UNIVERSIDAD POLITÉCNICA DE MADRID

**ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA DE MONTES,
FORESTAL Y DEL MEDIO NATURAL**

**Optimization Methods in Industrial Forest Plantations Management:
Linking Strategic and Tactical Planning Scales**

TESIS DOCTORAL

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2019

PROGRAMA DE DOCTORADO EN INVESTIGACIÓN FORESTAL
AVANZADA

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA DE MONTES,
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ACKNOWLEDGMENTS

This work is a result of a Full Scholarship Doctoral Program supported by the Brazilian National Research Council (CNPq). Through this assistance program funded by the Brazilian society my success was possible. To them, I offer my greatest thanks. Moreover, thanks to the Brazilian forest companies: Florestal Gateados LTDA and Suzano Papel e Celulose, in particular, to their Forestry Managers Mr Ian P. Sartorio and Ms Estela M de C. Ribeiro, for supporting this research.

I would also like to acknowledge the PhD Program in Advanced Forest Research of the Technical University of Madrid. My advisors, Luis Diaz-Balteiro and Carlos Romero, were vital to this work. It would not be possible without your advising, discipline, and research effectiveness. My sincere thanks for your enormous contribution and guidance. I also want to thank the rest of my team: Silvana, Inés, Marta, Esther and Klaus, for offering their friendship and support.

Finally, though not less important, thanks to the European Union's H2020 research and innovation program under the Marie Skłodowska-Curie grant agreement N.691149 (SuFoRun), for founding the research exchange programs of this work, in particular the Project Coordinator Dr. Jordi Garcia-Gonzalo and the partners Dr. Luis Diaz-Balteiro from the Technical University of Madrid-Spain, Dr. Luiz C. E. Rodriguez from the São Paulo State University-Brazil, and Dr. Keith Reynolds from the US Forest Service. Additionally, thank you Professor Woodam Chung from the Oregon State University-USA for your brilliant contribution, and also for make the International Doctorate mention possible.

ABSTRACT

The management planning performs a key role to the sustainability of the industrial forest plantations companies in the global market. Many kinds of optimization procedures were developed to support forest manager's decisions. However, there still existing challenging problems, such as the harvest scheduling generation, which includes criteria from different natures and time-scales, besides which, contain spatial compounds leading to the formulation of very complex combinatorial optimization problems. Specifically, to solve the harvest scheduling problem, forest managers established a hierarchical decision-process consisted of strategic and tactical levels. The former is associated with extended temporal horizons, whereas the latter focus on shorter periods of time and typically encompass further spatial requirements, including the road network. The problem arises not only from the integration between the results obtained from both levels but also from the implementation of new tactical optimization approaches to improve the efficiency of these harvesting operations. Fortunately, thanks to continuous computational advances, it is suitable to develop new optimization procedures to support forest managers. This dissertation focused on these two problems previously defined: the integration of strategic and tactical results and the implementation of new tactical optimization approaches.

Initially, it was carried out a critical survey of optimization methods in industrial forest plantations management. Despite the high number of publications applying optimization methods to forest management, it has got a few associated with the management of industrial forest plantations, specifically. Thus, considering strictly the applications of optimization methods techniques in these forest systems it has been analyzed 67 articles published in journals contained in the ISI Web of Science. It has been highlighted, among other aspects, the optimization techniques employed, their evolution, their hierarchical planning levels, the objective functions and constraints considered, and the type of software deployed. Results verified the frequent usage of the strategic Model I, spatial constraints and mixed integer programming, besides the strongly employment of multi-criteria techniques in recent years.

The first addressed problem was the linkage between strategic and tactical levels of the harvest scheduling problem using multi-criteria techniques. The existence of

multiple criteria of different nature is the rule rather than the exception in most of forestry scenarios. Therefore, it seems sensible to think that integrating strategic and tactical optimization models within a multi criteria context allows to approach the problem using models significantly more practical in many cases. Initially, it has been exposed the strategic and tactical theoretical models and after that, it was presented an integrated framework for dealing with this type of situation. In particular, two approaches called “Top-down” and “Integrated” has been formulated. To undertake this task, the multicriteria tool called “extended goal programming” has been resorted to. The functioning and the strengths of the integrated framework are illustrated with a case study of industrial forest plantation in Brazil. Results show that the framework allows the multiple criteria optimization and that it can achieve significant improvements including decision maker’s preferences.

The second addressed problem was the integration of tactical harvest scheduling and road network planning using the Fixed Charge Transportation Model. The problem consists of setting the stands to be harvested with specific volume production targets integrating spatial and temporal forest operations decisions, such as timber felling and extraction, road network construction/maintenance, and log transportation. Firstly, it has been presented the mathematical formulation of the optimization model followed by the model partitioning and solving procedure. Later, the functionality and performance of this optimization approach in solving the tactical harvest scheduling problem was illustrated using a case study corresponding to a large eucalyptus plantation company located in Brazil. Results show the optimization procedure allows the resolution of large-scale very complex tactical problems.

RESUMEN

Dentro de un mercado globalizado, la planificación del manejo forestal desenvuelve un papel primordial en la sostenibilidad de las compañías propietarias de plantaciones forestales industriales. Distintos procedimientos de optimización fueron desarrollados para apoyar las decisiones de los manejadores forestales. Sin embargo, todavía existen problemas críticos, como la generación del calendario de cortas, que incluye criterios de naturaleza y escalas de tiempo distintas, además de contener componentes espaciales que conducen a la formulación de problemas de optimización combinatoria extremadamente complejos. En concreto, para resolver el problema de la programación de cortas, los gestores forestales establecieron el proceso de decisión jerárquico formado por los niveles: estratégico y táctico. El primer nivel se asocia con largos horizontes de tiempo, mientras que el segundo nivel se enfoca en periodos de tiempo más cortos y generalmente abarca los requisitos espaciales, como la red de carreteras. El problema surge no solamente de la integración entre los resultados obtenidos de ambos niveles, sino también de la implementación de nuevos enfoques de optimización táctica para mejorar la eficiencia de las operaciones de aprovechamiento. Afortunadamente, gracias al constante avance computacional, se ha facilitado el desarrollo de nuevos procedimientos de optimización que permiten la resolución de estos problemas. Esta Tesis Doctoral se ha centrado en estos dos problemas previamente definidos: la integración de los resultados estratégicos y tácticos y la implementación de nuevos enfoques de optimización táctica.

Inicialmente, se llevó a cabo un estudio crítico a respecto de los métodos de optimización en la gestión de las plantaciones forestales industriales. Aunque existan muchas publicaciones que aplican métodos de optimización en la gestión forestal, existen pocas vinculadas específicamente con la gestión de plantaciones forestales industriales. Así, considerando estrictamente las aplicaciones de técnicas de optimización matemática en estos sistemas forestales han sido analizados 67 artículos publicados en revistas del ISI Web of Science. Se destaca, entre otros aspectos, las técnicas de optimización empleadas, su evolución, los niveles de planificación jerárquica, funciones de logro y restricciones consideradas y el tipo de software utilizado. Los resultados verificaron el uso frecuente del Modelo I, restricciones

espaciales y programación entera mixta, además del uso creciente de técnicas multicriterio en los últimos años.

El primer problema abordado ha sido la conexión entre el nivel estratégico y el táctico del problema de generación del calendario de cortas utilizando técnicas multicriterio. La existencia de múltiples criterios de distintas naturalezas es la regla y no la excepción en la mayoría de los escenarios forestales. Por lo tanto, parece sensato suponer que integrar modelos de optimización estratégica y táctica dentro de un contexto multicriterio permite abordar el problema utilizando modelos significativamente más prácticos en muchos casos. Inicialmente, han sido expuestos los modelos teóricos: estratégico y táctico, y después ha sido presentada una estructura integrada para hacer frente a este tipo de situación. En concreto, se han formulado dos aproximaciones llamadas “Top-down” e “Integrated”. Para realizar esta tarea, se ha recurrido a una herramienta multicriterio que se denomina “extended goal programming”. El funcionamiento y aptitudes de la estructura integrada presentada se ilustran con el caso de estudio de plantaciones forestales industriales en Brasil. Los resultados muestran que la estructura desarrollada permite optimizar múltiples criterios y que se pueden lograr mejoras significativas incluyendo las preferencias de los centros decisores.

El segundo problema abordado ha sido la planificación táctica del calendario de cortas y carreteras usando el *Fixed Charge Transportation Model*. El problema consiste en establecer los rodales que serán aprovechados con metas de producción de volumen específicas, integrando las decisiones espaciales y temporales en las operaciones forestales, tales como el aprovechamiento y extracción de madera, la construcción/mantenimiento de las vías de saca y el transporte hacia los destinos. Primero, se presenta la formulación matemática del modelo de optimización seguido del procedimiento de particionamiento y resolución del modelo. Después, la funcionalidad y desempeño del procedimiento de optimización en solucionar el problema de la programación de cortas a nivel táctico ha sido ilustrado usando un caso de estudio que corresponde a una compañía con extensas plantaciones de eucalipto ubicada en Brasil. Los resultados muestran que el procedimiento de optimización permite resolver problemas tácticos de larga escala y extrema complejidad.

1 INTRODUCTION

1.1 PUBLISHED ARTICLES UNTIL NOW

The first article published in this Thesis is a literature review of optimization methods in industrial forest plantations. The survey is published by the *Scientia Agricola* journal. ISSN 1678-992X. 2017 JCR impact factor of 1.383. It is the main agricultural, environmental and biological sciences journal of Brazil. DOI: <http://dx.doi.org/10.1590/1678-992x-2016-0479>.

Belavenutti, P.; Romero C.; and Diaz-Balteiro L. 2018. A critical survey of optimization methods in industrial forest plantations management. *Scientia Agricola*. 75(3): 239-245.

The second article published in this Thesis is a formulation of multi-criteria optimization models for integrating and solving the strategic and tactical hierarchical forest planning problems. The models are by the Forest Science journal. ISSN 0015749X. 2017 JCR impact factor of 1.364. It is one of the main forestry journals of the United State of America. DOI: <https://doi.org/10.1093/forsci/fxy052>.

Belavenutti, P.; Romero C.; and Diaz-Balteiro L. 2019. Integrating strategic and tactical forest management models within a multicriteria context. *Forest Science*. 65(2): 178-188.

1.2 GENERAL CONTEXT

Following the definitions provided by Rodriguez et al. (2014), the term industrial forest plantations is referring to areas dedicated to the cultivation of trees that end up been harvested or treated to satisfy direct or indirect human consumption needs. The demand is related to the supply industrial activities like fuel wood for drying gains, fibers for pulp production and sawn wood for building. It has become important the role of the forest plantations on the carbon fixation to the reduction of the other uses of natural resources and fossil fuel consumption. Furthermore, planted forest also can support environmental diversity protection increasing the area of forest interior habitats (Gustafson, 1998).

According to FAO (2010), it is estimated that 7% (264 million hectares) of the total forest area are planted forests. Specifically, Brazil is the first in Latin America.

Brazilian forest plantations are the object of this Thesis. Therefore, it is opportune to reveal some currently statistics: Following the 2017 report of Brazilian Tree Industry (IBÁ, 2017), it was verified that Brazil has approximately 7.8 million hectares covered by forest plantations. Eucalyptus plantations occupied 5.7 million hectares of the area of planted trees, while pine plantations occupy 1.6 million hectares. The forest plantation sector has had an important economic and social impact on the country's development, employing 510,000 people and contributing with 6.2% of the Brazilian Gross Domestic Product (GDP). Furthermore, the Brazilian forest industry protects natural areas. Thanks to these plantations, 5.6 million hectares are dedicated to conservation, including restoration areas, areas of permanent preservation (APPs), areas of legal reserve (LR), and areas of private natural heritage reserve (PNHR), which contribute directly to conserving biodiversity.

An initiative is the New Generation Plantations (NGP), a group composed by the participating governments and forest companies from around the world. They recognize the substantial potential of well-managed forest plantations to provide timber, conserve biodiversity and mitigate climate change (Silva et al, 2018). Thus, a well-performed forest management also might offer large and cost-effective opportunities of biodiversity conservation and climate change mitigation, what implies to achieve different goals, integrating operational and environmental criteria. Consequently, due to the important role played by the industrial forest plantations in providing diverse goods and services and the growing relevance in the supply of logs and raw materials, additional studies analyzing the optimization tools most often used in the management of these forest systems might be useful. Moreover, decision-making processes handled by forest managers require the generations of new mathematical optimization models and decision support systems to deal with scheduling, logistical and assignment problems (Borges et al. 2014a). These arguments support the main subject of this thesis, which is to propose new optimization tools for the management planning of industrial forest plantations.

1.3 THE CRITICAL SURVEY

The application of optimization methods to forest management has given rise to a successful line of investigation in recent decades. However, there have been few publications associated with the application of these techniques to the management of industrial forest plantations (considering those with short or medium rotations, always less than 50 years). This is a striking situation, given that the management of these intensive plantations requires methods able to provide to the manager with solutions to achieve the stated objectives. Thus, in specific forest plantation management books, there are few chapters devoted to these topics (e.g., Evans, 2009; Bauhus et al., 2010). A remarkable exception are the works by Weintraub et al. (2007) and Borges et al. (2014a). In this direction, there are several surveys on the application of these techniques in the broad field of forest management (e.g., Weintraub and Bare, 1996; Diaz-Balteiro and Romero, 2008; Uhde et al., 2015). Nevertheless, it has been verified that there are none specifically focused on this type of forest system. The same can be said in a contrary manner: reviews of forest plantations usually ignore the use of mathematical optimization approaches (Brockerhoff et al., 2008; Paquette and Messier, 2010; Pawson et al., 2013).

Therefore, a specific survey analyzing the studies with used optimization tools in the management of the industrial forest plantations is needed, due to the lack of additional reviews that furnish information, present arguments and justify the use of particular optimization methods to solve different problems found in these forest systems. Moreover, the review has to highlight innovation opportunities, and provide alternatives of mathematical modeling and applications. Also indicating the importance of non-productive and productive criteria and sustainability. To fulfill the gap, a critical survey of optimization tools in industrial forest plantations dealing with the above mentioned aspects is done and detailed in the main subtopics of the thesis.

1.4 THE LINKAGE BETWEEN STRATEGIC AND TACTICAL HIERARCHICAL LEVELS OF THE HARVEST SCHEDULING PROBLEM

It is well known that decision makers have traditionally used optimization techniques for addressing several timber harvest scheduling problems. Typically, the

purpose of this type of orientation consists in the optimization of the stands management prescriptions maximizing the profit or the commercial volume. Besides that, professionals are currently becoming specialized in controlling new software allowing to decompose the general timber harvest scheduling problem into a number of sub problems. These sub problems may include long-term (strategic) planning which contributes to the company's sustainability, or short-term (tactical or operational) planning which contributes to the operational efficiency, including the harvesting and the log transportation.

Conventionally, forest managers have been using hierarchical planning models to solve timber harvest scheduling problems. This hierarchy is established from strategic planning to tactical planning, and from the latter to operational planning (Weintraub and Bare 1996). However, in the past few years, forest planning models have become increasingly sophisticated thanks to technological advances and the inclusion of spatial components. Also, it is already habitual to integrate other criteria, not related to timber supply, and to interact with decision-makers using multi-criteria methods merged with group decision-making tools (Diaz-Balteiro and Romero, 2008). Nevertheless, there have not been any significant advances in these methods related to the connection between strategic and tactical planning, which has been generally dealt with by a top-down hierarchical approach (Kangas et al. 2014) within a single criterion context. There are two reasons for selecting this hierarchical approach: either because it is easier to link different time horizons (Church et al. 2000), or because strategic and tactical planning are nested in a DSS (Decision Support System), with a hierarchical structure (See ly et al. 2004). However, some authors find open problems when it comes to developing sound optimization models in a top-down approach (Rönnqvist et al. 2015). In short, it may create some discrepancies between planning levels, e.g., the inconsistencies of long-term timber supply (Paradis et al. 2013), and the effects of different spatial and temporal aggregation (Andersson and Eriksson 2007).

On the other hand, some authors have suggested alternative approaches to link strategic and tactical planning, given that the hierarchical approach presents discrepancies and suboptimal or even unfeasible solutions (Beaudoin et al. 2008). Thus, two of the pioneers following this line were Weintraub and Navon (1976), who proposed a monolithic approach, called “integrated”, as opposed to a hierarchical approach, called “sequential”, in order to address the strategic and tactical planning link.

Later, Weintraub and Cholaký (1991) defined an interactive hierarchical approach, called “top-down-bottom-up”, from the inclusion of harvesting targets between planning levels. Thereafter, Cea and Jofré (2000) proposed a clustering technique, “k-means”, to link the strategic and tactical planning. Recently, Troncoso et al. (2015) compared a monolithic “integrated” approach and a hierarchical “decoupled” one for the analysis of strategic and tactical problems; their results demonstrated that the integrated approach produces better outcomes. Additionally, some models have been formulated which also link tactical and operational planning (Beaudoin et al. 2008). Finally, Eyvindson et al. (2018) compared different models: hierarchical, monolithic and integrated in a regional planning problem in Finland using a goal programming methodology (GP).

GP is one of the optimization techniques most used in the field of forest management (Díaz-Balteiro et al., 2013), including works oriented towards plantations (Belavenutti et al., 2018). It makes sense that in industrial forest plantation management problems, where planning horizons are short, and where there is no unanimity when defining the duration of the tactical planning horizon, the versatility of some GP models such as extended goal programming (EGP) (Romero, 2001) can be very helpful. On the other hand, the large number of decision variables (prescriptions) as well as the significant number of criteria involved in this type of problem make applying other multi-criteria methods problematic. Besides this, these GP models can provide the manager with diverse attractive solutions, which enables decision-makers (DMs) to choose which one they consider to be the most suitable (Díaz-Balteiro et al., 2013). EGP has been used in the management of industrial plantations, but not in addressing these types of problems embracing jointly the strategic and the tactical perspectives (Giménez et al., 2013; Broz et al., 2016; Díaz-Balteiro et al., 2016).

Finally, it seems possible linking strategic and tactical multi-criteria models by interactive processes with the decision-maker. Thus, a framework for integrating and solving the strategic and tactical hierarchical problems of industrial forest plantations by interacting with decision-makers is developed to the first addressed problem of this dissertation.

1.5 INTEGRATING TACTICAL HARVEST SCHEDULE AND ROAD NETWORK PLANNING

Industrial forest plantation companies in Brazil usually implement hierarchical, top-down planning approaches to address stakeholders' interests, providing forest plans at various scales from long-term strategic plans to the set of stands to be harvested in the short-term planning horizon with specific volume production targets. Tactical-level planning is responsible for transferring the long-term strategic plans to relatively short-term timber harvest schedules while considering operational efficiency. Formulating and solving tactical planning problems thus often require incorporating spatial considerations, such as adjacency and access road network. Examples of hierarchical approaches for strategic and tactical forest planning in forest management are well described in Weintraub and Cholaký (1991), Kangas et al. (2014) and Troncoso et al. (2015). For industrial forest plantations, Belavenutti et al. (2019) introduced the hierarchical top-down and integrated approaches used to build linkage between strategic plan solutions and spatially explicit tactical harvesting schedules.

Tactical harvest scheduling involves the optimization of various forest harvesting operations to be carried out in space and time. The main operations include timber felling and extraction, road network construction/maintenance, and log transportation, which represent the most expensive activities in the management of forest plantations. The integration of road network into the tactical harvest scheduling problem may offer an opportunity to minimize the overall costs of timber harvesting and log transportation. This problem has been approached by forest transportation models, which their goal is to find the road network that minimizes both log hauling and road construction costs for timber management (Chung et al. 2008). When the problem contains both fixed (road construction) and variable (log hauling) costs of timber transportation, it is a special case of the Fixed Charge Transportation Problem (FCTP) (Contreras et al. 2008). The FCTP is one of the challenging problems of mathematical programming (Rönnqvist et al. 2015).

The main optimization tools applied for solving forest transportation problems including FCTP, are Mixed Integer Linear Programming (MILP) and heuristics methods (Belavenutti et al. 2017). However, given the NP-hard complexity of FCTP, only

medium size problems are solvable using MILP solvers in reasonable solution times (Kowalski 2005). For large-scale problems, the MILP technique suffers from large computational complexities and becomes impractical (Bettinger and Boston 2017). In order to overcome this limitation, heuristic techniques have been used and shown to be efficient in solving large, combinatorial planning problems especially with spatial constraints (Dong et al. 2016). However, heuristic optimization techniques do not guarantee the solution optimality, and it may not be a simple task to estimate the solution gap from the global optimum (Olsson and Lohmander, 2005). Akay et al (2013), provided background information on many optimization techniques used in forest road design and road network management problem. Current examples of solving the FCTP using MILP and Heuristic (ant colony optimization) are Ross et al. (2017) and Lin et al. (2016), respectively.

Since that only medium size FCTP problems are solvable using a MILP solver and real industrial forest plantation companies configure large FCTP problems, it seems possible to spatially partition the entire planning problem into multiple FCTP sub-problems to ensure its solvability. At this point, it has to be established a connection between these sub problems for contemplating the achievement of the general production targets. Thus, it might be developed a new optimization procedure for solving large-scale tactical harvest scheduling problems, by obtaining multiple FCTP sub-problems and iteratively solve them using MILP while varying volume targets for each sub-problem. This is the second addressed problem of this dissertation.

2 OBJECTIVES

The main objective of this thesis is to develop optimization tools for the planning problems found in the management of industrial forest plantations. Firstly, previous studies were analyzed for contextualizing the problem and identifying innovation requirements. The linkage between long-term strategic and medium-term tactical planning levels and the integration of tactical harvest schedule and road network planning are among the main identified challenging problems to increase the sustainability on management of industrial forest plantations. Thus, both strategic and tactical forest planning level have been addressed. To that end, we focused on solving existing problems found in real case studies of industrial forest plantations companies. Firstly, it is formulated strategic and tactical optimization models and alternative approaches for linking results are developed. Secondly, a new approach for optimize the tactical harvest schedule and road network planning is developed. To successfully accomplish the overall purpose of this thesis, it has been established the following objectives.

2.1 THE CRITICAL SURVEY OF OPTIMIZATION METHODS IN INDUSTRIAL FOREST PLANTATIONS

Due to the scarce applications found in the literature about the use of optimization methods in industrial forest plantations we aimed to analyze those papers in order to understand the main features as well as to detect the existing gaps in terms of mathematical modeling and implementable applications. Thus, as the first objective, we analyzed the employment of these techniques in the field of industrial forest plantations and critically examine several critical issues which were presented as the most important ones in the literature.

2.2 THE DEVELOPMENT OF THE FRAMEWORK FOR INTEGRATING AND SOLVING SIMULTANEOUSLY STRATEGIC AND TACTICAL MULTI-CRITERIA OPTIMIZATION MODELS

After fulfilling the first objective previously explained, we aimed to implement new suitable multi-criteria models and a framework for integrating and solving simultaneously the strategic and tactical hierarchical problems of forest management planning. Thus, as the second objective, we compared two approaches, by linking strategic and tactical multi-criteria models obtained from an interactive process with the decision-maker. The first approach, called Top-down, the strategic problem is carried out sequentially with the tactical problem, whereas in the second approach, called Integrated, both problems are solved simultaneously. The case study used to test and to illustrate the functioning of the proposed methodology was a typical industrial pine plantation company.

2.3 THE IMPLEMENTATION OF THE OPTIMIZATION PROCEDURE FOR INTEGRATING TACTICAL HARVEST SCHEDULE AND ROAD NETWORK PLANNING

Following the identified challenging problems of the industrial forest plantations management, we aimed to implement an optimization procedure to the tactical harvest schedule and road network planning. Many FCTP models are formulated spatially partitioning the entire forest plantation, and then they are interactively solved contemplating the general production targets. Thus, as the third objective we tested the performance of the implemented optimization procedure. The used case study was a large pulpwood eucalyptus plantation company, which was able to illustrate the functioning of the developed optimization procedure.

3 MATERIAL AND METHODS

Based on the first specific objective posed above, the subchapter 3.1 presents the methodology of the critical survey of optimization methods in the management of industrial forest plantations. In order to fulfill the second specific objective, the subchapter 3.2 presents the theoretical models' formulations, followed by a generalized framework to dealing jointly with strategic and tactical forest planning with multiple criteria. Then, subchapter 3.3 exemplify an application of the proposed methods to the typical pine plantation company located in the south of Brazil. Now in order to fulfill the third specific objective, the optimization approach for integrating tactical harvest schedule and road network planning is presented with the purpose of elucidating mathematical formulation concepts in 3.4. Then in 3.5, it has been tested on another real case study, the large pulpwood plantation company located in the mid-west of Brazil.

3.1 A CRITICAL SURVEY OF OPTIMIZATION METHODS IN THE MANAGEMENT OF INDUSTRIAL FOREST PLANTATIONS¹

This subchapter presents a literature review of optimization methods in the management of industrial forest plantations. Firstly, the literature on forest management and the application of the main mathematical optimization methods are briefly analyzed, highlighting forest plantations. Thus, analyzing the published articles in the ISI Web of Science using a search process referring to the technique used (plus “forest management”), and repeating the operation excluding the plantations (“not plantations”), the number of studies which actually relate to plantations can be identified by subtracting the latter from the former. Secondly, the main search has been made centered exclusively on articles appearing in the database ISI Web of Science (WOS) introducing the following search terms: “forest\$plantation* AND harvest\$schedule* OR operational\$research* OR linear\$program* OR integer\$program* OR non\$linear* OR multi\$criteria* OR decision\$system* OR goal\$program* OR multi\$objective* OR analytic\$process* OR stochastic\$optimization* OR heuristic*”. These searches were updated as of July 21, 2016. As a result, 203 articles were obtained and filtered to arrive

¹ This subchapter is based upon the paper by Belavenutti et al. (2018). The material presented here is a modified, updated and enlarged version of that paper.

at a final figure of 67 papers. A complete categorization of these papers according to different classificatory criteria is shown in Appendix 1.

One of the main reasons for filtering the initial set of 203 papers was the consideration of the term ‘plantation’ in short or medium rotations. Thus, 50 years of age was selected as a top limit for the rotation cut-off point, and we discarded 36 papers in accordance with this criterion. At this age, the appeal of the industry is reduced, and certain authors already talk about “older aged stands” (Pawson et al., 2013). Another reason for the exclusion of certain studies was the consideration of the industrial purpose of the plantations. Only those articles in which it was clear that the plantation was of an industrial nature (trees managed for industrial purposes) were considered. Thus, we deleted 32 papers related to restoration and conservation issues. Furthermore, we have not included papers based on uneven-aged stands (33) nor studies (36) whose objectives were exclusively non-productive objectives related to forest plantations, such as fire control and natural resource conservation. Finally, due to length constraints, we decided not to incorporate an explanation about the main features of the different optimization methods used in the field surveyed. Readers can find a description of these methods in other studies such as Diaz-Balteiro and Romero (2008), Kangas et al. (2015); Yoshimoto et al. (2016); Ezquerro et al. (2016).

In this section, the principal results of the bibliographical search made are shown, emphasizing topics which frequently appear when these techniques are employed. A number of these issues have been studied in specific generic papers (e.g., Rönqvist et al., 2015), but in our study certain concrete aspects of this type of forest system were highlighted. The numerical results of the search have been given in Appendix 1, where the topics follow the same numbering as the following sub-sections.

3.2 THEORETICAL MODELS AND GENERALIZED FRAMEWORK: DEALING JOINTLY WITH STRATEGIC AND TACTICAL FOREST PLANNING WITH MULTIPLE CRITERIA²

This subchapter presents new optimization models for dealing with a crucial problem in forest management: the integration of the strategic and tactical orientations within a realistic perspective which considers the existence of several management criteria of different nature. With this purpose in mind, will be presented first the strategic multi-criteria model followed by the tactical one. After that, two different approaches will be introduced with the purpose of integrating the strategic and the tactical orientations. Finally, a generalized framework model embedding all the previous orientations as particular cases will be formulated.

3.2.1 *Strategic model with multiple criteria*

It is widely accepted nowadays that a strategic forest planning model must consider, not only economic (e.g., net present value), but also environmental criteria (e.g. carbon uptake), plus the criteria leading to the classic normal forest like the even flow and the regulated forest policies. Unfortunately, within this new context, there is normally a significant degree of conflict among the criteria previously introduced. This fact implies the necessity to search for good compromises among the conflicting criteria. Regarding the different multi-criteria approaches available to address this type of problem, the extended goal programming (EGP) (see Romero 2001, 2004) seems to be especially appealing. This is due to the fact that the EGP approach can deal efficiently with complex problems involving many criteria and many decision variables as is usual in realistic forest management problems. Besides this, with this type of approach, it is possible to obtain the solution providing the best average achievement among all the criteria (efficiency), the solution with a more balanced achievement among solutions (equity) as well as compromises between these two types of solutions; for the application and assessment of the EGP approach in forest management issues, see Diaz-Balteiro et al. (2013). Now we propose the following reformulation of the

² This subchapter is based upon the paper by Belavenutti et al. (2019). The material presented here is a modified, updated and enlarged version of that paper

classic Model I (Johnsson and Scheurmann 1977) within the context of a EGP formulation:

Achievement function

$$\text{Min}(1-\lambda)D + \lambda \sum_{i=1}^I (\alpha_i n_i + \beta_i p_i) \quad (1)$$

Goals and constraints

$$\begin{aligned} (\alpha_i n_i + \beta_i p_i) - D &\leq 0 \quad \forall i \\ \left(\sum_{s=1}^S \sum_{m=1}^M c_{smi} x_{sm} + n_i - p_i \right) &= t_i \quad \forall i \\ n_i, p_i &\geq 0 \quad 0 \leq \lambda \leq 1 \end{aligned} \quad (2)$$

Endogenous constraints

$$\sum_{m=1}^M x_{sm} \leq A_s \quad \forall s \quad (3)$$

It should be noted that the negative and positive deviation variables of the respective goals are represented by " n " and " p " respectively, while the target values are represented by " t " (see Eq. (2)). To be more precise, t_i is the target level for the i th goal, n_i and p_i are the negative and positive deviations from target values of the i th goal, measuring their under-achievement and over-achievement, respectively. $\alpha_i = w_i / k_i$ if n_i is unwanted, otherwise $\alpha_i = 0$, $\beta_i = w_i / k_i$ if p_i is unwanted, otherwise, $\beta_i = 0$. The parameters w_i and k_i are the weights reflecting the preferential and normalizing purposes attached to the achievement of the i th goal, respectively. On the other hand, λ is a control parameter that weights the importance attached to the minimization of the weighted sum of unwanted deviation variables with respect to the minimization of the maximum deviation. Thus, for $\lambda = 0$, we have a Chebyshev achievement

function minimizing the maximum deviation and thus obtaining the "most balanced" solution, otherwise for $\lambda = 1$ we have a weighted achievement function minimizing the sum of deviations and thus obtaining the "best average" solution. For other values of control parameter λ belonging to the open interval $(0,1)$, intermediate solutions if they exist, can be obtained. That is, to some extent control parameter λ trades off "optimum average" versus "optimum balance". We will see throughout the presentation how this type of device is extremely useful for deriving efficient harvest schedules compromising the efficiency (optimum average) with the equity (optimum balance).

We move on now to the meaning of the variables and parameters of a technical nature. Thus, S measures the total number of stands considered, while M refers to the total number of possible strategic management prescriptions established according to Model I. x_{sm} are the decision variables of the model measuring the total area of stand s under management prescription m , and A_s represents the area of stand s . Finally, c_{smi} embeds the unitary contribution of stand s under prescription m for the generic strategic goal i .

3.2.2 Tactical Model with multiple criteria

As it is well known, the tactical forest planning models usually incorporate spatial criteria with the purpose of increasing connectivity and reducing the environmental impact as well as the cost associated with the harvest. In some situations, the model also incorporates the design of the road network (Öhman and Eriksson, 2010). In short, within a tactical orientation, the decision-making problem consists of establishing harvest schedules which takes into account not only the management prescription, but also the tactical spatial criteria considered. In short, the following EGP formulation within the structure of Model I with a tactical orientation is proposed:

Achievement function

$$\text{Min}(1-\lambda)D + \lambda \sum_{j=1}^J (\alpha_j n_j + \beta_j p_j) \quad (4)$$

Goals and constraints

$$\begin{aligned}
 (\alpha_j n_j + \beta_j p_j) - D &\leq 0 & \forall j \\
 \sum_{s=1}^S \sum_{k=1}^{TH} c_{sk} r_{sk} + n_j - p_j &= t_j & \forall j
 \end{aligned} \tag{5}$$

$$n_j, p_j \geq 0 \quad 0 \leq \lambda \leq 1$$

Management and operational constraints

$$\sum_{m=1}^M y_{sm} = 1 \quad \forall s \tag{6}$$

$$\sum_{m \in g(\sigma)} (y_{sm} - r_{sk}) = 0 \quad \forall s, k = 1, \dots, TH \tag{7}$$

$$y_{sm}; r_{sk} \in \{0, 1\}$$

The meaning of variables and parameters of a model composed by Equations (4-7) is similar to that of model (1-3) with the following changes and clarifications. Now J embeds the tactical goals considered and TH represents the planning horizon for the tactical exercise. On the other hand, Eq. (6) and (7) require some explanation. Eq. (6) requires each stand to receive only one management prescription. The sets of stand management prescriptions with their respective intervention period are included in Eq. (7). Thus, y_{sm} is a binary variable taking on a value 1 when the management prescription m is applied on stand s , otherwise it takes 0. In the same direction r_{sk} is another binary variable taking the value 1 only when the stand s is managed during the k th period of time while $g(\sigma)$ includes the set of productive management

prescriptions during the period k . Finally, c_{sk} measures the contribution of stand s th when it is managed in a period of time k th for the j th tactical goal.

3.2.3 The Top-down approach to link strategic and tactical models

In this sub-section it will be proposed a first approach for integrating the strategic and tactical models presented above. This approach is called Top-down has a hierarchical structure and embraces two steps. In the first step, the strategic model is solved and in the second step the results from the first step are transferred to the tactical model and suitably solved.

The Top-down approach implies, within our setting, solving the EGP model (1-3) for different values of control parameter λ , and including the preference weights provided by the decision-maker. In this way, obtaining the strategic solutions to be applied in the tactical planning horizon considered. Thus, the respective strategic prescriptions x_{sm} are transferred to the tactical planning by the management prescriptions y_{sm} , which implies a re-formulation of Eqs. (5-7), generating the new achievement function formulated below as Eq. (8). This new achievement function involves deviation variables corresponding to the tactical and strategic criteria. The corresponding new goals defined by Eq. (9) allow one to transfer the results obtained from the strategic to the tactical level. Thus, I embeds the strategic goals transferred to a tactical level and, consequently, c_{smi} measures the contribution of the stand s when it is managed according to the prescription m within the strategic goal i at a tactical level. It is important to note that the values of the deviation variables measure the discrepancies obtained in the two levels considered. Hence, the analytical formulation of the Top-down model is the following:

New Achievement Function

$$\text{Min}(1-\lambda)D + \lambda \left[\sum_{i=1}^I (\alpha_i n_i + \beta_i p_i) + \sum_{j=1}^J (\alpha_j n_j + \beta_j p_j) \right] \quad (8)$$

New goals and constraints

$$(\alpha_i n_i + \beta_i p_i) - D \leq 0 \quad \forall i$$

$$\sum_{s=1}^S \sum_{m=1}^M c_{smi} y_{sm} + n_i - p_i = t_i \quad \forall i \quad (9)$$

$$n_i, p_i \geq 0$$

3.2.4 The Integrated approach to link strategic and tactical models

Now we are going to present a second approach for the integration of the strategic and tactical orientations. In this way, following the literature (see Weintraub and Navon, 1976), we have called this second approach Integrated, since it aims to solve simultaneously the strategic and the tactical models. Within the Integrated approach the EGP model has been particularized including several values of control parameter λ , and considering jointly strategic and tactical criteria. To undertake this task, the strategic Eq. (2) and (3) and the tactical ones Eq. (5) and (7) are merged, which leads to the new achievement function formulated below as Eq. (10). Now Q embeds the strategic as well as tactical goals considered, each one with its specific time horizon. This approach needs the inclusion of Eq. (11) and (12) to allow the possibility of a continuous linkage between the tactical and strategic levels resulting an integrated solution. Hence, the analytical formulation of the Integrated model is the following:

New Achievement Function

$$\text{Min}(1-\lambda)D + \lambda \sum_{q=1}^Q (\alpha_q n_q + \beta_q p_q) \quad (10)$$

New integration constraints

$$(\alpha_q n_q + \beta_q p_q) - D \leq 0 \quad \forall q$$

$$A_s y_{sm} - x_{sm} \leq 0 \quad \forall s, m \quad (11)$$

$$\sum_{s=1}^S \sum_{m \in g(\sigma)} (vol_{smk} x_{sm}) - \sum_{s=1}^S \sum_{m \in g(\sigma)} (vol_{smk} A_s y_{sm}) \geq 0 \quad k = 1, \dots, TH \quad (12)$$

To understand the Integrated model it is important to note that Eq. (11) links the results corresponding to the strategic prescriptions x_{sm} to those corresponding to the tactical ones y_{sm} . Coherently, Eq. (12) prevents differences between timber flows obtained by strategic and tactical prescriptions, along the tactical planning horizon. Thus, vol_{smk} measures the total timber volume per hectare of stand s when it is managed according to the prescription m in the period k .

3.2.5 A Generalized Framework

In this sub-section we present a general framework that embeds as particular cases all the models presented up to now. In this way, we will demonstrate how just by implementing numerical changes in some auxiliary variables, then from the proposed general structure can be derived all the models introduced so far. This type of unification has not only theoretical interest but also practical one, especially thinking in building a decision support system for dealing in a very general way with strategic and tactical forest management problems simultaneously. The general model has some new particularities in terms of goals and constraints, explained below. The proposed structure of the generalized model is the following:

General achievement Function

$$\begin{aligned}
& \gamma_1 \left\{ \text{Min}(1-\lambda) D_1 + \lambda \left[\sum_{i=1}^I (\alpha_i n_i + \beta_i p_i) + \delta \sum_{j=1}^J (\alpha_j n_j + \beta_j p_j) \right] \right\} + \\
& \gamma_2 \left\{ \text{Min}(1-\lambda) D_2 + \lambda \sum_{q=1}^Q (\alpha_q n_q + \beta_q p_q) \right\}
\end{aligned} \tag{13}$$

Goals and constraints for the Top Down approach ($\gamma_1 = 1$ and $\gamma_2 = 0$)

$$(\alpha_i n_i + \beta_i p_i) - D_1 \leq 0 \quad \forall i \tag{14}$$

$$\delta [(\alpha_j n_j + \beta_j p_j) - D_1] \leq 0 \quad \forall j \tag{15}$$

$$\mu \left(\sum_{s=1}^S \sum_{m=1}^M c_{smi} x_{sm} + n_i - p_i = t_i \right) \quad \forall i \tag{16}$$

$$\delta \left(\sum_{s=1}^S \sum_{m=1}^M c_{smi} y_{sm} + n_i - p_i = t_i \right) \quad \forall i \tag{17}$$

$$\delta \left(\sum_{s=1}^S \sum_{k=1}^{TH} c_{sk} r_{sk} + \sum_{s=1}^S \sum_{k=1}^{TH} c_{vk} z_{vk} + n_j - p_j = t_j \right) \tag{18}$$

$$\delta \left(\sum_{s,l \in \mathbf{g}(L)} \sum_{k=1}^{TH} e_{slk} + n_j - p_j = t_j \right) \tag{19}$$

Goals and constraints for the Integrated approach ($\gamma_1 = 0$ and $\gamma_2 = 1$)

$$(\alpha_q n_q + \beta_q p_q) - D_2 \leq 0 \quad \forall q \tag{20}$$

$$\sum_{s=1}^S \sum_{m=1}^M c_{smq} x_{sm} + n_q - p_q = t_q \quad \forall q \in E \tag{21}$$

$$\sum_{s=1}^S \sum_{k=1}^{TH} c_{sk} r_{sk} + \sum_{v=1}^V \sum_{k=1}^{TH} c_{vk} z_{vk} + n_q - p_q = t_q \quad \forall q \in T \quad (22)$$

$$\sum_{s,l \in g(L)} \sum_{k=1}^{TH} e_{slk} + n_q - p_q = t_q \quad \forall q \in T \quad (23)$$

$$A_s y_{sm} - x_{sm} \leq 0 \quad \forall s, m \quad (24)$$

$$\sum_{s=1}^S \sum_{m \in g(\sigma)} (vol_{smk} x_{sm}) - \sum_{s=1}^S \sum_{m \in g(\sigma)} (vol_{smk} A_s y_{sm}) \geq 0 \quad k = 1, \dots, TH \quad (25)$$

Endogenous constraints (both approaches)

$$\sum_{m=1}^M x_{sm} \leq A_s \quad \forall s \quad (26)$$

$$\sum_{m=1}^M y_{sm} = 1 \quad \forall s \quad (27)$$

$$\sum_{m \in g(\sigma)} (y_{sm} - r_{sk}) = 0 \quad \forall s, k = 1, \dots, TH \quad (28)$$

Spatial constraints (both approaches)

$$N_\eta r_{sk} - \sum_{v \in g(\eta)} z_{vk} \leq 0 \quad \forall s \in g(\sigma), k = 1, \dots, TH \quad (29)$$

$$r_{sk} \geq e_{slk}; r_{lk} \geq e_{slk} \quad \forall (s, l) \in g(\theta, \sigma), k = 1, \dots, TH \quad (30)$$

Sign and logic restraints

$$\gamma_1, \gamma_2, \mu, \delta, y_{sm}, r_{sk}, r_{lk}, z_{rk}, e_{slk} \in \{0,1\} \quad n_i, n_j, n_q, p_i, p_j, p_q \geq 0 \quad 0 \leq \lambda \leq 1$$

Starting from the general achievement function shown in (13), the auxiliary parameters γ_1 and γ_2 take on a value 1 when considering Top-down or Integrated approaches, respectively. Otherwise they take on a value 0. In this way, this formulation embraces two general achievement functions within an EGP context. The first one corresponds to the Top Down approach ($\gamma_1=1$; $\gamma_2=0$), and the second one correspond to the Integrated approach ($\gamma_1=0$; $\gamma_2=1$). Additionally, auxiliary parameters μ and δ take on a value 1 when considering strategic or tactical criteria, respectively, otherwise it takes 0. Same as before, the subscripts i and j represents the strategic and tactical goals of the Top-down approach (see Eqs. (16)-(19)), Also, the subscript q represents the strategic or tactical goal for the Integrated approach while E embeds the different strategic goals and T embeds the tactical goals (see Eqs. (21)-(23)).

Some other decision variables of technical nature are included in the generalized model due to the new spatial constraints related to the road network and harvesting connectivity. Thus, c_{vk} measures the cost of road section v conditioned in the period k , while, e_{slk} are binary variables that represent the edge connecting harvesting intervention between r_{sk} and r_{lk} . Besides, N_η denotes the total number of road sections in the rout path η , $g(\eta)$ the set of road sections contained in the optimal rout path η , and z_{vk} is a binary variable that represents the road section v conditioned in the period k . Finally, $g(\theta)$ represents a pair of adjacent harvesting interventions.

Eqs. (26)-(28) corresponding to the endogenous constraints were previously explained. Nevertheless, it is important to highlight now that the variable y_{sm} plays an important role in the model because the stand management prescriptions could have different production levels when considering the same period of time. Furthermore, the

variable r_{sk} simplifies the model formulation by decreasing the number of spatial constraints. In this way, only the spatial constraints regarding the harvesting intervention are considered. These spatial constraints will consider the spatial distribution and promote the clustering of harvesting activities. Eq. (29) is a spatial constraint that connects the set of road sections between each harvesting intervention and the production destination, each set composing the optimal route path η . Finally, the spatial harvesting connectivity constraints (Eq. (30)) activate variables representing two harvesting interventions in adjacent stands and in the same period (see Augustynczyk et al. 2016).

3.2.6 A Pragmatic Procedure for the Elicitation of Decision Maker Selected Criteria and Preferences

The sequential procedure consists of three interactions with the decision-maker: (i) To select the strategic and tactical criteria. (e.g., Diaz-Balteiro and Romero 1998) After that, the respective programming models are formulated to get the Pay-off Matrix. Thus, in this matrix the DM is provided with the optimum values of each criterion, what allows to quantify the degree of conflict between criteria as well as to obtain targets of reference (e.g., Diaz-Balteiro and Romero 1998); (ii) To elicit the preferential weights attached to each criterion, as well as the respective target values, and (iii) To select the best solutions in each model according to the values of control parameter λ . Thus, the EGP models are formulated and solved following the “Top-down” and Integrated approaches. These stages are explained in more detail in the following subsections with the help of a case study. Figure 1 summarizes the method proposed.

Figure 1. Scheme of the methodology used.

3.3 APPLICATION OF THE GENERALIZED FRAMEWORK

The application of the generalized framework corresponds to a real case study. Suitable silvicultural systems are adopted to simulate the growth and yield of the forest stands. Then, Model I management prescriptions are generated and finally, optimization models are formulated according to the decision-maker preferences elicited through interactive process.

3.3.1 Case study

The company *Florestal Gateados Ltd.*³ (Figure 2) is located in Santa Catarina State, Brazil. The total area covers 18,435 ha of natural forests and forest plantations. The natural forests consist of a Private Natural Heritage Reserve⁴ (PNHR), a kind of protected area that is voluntarily established on private lands and legally recognized by the federal, state and local government. The PNHR is made up by 11,007 ha, 58% of the total company surface. Management activities are prohibited in this area, except tourism. The economic benefits of the PNHR come from the decreasing of the specific Rural Taxes and facilities on obtaining credits from Brazilian institutions, such as the National Bank of Economic and Social Development (BNDES).

The forest plantations include stands of pine, eucalyptus and araucaria. Most of them are pine stands which covers 6,440 ha, consisted of 1,661 stands of loblolly pine (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm.). There are also 162 stands of eucalyptus (*Eucalyptus dunnii* Maiden) covering 416 ha and 173 stands of araucaria (*Araucaria angustifolia* (Bertol.) Kuntze) covering 489 ha. Table 1 presents the distribution of the company surface according to its purpose, including the natural forest and the forest plantations.

Table 1. Distribution of the company surface.

Purpose	Forest type	Surface (ha)
Conservation	natural forest	11,007
Production	pine	6,440
Production	eucalyptus	416
Production	araucaria	489

Source: Compilation based on information supplied by the company.

The main economic sustainable activity of the company comes from the pine stands, and it is about the production of varied log pine classes to the internal and exportation market. Despite the role of the pine stands, eucalyptus and araucaria stands represent an alternative experiment to diversify the company's timber production, but they are not included in the sustainability production targets of the company due to the

³ <http://www.gateados.com.br/>

⁴ <https://www.rppn.org.br/sobre>

small amount of surface dedicated to these species and the current instability of its prices at the regional market. Thus, the sustainability annual production target of the company is 238 Mm³ of log pines, of which 27.8 Mm³(12%) are high quality logs (basal logs managed with prune branches operations for producing clear wood). Due to the complexity of establishing market prices and volume targets for eucalyptus and araucaria, the company does not include these stands in the optimization of forest management. Moreover, these stands are usually designated to alternative uses, such as scientific experiments and after the clear cut, new species have been planted (e.g. *Cryptomeria japonica* (L. F.) Don., *Cunninghamia lanceolata* (Lamb) Hook and the Brazilian *Ilex paraguariensis* A. St.-Hil.). Thus, it is considered only the pine stands in the optimization of forest management of this study. The pine stands of the company are described in more detail below.

Figure 2. *Florestal Gateados Ltd.*

3.3.2 *Pine stands*

The current volume stock of the *Pinus* spp considering the entire forest plantation is 1.5 MMm³. Table 2 shows the general information of the pine stands for

each five years' age class, defined according to the stand age variations and its management conditions. The average annual increment of *Pinus* spp. stands is 42 m³.ha.yr at 18 years of the stand age.

Table 2. General information.

Age class	Area	N° stands	Density (n° trees)	Dominant height (m)
[≤5]	2,037	561	1,911	-
[6-10]	598	165	1,369	15
[11-15]	422	99	781	22
[16-20]	152	43	482	25
[21-25]	501	215	331	28
[26-30]	745	187	275	33
[≥ 31]	1,986	391	241	34

Source: Compilation based on information supplied by the company.

Figure 3 presents the age class distribution of *Pinus* spp in the forest plantation. Stands older than 27 years consists 31% of the total area, while 27% of the area is consisted by stands younger than 6 years old. There are a few stands with ages between 6 and 27 years, only 41% of the total.

Figure 3. Age classes distribution of Pinus spp.

Figure 4 presents the distribution of the stand dominant heights at the current ages. This information is an input to the simulation of the growth and yield of the forest

stands, the corresponding procedure is explained below. Dominant ages from the previous silvicultural rotations are provided to the stands younger than 6 years.

Figure 4. Stand dominant heights of Pinus spp.

3.3.3 Commercialized timber assortments and production costs

The company commercializes 5 different timber assortments of pine (Table 3), differing in diameter, length and quality. On one hand, the veneer logs are destined to the exportation market, achieving high prices. However, they are clear wood which requires longer rotation periods (>18 years), thinning and pruning operations. On the other hand, pulpwood logs don't need long rotation periods, thinning and pruning. Nevertheless, there is no demand for pulpwood logs in the exportation market and the respective prices are very low in the local market.

Table 3. Timber assortments.

Assortment	Dimeter (cm)	Lenght (m)	Price (\$/m ³)
Pulpwood	$\geq 8 < 18$	2.40	5.0
Saw-log 1	$\geq 18 < 25$	2.60	7.7
Saw-log 2	$\geq 25 < 35$	2.60	13.6
Veneer 1	$\geq 35 < 42$	2.20	19.2
Veneer 2	> 42	2.20	25.9

Source: Compilation based on information supplied by the company.

The costs of planting, control and maintenance of the stands are provided by the company, according to the number of planted trees (Table 4). The control includes operations of replanting and weed and ant control. The maintenance includes five annual pruning operations ranging from 3-7 year of the stand age. There is also a fixed annual administration cost of 12.5 \$/ha.

Table 4. Costs of planting, control and maintenance of the company stands.

N° of trees		1.600	1.111
Operation	Age (years)	Cost (\$/ha)	Cost (\$/ha)
Planting/control	0	1025	827
1 ^a pruning	3	91	63
2 ^a pruning	4	106	74
3 ^a pruning	5	91	63
4 ^a pruning	6	90	62
5 ^a pruning	7	91	63

Source: Compilation based on information supplied by the company.

The costs of thinning and clear cut interventions of the company stands are also estimated according to the number of planted trees (Table 5). Additionally, to the operational costs we included the log loading expenditures (1.6 \$/ton).

Table 5. Costs of thinning and clear cut interventions.

N° of trees		1.600	1.111
Operation	Age (years)	Cost (\$/ton)	Cost (\$/ton)
1° thinning	8-12	43	43
2° thinning	13-17	43	43
3° thinning	18-22	30	30
Clear cut	23-27	27	27

Source: Compilation based on information supplied by the company.

3.3.4 *Defining management prescriptions*

Silvicultural systems are used for simulating the growth and yield of the forest stands. In this study, they allow pre-commercial thinnings and the final clear cut harvesting intervention. Different silvicultural systems are simulated for each stand and they are used for the generation of management prescriptions. Implementing these stand management prescriptions are the first step of the optimization process, following EGP formulation within the structure of Model I. Where the decision variable x_{sm} represents the area of the stand s under the management prescription m . Therefore, when considering the stand s managed during a strategic (long-term) planning horizon, successive silvicultural systems are combined generating the set of management prescriptions m . Moreover, according to the EGP formulation within the structure of Model I, these stands management prescriptions x_{sm} are the main technical decision variables, composing constraints and goals, such as the endogenous constraints and strategic goals. In this study, for generating the stands management prescriptions x_{sm} it is adopted a strategic planning horizon covering one complete rotation interval of 30 years, established by the company. The procedure of simulating silvicultural systems, implementing stand management prescriptions and formulating the optimization models are in-depth explained in the following subsections.

3.3.5 *Silvicultural systems*

The current age classes distribution of *Pinus* spp. is very uneven due to the implementation of uneven production flow policies by the company during the last years. Thus, for achieving the age class and the production flow regulation, which are integrated on the optimization procedure of this study, these stands are requiring the adoption of exception silvicultural systems which allow the performance of non-trivial ranges of harvesting interventions, in addition to the standard ones currently used by the company. These silvicultural systems allow several options of pre-commercial thinnings and the final clear cut harvesting intervention, which are performed on different ranges of ages groups (see Fiorentin et al. 2017). Therefore, two different silvicultural systems were simulated: Standard and Exception. Only silvicultural systems with ranges higher

than four years between two consecutive harvesting interventions were simulated, so that they produce important effects on forest growth.

The Standard system, popularly known as “*utility system*”, is widely applied in plantations of southern Brazil and its main purpose is to produce multiple assortments for the market of pulp wood, sawn wood and veneers. The Standard systems (Figure 5) starts with the initial density of 1.600 and 1.111 trees/ha, allowing two or three pre-commercial thinnings occurring in these ranges of ages: 8-12, 13-17 and 18-22 years, followed by a clear cut ranging from 23-27 years of stand age. The third thinning is replaced by the clear cut on the Standard system with two pre-commercial thinnings, producing a shorter rotation interval. Regarding the intensity of the interventions, in the first thinning, 20% of the trees are systematically removed for operational reasons (one line out of every 5 lines of the plantation) and then 50% of the worst remaining trees in the plantation are removed (known as selectively thinning from below). Thus, in the second thinning, 40% of the worst trees are selectively removed and finally, in the third thinning, 30% of the worst trees are selectively removed. Additionally, the initial mortality rate of 5% of the trees is considered for several technical reasons. For example, starting from an initial density of 1.600 trees/ha, 80 trees die by the initial mortality remaining 1.520, on the first thinning 912 trees are harvested, remaining 608 trees, in the second thinning 243 trees are harvested, remaining 365 and in the third thinning 109 trees are harvested, remaining 256 to the clear cut.

Figure 5. Ranges of age groups for management interventions of the Standard systems.

The Standard systems are strictly suitable to simulate the growth and yield of the stands younger than 27 years which received pre-commercial thinnings within the Standard ranges of interventions. Nevertheless, to the other stands, the Exception systems are developed for simulating the growth and yield. Exception systems are simulated individually for each stand, taking in account the available information such as: age, dominant high, basal area and number of trees. The Exception systems (Figure 6) include a clear cut between 27-31 years or an old thinning in the same range of ages followed by a clear cut between 32-40 years. Thus, in the thinning, 50% of the worst trees are selectively removed.

Figure 6. Ranges of age groups for management interventions of the Exception systems.

3.3.6 *Simulating silvicultural systems*

The management systems are implemented using the SisPinus® growth and yield simulator (EMBRAPA, 2011). The simulator uses an extensive dataset containing information of Brazilian forest plantations, estimating growth and yield according to the available input data, which are necessary for producing individual stands simulations. For the simulations, the software automatically provides site indexes relating to the stand dominant height. There are two different software configurations in relation to the used input data, the minimal configuration uses only general information such as site index, number of planting trees, ages of interventions and intensity of interventions and produced timber assortments, while the maximal configuration requires more specific information based on the stand age reference, such as number of trees and its basal area, besides the corresponding general information. For simulating Standard silvicultural systems, the minimal configuration is used, while for simulating Exception silvicultural systems, the maximal configuration is used, allowing more precise results.

The profitability of the silvicultural systems is tested using the commercialized timber assortments and production costs previously defined and applying a discounting rate of 8% based on the Brazilian Selic rate of 2017 (Selic, 2017). Silvicultural systems

are evaluated according to the Land Expectation Value (LEV) and Total Volume, for three site indexes of the company. The LEV is the economic tool for evaluating the value of the bare land in perpetual timber production and is often used to value even-aged pine plantations. The value taking in account the Net Present Value (NPV) of all revenues and costs associated to the same forest system perpetually, according to Faustmann's hypothesis. As the LEV is not just associated with one rotation of timber at a specific time period, this economic tool allows the comparison of several silvicultural systems with different rotation periods, unlike the NPV. More definitions and formulations of NPV and LEV are found in Diaz-Balteiro et al. (2014b).

The Standard silvicultural systems are the most appropriated to the establishing stands of the forest plantation, as explained before. Due to this fact, the results of the simulated Standard systems in terms of productivity and profitability are identified for selecting the best ones to compose the stands management prescriptions following to the corresponding site indexes. To simplify the simulation of stands management prescriptions by the software it was identified three different site indexes in the forest plantation. Site index I is corresponding to the range of dominant height of 24-26 m at the reference age of 15 years (40 % of the total forest plantation area). While site indexes II and III are corresponding to the ranges of 22-24 and 22-20 m, respectively consisting of 34% and 26% of the total area. Tables 6-8 highlights the best results of the simulated Standard systems, considering complete silvicultural rotations to the corresponding site index and initial numbers of replanting trees/ha. As for the site index I, on one hand, the results of the systems with 1,111 trees/ha and three pre-commercial thinnings, provided maximal values for the LEV, with 7.718 \$/ha. On the other hand, the system with 1,600 trees/ha and three pre-commercial thinnings, provided maximal values for Total Volume, with 1074 m³. On average, systems from both site indexes give better results of LEV with 1,111 as the initial number of replanting trees/ha. Whereas, better results of Total Volume corresponded to 1,600 trees/ha.

Table 6. Bests silvicultural systems to the site index I, maximizing LEV and Total Volume for 1,111 and 1,666 trees/ha.

N ° of trees	Nº of th.	Age of interventions (years)				LEV (\$/ha)	Vol. (m³)
		1 ^a th.	2 ^a th.	3 ^a th.	c.c.		
Max LEV							
1,111	2	8	13	-	21	7,718	669
1,111	3	8	13	18	23	5,161	732
Max VOL							
1,600	2	12	17	-	22	3,506	894
1,600	3	12	17	22	27	3,636	1047

Where: c.c. = clear cut, th. = thinning. Source: Own elaboration.

Table 7. Bests silvicultural systems to the site index II, maximizing LEV and Total Volume for 1,111 and 1,666 trees/ha.

N ° of trees	N° of th.	Age of interventions (years)				LEV (\$/ha)	Vol. (m³)
		1 ^a th.	2 ^a th.	3 ^a th.	c.c.		
Max LEV							
1,111	2	8	13	-	22	14,690	637
1,111	3	10	14	18	23	16,175	710
Max VOL							
1,600	2	12	17	-	22	10,493	818
1,600	3	12	17	22	27	11,076	965

Source: Own elaboration.

Table 8. Bests silvicultural systems to the site index III, maximizing LEV and Total Volume for 1,111 and 1,666 trees/ha.

N ° of trees	N° of th.	Age of interventions (years)				LEV (\$/ha)	Vol. (m³)
		1 ^a th.	2 ^a th.	3 ^a th.	c.c.		
Max LEV							
1,111	2	8	13	-	22	12,001	575
1111	3	9	13	18	23	13,501	624
Max VOL							
1,600	2	12	17	-	22	9,635	749
1,600	3	12	17	21	27	10,531	886

Source: Own elaboration.

3.3.7 Implementing management prescriptions

The management prescriptions cover strategic planning horizon established by the company of 30 years with annual periods. The site index and the actual stage of the stand, in terms of age and management condition, are taken in account when selecting silvicultural systems for implementing its management prescriptions. For stands younger than 27 years, management prescriptions are implemented combining two Standard silvicultural systems. Additionally, after the clear cut intervention only the bests Standard systems previously defined are selected to compose the management prescriptions. While, for stands equal to or older than 27 years, management prescriptions are implemented combining the Exception systems and the bests Standard systems. It has been implemented 64.862 management prescriptions for the 2,501 stands, on average it is 26 management prescriptions for each stand. Table 9 shows an example of the management prescriptions implemented for a stand with 27 years, 315 trees/ha, dominant high of 22 m and a basal area of 35,5 m²/ha. Consequently, the stand has 60 management prescriptions, produced by the combinations between 15 different Exception systems and the 4 best Standard systems.

Table 9. Management prescriptions of the 27 years stand, 315 trees/ha and basal area of 35,5 m²/ha.

Prescriptions	Exception system	Standard system	Age of interventions (years)						Vol. (m ³)	NPV (\$/ha)
			1 ^a th.	1 ^a c.c.	1 ^a th.	2 ^a th.	3 ^a th.	2 ^a c.c.		
1	1	1	28	35	12	17	22	-	1,091	15,462
2	1	2	28	35	-	12	17	22	1,475	16,851
3	1	3	28	35	8	13	18	-	1,313	17,867
4	1	4	28	35	-	8	13	21	1,251	17,574
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
56	15	1	-	28	12	17	22	27	1,463	16,021
57	15	2	-	29	-	12	17	22	1,105	16,474
58	15	3	-	30	8	13	18	23	1,186	16,485
60	15	4	-	31	-	8	13	21	1,141	15,591

Where: c.c. clear cut and th. thinning. Source: Own elaboration.

Table 10 shows an example of the management prescriptions implemented for a 1 year stand with 1,111 trees/ha. Consequently, the stand has only 2 management prescriptions, produced by the combinations between the bests Standard systems.

Table 10. Management prescriptions of the 1 year stand with 1,111 trees/ha.

Prescriptions	Standard system	Age of interventions (years)						Vol. (m ³)	NPV (\$/ha)
		1 ^a th.	2 ^a th.	3 ^a th.	1 ^a c.c.	1 ^a th.	1 ^a th.		
1	1	8	13	-	21	8	-	1.338	12.776
2	2	8	13	18	23	-	-	1.464	16.453

Source: Own elaboration.

Additionally, the carbon sequestration has been calculated for each management prescription using the stock change method, defined by the Intergovernmental Panel on Climate Change (IPCC). Therefore, carbon sequestration of management prescriptions has been calculated as the estimation of gains and losses of carbon due to the growth of trees and their removal, computed in physical units (Pasalodos-Tato et al., 2017). The method considers the change in stock between the initial and final periods. Thus, the initial carbon stock is corresponding to the initial period (year 0 of the planning horizon), when any management prescription has been selected, and the final carbon

stock is corresponding to the last period (year 30 of the planning horizon), when the stand has been managed according to the selected management prescription. In order to compute the carbon sequestration, we considered a timber density of 0.57 t/m³ and carbon content of 0.41 % (EMBRAPA, 2011). Table 11 shows an example of the results of the carbon sequestration corresponding to the management prescriptions implemented for the same stand with 27 years, 315 trees/ha, dominant high of 22 m and a basal area of 35,5 m²/ha. In this case, the results of the carbon sequestration are negative due to the differences between the initial stock and the final stock.

Table 11. Carbon sequestration of the 27 years stand, 315 trees/ha and basal area of 35,5 m²/ha.

M.p.	E.s.	S.s.	Age of interventions (years)						I.s. (ton. C)	F.s. (ton. C)	C.s. (ton. C)
			1 ^a th.	1 ^a c.c.	1 ^a th.	2 ^a th.	3 ^a th.	2 ^a c.c.			
1	1	1	28	35	12	17	22	-	103	79	-24
2	1	2	28	35	-	12	17	22	103	0	-103
3	1	3	28	35	8	13	18	-	103	69	-34
4	1	4	28	35	-	8	13	21	103	7	-96
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮		⋮
56	15	1	-	28	12	17	22	27	100	2	-98
57	15	2	-	29	-	12	17	22	100	53	-47
58	15	3	-	30	8	13	18	23	100	7	-93
60	15	4	-	31	-	8	13	21	100	16	-84

Where: M.p. Management prescription, E.s. Exception system, S.s. Standart system, I.s. Initial stock, F.s. Final stock, C.s. Carbon sequestration. Source: Own elaboration.

Table 12 shows the results of the carbon sequestration corresponding to the management prescriptions implemented for the 1 year stand with 1,111 trees/ha. Now, the results of the carbon sequestration are positive due to the differences between the initial and final carbon stock.

Table 12. Carbon sequestration of the 1 year stand with 1,111 trees/ha.

M.p.	S.s.	Age of interventions (years)						I.s. (ton. C)	F.s. (ton. C)	C.s. (ton. C)
		1 ^a	2 ^a	3 ^a	1 ^a	1 ^a	1 ^a			
		th.	th.	th.	c.c.	th.	th.			
1	1	8	13	-	21	8	-	0	53	53
2	2	8	13	18	23	-	-	0	40	40

Source: Own elaboration.

3.3.8 *Spatial requirements*

The main company woodyard is connected to the pine stands by a road network made up by 1,220 main and secondary road sections. Figure 7 presents the spatial distribution of the spatial compounds of the productive area: pine stands, roads and company woodyard.

Figure 7. Spatial distribution of the spatial compounds in the productive area.

For integrating some spatial requirements in the optimization procedure, new datasets are generated. The first one corresponds to the maintenance road costs which is considering the main road sections (5,000 \$/km) and secondary road sections (10,000

\$/km). This dataset consists of the optimal road paths between each harvesting intervention and the production destination (the Company woodyard). The optimal path is obtained by minimizing the annual road maintenance cost, to the log transportation. The procedure consisting of three steps is implemented using the network analysis package igraph⁵. In the first step, the forest road network is converted from a geospatial vector (shapefile) to an adjacent matrix, which reflects the intersections between road sections. In the second step, a weighted graph is generated integrating the adjacent matrix and the annual maintenance cost of the road sections. In the third step, the Dijkstra's shortest path algorithm is applied to the harvesting interventions from the stand management prescriptions, obtaining the optimal road path between the nearest road section and the Company woodyard, with the minimal annual maintenance cost. At this point, the nearest road section is responsible for allocating the log piles produced by the harvesting intervention from the stand management prescriptions. Figure 8 shows firstly the graph projection representing the complete road network and secondly an example of the set of shortest paths obtained when considering several nearest road sections allocating the log piles. Only 232 road sections of the 1,220 existing roads are conditioned in this example. The procedure of optimizing the used road network with shortest paths is obtaining the operational road network minimizing the annual maintenance cost, given a year of the planning horizon. This information is integrated to the problem by the spatial constraints of the optimization models previously defined.

⁵ <https://igraph.org/>

Figure 8. Graph projection of the complete road network and example of the obtained shortest paths.

Additionally, the second generated dataset corresponds to the identification of harvesting interventions in adjacent (neighbor) stands given a year of the planning horizon. The procedure also uses the igraph package. The forest stands are converted from a geospatial vector (shapefile) to an adjacent matrix, which reflects the adjacency between stands. Thus, this information and the information of harvesting interventions from the stand management prescriptions, are joined. Finally, it is possible identifying when two harvesting interventions in adjacent stands and in the same year are produced. Figure 9 show an example of the adjacency identification of the harvesting interventions given a year of the planning horizon. There are harvesting interventions in adjacent and non-adjacent stands. This information is also integrated to the problem by the spatial constraints of the optimization models previously defined.

Figure 9. Identification of adjacent and non-adjacent harvesting interventions given a year of the planning horizon.

3.3.9 Problem Formulation

In the first interaction, the decision-maker selected six strategic criteria: NPV, Total volume, Carbon sequestration, Even flow of commercial volume, Even flow of veneer log volume and an equal area in each of the five year age-classes at the end of the planning horizon. On the other hand, two criteria were selected for tactical purposes: Operational cost and Harvesting connectivity of each period. These tactical criteria consider the spatial distribution and promote the clustering of harvesting activities.

In the second interaction, the decision-maker decides on the preferential weight of each criterion and indicates the target for each strategic and tactical goal. Also, the strategic planning horizon (PH) of 30 annual periods and the tactical planning horizon (TH) of 3 yearly periods were established. The strategic and tactical prescriptions for each stand consider the management alternatives previously defined.

The mathematical formulation of the generalized framework for the integration of strategic and tactical models is presented in the Appendix 2. Starting from the Top-down approach, the achievement function Eq. (A1) includes the normalized and weighted deviation variables of each strategic criterion. Besides, Eqs. (A1d)-(A7) show the strategic goals in this approach. Thus, Eq. (A2) corresponds to the NPV criterion, Eq.(A3) to the Total volume, and Eq. (A4) embraces the Carbon sequestration objective, while the rest of the goals, regarding technical issues (Age class regulation, Even flow commercial volume and Even flow veneer log volume), are represented by Eqs. (A5)-(A7). The mathematical formulation of the tactical achievement function is described in Eq. (B1), including the normalized and weighted parameter of each tactical criterion and the corresponding constraints (Eq. (B1d)). Eqs. (B2)-(B7) show the transference of strategic results, while Eqs. (B8)-(B9) include the tactical goals: Operational cost and Harvesting connectivity. Finally, the Integrated approach begins with the achievement function and EGP constraints shown in Eqs. (C1)-(C1d), while the goals are presented in Eqs. (C2)-(C9).

3.3.10 Problem Resolution

Once the strategic and tactical models had been formulated, the problem was solved using the two approaches defined above. In the Top-down approach, the first step was to optimize the strategic forest management model Eqs. (A1)-(A8). The second step was to formulate the tactical Top-down model replacing the achievement function in Eq. (A1) by Eq. (B1), and the deviations included in Eq. (A1d) by Eq. (B1d). In addition, the goals regarding the transfer of strategic results have been added in Eqs. (B2)-(B7) as well the tactical goals Eqs. (B8)-(B9). Finally, considering the EGP formulations, we simulated three scenarios modifying the value ($\lambda = 0$, $\lambda = 0.5$ and $\lambda = 1$). In the Integrated approach, the model was formulated to include the achievement

function Eq. (C1) and the deviations Eq. (C1d), as well as the strategic Eqs. (A2)-(A8) replicated now as Eqs. (C2)-(C7) and incorporating the tactical constraints Eqs. (C8)-(C9).

As in the previous approach, we simulated three scenarios modifying the value ($\lambda = 0$, $\lambda = 0.5$ and $\lambda = 1$), and the third interaction with the decision-maker consisted precisely of selecting the most attractive solutions according to the results obtained, using the two approaches and possible alternatives according to the values of previously mentioned. The same as in the second interaction, the procedure was developed through a “pairwise” comparison format, following Saaty’s verbal scale (Saaty, 1977). Finally, the optimization models were solved using CPLEX 12.7 in an Intel® Core™ i7-7700U 3.60GHz with 16 Gb of RAM. The stopping conditions of the optimization were two hours of processing time and gap between the current solution and the relaxed solution of below 2%.

3.4 PARTITIONING AND SOLVING OPTIMIZATION PROCEDURE: INTEGRATING HARVEST SCHEDULE AND ROAD NETWORK PLANNING WITH TRANSPORTATION MODELS.

This sub-chapter presents a new optimization procedure for dealing with the other crucial problem in forest management: the integration of the tactical harvest schedule and road network planning. With this purpose in mind, will be presented first the mathematical formulation of the FCTP, and secondly, the pseudocode of the partitioning and solving procedure.

3.4.1 *The Fixed Charge Transportation Model (FCTM)*

Typically, the FCTM is suitable for solving the harvesting problem due to the main aspects of the model being related to the performance of operational activities. In short, besides the harvesting revenues, the model includes a variable transportation cost which depends on the flow volume and considers the road segments comprising the hauling route associated with a given harvesting intervention. Additionally, the model

requires that the used road segments must be conditioned in the same planning period, being this the fixed road cost. Thus, in order to formulate the FCTM, we represent the forest road network as a graph where the intersections between road sections are made up by a source node (i) and a sink node (j).

The proposed model has the following mathematical structure:

Achievement function

$$MinZ = \sum_{s=1}^S \sum_{p=1}^{PH} c_{sp} r_{sp} + \sum_{i,j=1}^N \sum_{p=1}^{PH} c_{ijp} z_{ijp} + \sum_{i,j=1}^N \sum_{p=1}^{PH} u_{ijp} f_{ijp} \quad (1)$$

Constraints

$$f_{i\bar{c}p} \geq t_{volp} \quad i \in n\bar{c}, \forall p \quad (2)$$

$$\sum_{p=1}^{PH} r_{sp} = 1 \quad \forall s \quad (3)$$

$$\sum_{j \in ns} f_{sjp} = Vol_{sp} r_{sp} \quad \forall s, p \quad (4)$$

$$\sum_{j \in ns} f_{sjp} + \sum_{i \in N_j} f_{ijp} - \sum_{k \in N_j} f_{jkp} = 0 \quad \forall j, p \quad (5)$$

$$f_{ijp} + f_{jip} - Mz_{ijp} \leq 0 \quad \forall j, p \quad (6)$$

$$r_{sp}, z_{ijp} \in \{0, 1\}$$

The objective function (1) minimizes the total operational costs, where r_{sp} is a binary variable which takes the value of 1 when forest stand s is harvested during the p th period of time, and 0 otherwise; c_{sp} represents the harvesting cost of stand s ; z_{ijp} is a binary variable representing the use of the road section existing between source node i and sink node j . The value of 1 indicates the road section will be used in period p , otherwise it becomes 0; c_{ijp} represents the fixed road section cost; f_{ijp} is the annual

volume flow transported over the road section from source node i to sink node j during the p th time period; u_{ijp} represents unit transportation cost over the road section from i to j ; N represents the total of nodes from the road network; and TH is the total number of tactical planning periods.

Eq. (2) ensures the annual volume targets are met, where t_{volp} represents the timber volume production target during the p th time period; where $\bar{nc}$ represents the node accessible from company log yard denoted by the end node $\bar{c}$ and f_{icp} represents the total flow transported over the road section from source node i to end node $\bar{c}$ in time period p . Eq. (3) ensures that stand s can be harvested only once within the planning horizon (Johnson and Scheurman 1977). Eq. (4) creates the source flow for the system, where $\bar{ns}$ represents the node accessible from the stand source nodes $\bar{s}$; Vol_{sp} determines harvest volume in stand s when harvested in period p , and assigns the volume to the volume flow (f_{sjp}) over the road section from stand ($\bar{s}$) to its corresponding sink node j . Eq. (5) are the conservation flow constraints, ensuring that the incoming flow of the road segment f_{ijp} is less or equal the outgoing flow f_{jkp} . Moreover, it adds the flow variable f_{sjp} when $j \in \bar{ns}$. Finally, Eq. (6) ensures that a road section from source node i to sink node j is open and available in period p for the timber flow. M represents an arbitrary large number.

3.4.2 Partitioning and solving optimization procedure

In order to overcome the limitation of the MILP approach in solving large FCTM problems, we partition the large problem into multiple sub-problems (named harvesting blocks) to ensure the solvability of the MILP approach. Each harvesting block is consisted by a subset of adjacent stands and road sections. The selection process of each one must attend specific criteria to avoid the existence of a significantly large number of sub-problems and at the same time ensure its solvability. One criterion is controlling the stands number in each harvesting block for generating sub-problems relatively easy to solve. Another is the connection between the selected stands, the road

sections and the production destination. Accordingly, one sub-problem is formulated for each harvesting block, generating the set S .

Moreover, to compute the initial annual volume targets for each sub-problem an initial solution is used. It is extremely important to represent the annual entire forest volume production requirements during TH when generating the initial solution because the optimization procedure works interactively with these values. A simple process for the initial solution generation is illustrated below. Once the initial solution is obtained the initial targets are transferred to the respective sub-problems by replacing t_{vol} .

Although each sub-problem can be solved independently using MILP in a reasonable solution time, the merge of the sub-problem solutions may not guarantee the global optimum to the entire problem. To improve the solution quality of the entire problem, we implement an optimization procedure that solves the sub-problems iteratively while exchanging volume production targets between sub-problems. This procedure constantly searches for lower cost solutions to the entire problem, while meeting the volume production requirement of the entire problem. This is a systematical process where two sub-problems are selected first and then volume production targets of the two sub-problems are swapped.

Table 13. Pseudocode of the partitioning and solving procedure.

```

for  $n = 1$  to  $nSubProblems$ 
    Solve sub-problem  $S_n$  obtaining  $C_n$ 
next  $n$ 
for  $i = 1$  to  $Iterations$ 
    Randomly select ( $S_a, S_b, P_\alpha$  and  $P_\beta$ )
    for  $j$  in  $\nu$ 
        Solve  $S_a$  and  $S_b$  with updated targets ( $t_{vol} = t_{vol \wedge j}$ ) for  $P_\alpha$  and  $P_\beta$ 
        If  $(C_a + C_b) - (C_{aNEW} + C_{bNEW}) \geq 0$ 
            Save the updated target ( $t_{vol} = t_{vol \wedge j}$ ) Else discard
        end if
    next  $j$ 
next  $i$ 

```

In the pseudocode shown in Table 13, $nSubProblems$ represents the total number of sub-problems. Each sub-problem (S_n) is solved using MILP to its optimality, and the objective function value (C_n) meaning the total cost of the sub-problem is saved. Then, two sub-problems (S_a and S_b) and two planning periods P_α and P_β , where $P_\alpha < P_\beta$ and $p_\alpha \in (TH - 1)$, are randomly selected in each iteration. Exchanged Volume (ν) is the amount of timber volume that can be exchanged between the selected sub-problems and periods. The exchangeable timber volume depends on the capacity and flexibility of the sub-problems in the selected time periods. The optimization procedure systematically tests different amounts of exchange ranging between 100%, 50% and 10% of the maximum volume exchange capacity of the two sub-problems. Volume exchange is reflected on the new target volumes ($t_{volp} = t_{volp} \wedge_j$). If the new sub-problems with updated volume targets are feasible and their solutions ($R_{aNew} + R_{bNew}$) are better than the previous solutions ($R_a + R_b$), the new solutions are stored for the next iteration. We implemented this optimization procedure using Gurobi Optimizer 8.1 with R Interface in an Intel® Core™ i7-7700U 3.60GHz with 16 Gb of RAM.

3.5 APPLICATION OF THE PARTITIONING AND SOLVING OPTIMIZATION PROCEDURE

The application of the partitioning and solving optimization procedure corresponds to a real case study, which provided the set of stands to be scheduled to the harvesting during the tactical horizon and specified its production targets.

3.5.1 Case study

The case study is a large industrial plantation forest of 125,974 ha owned by the company *Suzano Papel e Celulose*⁶, located in Mato Grosso do Sul State, Brazil (Figure 10). The forest consists of 2,935 stands of *Eucalyptus* spp, producing pulpwood as a

⁶ <http://www.suzano.com.br/>

main product. The road network includes 145 arterial road sections totaling 516 km and 3,740 collectors totaling 4,225 km. The entire forest area is partitioned into 20 harvesting blocks based on geographic locations and proximity of individual stands. Each harvesting block contains 147 stands on average.

Figure 10. The study forest partitioned into 20 harvesting blocks.

The study forest includes only forest stands that are available for harvesting in the next 6 years as the result of the long-term strategic planning, and therefore the current age-class distribution is uneven (Figure 11). The forest company established a minimum volume production target at 83,350 Mm³/year for the entire forest.

Figure 11. Age classes distribution of the study forest.

3.5.2 Management prescriptions

Tactical planning horizon is set at 6 years (TH), and clear cutting of the stand at minimum age of 4 years is used as the timber harvesting practice by the company. Therefore, possible management prescriptions for each stand and corresponding harvest volumes are established along the TH according to the classic Model I formulation approach (Johnson and Scheurman 1977). Stand growth was estimated according to the growth rates supplied by the company.

3.5.3 Production costs

We use the average costs for harvesting, logging transportation and road network maintenance with an annual discounting rate of 5%. The harvest cost is calculated considering the average individual volume and number of trees, ranging from 2.2 to 3.3 $\$/m^3$, including tree felling, processing, skidding and loading. The variable transportation cost for each road section is calculated using an average haul rate of 0.1 $\$/m^3/km$. The road network consists of arterial paved roads and collector unpaved roads, and the road maintenance cost incurs only on unpaved roads. Fixed costs of road maintenance were established for two unpaved road classes: main (12,500 $\$/km$) and secondary roads (6,500 $\$/km$). New road construction is not an option in this forest, and thus is not considered in this study.

3.5.4 Solution procedure and evaluation

Following the optimization procedure above, one FCTM is formulated for each harvesting block of the study forest, providing the set S with 20 sub-problems. In order to illustrate a simple process for the initial solution generation and consequently to establish initial annual volume targets for each sub-problem, a classic LP Model I problem is formulated for the entire forest and solved to minimize the total harvesting cost subject to the volume production requirement of 83,350 Mm³/year. This LP solution is then transferred to each sub-problem for the initial volume targets based on the area and age class distribution of the sub-problem. Finally, the sub-problems are iteratively solved by the optimization procedure previously described, producing optimal solutions for each sub-problem. These optimal problems are then combined to represent one “*optimized solution*” for the entire forest. Maximum solution time is limited to 24 hours for this procedure.

For performance evaluation of our optimization procedure, we formulated a single large FCTM for the entire forest subject to the annual volume production requirements established by the company. As expected, due to the problem complexity it was impossible to obtain an integer solution bound within the 24-hour solution time limit. However, providing a MIP start (see Gurobi Optimizer Reference Manual, 2018) to the single large FCTM allows solution evaluation in terms of solution gap from the global optimum. This technique specifies start values for particular model variables, most commonly the integer variables. The results obtained from the initial LP model and *optimized solutions* (i.e., the merge of sub-problem solutions) are used as the MIP starts to the single large FCTM. Both MIP starts exclusively specify the value of the stand harvesting variables, r_{sp} . Thus, the single large FCTM are optimized using two different MIP starts (hereafter referred to as scenarios 1 and 2). The performance of our partitioning and solving optimization approach is then evaluated by comparing the two scenario solutions of the single large FCTM.

4 RESULTS

4.1 THE CRITICAL SURVEY

In the following subsections it is described the results of the critical survey of optimization methods in the management of industrial forest plantations, such as the general aspects of the papers, the most employed techniques, the hierarchical planning levels, the strategic Model I and II, the multicriteria techniques, common goals and constraints, and sustainable aspects. After relating these results, the trends in the use of optimization methods in industrial forest plantations are highlighted.

4.1.1 General aspects

As mentioned previously, 67 papers in all corresponding to the period from 1986-2016 were selected in the second search. As can be seen in Appendix 1 (3.0), 68 % corresponded to case studies, the rest being methodology proposals. Almost all the studies used deterministic techniques and, from a geographical perspective, Brazil was the country most represented providing nearly 38 % of the papers, followed a good distance behind by countries such as Spain, Chile, Colombia, Cuba, Mexico, New Zealand and Venezuela. Moreover, the species most commonly represented were those belonging to the genus *Eucalyptus* (in 53 % of the papers), followed by those corresponding to the genus *Pinus* (30 % of the papers). As for expansion over time, there has been a notable increase since 2000. In fact, the number of publications in this field in the current century represents almost 90 % of the total number of papers published to date, as is shown in Figure 14.

Figure 12. Temporal evolution of the number of papers.

4.1.2 Which techniques are usually employed the most?

First, we grouped the main optimization techniques found in the papers reviewed following a scheme similar to that found in Ezquerro et al. (2016). Three sizeable groups of techniques were defined. The first is called Classic Optimization Techniques and includes: Linear Programming, Integer Programming, Mixed-Integer Programming and Dynamic Programming. The second group was called Metaheuristics (MH), which includes: Simulated Annealing, Genetic Algorithms and Tabu Search. Finally, the last group involved Multi-Criteria Decision Making Techniques (MCDM) including the two most widely used methods in the field surveyed: Goal Programming (GP), and Analytic Hierarchical Process (AHP).

The results collected in Appendix 1 (3.1), show, how out of the 3 large groups, classic optimization is the most represented, followed by MCDM techniques, and, finally, the set of MH methods. With regard to the techniques themselves, and taking those used in at least three studies, the two most recurring ones were MILP and GP. However, what captures the attention is how these techniques were used in a different way according to whether the study reports an actual case study or implies a theoretical reflection. As can be noted in the case of MH, most of the works were theoretical mod-

els, whereas in the case of the use of multi-criteria techniques, over 91 % were carried out in case studies.

4.1.3 Planning levels: strategic, tactical and operational

Starting from the basis that, in the literature, different optimization methods have frequently been used to address different forest management problems (Weintraub and Bare, 1996; Kaya et al., 2016; Yoshimoto et al., 2016), the temporal aspect of applying these techniques in industrial forest plantations was analyzed. When considering different planning times, the classic definitions of strategic, tactical and operational levels were taken into account (McDill, 2014; Borges et al., 2014b), bearing in mind that they are usually organized hierarchically (Banhara et al., 2010). In Appendix 1 it is noted that most of the papers analyzed relate to the strategic level, the number of papers on the other two levels being very similar. On the other hand, it is interesting to note that, in seventeen cases, the studies combine more than one level of planning. In this sense, the combination of tactical and operational planning is the most frequent in these cases, as shown in Appendix 1.

4.1.4 Which strategic forest planning model is the most used?

Once it has been verified that it is at the strategic forest planning stage when these optimization methods are used most, it should be asked which strategic planning model is the one most employed, following the nomenclature of Johnson and Scheurman (1977). The results of our review show that Model I is more commonly applied compared to Model II (Appendix 1, 3.3), although in many cases the authors have not specified the model used. Indeed, only 17 papers specify if Model I or Model II appears. It should be pointed out that although there are signs in other studies that a particular model has been deployed (generally Model I), the criterion of quantifying only those which were explicitly defined by their authors was adopted.

4.1.5 *Is the logic still mono-criterion or is the tendency for other objectives to be included in these models?*

Figure 13 shows the temporal evolution of the use of optimization methods in these forest systems. It can be seen how they have undergone a notable upsurge since the year 2000, especially with regard to the use of the MH and MCDM methods. In effect, up to that year, there was hardly any representation of these two sizeable groups of techniques. However, in the past few years, their use has increased, especially multi-criteria techniques, whose number from the year 2000 exceeded papers using classic optimization methods.

Figure 13. Temporal evolution of the main optimization technique groups.

In Appendix 1 (3.4) it can be seen how the objective function most widely used is the maximization of NPV. Notwithstanding, in the last few years a significant number of papers including objective functions with a non-productive orientation such as biodiversity conservation and environmental protection have appeared.

4.1.6 *Other theory developments*

In addition to the techniques described above, on many occasions it is customary to find methodologies combining more than one optimization technique. In such cases, a number of authors call them hybrid methods (Uhde et al., 2015). On the other hand, in

recent years, an increase in the application of the Decision Support Systems (DSS) method in forest management (Borges et al., 2014c) has been observed. For this reason, the articles proposing these methods have been quantified. The latest theory development considered has been the use of group decision making models in the management of this type of plantation. The results in Appendix 1 (3.5) show how the degree of usage of these methodologies is similar with respect to the others, although those with the greatest presence are the DSS. Although no graph illustrating this fact has been shown, the temporal evolution of the papers employing these techniques does not exactly follow the pattern shown in Figure 2. Thus, DSS were resorted to with greater frequency in the first decade of the 20th century than in the current one. Finally, all the methods considered up to now were of a deterministic nature. No non-deterministic methods (stochastic, Monte Carlo, etc.) have been specified because they were used on very few occasions according to the articles reviewed.

4.1.7 Integration of other non-productive objectives

In section 3.4 of the Appendix it has already been suggested from time to time that the objectives considered in the management of these plantations have not always been of a productive nature. One of the most important objectives, fundamentally due to certain controversies associated with this type of forest system (Calviño-Cancela, 2013), is biodiversity. Another important one is the protection of the ecosystem, related to the quality of the soil, water and landscape (Silva et al., 2010). Along with the eleven studies in which environmental resources appear as objectives, it should be taken into account that, on other occasions, it was decided to introduce them as constraints or, indirectly, by what are known as spatial constraints. Although it cannot be said that these constraints are always univocally related to objectives relating to conserving environmental resources, their inclusion in forest management does at least make the achievement of this type of objective easier (Baskent and Keles, 2005). In short, it can be stated that these types of objectives have a growing presence in the management of these plantations. Figure 14 shows this, and it is significant that not until 2007 did the first study considering biodiversity as an objective in industrial forest plantation management appear.

Figure 14. Temporal evolution of the number of papers which consider biodiversity as an objective.

4.1.8 *What constraints and decision variables are usually employed the most?*

Appendix 1 (3.7) gives the constraints most commonly incorporated into forest management problems, and the frequency with which they appear in the articles analyzed is quantified. It can be seen that the most frequent constraint is the one associated with the procurement of a certain volume per period, followed by spatial constraints, the achievement of a homogeneous production throughout a specific period of time, and those associated with specific logistic problems. Of all of these, the spatial types stand out, since the results show that they have been used many times in applying strategic planning Model I with the help of binary variables. In many studies, classic optimization methods were used requiring an enormous computational resolution effort (i.e., Augustynczyk et al., 2016; Silva et al., 2016). Finally, the type of decision variables used in these models has been calculated. Although cutting area variables remain prevalent, other variables associated with other kinds of problems (logistics, environmental) are significant.

4.1.9 Plantations and sustainability

For some years, several authors (e.g., Diaz-Balteiro, 2007; Fernandes, 2008; Gerber, 2011; Calviño-Cancela et al., 2012; Andersson et al., 2016) have been proposing to introduce the issue of sustainability into the management of forest plantations, with the purpose of balancing productive and non-productive (e.g., biodiversity conservation) orientations (Calviño-Cancela, 2013).

Given that there is considerable consensus on the idea of tackling sustainability problems by means of a set of criteria and indicators (Wolfslehner and Vacik, 2008), in principle, we find ourselves facing discrete type problems; that is, if we are faced with a finite set of plantations, we must choose the most sustainable one. Indeed, if we accept this type of scenario, it would seem that the MCDM techniques are the most adequate ones because they permit the integration of criteria and indicators of different natures in a very straightforward way (Diaz- Balteiro et al., 2017). As can be seen in Appendix 1, GP is the MCDM most commonly used technique for the purpose of aggregating criteria and indicators in order to obtain the most sustainable plantation (Diaz-Balteiro et al., 2016a, b), or the most sustainable alternative management for a plantation (Giménez et al., 2013). However, in other instances, and for the same basic purpose, other multi-criteria techniques have been employed.

4.2 THE APPLICATION OF THE GENERALIZED FRAMEWORK

The results from the application of the optimization models are following. Table 14 shows the Pay-off Matrix obtained by means of the individual optimization of each criterion, either strategic or tactical. The elements of this matrix measure the deviations in relation to the respective ideal values. It should be noted that those ideal values are represented in bold type, whereas the worst possible values or anti-ideal ones are underlined. For information purposes, at the bottom of this matrix the values of the three criteria are shown (*NPV*, *Total volume* and *Carbon sequestration*), which can be usually associated with the maximization of a strategic objective. In that table, an important conflict is observed between the criteria, especially with regard to *Carbon*

sequestration and to *Even flow veneer log volume*. It should be emphasized that the value of the criterion associated with carbon sequestration is negative when any one of the five remaining criteria is optimized.

Table 14. Pay-off Matrix for the strategic and tactical criteria. Matrix values represent deviations in relation to the ideal or optimal values. Bold figures denote ideal deviations, and italic figures denote anti-ideal deviations.

Criteria	Strategic						Tactical	
	<i>NPV</i>	<i>Vol</i>	<i>Carb</i>	<i>ACR</i>	<i>FVol</i>	<i>FLog</i>	<i>Cost</i>	<i>HCon</i>
<i>NPV</i> (MM\$)	0	15.3	<u>74.6</u>	17.1	25.7	36.9	-	-
<i>Vol</i> (MMm ³)	1.8	0	<u>3.9</u>	1.8	1.3	3.0	-	-
<i>Carb</i> (Mt)	<u>646</u>	544	0	535	355	497	-	-
<i>ACR</i> (ha)	1,300	<u>3,048</u>	2,967	0	741	2,439	-	-
<i>FVol</i> (Mm ³)	3,676	<u>5,881</u>	3,461	2,088	0	1,904	-	-
<i>FLog</i> (Mm ³)	1,053	<u>1,161</u>	582	578	633	0	-	-
<i>Cost</i> (MM\$)	-	-	-	-	-	-	0	<u>4.6</u>
<i>HCon</i>	-	-	-	-	-	-	<u>3,421</u>	0

Additional information: values (not deviations) of the three criteria more habitually used in strategic planning models

<i>NPV</i> (MM\$)	114.5	99.2	<u>39.9</u>	97.4	88.8	77.6	-	-
<i>Vol</i> (MMm ³)	6.7	8.5	<u>4.6</u>	6.7	7.2	5.5	-	-
<i>Carb</i> (Mt)	<u>-377</u>	-275	269	-266	-86	-228	-	-

Where: *NPV* Net Present Value, *Vol* Total Volume, *Carb* Carbon Sequestration, *ACR* Age class regulation, *FVol* Even flow commercial volume, *FLog* Even flow veneer log, *Cost* Operational cost, *HCon* Harvesting connectivity (total of adjacent stands interventions). Source: Own elaboration.

Table 15 displays the normalization factor (obtained from the results of the Pay-off Matrix) and preferential weights attached by the decision-maker to the different goals. The AHP method implemented for quantifying the preferential weights of each criterion is detailed in Appendix 3.

Table 15. Normalization factor and preferential weights attached by the decision-maker to the different goals.

Criteria	Normalization factor	Weights		
		Strategic	Tactical	Integrated
<i>NPV</i> (MM\$)	13,4	0,17		0,13
<i>Vol</i> (MMm3)	255,4	0,06		0,04
<i>Carb</i> (Mt)	328,1	0,09		0,07
<i>ACR</i> (ha)	1548,0	0,10		0,07
<i>FVol</i> (Mm3)	170,0	0,15		0,11
<i>FLog</i> (Mm3)	861,3	0,44		0,33
<i>OpCost</i> (\$)	214,7		0,25	0,06
<i>HarvCon</i>	292,3		0,75	0,19

Source: Own elaboration.

Table 16 displays the results obtained in the criteria space according to the approach considered, and the value of control parameter λ . In relation to the responses resulting from the 3rd iteration with the decision-maker for the Top-down models, the scenario of $\lambda = 1$ was the one selected (in bold type in Table 11). Again, according to the decision-maker, for the Integrated models, the scenario of $\lambda = 0.5$ presents the preferred solution (also in bold type in Table 11). Finally, the decision-maker prefers the results of the Integrated scenarios to the Top-down ones, if the two scenarios are compared with each other.

Table 16. Preference values and results, in the criteria space, for the different values of control parameter λ .

Criteria	Top-down			Integrated		
	$\lambda = 1$	$\lambda = 0.5$	$\lambda = 0$	$\lambda = 1$	$\lambda = 0.5$	$\lambda = 0$
<i>NPV</i> (MM\$)	96.3	89.3	86.0	94.6	97.0	95.4
<i>Vol</i> (MMm ³)	6.8	6.5	6.2	6.9	6.9	6.5
<i>Carb</i> (Mt)	-117	1	15	-92	-74	-220
<i>ACR</i> (ha)	6,521	6,384	5,697	6,453	6,521	5,354
<i>FVol</i> (Mm ³)	556	1051	1904	614	599	2064
<i>FLog</i> (Mm ³)	122	147	137	129	163	316
<i>UnitCost</i> (\$/m ³)	4.8	5.1	6.3	5.2	6.7	8.3
<i>ConHInt</i>	1.4	1.3	1.3	1.7	1.8	1.8

Where: *UnitCost* Operational unit cost, *ConHInt* Connectivity of harvesting interventions. Note: In order to permit a better comparison between the scenarios, the tactical criteria used were the Operational unit cost, obtained from dividing the result of the criterion *Operational cost* by the commercial volume produced in the tactical periods, and the *Connectivity of harvesting interventions*, obtained from dividing the result of the criterion *Harvesting connectivity* by the total of the tactical harvesting interventions. Source: Own elaboration.

However, the evaluation of the two scenarios previously selected (Top-down $\lambda = 1$ and Integrated $\lambda = 0.5$) requires a higher level of details in some of the criteria that are of great importance to the decision-maker. It should be pointed out that, for the even flow criteria, related to the *commercial volume*, and to the *veneer log volume*, the two scenarios selected by the decision-maker obtained, on average, a result of over 92% in their respective targets (Figures 15-18). However, some periods can be identified in which those ideal values were not reached, or, on the contrary, had been surpassed.

Figure 15. Results of the production flow of commercial volume of the Top-down $\lambda = 1$ scenario. The values in brackets refer to the result in % reached in relation to the value of the target considered.

Figure 16. Results of the production flows of commercial volume of the Integrated $\lambda = 0.5$ scenario. The values in brackets refer to the result in % reached in relation to the value of the target considered.

Figure 17. Results of the production flows of veneer log of the Top-down $\lambda = 1$ scenario. The values in brackets refer to the result in % reached in relation to the value of the target considered.

Figure 18. Results of the production flows of veneer log of the Integrated $\lambda = 0.5$ scenario. The values in brackets refer to the result in % reached in relation to the value of the target considered.

It is interesting to note that the criterion *Connectivity of harvesting interventions* is of paramount importance at a tactical level for being an indicator of the spatial result

of the annual harvesting schedule. In this sense, it should be taken into account that the Integrated approach for $\lambda = 0.5$ gives the best result in comparison with the Top-down approach for $\lambda = 1$. The image of the annual result of the harvesting schedule (Figure 19), reaffirms that the Integrated approach for $\lambda = 0.5$ performs better in the aggregation of harvesting interventions (forming harvesting blocks along the tactical planning horizon) compared with the Top-down approach.

Figure 19. Spatial and temporal distribution of the harvesting schedule for the Top-down $\lambda = 1$ and Integrated $\lambda = 0.5$. Harvesting interventions in each year of the tactical planning horizon are shown.

The results of the thinning and clear cut areas in the tactical planning horizon of the Top-down $\lambda = 1$ and Integrated $\lambda = 0.5$ scenarios are quite different (Figures 20 and

21). While in the Top Down $\lambda = 1$ the results of the total thinning and clear cut areas are similar, in the Integrated $\lambda = 0.5$ the total thinning area is double of the total clear cut area. These result helps to understand the differences between the production unit cost of the Top-down $\lambda = 1$ and Integrated $\lambda = 0.5$ scenarios. The lower production unit cost of the Top-down $\lambda = 1$ follows the increase in the total clear cut area and consequently the decrease in thinning. The clear cut has a higher efficiency in volume production per area when compared to the thinning, transferring a lower production unit cost.

Figure 20. Thinning and clear cut areas in tactical planning horizon of the Top-down $\lambda = 1$

Figure 21. thinning and clear cut areas in tactical planning horizon of the Integrated $\lambda = 0.5$.

4.3 THE APPLICATION OF THE PARTITIONING AND SOLVING OPTIMIZATION APPROACH

Scenarios 1 and 2 are corresponding to the results of the single large FCTM, when using the MIP start provided from the initial LP solution and *optimized solutions*, respectively. Table 2 presents the results of scenarios 1 and 2, where the total cost includes harvesting, transportation and road maintenance costs. Scenario 1 results in the objective function value of 248 MM.\$ with a solution gap of 27 % from the optimal, while scenario 2 results in 187 MM.\$ with a gap of 3 %. The solver was not able to achieve integer bounds with any lower gaps using these MIP starts within the given solution time limit (i.e., 24 hours). Due to a complexity of the single large FCTM, a gap of 3% appears to be satisfactory. It is noteworthy to compare the harvesting and road costs of the two scenarios. Scenario 1 has much higher road network related costs than Scenario 2 (136 MM.\$ in Scenario 1 vs. 73 MM.\$ in Scenario 2) whereas harvesting costs were similar in both scenarios (111 MM\$ vs. 114 MM.\$). The higher road network costs in Scenario 1 are reflected on the unit production cost, which is 4,9 \$/m³ that is 27% higher than Scenario 2.

Table 17. Comparisons of Scenario 1 and 2 in terms of operational costs, volume production and solution gap.

Scenario	1 (<i>starting solution</i>)	2 (<i>optimized solution</i>)
Harvesting (MM.\$)	111 (45%)	114 (61%)
Road cost - maintenance (MM.\$)	95 (39 %)	35 (19%)
Road cost - transporting (MM.\$)	40 (16%)	38 (20%)
Total cost (MM.\$)	248 (100%)	187 (100%)
gap (%)	27	3
Volume production (M.m ³)	50,294	52,024
Unit production cost (\$/m ³)	4,9	3,6
Used road network distance (Km)	15,348	5,620

Figure 22 shows the volume productions from individual harvesting blocks (i.e., 20 sub-problems) in each time period under different scenarios. All 20 sub problems in Scenario 1 resulted in producing volume flow in every time period, whereas most sub-problems in Scenario 2 produce harvest volume flow in maximum two time periods only. Producing timber volume in each harvesting block means continuous maintenance of access roads every year, which may increase road network related costs. This is reflected on the road costs estimated in Scenario 1. Figure 22c shows the difference in volume production between Scenarios 1 and 2 (i.e., Scenario 2 – Scenario 1), which indicates the optimization procedure was able to further minimize the total costs by exchanging volume production targets among sub-problems.

Figure 22. Comparisons of the two Scenario solutions in terms of the production flow of individual sub-problems in 6 time periods.

The Figure 23 shows the spatial and temporal distribution of the harvesting schedule developed in Scenario 2. Even though there was no spatial connectivity requirement considered in the optimization model, the results show spatiotemporally concentrated harvest patterns. For example, harvesting in period 1 is performed mostly in the upper quadrants in Figure 5, while harvesting in period 6 occurs mostly in the under quadrants. The clustered harvest patterns may be beneficial as they lead to more efficient harvest operations with use of fewer road sections. The benefit is proved by

Scenario 2 that resulted in the use of total 5,620 km of road sections throughout the planning periods, which is a 63% reduction in road use compared to Scenario 1.

Figure 23. Spatial and temporal distribution of the harvesting schedules developed in Scenario 2. Harvesting interventions in each year of the tactical planning horizon are shown.

5 DISCUSSION

5.1 TRENDS IN THE USE OF OPTIMIZATION METHODS IN INDUSTRIAL FOREST PLANTATIONS

The survey made on optimization methods for the management of industrial forest plantations has shown that it is a topical and timely subject reaching a very notable publication level in recent years. These types of forest system are of increasing economic importance (Rodriguez et al., 2014), especially in certain countries. However, there is no direct relationship between countries which produce the most industrial roundwood (following Payn et al., 2015) and the number of papers included in this study should not be expected. In fact, there are few studies emanating from countries such as China, the USA or India. One exception to this is Brazil, the country considered to be the most suitable for making this type of investment in the period from 2005-2011 (Cubbage et al., 2014). However, this result was to be expected, given its immense forest area covered with industrial forest plantations (Rodriguez et al., 2014). Generally, it has shown a significant publication level in recent years, especially for species of eucalyptus and pine.

The Operations Research (OR) techniques most frequently employed are LP, MILP and a MCDM method GP. However, it should be noted the scarcity of papers hybridizing methods. These results obtained differ from those of Ezquerro et al. (2016), who analyzed 179 papers in a study on their use in problems related to biodiversity conservation. Thus, the classic optimization group is the one least used, and as for those most employed, the favorite is Simulated Annealing, followed by integer linear programming (ILP). Yoshimoto et al. (2016) analyzed forest management optimization methods differentiating stand, forest and landscape levels using a database of 85 papers. In the results at the stand level, MH methods predominated, whereas at the forest level MILP and LP were the most prominent. Those two techniques, in inverse order, were also those most used at the landscape level.

The results of the use of these techniques at the different planning levels habitually considered in forest management show a predominance of strategic planning, although there are numerous examples of tactical and operational planning. Despite expectations, considering the problem being dealt with, that there should be many studies devoted to operational planning, this is not commonplace when objectives not

having a production orientation such as biodiversity are integrated (Ezquerro et al., 2016). On the other hand, and although integration between the diverse levels is not always easy (Rönnqvist et al., 2015) or univocal (Kangas et al., 2014; McDill, 2014), a high percentage of studies combining more than one management level has been found, specifically, those unifying strategic planning with operational aspects, which seems to provide a balance between economic and environmental benefits (Augustynczyk et al., 2016). It is also important to remark that the existence of different planning scales (strategic, tactical and operational) implies the existence of several sub problems, mostly solved independently. Optimization approaches for linking and solving sub problems are frequently applied to particular cases. These results also highlight the importance of obtaining decision support systems to solve the general problem by integrating different specific sub problems with different planning scales.

With regard to the strategic planning models, the reasons for justifying the selection of one or the other are not clear, although, recently, this aspect has triggered an interesting debate in the literature. Thus, McDill et al. (2016) maintain that Model II outperforms Model I the more the periods in the action horizon and the more the silvicultural operations are employed. However, Martin et al. (2017) suggest that Model I outperforms Model II in spatial models. Both conclusions could justify Model I as being the most commonly selected in industrial plantations. In fact, from 2010 onwards, no studies deploying Model II in this type of forest system were found. Additionally, in recent years a percentage increase in studies using MCDM techniques has been observed. This tendency has been seen in other studies reviewed on the employment of MCDM techniques in diverse spheres (Diaz-Balteiro and Romero, 2008; Diaz-Balteiro et al., 2017). However, unlike the work of Diaz-Balteiro and Romero (2008), the number of studies which can be included under the heading “harvest scheduling” or “extended harvest scheduling” is clearly on the rise. There is no doubt that the use of hybrid methodologies enables a resolution of complex problems that would not be easily tackled by any single technique (Hernández et al., 2014). However, the number of papers with this orientation is not very significant. Thus, in Ezquerro et al. (2016) the number of articles in which more than one optimization technique is combined is no more than 35 %. This combination of techniques is often clearly present in the context of collective decision-making. Thus, several authors suggest suitable aggregation of the preferences of the different stakeholders in management models for these types of

plantations, since these preferences clearly affect the final results obtained (Diaz-Balteiro et al., 2016a). Finally, it is interesting to note that very few studies in this field incorporate uncertainty or risk elements into the analysis (Yoshimoto et al., 2016). The consideration of biodiversity management as an objective could have obvious implications in aspects like the cutting areas, the forest rotation length employed, silviculture, etc. However, indirectly, these plantations could be of indirect benefit to these non-productive objectives if this does not require altering natural forests (Brockhoff et al., 2008). Nevertheless, from an operational point of view, the inclusion of this objective usually implies that tactical and operational planning gain in importance, it being necessary to resort to different optimization tools from those of classic linear programming (Ezquerro et al., 2016), including hybrid methods. It is no coincidence that biodiversity has appeared as an objective, as is shown in Figure 2, in a manner parallel to the expansion in the use of MH and MCDM techniques. As stated by Yoshimoto et al. (2016), the employment of MH was accentuated when spatial aspects appeared. It should be emphasized that, as shown in Appendix 1, spatial constraints are used reasonably frequently. One of the differentiating aspects in relation to the forest management usually carried out in other forest systems is the comparatively scant presence of constraints generally associated with the idea of a normal forest. Indeed, if it is assumed that this idea can be replicated by obliging simultaneous compliance with regulation conditions, and even-flow and ending forest inventory, it has been verified that, in no case have these constraints been introduced simultaneously. Specifically, it can be seen how the least represented constraint is the one relative to ending forest inventory, and this would seem to be logical since the persistence of these forests is assumed to be ensured. It has been demonstrated that, on occasions, the fulfillment of one of these objectives (even-flow volume) in certain plantations clashes with the achievement of a certain structure in the forest (Bertomeu et al., 2009), in spite of defining diverse GP models. Also, in Piazza and Pagnoncelli (2014), optimal solutions have been found which do not converge into a normal forest structure, whereas Zhai et al. (2014) consider this type of structure to be unrealistic for the plantation case, which is a controversial issue.

5.2 THE GENERALIZED FRAMEWORK TO SOLVE HIERARCHICAL STRATEGIC AND TACTICAL MULTI-CRITERIA FOREST PROBLEMS

The developed Generalized Framework allowed to formulate multi-criteria models representing two different approaches for embedding strategic and tactical planning, taking into account the decision maker's preferences, and addressing economic, technical and environmental criteria. Further, for each approach, several solutions have been calculated according to different values of the control parameter λ which trades off the "optimum average" with the "optimum balance" (i.e., trading-off efficiency versus equity).

If the two approaches employed are compared in the light of the results obtained in Table 2, it can be seen that the results are reasonably alike, although, for some criteria, better results are procured by the Top-down approach (even flow deviations and operational unit cost), whereas for other criteria the one selected would be, everything else being equal, the Integrated approach (*Connectivity of harvesting interventions*). In the end, taking into account the results shown in Table 2, none of the solutions dominate, although the decision-maker has chosen the Integrated approach and a value of $\lambda = 0.5$. Also, it is surprising that, for each approach, the decision-maker has selected a different scenario, which, logically, means a different preferential interpretation (Díaz-Balteiro et al. 2013).

Analyzing other works on these lines, it seems that there is no unanimity on which approach should be selected. Starting from the basis that the case studies are different, Beaudoin et al. (2008) show that the Top-down approach holds some advantages when measuring the impact of the results of the upper level on the lower one, in anticipation of future problems. However, Troncoso et al. (2015) and Bouchard et al. (2017) give evidence of the superiority of the results of integrated monolithic approaches in improving the "forest profitability" of the respective companies. Also, it is worth noting that GP has already been used in tactical planning problems including spatial issues. Thus, Silva et al. (2010) raise some environmental objectives (soil erosion, contamination of water resources and visual impact of harvesting). However, Gómez et al. (2011) show a model that hybridizes a non-linear GP model with a metaheuristic one called SSPMO (Scatter Search Procedure for Multi objective

Optimization, Molina et al., 2007), incorporating spatial constraints (ARM). Finally, also in Augustynczyk et al. (2016) GP models are formulated to integrate spatial objectives, in this case linked to adjacency constraints. The spatial issues shown in these papers could be incorporated into the generalized framework explained above.

However, it has also been proven that the complexity of the problem could have a notable influence when selecting one approach or another. In this regard, Eyvindson et al. (2018) recommend selecting the approach in terms of the complexity of the case study analyzed. To be specific, the tactical criteria considered in this work (harvesting connectivity and operational cost), are not extended along the whole strategic planning horizon, due to the computational complexity of the formulated spatial constraints with integer variables. Most of the times the traditional optimization techniques such as Integer Programming, produce some limitations due to the size and complexity of the formulated models (Bettinguer et al. 2015). This makes it impossible for them to be resolved unless other techniques like metaheuristics are used (Bachmatiuk et al. 2015; Dong et al. 2015; Augustynczyk et al. 2016). The heuristic techniques overcome the limitations of the integer programming, since they have shown a high potential in solving spatial problems because the respective objectives are easily represented by computer programming than linear or integer programming (Dong et al. 2016).

Analyzing the relation between the results of the tactical criteria: production unit cost and the strategic selected management prescriptions, which transferred the differences between the total clear cut thinning area previously explained, it is observed evidences that these spatial tactical criteria might change the type of harvesting interventions and consequently damage the optimal management prescriptions of the stands. However, once tactical criteria promoting harvesting clustering are incorporated in the short-term forest planning, besides increasing profit margins such as the reduction of the operational costs, by decreasing the used road network and machinery displacements, it reduces the fossil fuel consumption and other non-renewable resources used in road maintenance, contributing in the protection of environmental resources. Moreover, clustering harvesting may also be useful to provide interior habitats across the landscape promoting biodiversity maintenance (Gustafson, 1998).

The results obtained for the criteria of strategic nature are close to the ideal values shown in the Table 1, except for the criterion associated with carbon capture. This result is explained by the initial structure of the forest age classes, that is somewhat

unbalanced, as is shown in Figure 2. This situation has already been noted in other works which used similar multi-criteria techniques (Diaz-Balteiro and Romero 2003). Also, given the initial unbalanced structure of this forest plantation, modifications of this criterion could have been entered in the EGP models, with the aim of tempering this situation. Some examples in this respect can be consulted in Bertomeu et al. (2009), Diaz-Balteiro et al. (2009a) and Hernández et al. (2014).

In another direction, decision-makers are looking for efficiency as well as effectiveness to the new methods, that might provide communication of information needed for developing their decision processes. Thus, it is of interest to note the interactive challenge offered by this methodology. Indeed, the decision-maker not only selects the criteria, the weights associated with them and the targets related to each goal, but he also chooses the optimal solution of each approach, selecting a posteriori the value of λ in each case. Therefore, it would seem to be relatively simple to extend this methodology to a set of stakeholders, which constitutes an open problem nowadays in the field of operations research in forestry (Rönnqvist, 2015). Concretely, the proposal would be to hybridize this technique (EGP) with a group decision model to integrate the preferences of different stakeholders on the lines shown in Diaz-Balteiro et al. (2009b) or Aldea et al. (2014). One possible future line of research for this type of forest system would be to introduce other ecosystem services and incorporate them into these hybrid models. One example can be found in Borges et al. (2017). On the other hand, it also seems interesting to extend these types of models to non-deterministic scenarios, either introducing risk as an additional component of a GP model (Diaz-Balteiro et al. 2014), or merging GP models with stochastic elements, as proposed by some authors (Eyvindson and Kangas 2014; Álvarez-Miranda et al. 2018). This direction as it is stated by Eyvindson and Kangas (2018), will require, not only changes in the models, but probably also changes in the formulation of the criteria considered in the exercise.

Moreover, according to Borges et al. (2014c) the usefulness of optimization models for industrial forest management scheduling depends on the possibility of its encapsulation in computerized modules within a DSS. Traditionally, DSS for industrial forest management scheduling often addressed the optimization of a single strategic objective such as the NPV, under a context of timber flow regulation. Now, the new generation of DSS address other spatial and temporal scales (e.g., Reynolds et al. 2008 and Wikström et al. 2011). Furthermore, the need for automation of strategic, tactical

and operational decision processes drove the development of new DSS to industrial forest management planning. At this point, the proposed framework of this study might be the embryo of a new DSS thanks of its modular structure. This structure allows dealing with forest management problems of different nature, such as the traditional strategic ones and the spatially-explicit forest management problems, by activating and deactivating different modules of the generalized model. These modules are controlled by different particularizations of the existing auxiliary parameters, which makes the process easier for adapting the different existing subproblems.

On the one hand, to the future studies it seems like improvements should focus on the generation of new methods for transferring information from the strategic to the tactical and operational level in the form of goals, objectives, or targets. Example: targets between planning levels can be changed by implementing interactive processes, where the strategic and the tactical model are solved many times recursively, guiding the solution to achieve more efficient results. On the other hand, to the integration of the tactical and the operational levels, new heuristic methods and model decomposition approaches should be tested. The link between tactical-operational levels must be explored because it involves many challenging problems, such as the fixed charge mixed-integer programming problem, which simultaneously optimize the spatial allocation of forest harvest, road network and transportation costs.

5.3 THE PARTITIONING AND SOLVING OPTIMIZATION PROCEDURE TO SOLVE LARGE FORESTRY FCTM

The importance of developing efficient methods which are capable of solving very large problems and at the same time generate near-optimal solutions in tactical forest planning of forest plantations, is highlighted by Marques et al. (2014). In this study, a novel partitioning and solving optimization approach has been developed and presented to solve challenging very large FCTM problems. Our approach requires a pre-determined set of sub-problems. This task seems feasible in tactical forest harvest scheduling problems especially for the forest where harvesting blocks of stands are logically grouped and located, leading towards to the main exit road.

This approach was specifically developed to improve tactical planning solutions for extensive industrial forest plantation management, but the applications could be extended to other forest systems. Our study proves tactical planning solutions can be significantly improved by integrating harvest and road management activities in the FCTM.

The results obtained for road costs in Scenario 2 highlights the importance of efficient methods of integrated problem formulation and solving for the management of industrial plantation forests. Even though Scenario 1 comes to an extreme case due to the non-spatially explicit nature of the formulated Model I, Scenario 2 significantly decreased road costs by 47%. Ross et al. (2017) formulated a variation of the FCTM for Washington State Forests in the United States. This variation used the Model II (Johnson and Scheurman 1977) and endogenous road costs which produced satisfactory results reducing the overall road cost by 15.4% and active road distance by 14.5%.

Comparisons might be less expressive if Scenario 1 corresponded with the best effort of the company (another spatially explicit tactical planning optimization model). However, small improvements up to 1% between results of Scenario 1 and Scenario 2 might be considered significant in this extreme case. By the way, as the road network account for a great portion of the total cost of forest operations, by minimally improving its effectiveness the forest companies are more competitive (Karlsson et al. 2004 and Contreras et al. 2008).

In another direction, extensive applications of FCTM in forest transportation planning are made including side constraints, based on attributes of the road sections, allowing the incorporation of environmental or social criteria. One important environmental criterion in forest plantations is the potential sediment yield from unpaved forest roads (Bravo-Linares et al. 2018). Examples of incorporating sediment yield constraints into the FCTM are Contreras et al. (2008) and Lin et al. (2016). Both studies investigated the use of ant colony optimization methods and compared their performance against MILP, highlighting the efficiency of the heuristic methods. The problem that arises when using MILP models is the problem size limitation and complexity (Contreras et al. 2008) and, to our knowledge, there has been no MILP approach applied to solving very large FCTM problems with side constraints for

environmental or social criteria. Our partitioning and solving optimization approach might be able to offer an alternative solution approach to efficiently solve large FCTM problems with additional side constraints. Future studies will have to explore this possibility.

Moreover, our optimization procedure can be easily incorporated into any decision support systems that optimize road networks in tactical forest planning. An example is RoadOpt, which automatically formulates FCTM to solve forest transportation problems and works as an extension program to ArcMap from ESRI (Karlsson et al. 2006). Another example is *SNAP for ArcGIS*[®], which optimizes both harvest schedule and road network planning using two separate heuristic algorithms (i.e., simulated annealing for harvest scheduling and heuristic network algorithm for forest transportation planning) (Chung et al. 2012). With further development and improvement, our partitioning and solving optimization procedure may provide an alternative optimization tool for decision support systems that can produce efficient and high quality solutions to the challenging integrated harvest scheduling and road network planning problems.

5 CONCLUSIONS

The main conclusion as well as most important contribution derived from this research, is to verify how the new proposed approaches, which integrate the tactical and strategic dimensions and optimize the harvesting operations of industrial forest plantations can considerably improve the efficiency of the management of this type of forest systems. In fact, the proposed procedures can easily be embedded in the management planning of these companies, adapting to the existing workflows and operations going on at present. Moreover, the used software's are usually employed by the forest managers what simplify the required background in order to implement these procedures. It is important to highlight that the case studies, corresponding to industrial forest plantations companies, have play an essential role to test the applicability and effectiveness of the proposed new approaches.

After this preliminary and basic statement, it will state in detail the level of achievement of the different objectives raised in the research. Let`s start with the conclusions derived from the critical survey of the use of optimization tools in industrial forest plantations management. In this direction, it can be concluded:

- The survey showed that in recent years there is a significant increase in the publication level in the field of optimization methods in industrial forest plantation management and Brazil is the country that turns up most of these works specifically concerning with eucalyptus and pine species.
- It has also been identified a scarce usage of hybrid OR techniques, such as classic optimization with MCDM or heuristics. However, since many studies concluded that stakeholder preferences clearly affect the obtained results, the use of classic optimization with MCDM methods seem a suitable tool for the aggregation of these preferences. Besides that, some complex problems would not be easily tackled by any single technique and consequently the hybrid of classic optimization with heuristic techniques is indicated to enable its resolution.
- Most of the papers used the maximization of NPV as the basic objective function and the inclusion of environmental and operational concerns appeared significantly. This fact corresponds to the initiatives of introduce the issue of

sustainability into the forest plantation management, with the purpose of balancing productive and non-productive orientations.

- Optimization approaches with multiple hierarchical planning levels were unusual. Specifically, the integration of strategic and tactical planning is not that common. It represents a clear challenge for effectively achieving a sensible forest plantation management, once the linkage between long-term results and harvesting operations must be optimized.
- Finally, in practice the survey elucidated the identification of the most challenging problems in these forest systems, such as the linkage between hierarchical planning levels, and supported the selection of optimization approaches to the management planning of industrial forest plantation companies, which are the objects of this study.

Regarding the integration of strategic and tactical forest management models within a multicriteria context, the main conclusions derived from this work are the following:

- This first addressed problem has been solved by developing the Top-down and the Integrated optimization approaches to link the strategic and the tactical levels of the harvest scheduling problem with multi criteria. Consequently, it was possible to consider strategic and tactical criteria from different natures, combining management strategies with operational activities.
- The forest plantation company, *Florestal Gateados*, was used as the case study in order to compare the Top down and the Integrated approaches. It was predefined a sequential process consisted of three interactions with the decision-maker (the company forest manager) to the selection of strategic and tactical criteria and the respective preferences. This sequential process was implemented using the AHP method and has shown to be effective for the identification of importance criteria and preferences.
- In the results analysis, criteria and stakeholder preferences interact with each other, making it hard to conclude cause and effect in some cases. The most conflictive criterion was of environmental nature like the carbon capture. It

denotes the importance of quantifying the influence of no-productive criteria in forest plantation management.

- Overall, the optimization procedures resulted on profitable forest management policies, presenting a satisfactory spatial distribution of scheduled stands from the operational view and causing reasonable strategic criteria reductions. Moreover, the reduction of machinery displacement thought inclusion of spatial requirements also given the possibility of substantial environmental benefits.
- The Integrated approach represents the strongest alternative to formulate harvesting scheduling problems with aggregation of harvesting activities requirements. However, results have shown that both approaches achieve relevant outcomes and the Top down approach requires less computational burden due to the less combinatorial complexity of the optimization problems. In conclusion, it is suggested to select one or another approach when the problem resolution is affected by its computational complexity.
- The proposed general framework corresponds to a modular structure capable to firstly formulate strategic and tactical EGP models and secondly to link these models by a Top down or Integrated approach, supported by interactions with decision-makers. Thus, it includes the decision maker's preferences in a more compact model that allows the inclusion of different spatial issues. These aspects support its utilization as the optimization module for the formulation of a new operational decision support system.

Regarding the partitioning and solving procedure for optimizing the tactical harvest scheduling and road network planning, the main conclusions derived from this work are the following:

- This second addressed problem has been solved by developing a novel partitioning and solving optimization approach which solved challenging very large tactical forest problems. Thanks to its interactively process, the optimization procedure is capable of connect and solve several medium-size FCTMs using the MILP solver interface, and of obtain a near-optimal general solution considering the solving time limit of 24 hours.

- The harvesting efficiency of the tactical problem was significantly improved once harvest scheduling and road network planning were integrated. Consequently, it was possible to optimize fixed and variables costs derived from main operational activities: timber felling and extraction, road network maintenance, and log transportation. These facts reinforce the importance of directly control the operational unit cost when producing tactical harvest plans.
- A large plantation was used as the study case in order to illustrate the functionality and performance of the optimization procedure. In addition to the economic benefits of operational efficiency caused by the developed procedure, the reduction of the used road network and consequently the machinery displacement, generates significant environmental benefits.
- Forest managers are benefited by the information of the optimal transportations routes and volume flows determined by the results of the FCTM, without requiring pre-defined routes or post-processing procedures. Moreover, including possibilities of building new road segments in the FCTM formulation, they could evaluate how different access investments affect the harvesting and transporting activities. Besides that, network constraints, such as flow capacity constraints, could also be incorporated integrating others operational concerns.

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7 Appendix 1

Main search results.

3.0. General Results			
Number of papers		67	
% Case studies			69 %
% Theoretical Papers			31 %
Papers with deterministic models			98 %
Papers with non-deterministic models			3 %
Countries more represented			
	Brazil	25	37 %
	Spain	7	10 %
	Chile	6	9 %
	New Zealand	3	5 %
	Colombia	3	5 %
	México	3	5 %
	Cuba	3	5 %
Tree species more represented			
	<i>Eucalyptus</i> spp.	35	52 %
	<i>Pinus</i> spp.	20	30 %
3.1. OR Techniques used			
OR Group	OR Technique	number of papers	% case studies
Classic Optimization		36	77
	Linear Programming	11	
	Integer Programming	5	
	Mixed Integer Programming	16	
	Dynamic Programming	4	
Metaheuristics		20	25
	Simulated Annealing	4	
	Genetic Algorithms	6	
	Tabu Search	3	
	Other	7	

MCDM Techniques	23	91
Goal Programming	14	
AHP	5	
Other	4	
3.2. Temporal scale in the planning		
Temporal Scale	number of papers	
Strategic	42	
Tactical	16	
Operative	20	
Papers with more than one temporal scale		
Strategic and Tactical	6	
Strategic and Operative	3	
Tactical and Operative	8	
3.3 Strategic Models		
Model	number of papers	
Model I	13	
Model II	4	
3.4. Objective Functions		
More represented Objective Functions	number of papers	
Max NPV	45	
Max Volume	12	
Min Costs	14	
Biodiversity	11	
3.5. Other Methodological Issues		
Issue	number of papers	
Methodologies with more than one OR technique	11	
Group Decision-Making	10	
Decision Support Systems	14	
3.7. Main constraints used in these models		
Constraint	number of papers	
Spatial	22	
Carbon	9	
Other (biodiversity, environmental...)	11	

Volume per period (pulpwood, roundwood, etc.)	46
Regulation	11
Even flow volume	20
Ending forest inventory	2
Road systems	13
Other logistic constraints	20
<hr/>	
Type of Decision Variables	
Area	42
Products	4
Harvest machines	6
Road networks	8
Environmental variables	4
Other	3

OR = Operations Research; MCDM = Multiple Criteria Decision Making; AHP = Analytical Hierarchical Process; NPV = Net Present Value; The complete list of references that comprise Appendix 1 can be made available upon request from the authors.

8 Appendix 2

Top-down approach

Strategic achievement function [$\gamma_1 = 1, \gamma_2 = 0, \mu = 1$ and $\delta = 0$]

$$\text{Min}(1 - \lambda) D_1 + \lambda (2.3n_1 + 14n_2 + 149p_3 + 28(n_4 + p_4) + 25(n_5 + p_5) + 380(n_6 + p_6)) \quad (\text{A1})$$

Strategic goals [$\mu = 1$ and $\delta = 0$]

$$2.3n_1 \leq D_1$$

$$14n_2 \leq D_1$$

$$149p_3 \leq D_1 \quad (\text{A1d})$$

$$28(n_4 + p_4) \leq D_1$$

$$25(n_5 + p_5) \leq D_1$$

$$380(n_6 + p_6) \leq D_1$$

$$\sum_{s=1}^{2551} \sum_{m=1}^M NPV_{sm} x_{sm} + n_1 - p_1 = 103,305,019 \quad (\text{A2})$$

$$\sum_{s=1}^{2551} \sum_{m=1}^M VOL_{sm} x_{sm} + n_2 - p_2 = 7,650,016 \quad (\text{A3})$$

$$\sum_{s=1}^{2551} \sum_{m=1}^M (CS_{sm} - CE_{sm}) x_{sm} + n_3 - p_3 = 242,106 \quad (\text{A4})$$

$$\sum_{s=1}^{2551} \sum_{m=1}^M x_{sma} + n_4 - p_4 = 1,235 \quad a = 1, \dots, 5 \quad (\text{A5})$$

$$\sum_{s=1}^{2551} \sum_{m=1}^M Vc_{smk} x_{sm} + n_5 - p_5 = 238,309 \quad k = 1, \dots, 30 \quad (\text{A6})$$

$$\sum_{s=1}^{2551} \sum_{m=1}^M Vl_{smk} xm + n_6 - p_6 = 27,841 \quad k = 1, \dots, 30 \quad (\text{A7})$$

Subject to Eq.14.

Tactical achievement function [$\gamma_1 = 1, \gamma_2 = 0, \mu = 0$ and $\delta = 1$]

$$\text{Min}(1 - \lambda) D_1 + \lambda (1.7n_1 + 10n_2 + 112p_3 + 22(n_4 + p_4) + 19(n_5 + p_5) + 285(n_6 + p_6) + 54n_7 + 13p_8) \quad (\text{B1})$$

$$1.7(n_1) \leq D_1$$

$$10(n_2 + p_2) \leq D_1$$

$$112(n_3 + p_3) \leq D_1$$

$$22(n_4 + p_4) \leq D_1$$

$$19(n_5 + p_5) \leq D_1 \quad (\text{B1d})$$

$$285(n_6 + p_6) \leq D_1$$

$$54(n_7) \leq D_1$$

$$13(p_8) \leq D_1$$

Transference of strategic results $\delta = 1$

$$\sum_{s=1}^{2551} \sum_{m=1}^{Mt} NPV_{sm} x_{sm} + n_1 - p_1 = npv^* \quad (B2)$$

$$\sum_{s=1}^{2551} \sum_{m=1}^{Mt} VOL_{sm} x_{sm} + n_2 - p_2 = vol^* \quad (B3)$$

$$\sum_{s=1}^{2551} \sum_{m=1}^{Mt} (CS_{sm} - CE_{sm}) x_{sm} + n_3 - p_3 = carb^* \quad (B4)$$

$$\sum_{s=1}^{2551} \sum_{m=1}^{Mt} x_{sma} + n_4 - p_4 = acr^* \quad (B5)$$

$$\sum_{s=1}^{2551} \sum_{m=1}^{Mt} Vc_{smk} x_{sm} + n_5 - p_5 = fvol^* \quad k = 1, \dots, 30 \quad (B6)$$

$$\sum_{s=1}^{2551} \sum_{m=1}^{Mt} Vl_{smk} x_{sm} + n_6 - p_6 = FLog^* \quad k = 1, \dots, 30 \quad (B7)$$

It should be noted that the right hand terms of equations (B2)-(B7) are transference targets. Thus, in each strategic scenario for several values of λ , a different strategic result is obtained, implying different target values. The values of the tactical targets, which transfer strategical results, differ according to the formulated scenario following the respective value.

Tactical goals [$\delta = 1$]

$$\sum_{s,l \in g(L)} \sum_{k=1}^3 e_{slk} + n_7 - p_7 = 8,562 \quad (\text{B8})$$

$$\sum_{s=1}^{2551} \sum_{k=1}^3 c_{sk} r_{sk} + \sum_{s=1}^S \sum_{k=1}^3 c_{vk} z_{vk} + n_8 - p_8 = 3,501,652 \quad (\text{B9})$$

Subject to Eq.15-18.

Integrated approach

Integrated achievement function [$\gamma_1 = 0$ and $\gamma_2 = 1$]

$$\text{Min}(1-\lambda) D_2 + \lambda (1.7n_1 + 10n_2 + 112p_3 + 22(n_4 + p_4) + 19(n_5 + p_5) + 285(n_6 + p_6) + 54n_7 + 13p_8) \quad (\text{C1})$$

$$1.7(n_1) \leq D_2$$

$$10(n_2 + p_2) \leq D_2$$

$$112(n_3 + p_3) \leq D_2$$

$$22(n_4 + p_4) \leq D_2$$

$$19(n_5 + p_5) \leq D_2 \quad (\text{C1d})$$

$$285(n_6 + p_6) \leq D_2$$

$$54(n_7) \leq D_2$$

$$13(p_8) \leq D_2$$

Goals

$$\sum_{s=1}^{2551} \sum_{m=1}^M NPV_{sm} x_{sm} + n_1 - p_1 = 103,305,019 \quad (C2)$$

$$\sum_{s=1}^{2551} \sum_{m=1}^M VOL_{sm} x_{sm} + n_2 - p_2 = 7,650,016 \quad (C3)$$

$$\sum_{s=1}^{2551} \sum_{m=1}^M (CS_{sm} - CE_{sm}) x_{sm} + n_3 - p_3 = 242,106 \quad (C4)$$

$$\sum_{s=1}^{2551} \sum_{m=1}^M x_{sma} + n_4 - p_4 = 1,235 \quad a = 1, \dots, 5 \quad (C5)$$

$$\sum_{s=1}^{2551} \sum_{m=1}^M Vc_{smk} x_{sm} + n_5 - p_5 = 238,309 \quad k = 1, \dots, 30 \quad (C6)$$

$$\sum_{s=1}^{2551} \sum_{m=1}^M Vl_{smk} x_{sm} + n_6 - p_6 = 27,841 \quad k = 1, \dots, 30 \quad (C7)$$

$$\sum_{s, l \in g(L)} \sum_{k=1}^3 e_{slk} + n_7 - p_7 = 8,562 \quad (C8)$$

$$\sum_{s=1}^{2551} \sum_{k=1}^3 c_{sk} r_{sk} + \sum_{s=1}^{2551} \sum_{k=1}^3 c_{vk} z_{vk} + n_8 - p_8 = 3,501,652 \quad (C9)$$

Subject to Eq.12-18.

9 Appendix 3

The Analytic Hierarchical Process (AHP), developed by Thomas L. Saaty (1977, 1980), is a multicriteria decision-making method which, consists of contextualizing the problem hierarchies and interacting with the decision maker, for identify the preferences about the identified hierarchical levels (see Romero C., 1993).

Given than there are long-term strategic and tactical criteria in this exercise, we have made a particularization dividing the contextualized problem in two parts. Firstly, two groups of criteria are created: *a) Strategic* and *b) Tactical*. Then, one specific pairwise comparison is made for each group (questions 1-8). Secondly, both groups are compared by single general pairwise comparison (question 9). Note than the questions scale ranges from “equally important” to “extremely more important” and presents the total of four levels of preferences. Bold letters denote the decision-maker answers.

a) Strategic criteria pairwise comparison

It corresponds to the paired criteria survey of the strategic level. Thus, three general strategic criteria groups are stablished:

1. Production criteria: NPV and Total volume

2. Environmental criteria: Carbon sequestration

3. Technical criteria: Even flow of commercial volume, Even flow of veneer log volume and an equal area in each of the five year age-classes at the end of the planning horizon

1. Production x environmental group criteria

- a) the production criteria are equally important than the environmental criteria
- b) the production criteria are moderately more important than the environmental criteria
- c) the production criteria are strongly more important than the environmental criteria

- d) the production criteria are very strongly more important than the environmental criteria**
- e) the production criteria are extremely more important than the environmental criteria
- f) the environmental criteria are moderately more important than the production criteria
- g) the environmental criteria are strongly more important than the production criteria
- h) the environmental criteria are very strongly more important than the production criteria
- i) the environmental criteria are extremely more important than the production criteria
- ☐ ...

2. Environmental x technical group criteria

- a) the environmental criteria are equally important than the technical criteria
- b) the environmental criteria are moderately more important than the technical criteria
- c) the environmental criteria are strongly more important than the technical criteria
- d) the environmental criteria are very strongly more important than the technical criteria
- e) the environmental criteria are extremely more important than the technical criteria
- f) the technical criteria are moderately more important than the environmental criteria
- g) the technical criteria are strongly more important than the environmental criteria
- h) the technical criteria are very strongly more important than the environmental criteria**
- i) the technical criteria are extremely more important than the environmental criteria
- ☐ ...

3. Production x technical group criteria

- a) the production criteria are equally important than the technical criteria
- b) the production criteria are moderately more important than the technical criteria
- c) the production criteria are strongly more important than the technical criteria
- d) the production criteria are very strongly more important than the technical criteria
- e) the production criteria are extremely more important than the technical criteria
- f) the technical criteria are moderately more important than the production criteria**

- g) the technical criteria are strongly more important than the production criteria
- h) the technical criteria are very strongly more important than the production criteria
- i) the technical criteria are extremely more important than the production criteria
- ☐ ...

4. NPV x total volume criterion

- a) the criterion NPV is equally important than the criterion total volume
- j) the criterion NPV is moderately more important than the criterion total volume**
- b) the criterion NPV is strongly more important than the criterion total volume
- c) the criterion NPV is muito fortemente more important than the criterion total volume
- d) the criterion NPV is extremely more important the criterion total volume
- e) the criterion total volume is moderately more important than the criterion NPV
- f) the criterion total volume is strongly more important than the criterion NPV
- g) the criterion total volume is very strongly more important than the criterion NPV
- h) the criterion total volume is extremely more important the criterion NPV
- ☐ ...

5. Even flow commercial volume x even flow veneer log volume criterion

- a) the criterion even flow commercial volume is equally important than the criterion even flow veneer log volume
- b) the criterion even flow commercial volume is moderately more important than the criterion even flow veneer log volume
- c) the criterion even flow commercial volume is strongly more important than the criterion even flow veneer log volume
- d) the criterion even flow commercial volume is muito fortemente more important than the criterion even flow veneer log volume
- e) the criterion even flow commercial volume is extremely more important the criterion even flow veneer log volume

k) the criterion even flow veneer log volume is moderately more important than the criterion even flow commercial volume

f) the criterion even flow veneer log volume is strongly more important than the criterion even flow commercial volume

g) the criterion even flow veneer log volume is very strongly more important than the criterion even flow commercial volume

h) the criterion even flow veneer log volume is extremely more important the criterion even flow commercial volume

□ ...

6. Even flow commercial volume x age-class regulation criterion

a) the criterion even flow commercial volume is equally important than the criterion age-class regulation

l) the criterion even flow commercial volume is moderately more important than the criterion age-class regulation

b) the criterion even flow commercial volume is strongly more important than the criterion age-class regulation

c) the criterion even flow commercial volume is muito fortemente more important than the criterion age-class regulation

d) the criterion even flow commercial volume is extremely more important the criterion age-class regulation

e) the criterion age-class regulation is moderately more important than the criterion even flow commercial volume

f) the criterion age-class regulation is strongly more important than the criterion even flow commercial volume

i) the criterion age-class regulation is very strongly more important than the criterion even flow commercial volume

j) the criterion age-class regulation is extremely more important the criterion even flow commercial volume

□ ...

7. Even flow veneer log volume x age-class regulation criterion

- a) the criterion even flow veneer log volume is equally important than the criterion age-class regulation
- b) the criterion even flow veneer log volume is moderately more important than the criterion age-class regulation
- c) the criterion even flow veneer log volume is strongly more important than the criterion age-class regulation**
- d) the criterion even flow veneer log volume is muito fortemente more important than the criterion age-class regulation
- e) the criterion even flow veneer log volume is extremely more important the criterion age-class regulation
- f) the criterion age-class regulation is moderately more important than the criterion even flow veneer log volume
- g) the criterion age-class regulation is strongly more important than the criterion even flow veneer log volume
- h) the criterion age-class regulation is very strongly more important than the criterion even flow veneer log volume
- i) the criterion age-class regulation is extremely more important the criterion even flow veneer log volume

□ ...

b) Tactical criteria pairwise comparison

It corresponds to the paired criteria survey of the tactical level. Thus, these two tactical criteria are established:

1. Operational cost: Operational cost of the tactical planning horizon
2. spatial connectivity: Harvesting connectivity of each tactical period

8. Operational cost x spatial connectivity.

- a) the criterion operational cost is equally important than the criterion spatial connectivity
- b) the criterion operational cost is moderately more important than the criterion spatial connectivity
- c) the criterion operational cost is strongly more important than the criterion spatial connectivity
- d) the criterion operational cost is very strongly more important than the criterion spatial connectivity
- e) the criterion operational cost is extremely more important than the criterion spatial connectivity
- f) the criterion spatial connectivity is moderately more important than the criteria of operational cost**
- g) the criterion spatial connectivity is strongly more important than the criteria of operational cost
- h) the criterion spatial connectivity is very strongly more important than the criteria of operational cost
- i) the criterion spatial connectivity is extremely more important than the criteria of operational cost
- ...

Second part

In the general pairwise comparison both strategic and tactical groups are compared. Then, two general criteria groups are established:

1. Strategic group (*Production, Environmental e Technical*)
2. Tactical group (Operational and spatial connectivity)

9. Strategic group x tactical group.

- a) the strategic criteria are equally important than the tactical criteria
- b) the strategic criteria are moderately more important than the tactical criteria**

- c) the strategic criteria are strongly more important than the tactical criteria
- d) the strategic criteria are very strongly more important than the tactical criteria
- e) the strategic criteria are extremely more important than the tactical criteria
- f) the tactical criteria are moderately more important than criteria of strategic criteria
- g) the tactical criteria are strongly more important than criteria of strategic criteria
- h) the tactical criteria are very strongly more important than the strategic criteria
- i) the tactical criteria are extremely more important than the strategic criteria
- ...