = planning horizon; NPV_{ij} = net present value ($) of i-th stand following j-th management alternative; VOL_{ijk} = volume (m^3) produced at i-th stand following j-th management alternative on period k; MinMax = lowest of the maximum production possible in PH; MaxMin = highest of the minimum production possible in PH; VOLDEV = absolute deviation of volume (m^3) in consecutive years; X_{ij} = fraction of area (ha) of i-th stand following j-th management alternative; A_i = total area (ha) of i-th stand at the beginning PH; M = total number of stands; and N = total number of management alternatives of i-th stand.

The performance analysis of each optimization strategy was based on iteration numbers required to obtain the optimal solution; in the forest structure after regulation; in the dynamic of the gross and net revenue and the costs involved in each planning horizon; and in the timber volume and financial returns obtained for each one.

Solving the problem

The resolution of the proposed problem was performed using the Op-Timber-LP® software that optimizes strategic forest planning. This software may run various calls with the SisPinus® growth and yield simulator (Oliveira, 1995), and the LINGO®, developed by LINDO Systems INC for the optimization of linear and non-linear programming problems.

The simulation of the different management alternatives by stand was performed using SisPinus®, which was configured with the fifth-degree polynomial equation to estimate the volume for each timber assortments. In addition, the total volume estimates for each stand were obtained adding the assortments produced in each class. Then simulated management alternatives were optimized by adopting Simplex algorithm using LINGO® software. Finally, the planning horizon was determined as 50 years, in order to ensure that the forest regulation of the pine stands be regulated in approximately two forest rotations.

RESULTS AND DISCUSSION

The optimization strategies proposed for regulating timber production of the pine stands resulted in feasible solutions. The iteration number required to achieve the optimum showed large variations among the mathematical models. The smallest iteration number was equal to 119 and was obtained in the Strategy 1 that maximized the assortment productions, followed by Strategy 2 with 173 iterations; where the objective was to maximize the net present value.

On the other hand, the Strategy 3, which minimized the difference between the maximum and minimum annual production, resulted in the highest iteration number and was equal to 609. This result was close to the iteration number of 598 obtained in Strategy 4, which minimized the absolute deviations of the timber assortment production between consecutive years. These results are directly correlated with the more complex formulation in the minimization mathematical models and their additional constraints.

The pine stands structure was regulated in all optimization strategies (Figure 3). The models provided even-flow productions for the company consumption, besides the industrial demands of 96,000 m^3 were reached in all planning horizons. According to Hahn et al. (2014), the even-flow production offers the possibility to balance goals such as similar harvests at different points over time. However, overproduction of timber assortments was obtained in all periods of the planning horizon, which were destined for sale on the forest market.

The strategies formulated with the minimization objective function resulted in homogeneous production of the total timber volume (Figure 3), when compared to the maximization strategies, especially during the early years of the planning horizon, where productions were less homogeneous. Strategy 3 also provided homogeneous production of timber volume in many periods (Figure 3). This result was similar to that obtained in the Strategy 4, in which the produced timber volume was very close between consecutive years. For both minimization strategies, the maximum annual volume production was lower than 300,000 m^3.

On the other hand, Strategy 1 resulted in high timber volume productions in many periods of the planning horizon, being higher than 1,000,000 m^3 in the first year (Figure 3). However, lower variations were observed in the Strategy 2, where the maximum volume was close to 600,000 m^3 in the first period. Similar results were obtained by Carvalho (2012), where the volume was always lower for the minimization models. According to this author, the cost minimization methods are very interesting to supply the industry demands with smaller cutting areas.

Strategy 1 resulted in larger values of gross and net revenues in the years of higher production (Figure 4). This result was similar to that observed in Strategies 2 and 3, but at lower intensity. However, the costs and revenues were almost constant to that of Strategy 4 during all planning horizons.

In some years of the planning horizon, negative net revenues were obtained in all optimization strategies (Figure 4), indicating that the obtained revenues were not able to overcome the costs involved during those periods. These results can be associated to the periods in which the area size submitted to the first thinning was quite large. Thus, the most part of the produced timber assortment was destined to pulpwood class, due to the sizes of the trees with low economic value.

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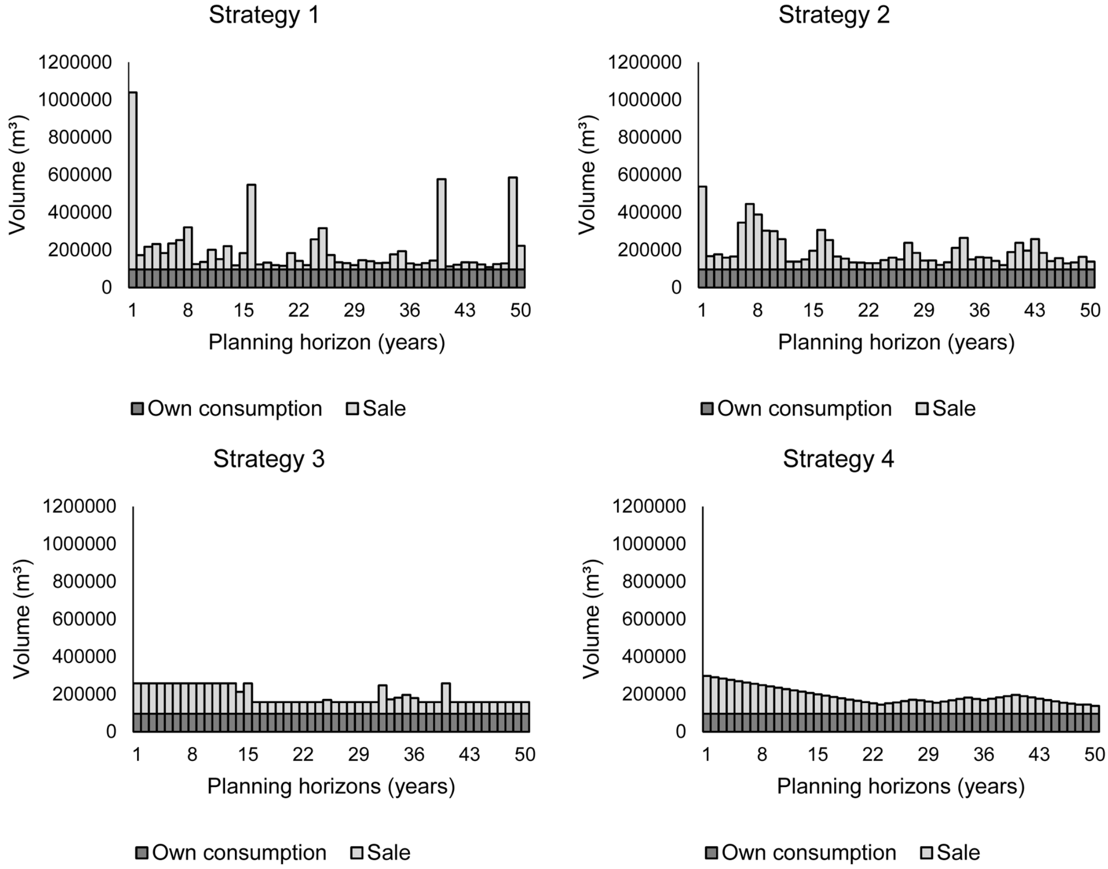

Figure 3. Timber volume for company consumption and for sale obtained by optimization strategies simulated for the pine stands.
Figura 3. Volume de madeira para consumo interno e para venda obtido por estratégia de otimização simulada para os povoamentos de pinus.

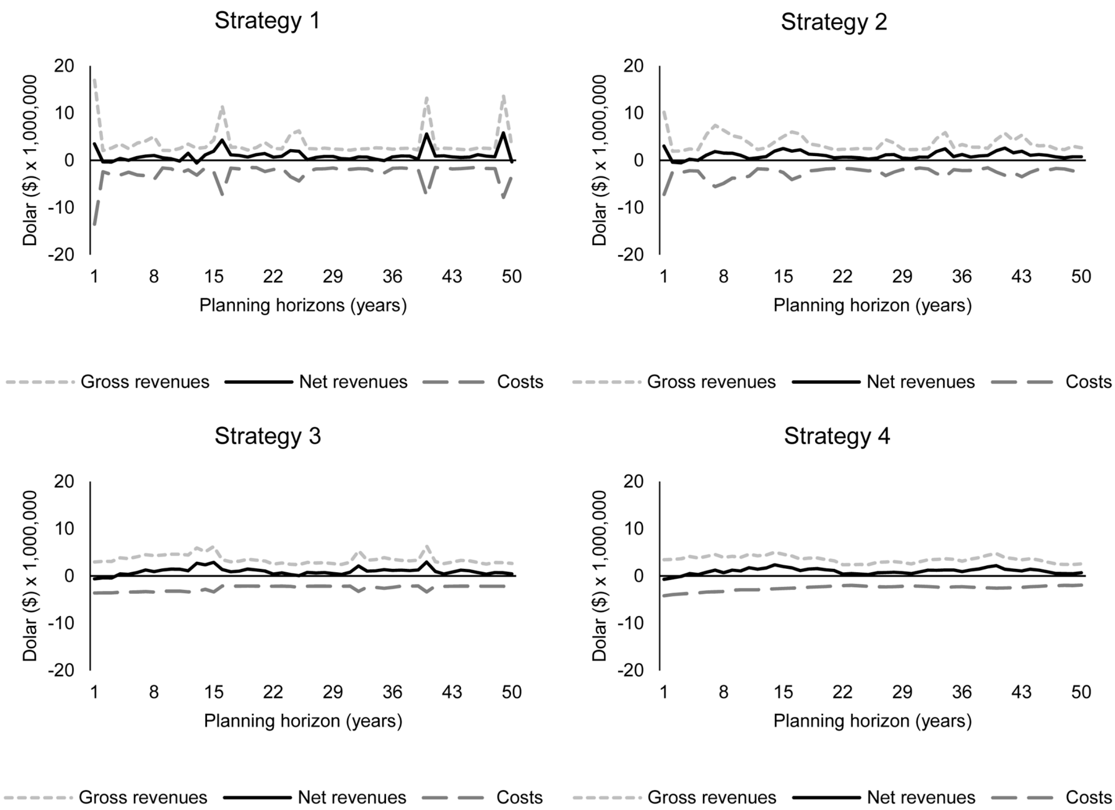

Figure 4. Gross and net revenues and costs obtained by optimization strategies simulated for the pine stands.
Figura 4. Receita bruta e líquida e custos obtidos por estratégia de otimização simulada para os povoamentos de pinus.

Strategy 1 resulted in the largest annual timber production, while the largest financial return was obtained using Strategy 2 (Table 3). This fact also indicates that the maximum production does not affect the maximum revenue. The results obtained in this research were similar to those of Carvalho (2012), where the largest production and financial return were reached by the models that maximized the forest production and net present value, respectively.

Table 3. Annual average and total of timber volume, and financial returns obtained by optimization strategies simulated for pine stands.
Tabela 3. Média anual e total de volume de madeira e retorno financeiro obtido por estratégia de otimização simulada para os povoamentos de pinus.

Optimization strategy	Average	Total
Timber volume (m^3)		
Strategy 1	228,283.91	11,414,195.62
Strategy 2	196,935.51	9,846,775.74
Strategy 3	193,389.14	9,669,456.96
Strategy 4	191,933.66	9,596,683.16
Financial returns ($)		
Strategy 1	1,033,012.93	51,650,646.50
Strategy 2	1,096,516.19	54,825,809.55
Strategy 3	988,485.38	49,424,269.11
Strategy 4	1,023,114.96	51,155,747.77

The minimization models, although providing lower financial returns when compared to maximization models (Table 3), were very efficient to regulate thinning and clear-cutting, resulting in more homogeneous production over time, especially in the first years of the horizon planning. In this sense, both minimization strategies were interesting to reduce the operational problems that may occur. Therefore, the model that minimized the production deviations between consecutives years (Strategy 4) presented the best result, due to larger financial returns.

In forest-harvest problems found in literature, we note that there is a preference for using integer linear programming (IP), such as observed in Gomide et al. (2013); because the linear programming (LP) may lead to the fragmentation of the forest stands. However, Silva et al. (2003) compared solution methods of forest regulation, where the formulation of the problem by IP reduced the objective function value in more than 8% in relation to LP. Moreover, the authors mentioned the solution algorithm utilized for IP problems, usually the Branch and Bound algorithm, despite the advantage in determining an interesting operational solution, may present computationally unsoluble problems with large number of variables. Integer linear programming (IP) was used by Silva et al. 2016 too, and this technique was applied to minimize the production costs from harvest activities and forest road maintenance.

Recently, Pereira et al. (2015) developed a strategic forest planning methodology using goal programming (GP) that integrates two different silvicultural activities, where the objectives were to produce timber and pine seed. The authors commented that the GP models are more attractive than in the case where only one production is maximized. Another advantage of this method is its flexibility in incorporating other silvicultural regimes.

CONCLUSIONS

The optimization strategies tested are efficient to regulate the forest structure of the pine stands, providing annual even-flow production to supply the industrial demand. However, the maximization models generated high timber productions in some periods, which must be avoided.

The minimization strategies are very promising and have potential to be applied as an auxiliary tool in the non-spatial forest planning. Additional studies involving these formulations in spatial planning are recommended, as well as others studies that involve forest optimization, such as thinning and timber transport.

The minimization models show similar results and can be recommended. Strategy 4, with absolute deviations of volume by assortment between consecutive years is more adequate for obtaining satisfactory financial returns and homogenous timber productions over the planning horizon.

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