UNIVERSIDAD POLITÉCNICA DE MADRID

ESCUELA TÉCNICA SUPERIOR DE INGENIEROS DE MONTES,
FORESTAL Y DEL MEDIO NATURAL

**FOREST MANAGEMENT DECISION SUPPORT SYSTEM
FOR FOREST PLANTATIONS IN BRAZIL:
A MULTICRITERIAL APPROACH**

TESIS DOCTORAL

SILVANA RIBEIRO NOBRE

Ingeniera Agrícola

2019

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To Luiz,

who masters the art of turning dreams into reality.

*“Castelos nascem dos sonhos,
Para no real acharem o seu lugar”*

*“Castles born out of the dreams,
So, they find their place in the real world.”*

Oswaldo Montenegro

Forest Management Decision Support System for Forest Plantations in Brazil: a multicriterial approach.

Silvana Ribeiro Nobre

Abstract

Forests have been the primary source of fibers, food, water, biodiversity, energy, recreation, scenic beauty, and environmental services. Forest management science encompasses the challenge of working with forests in a way that produces required benefits now without compromising future benefits and choices. The concept of optimized forest management has become broader in recent decades. Pressure toward social, economic, and environmental sustainability pushes up research to cover these demands by improving models, introducing new methods, and adding holistic planning approaches in forest management decision support systems (FMDSS). The conflicts that arise between the desire to consume natural resources and the desire to preserve them make the multicriteria decision theory necessary. Brazil, one of the ten largest timber producers in the world, has the second largest forest cover on the planet. It also uses optimization models that represent the growth of forests integrated with decision support systems that assist managers in their decisions. However, forest planning models and applied decision support systems are not uniformly developed and available for all types of problems encountered in the country. Brazilian forest plantation managers have to face many conflicts when continuously seeking gains regarding efficiency (higher productivity at lower costs) and efficacy (higher profits with minimum social and environmental impacts). Leading producing countries on timber, pulp, and fiberboard have their managers constantly interact to fine-tune industry processing demands vis-a-vis the demands of highly productive fast-growing forest plantations. The decision process in such cases seeks a compromise that accommodates frequently conflicting objectives. Therefore, this research work aims to develop a forest management decision support system (FMDSS) based on multicriteria decision-making (MCDM) techniques to support group decision-making (GDM) in the diversified context of forest plantations in Brazil. Explicitly, the objective is developing a set of models to optimize forest management embedded in a DDS to meet the needs of the decision-makers of the different types of forest plantation organizations that operate in Brazil. This set of models encompasses multicriteria mathematical programming models, processes, and data models structured in such a way to be versatile enough to support interactive group decision-making.

FORSYS, an FP0804 European COST action and a representative case study that could contribute to the understanding of the use of FMDSS worldwide, was used to outline the forest manager's main concerns. Also, a Sao Paulo forest restoration case exposed essential guidelines regarding Knowledge Management (KM) design to support a robust FMDSS adequately. A generalizable mathematical programming model was developed and embedded in a Forest Management Group Decision Support System (FMGDSS), called Romero©. The FMGDSS was developed by following the multi-criteria decision theory rigorously and the guidelines provided by the two previously mentioned case studies. Another case study illustrates how Romero© can support large-scale multi-stakeholder's decision processes. A vertically integrated pulp company situation was simulated to provide a real scenario where forest managers tend to shorten the rotations due to the usually high-interest rates practiced in the Brazilian banking system; meanwhile, the industrial managers tend to ask for larger ones due to the positive correlation between age and wood density. Romero© demonstrated its abilities to support interaction among stakeholders that have different expectations regarding forest management. Expressly, the hypothesis that mill managers initially have, that older ages rotation could improve mill production, was not confirmed. Romero©'s support was essential to consider and inspect all aspects of the solution; it was an information-based decision-making process as preconized by literature. An overall conclusion is that Romero©'s development potentially contributes to forest management research applying MCDM techniques and compromise to industrial forest plantation problems. Furthermore, through the case study application, Romero© demonstrated that strategic scenario analysis is still a key tool to evaluate future impacts of short-term decisions.

Keywords

Multicriteria Decision Making, Decision Support System, Forest Management Decision Support System, Group Decision Making, Sustainable forest management, Collaborative Decision Making, Compromise Programming

Resumen

Los bosques han sido la fuente principal de fibras, alimentos, agua, biodiversidad, energía, recreación, belleza escénica y servicios ecológicos. La ciencia de la gestión forestal abarca el desafío de trabajar con los bosques de una manera que produzca los beneficios requeridos ahora sin comprometer los beneficios y opciones futuros. El concepto de manejo forestal optimizado se ha ampliado en las últimas décadas. La presión hacia la sostenibilidad social, económica y ambiental impulsa la investigación para cubrir estas demandas mediante la mejora de modelos, la introducción de nuevos métodos y la adición de enfoques de planificación amplia en el Sistema de Apoyo a la Decisión Forestal (FMDSS). Los conflictos que surgen entre el deseo de consumir recursos naturales y su conservación hacen necesario el empleo de la Teoría de la Decisión Multicriterio. Brasil, uno de los diez mayores productores de madera del mundo, tiene la segunda cubierta forestal más grande del planeta. También utiliza modelos de optimización que representan el crecimiento de los bosques integrados con sistemas de apoyo a decisiones. Sin embargo, los modelos de planificación forestal y los Sistemas de Apoyo a la Decisión no están desarrollados de manera uniforme, tampoco están disponibles para todos los tipos de problemas encontrados en el país. Los gestores de plantaciones forestales brasileñas tienen que enfrentar frecuentes conflictos cuando buscan ganancias relacionadas con la eficiencia (mejor productividad a costos más bajos) y eficacia (más ganancias con el mínimo impacto social y ambiental). Los principales países productores de madera y celulosa tienen a sus gestores interactuando constantemente para ajustar las demandas de procesamiento de la industria frente a las demandas de plantaciones forestales de rápido crecimiento y altamente productivas. El proceso de decisión en tales casos busca un compromiso que acomode objetivos en conflicto. Por lo tanto, esta tesis doctoral tiene como objetivo desarrollar un Sistema de Apoyo a la Decisión de Gestión Forestal (FMDSS) basado en técnicas de Toma de Decisiones Multicriterio (MCDM) para respaldar la Toma de Decisiones en Grupo (GDM) en el contexto diversificado de plantaciones forestales en Brasil. De hecho, el objetivo es desarrollar un conjunto de modelos para optimizar el manejo forestal integrado en un DDS para satisfacer las necesidades de los tomadores de decisiones de los diferentes tipos de organización de plantaciones forestales que operan en Brasil. Este conjunto de modelos abarca modelos de programación matemática, modelos de procesos y de datos estructurados para que sean lo suficientemente versátiles como para apoyar la toma de decisiones interactivas. FORSYS, una acción COST europea FP0804, un caso de estudio representativo que podría contribuir a la comprensión del uso de FMDSS en todo el mundo, se utilizó para describir las principales preocupaciones de los gestores forestales. Además, un caso de

restauración de bosques de Sao Paulo expuso pautas esenciales con respecto al diseño de la Gestión del Conocimiento (KM) para apoyar adecuadamente un FMDSS robusto. Se desarrolló un modelo de programación matemática generalizable y se integró en un Sistema de Apoyo a la Decisión, llamado Romero©. El DSS se desarrolló siguiendo rigurosamente la teoría de la decisión multicriterio y las pautas proporcionadas por los dos estudios de caso mencionados anteriormente. Otro estudio de caso ilustra cómo Romero© puede apoyar procesos de decisión a gran escala de múltiples stakeholders. Se simuló una situación de una compañía de celulosa integrada verticalmente para proporcionar un escenario real en el que los gestores forestales tienden a acortar las rotaciones debido a las tasas de interés generalmente altas practicadas en Brasil, mientras que los gestores industriales tienden a solicitar rotaciones más largas debido a la correlación positiva entre la edad y la densidad de la madera. Romero© demostró sus habilidades para apoyar la interacción entre stakeholders que tienen expectativas diversas con respecto al manejo forestal. De manera expresa, no se confirmó la hipótesis de que los gerentes industriales tenían inicialmente que la rotación en edades mayores podría mejorar la producción industrial. El apoyo de Romero© fue esencial para considerar e inspeccionar todos los aspectos de la solución, fue un proceso de toma de decisiones basado en información preconizado por la literatura. La conclusión general es que el desarrollo de Romero© contribuye potencialmente a la investigación de manejo forestal con aplicación de técnicas de MCDM y programación compromiso. Además, a través de la aplicación del caso de estudio, Romero demostró que el análisis de escenarios estratégicos sigue siendo una herramienta clave para evaluar los impactos futuros de las decisiones a corto plazo.

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Acronyms

DSS	Decision Support System
FMDSS	Forest Management Decision Support System
FMTDSS	Forest Management Team Decision Support System
GDM	Group Decision Making
MCDM	Multi Criteria Decision Making
FORSYS	Cost Action n FP0804
COST	European Cooperation in Science and Technology
CR	Country Report
KM	Knowledge Management
M&M	Models and Methods
PP	Participatory Planning
LL	Lessons Learned
IT	Information Technology
OR	Operations Research
LP	Linear Programming;
MIP	Mixed Integer Programming;
MOLP	Multi-Objective Linear Programming;
AML	Algebraic Modeling Language
DP	Dynamic Programming;
NLP	Non-Linear Programming
AHP	Analytical Hierarchy Process
CP	Compromising Programming
NPV	Net Present Value
LEV	Land Expectation Value
NPV	Net Present Value
LEV	Land Expectation Value
MAI	Mean Annual Increment
XML	eXtensible Markup Language
SQL	Structured Query Language
DBMS	Database Management System

1. INTRODUCTION

1.1.Motivation

Forests are relevant components in the history of civilizations (Leão, 2000). The economic development of modern society has relied on the exploitation of natural resources (Jürgensen et al., 2014; Lindquist et al., 2012; Payn et al., 2015), mainly wood and non-wood products (FAO, 2012). Forests have been the primary source of fibers, food, water, biodiversity, energy, recreation, scenic beauty, and ecological services (FAO, 2015). Recognition that the production and protection functions of forests must be sustained by sound management practice is not new (MacDicken et al., 2015). Forest management science encompasses the challenge of working with the forests in a way that produces required benefits now without compromising future benefits and choices (Wang, 2004).

Optimized forest management, which began in the 1960s in North America and Europe from preliminary harvest scheduling, have expanded its scope to meet new needs over the last 5 decades (Eriksson et al., 2014). Brazil, one of the ten largest timber producers in the world, has the second largest forest cover on the planet (FAO, 2015; Stape et al., 2010). It also uses optimization models that represent the growth of forests integrated with decision support systems that support managers in their decisions. However, forest planning models and applied Decision Support Systems are not uniformly developed and available for all types of problems encountered in the country (Diaz-Balteiro et al., 2014; Rodriguez and Nobre, 2014) and still does not meet recent needs that must consider multiple objectives, group decision-making support and latest environmental demands (Eriksson et al., 2014).

The concept of optimized forest management has become broader in recent decades. Pressure toward social, economic and environmental sustainability push up research to cover these demands by improving models, introducing new methods and adding holistic planning approaches in Forest Management Support System (FMDSS) (Acosta and Corral, 2017; Ananda and Herath, 2009; Vacik and Borges, 2016). FMDSSs have been evolved through integrated methodologies, such as Multicriteria Decision Making (MCDM). Many authors agree that the conflicts that arise between the desire to consume natural resources and the preservation of forests make it necessary (Álvarez-Miranda et al., 2016; Diaz-Balteiro and Romero, 2008).

Moreover, forest plantation managers face many other conflicts when continuously seeking gains regarding efficiency (higher productivity at lower costs) and efficacy (higher profits with

minimum social and environmental impacts). Leading producing countries on timber, pulp and fiberboard have their managers constantly interacting to fine-tune industry-processing demands vis-a-vis the demands of highly productive fast-growing forest plantations. The decision process in such cases seeks a compromise that accommodates frequent antagonisms.

The eucalyptus clones that have a best response in nurseries are not necessarily the best ones considering performance during the first years after establishment, or even during an eventually dry season (Nobre and Rodriguez, 2014). Often, genetic material prepared to have excellent performance in the fields are not the best ones in terms of industry processing in the mill they are going to be delivered (Kavaliauskas et al., 2018; Kelty, 2006; Lopes and Garcia, 2002; Mokfienski et al., 2008). MCDM can achieve sustainable use of forest resources through by facilitating collaborative decision-making and conflict resolution (Ananda and Herath, 2009).

Collaborative decision-making calls for interaction and for a FMDSS that seeks to integrate the decision-maker's own insights with the computer's information-processing capabilities to improve decision-making (Sheppard and Meitner, 2005). In this context, the group decision making approach has become a relevant tool to minimize fails in stakeholders involvement in planning process (Boukherroub et al., 2018; Eyvindson et al., 2018).

On the other hand, computer science has enlarged the definition of a DSS to encompass not only the mathematical models but also all the agents, processes and data that allows the system operation (Alyoubi, 2015; Bohanec, 2009; Power and Sharda, 2007). The solution of large forest management problems is made possible by the incredibly evolution of the technology over the last decades. Not only in terms of processing capacity, but the computer science offers improvements in terms of data storage, modeling data tools, graphical user interfaces, solution visualization, and specialized programming languages.

According to Vacik and Lexer (2014), a significant gain can be made in a FMDSS if models and methods are developed innovatively to capture the changing dynamics of forest management using the most new available technology. These authors concluded from their research that the increasing trend to simple applications and modularity of tools will support the design of new DSS architectures, which can be easily adapted to these changing dynamics.

1.2. Solution Outline

Regarding the increasing trend of modularity to address the forest management changing dynamics (Section 1.1); this research focus on the integration of different decision supporting tools, which can be used to develop a complex FMDSS. The aim is to develop a framework that integrates a set of models to deal with the expectations of different stakeholders involved in the management of large-scale industrial forest plantations in Brazil.

The proposed FMDSS intend to be a Forest Management Team Decision Support System (FMTDSS) because, beyond encompassing MCDM techniques, processes and data models, it has been developed to support interaction among stakeholders to handle conflicting goals. Figure 1 illustrates the object of this work that put together the most modern technology in an innovative way to offer the decision-makers an opportunity to work as a team.

Figure 1 – Solution Outline

1.3. Thesis Organization

In the following paragraphs there is an overview on the contents of this thesis. Also, **Figure 2**, shows an overall organization and the relationship among the chapters.

Chapter 2 presents the literature review with the main topics related to the research work that support this thesis into three complementary aspects. The first aspect, presented in **Section**

2.1, comprises the recent evolution of a FMDSS, object of this thesis, and points out to the need of understanding the research challenges and how the end users have perceived its available features. It also presents the Knowledge Management (KM) definitions and literature recommendation on how to organize information, and what are the relevant facets that might contribute to the development of a helpful FMDSS.

The second aspect comprises the relevance of data and process modeling to correct integrate required information into a FMDSS. **Section 2.2**, starts from definitions on FMDSS based on Knowledge Management, describes the needs of data organization in native species plantations for restoration, and industrial forest plantations in Brazil.

Figure 2 - Thesis Organization

The last aspect is related to the use of Multicriteria techniques embedded in FMDSSs that aims to allow participatory decision making, which is the focus of the development. In **Section 2.3**, I present the recent publications related to the application of MCDM to participatory planning and group decision making.

Based on the demands raised from literature review presented in **Chapter 2**, the **Chapter 3** presents the detailed objectives of the research work. **Chapter 4, 5, 6** and **7** are related to the four objectives of the research, respectively. **Chapter 4** comprises the point of view of FMDSS practitioners; describes the FORSYS case study used to understand the needs and gaps pointed

out by local researchers of 26 countries worldwide. **Chapter 5** includes an analysis of an active restoration case in Brazil to understand the needs on processes and data models of a FMDSS.

Chapter 6 presents the models proposed to compose the FMTDSS. It encompasses the mathematical programming models, the system architecture and the technology description according to the recommendations of the literature review. **Chapter 7** describes the application of the proposed FMTDSS to a typical industrial plantation case. Finally, **Chapter 8** presents the discussions of the results and contributions of the research work and **Chapter 9** present the conclusions and next steps.

2. FMDSS - FOREST MANAGEMENT DECISION SUPPORT SYSTEM

2.1. Decision Support System (DSS) and Forest Management (FM)

According to the information technology (IT) literature, from a functional perspective; an Information System (IS) is a technologically implemented medium for the purpose of recording, storing, and distributing information or linguistic expressions as well as for the supporting of inference making. From a structural perspective; an IS consists of a collection of components such as people, processes, data, models, technology, forming a cohesive structure which serves some organizational purpose or function (Bourgeois, 2014).

Decision Support System (DSS) is a particular case of an IS when an interactive computer-based system support decisions of the people involved in the processes using data, models, processes and technology (Power, 2002). Therefore, a DSS inherits all the characteristics of an Information System. Among all, for the purpose of this work, we highlight the fact that people, processes and data take part to a DSS as well as models and technology. This characteristic, an integration of those components into a DSS, will lead the considerations and discussions which contribute to the structure this research work.

On the other hand, according to reviews about the theme, forest management generally refers to the ways and processes of managing forest resources to meet society's varied needs, today and tomorrow, without compromising the ecological capacity and the renewal potential of the forest resource base (Wang, 2004). However, the concept of Forest Management has widened over the last decades. In the early 1970s, forests were seen as a source of wood and a forest decision maker had to establish an optimal harvest schedule subject to economic constraints (Ware and Clutter, 1971). Contemporary decision makers have to deal with many other environmental, social, and economic variables such as biodiversity, water resource protection, scenic beauty, recreation, and carbon stocks (Başkent et al., 2014; Myllyviita et al., 2014). One of the important responses to the impact of these larger issues on forestry was that 76 countries have updated their forest policy statements since 2000, and 69 countries have had their current forest law amended since 2005 (FAO, 2010). These changes have contributed to consolidating the demand for better systems to support contemporary challenges.

Due to the amount of data and relevance of the decisions, Forest Management demands for specialized DSS developments (Vacik and Lexer, 2014), called Forest Management Decision Support Systems (FMDSS). These specialized type of DSS are designed worldwide to address

three levels of organizational decisions (strategic, tactic and operational), all possible temporal (long-term and short-term decisions) and spatial (stand, forest and regional levels) dimensions (Borges et al., 2014b; Kangas et al., 2008).

Modern FMDSS must take into account a range of different goods, services, and aspects related to environmental management like wildlife (Hof and Haigh, 2007; Korosuo et al., 2013), fire risk (Wei et al., 2014), landscape management, windthrow damage (Fontes et al., 2010), Besides, FMDSS consider constraints under climate change (Rammer et al., 2014), logistical operation uncertainties (Epstein et al., 2007; Marques et al., 2013), and road upgrade management (Flisberg et al., 2014). Modern FMDSS consider multiple objectives and use knowledge from management science, like multiple criteria decision making (MCDM), in their applications to current forest management problems (Diaz-Balteiro and Romero, 2008; Myllyviita et al., 2014; Vacik and Lexer, 2014). In addition, a new social environment is leading to a complex context of multiple stakeholders involved in participatory planning (Eriksson et al., 2013; Martins and Borges, 2007; Valls-Donderis et al., 2014), when stakeholders are allowed to merge their preferences with the others' choices, exert influence, be influenced, and express opinions (Bruña-García and Marey-Pérez, 2014). For the efficiency of the MCDM methods application, Group Decision Making (GDM) methods can be added to the context of FMDSS (Acosta and Corral, 2017; Ortiz-Urbina et al., 2019) and could become a Forest Management Group Decision Support System (FMGDSS).

Usually, FMDSS have to include modern computer technologies to address new demands such as climate change requirements, new country regulations, and new requirements from markets (Rammer et al., 2014; Rauscher et al., 2005). In order to overcome the technology barriers encountered in solving ever more complex forest models, new mathematical methods have had to be developed (Vescoukis et al., 2012). In addition, new heuristics have been developed to address massive spatial problems; dynamic, goal and stochastic programming have been applied to bring flexibility to management plans (Baskent and Keles, 2005; Eyvindson and Kangas, 2014; Hof and Haigh, 2007; Wei et al., 2014).

Recent developments in information technology have enabled such improvements, but have also influenced the concepts of modern DSS, and their application to contemporary challenges in Forest Management (Vacik and Lexer, 2014). Easy access to centralised systems based on the internet and databases, for example, have enabled multiple stakeholders to share responsibility for decisions (Rammer et al., 2014). New technologies such as laser scanning

have enabled the development of DSS that access detailed tree-level information (Vauhkonen et al., 2014).

2.2. The role of Knowledge Management (KM) for FMDSS

2.2.1. Monitoring as a module of a FMDSS

From the forest management perspective, Knowledge Management (KM) supported by information technology is needed to deal with the huge amount of data that describes the territory, forest silviculture activities, and production over time (McDill, 2014). Analysing the use of KM in the decision support system (DSS) that intends to monitor the environment, Cortés et al. (2001) point out that a DSS tool can maximize the performance of a process and minimize the negative impacts of faults.

KM, according to Plunkett (2001), is the conscious strategy of putting knowledge into action as a mean to increase organizational performance. Technologies that support KM are available and effective (Rauscher et al., 2007). The role of information technology (IT) is to store and to provide access to knowledge (Plunkett, 2001). KM uses technology to identify, create, structure, and share knowledge with the goal of improving decision-making (Tyndale, 2002). To increase performance and improve decision-making gradually, in each iteration of a planning process, computerized tools may be useful because of their ability to store, retrieve, display and organize knowledge (Hujala et al., 2013).

They emphasize that the effectiveness of an environmental DSS involves a “continuous intelligent monitoring system”. Because of the significance of the decision impacts, environmental DSSs must allow knowledge-based decisions. Bagstad *et al.* (2013) analyzed 17 ecosystem services DSS and found that there is a general need for more investments in organizing data from previous processes, sharing existing data, and improving the quality of input data. Researchers stressed the importance of KM in forest management processes in a collection of 80 lessons extracted from 31 cases in 10 different countries. Almost half of them had KM as a major theme in the group of concerns (Gordon et al., 2013). Authors (Vacik et al., 2013) also say that a KM base is the main output of a monitoring system because it is created upon a sequence on information, which are data treatment output and these data are gathered by a monitoring system.

McDill (2014) and other authors (Vacik and Lexer, 2014) consider the monitoring process to be an important part of the planning process. That is, to be complete, a planning process must include the monitoring phase **Figure 3**. If the monitoring and planning processes are integrated, the information used in supporting a decision can be compared to the achieved outcome, which enables better decision-making in the future (Rauscher et al., 2007). It is important to highlight the fact that the Enterprise Resource Planning systems used in larger enterprises have been being built to integrate the planning and monitoring processes since the early 1990s (Blount et al., 2016) and are still extensively being used all over the world (Dechow and Mouritsen, 2005; Gholamzadeh Chofreh et al., 2016; Park and Jeong, 2013; Saade and Nijher, 2016).

Figure 3 - Planning Process (McDill, 2014)

A proper KM tool supported by information technology responds to questions regarding who produces and how much, which regions best suit each kind of production, and what the social, economic, and ethical consequences of a reduction or an increase in forest production may be (Rauscher et al., 2007). The answers to those questions could guide managers in their decisions. However, this is only possible if the parameters used to plan are based on that information. Some authors remark that managers and decision makers should not be overwhelmed by data because what they need is not “more information” but values, priorities, and clarity about preferences (Ekbja and Reynolds, 2007; McElroy, 2000; Vacik et al., 2013). Therefore, data about the process must be treated and organized in a useful manner to forest decision-makers and managers.

In addition, forest managers usually face uncertainties regarding future environmental conditions, social demands, changing trends, and projected performances of markets for forest products (Rist et al., 2016; Vacik and Lexer, 2014). Therefore, adaptive management has been viewed as a very promising conceptual framework for defining forest management (Rist et al.,

2016; Vacik and Lexer, 2014). Adaptive management is a continuing cycle of four activities, namely planning, implementation, monitoring, and evaluation, in which monitoring and data interpretation play essential parts in the whole planning cycle (Dickinson et al., 2016).

As planning cycles evolve, a tool to monitor performance indicators is needed to allow forest managers to compare outcomes among cycles. To achieve the improving process, all the verifiers of the indicators have to be well known and registered (McDill, 2014). According to Meng and Minogue (2011), practitioners consider monitoring models based on key performance indicators (KPI) are very effective systems. KPIs link performance with objectives and processes because the objective of the project is expressed in terms of values of indicators to be achieved (Shohet and Nobili, 2016).

The need of having a supportive monitoring component leads to the need for an applicable set of models to guide the development and integration into a modern Forest Management DSS. This need motivated the authors to conduct this research. Even though many authors agree that data from the monitoring process takes part in the forest planning process, the forest academia has focused on the planning part of the problem. Planning parameters, efficient methods of solving planning problems, and stakeholder involvement have received the largest share of attention from forestry academia over the last 50 years (Borges et al., 2014b; Eriksson et al., 2013, 2014; Gordon et al., 2013; Nobre et al., 2016). In terms of forest planning, the modelling of a planning problem usually involves some sort of scheduling or assignment in the future. Monitoring processes also need models, reliable methods (Thompson, 2014), and the involvement of stakeholders to represent forest realities accurately.

Once defined, the outcomes of a plan have to be monitored by means of performance indicators that were specially defined to measure how close the managed forest is to reaching expected goals and whether the planned interventions have been effective. Unfortunately, and probably due to the spatial scale of most forest problems, technological limitations, and the large amounts of data needed, the detailed integration and modelling of the monitoring phase is not usually considered when dealing with forest management planning formulations (Dickinson et al., 2016).

As already pointed out, comprehensive Environmental DSS, Forest Management DSS, and Ecosystem Services DSS should have as one of their building blocks a reliable monitoring model. That also applies to an environmental and forest DSS. Under the perspective of a DSS conceptual frame we are presenting a monitoring module that composes an FMDSS. And this module is carefully designed to improve planning iterations incrementally.

2.2.2. Management improvements through monitoring

In the **Sections 1**, we could see that the purpose of monitoring is to generate useful information to answer the motivating questions from many different perspectives. Adaptive management concepts go beyond and insert the monitoring in an iterative decision-making cycle (Reynolds et al., 2016). It goes beyond improving planning iterations and includes a quantitative learning process to combine (i) effectiveness monitoring and (ii) predictive models quantifying the expected outcomes.

The adaptive management cycle has critical trigger points to ensure that corrective actions will be taken if any restoration targets are not being achieved (Viani et al., 2017). If environmental uncertainty is a major concern, monitoring under adaptive management should, ideally, lead to learning. Therefore, the adaptive management means mid-course corrections and large-scale changes in management direction (Gatica-Saavedra *et al.*, 2017; Durigan & Ramos, 2013) based on knowledge gained from monitoring.

According to Reynolds et al. (2016), for monitoring associated with management actions, the updated models inform the next cycle of management. Consequently, the system model is refined by integrating the new observations into the quantitative model.

However, to be embedded in an adaptive management framework, a monitoring system requires a limited number of indicators that are repeatable, sensitive to change, and affordable (White et al., 2017). The choice of suitable ecological indicators is a challenge for monitoring ecosystem quality. According to Durigan *et al.* (2016) indicators should be easy to apply and, in the case of forest restoration, they should represent the gradual recovery of biodiversity, relevant ecological processes, and ecosystem services resulting of interventions.

As an example, Sao Paulo State developed a protocol to evaluate restoration success which requires only three ecological indicators: (a) native vegetation ground cover; (b) density of native plants spontaneously regenerating; and (c) number of spontaneously regenerating native plant (Chaves et al., 2015; Rodrigues et al., 2013; Viani et al., 2017).

2.2.3. Requirements of a monitoring conceptual model

A monitoring model comprises (i) a process to gather data, information, or knowledge related to the facts of interest; (ii) a method to store and transform those data into information; and (iii) routines to interpret trends and produce outcomes (Bolloju et al., 2002). Due to the

components of a model, databases have become valuable assets to any organization (Tyndale, 2002) mainly because of important improvements in information technology that have allowed the processing of new types of data, such as spatial, audio, and video data and the efficient processing of large database management applications. The observed improvements are even more noteworthy in forest management problems dealing with large-scale spatial constraints and operations occurring simultaneously in many isolated places.

The more complex the demands from the managers are and the more diverse the expectations of various user groups become, the greater the complexity of the models designed for use in DSS is (Vacik and Lexer, 2014). The complexity of the models requires parameters that represent reality, and the aim of a monitoring model is to gather together data and interpret them to create knowledge about the process. New knowledge about the forest process may become available if the system is correctly used, and this knowledge should result in new goals and revised parameters. This is precisely the aim of a monitoring component of a DSS: guaranteeing the knowledge expansion (Bolloju et al., 2002). At each cycle, the result of the evaluation activity gives feedback on the planning activity so that adaptive learning can take place (Vacik and Lexer, 2014).

By doing a search in the ISI's Web of Science for publications from the last five years on forestry and environmental science issues through articles and reviews using the keyword "forest monitoring," we found 35 papers with forest monitoring as the focus. Of these, 22 related to inventory modelling, growing, or biomass measurement, and 10 strengthened the importance of having data integration, at least among a sequence of measurements. The other 13 are related to land use, deforestation, and other environmental issues; and 7 reinforce the integration of other monitoring systems. Only one of these articles declares that the monitoring system would "facilitate better management plans." Even though all of them describe how they transform measured data into information on biomass growing or stock and land use, none of them is related to silviculture activities or costs control.

It seems, from this recent forestry publication presented in the last paragraph that the usual concept of the monitoring means forest inventory and land use analysis. However, in general business, monitoring systems and control systems are related not only to productivity but also to control costs and activities related to productivity to produce better plan parameters (Jannuzzi et al., 2014).

Moreover, when it comes to ecosystem restoration, the focus is changing from forest structure and forest composition to restoring ecosystem processes. First, the emphasis was the return of

structure (e.g., nutrients and selected plant species) rather than the repair of processes (e.g., hydrology, nutrient cycling, and energy capture). Second, the focus was on specific sites without considering the landscape context. Third, the concept was a “restore” program at the completion rather than the beginning of natural repair processes. A focus on returning structural components to functionally damaged ecosystems does not necessarily lead to the development of self-repairing ecosystems (Whisenant, 1999).

Therefore, the change from “forest monitoring” to “ecosystem monitoring” is a forest restoration requirement. The aim of a forest plantation is no longer an establishment of a production forest but a re-establishment of ecosystem processes (Albert et al., 2015; Bodini, 2012; Chaves et al., 2015; Durigan et al., 2016; Durigan and Ramos, 2013; Gatica-Saavedra et al., 2017; Reynolds et al., 2016; Whisenant, 1999).

According to the literature, a conceptual monitoring model is defined as the intellectual foundation upon which a monitoring program rests as it makes the connection between system drivers (including management actions) and the fundamental objectives explicit, thus helping clarify exactly what should be monitored (Reynolds et al., 2016). Finally, some requirements are essential to conceptual models:

- should consider the activities or interventions, and their relationships to the fundamental objective (Reynolds et al., 2016);
- should clarify the main types of uncertainties associated with management decision making such as (i) environmental variation — inherent stochastic variation in environmental factors; (ii) partial controllability — imprecise application of management actions; (iii) partial observability — imprecise measurement of the system; and (iv) structural uncertainty — lack of understanding about relationships between system state and drivers, e.g., uncertainty in defining the model itself (Reynolds et al., 2016). The model should allow the monitoring program to control and/or reduce each of them;
- should allow information be presented in multiple ways to address the needs of different stakeholders and translated into a user-friendly decision support tools (Albert et al., 2015; Reynolds et al., 2016);
- should be a systemic model to be applied as conceptual bases and should represent the real systems (Bodini, 2012);
- data interpretation component must be integrative; thus, model applications can be used profitably to attain a strategy of predictive monitoring. A system can be

predictive only if planning could be translated into new structural configurations of flows of activities (Bodini, 2012).

2.3. Multicriteria decision making (MCDM) contributions to FMDSS

Multi-criteria decision making (MCDM) could be defined as a method to support decision-making, by exploring the balance between the pros and cons of different alternatives to accomplish a specific goal. It assists in framing decision problems, illustrating the performance of alternatives across criteria, exploring trade-offs, formulating a decision and testing its robustness (Esmail and Geneletti, 2018).

Five review articles published over the last 5 years (from 2015 to 2019) on multicriteria techniques applied to forest management were analyzed (Acosta and Corral, 2017; Belavenutti et al., 2018; de Castro and Urios, 2016; Esmail and Geneletti, 2018; Ezquerro et al., 2016a). Even though all of them identify methods applied to forest management case studies and theoretical situations, the focus of each one is slightly different bringing various aspects to our discussion on the use of MCDM application to FMDSS.

Belavenutti et al. (2018) analyzed 203 articles on Operations Research applications into Forest Management published from 1986 to 2016. From those articles, 76 (37%) are related to industrial forest plantations (IFP) and published in this century. Twenty-five articles (12%) are about IFP in Brazil and were all published after 2000. The authors created three groups of methods applied to IFP: (i) Classic Optimization Techniques, and (ii) Meta-heuristics, (iii) Multicriteria Decision Making (MCDM) Techniques. The most used methods are those from group one. However, after 2011, papers of groups 2 and 3 exceeded the papers from group one. Moreover, among Brazilian applications, there are a few references to the use of only one of the methods of MCDM: Goal Programming. Furthermore, only ten articles, among those 67 on IFP, mention the use of Group Decision Making (GDM) techniques and they are not among Brazilian Case Studies.

Acosta and Corral (2017) selected 213 papers published in the last two decades taking into account their relevance based on the number of citations received and the scientific character of the publications in which they have been published. This review focused on the implementation of several MCDM approaches in participatory planning processes. According to the authors, the diversity of dimensions (environmental, social, and economic) has

determined the search for tools and methods such as MCDM techniques. The authors classified the papers according to the degree of decision-making participation, in the way that alternatives and criteria were selected and how the MCDM method was applied. The more technocratic are those that include the social actors only in the input phase claiming for data and information about the problem. The average ones are those that involve social actors in an assessment procedure with structured questions. The more participatory ones are those methods that allow conveying, and debating opinions and responsibilities is the focus group. This type of debate contributes to the emergence of new alternatives, which in some cases could be more viable than those raised at the beginning of the processes. According to the authors, the more participatory the process is, the better the decision-making process will be.

De Castro and Urios (2016) focused on the use of MCDM in Forest Management of protected areas. Like Acosta and Corral (2017), these authors also found a significant relation between the two dimensions: methods and participation. They reviewed 164 articles on MCDM in protected areas from 2000 to 2016. They noticed that the use of multi-criteria techniques in protected areas has been crucial to solve problems regarding “how to manage.” The methods have been most commonly used to analyze decision making related to land use, zoning and management problems. The authors classified the level of participation similar to Acosta and Corral (Acosta and Corral, 2017): (i) no-participatory, (ii) participatory without collaboration, and (iii) collaborative participation. They concluded that multi-criteria analysis in collaborative decision making could be a useful tool for implementing good governance of the protected areas.

Esmail and Geneletti (2018) identified 86 papers that describe MCDM applications to a range of topics related to forest and environmental management published from 1996 to 2016. Only 3 (6%) case studies were in South America, one in Brazil, one in Chile and the last one in Argentina. They structured their analysis based on MCDM process consisting of three essential stages: (1) decision context and problem structuring, (2) analysis and (3) decision. During the first stage, only 15% of the alternatives were defined together with the stakeholders; in 49% of the problems, the authors formulated the criteria without input from stakeholders. During the second phase (analysis), about 22% involved stakeholders in defining the criteria assessment (the quantification of the performance of each alternative against each criterion specified in the first stage) and 17% in assigning sets of criteria weights. In the third state, few articles included detailed information to support decision-making. Almost half of the reviewed applications only provided an overall ranking of the alternatives or overall suitability. Fewer articles (15%) reported multiple rankings, reflecting different perspectives, and 8% performed

the analysis of the preferences of stakeholders. According to the authors, the resulting phase of an MCDM application, in light of its purpose, is the most critical stage to assist people in making decisions. Therefore, a successful MCDM application should always include a sensitivity analysis of the trustworthiness and robustness of its conclusions to be examined by the stakeholders.

Ezquerro et al. (2016b) explored 179 papers that use different Operations Research (OR) methods to integrate biodiversity issues into their planning models over the last three decades. They observed 18 different OR methods applied to Forest Management problems. Most of the papers, 41.9%, use MCDM methods, almost all published after the year 2000. The percentage rises to 46.9% if only the case studies are considered. Among the papers analyzed, 10.8% (19 articles) refers to GDM method to support decisions. They also observed that 54% of the solutions combine more than one OR method to address the integrations of biodiversity in Forest Management. According to the authors, those findings suggest that, as some other authors indicate, biodiversity management problems have more than one dimension, which makes MCDM fits very well.

Considering industrial forest plantations, protected areas, nature conservation, biodiversity or even general applications, the review paper's authors agree on the suitability of the MCDM method to Forest Management problems. Besides, the growing number of papers after the year 2000 shows that it is at the beginning of the development process, more than 50 years after the classic optimization techniques start in Forest Management. Moreover, it is not equally distributed among the continents and sectors (Acosta and Corral, 2017; Belavenutti et al., 2018); fewer applications were found in Brazil, which is the object of this research work.

We also can observe a few recent inclusions of GDM method addressing Forest Management problems (Ortiz-Urbina et al., 2019). This fact happens together with the hybridization of MCDM and GDM in many other economic sectors to address sustainability problems (Diaz-Balteiro et al., 2016a). In the next section, we are going to analyze the requirements of the industrial forest plantations regarding Forest Management and the probable suitability of the GDM application to these problems.

3.4. Group Decision Making (GDM): Industrial Plantations requirement for a FMDSS

The literature defines Group Decision Making as (i) a method that promotes collaborative decision making, or a (ii) situation faced when individuals collectively make a choice from the alternatives before them or (iii) a social choice method or (iv) a participatory decision-making method (Acosta and Corral, 2017; Bruña-García and Marey-Pérez, 2014; Diaz-Balteiro et al., 2016b; Ezquerro et al., 2016a; Segura et al., 2015).

Participation and transparency are among the core principles of governance included in the United Nations Development Programme Report on Human Resilience (UNDP, 2011). Participatory decision-making based on a solid foundation of fact is probably one efficient method of taking into consideration the interests of diverse stakeholders groups (Nemati et al., 2002; Secco et al., 2014). Due to the need of disruption with business-as-usual approaches and adoption of sustainable production patterns (UNDP, 2018), there is increasing desire for participation and transparency to improve the process (Bruña-García and Marey-Pérez, 2014; Secco et al., 2014).

Bruña-García and Marey-Perez (2014), conducted a review of stakeholders participation processes in forest planning over the last forty years. The authors stated that participation starts as a process by which people begin to understand their political role and the need for a legitimate conciliation of opinions and a contribution to the planning process. However, in the end, through participation, people can exchange information, express opinions, articulate interests and, most importantly, have the potential to influence the final results.

Bruña-García and Marey-Perez (2014) concluded that, from a theoretical and philosophical perspective, there is no doubt that public participation is essential for our democratic societies. It is a valuable tool to reach consensus, manage conflicts and improve forest management. However, this theoretical clarity is not fully translated into its application. Participation is severely conditioned by the interests of dominant groups that see it as a threat to their interests. Moreover, there is a lack of training which prevents people from facing the participative processes with guarantees.

Most importantly, from the historical perspective, over extensive bibliography consulted, Bruña-García and Marey-Perez (2014) observed that participatory planning has not been included as a required element for the development of forest planning; however, many authors agree that the success of forest plans depends on the representativeness and

involvement of the different groups of stakeholders. Also, there has been a growing interest in public participation, and its application and the number of publications is concentrated in the last decade confirm that participation represents one of the future fields of development and innovation in forest planning.

Bruña-García and Marey-Perez (2014) also concluded that new information technologies could make the decision-making more transparent, fluent and equal. Additionally, it is necessary to develop processes of participation with higher involvement of participants in final decision-making phase, following the same perspective of the reviewers of the previous section (de Castro and Urios, 2016; Esmail and Geneletti, 2018).

In harmony of the concept that participation is a process in constant development and it comprises a higher involvement of the decision-makers, Nemati et al. (2002) proposed a different direction for DSS for the future. This new direction is based on an expanded purpose of DSS to a DSS able to improve knowledge where the effectiveness of a DSS would be measured based on how well it enhances knowledge, how well it improves the understanding of the decision maker and thereby how well it improves his/her decision.

Diaz-Balteiro et al. (2016b), conducted a review on MCDM applied to sustainability measurements in many economic industrial sectors. They verified that the use of MCDM techniques hybridized with GDM techniques is quite common, and the use of both techniques addressing sustainability problems has risen over the last few years. On the other hand, Bruña-García and Marey-Perez (2014), verified that case studies on GDM applied to forest management are not well distributed. They found more than 60 publications in the USA, Finland, and Canada and no one in South America over the last 40 years.

A lack of research on MCDM and GDM applied to Forest Management is relevant considering the significance of forests in Brazil (Rodriguez et al., 2014). Russia, Brazil, Canada, the United States, and China account for more than half of the total forest area (53%) in the world, and Brazil was the country with the highest annual increase in planted forest areas from 2005 and 2010 (Rodriguez et al., 2014) and one of the best in planted forest productivity (Stape et al., 2010). Moreover, Brazil has 7.84 million hectares of planted trees; the sector is responsible for 91% of all wood produced for industrial purposes in the country, and 6.2% of the Brazilian GDP (IBÁ, 2017).

It is essential to highlight that many types of conflicts involving industrial forest plantations, mainly in Southern Hemisphere, arise as a result of disregarding local community perceptions

and its participation in the introduction of these plantations. Those conflicts usually have an environmental nature or social-economic reasons. Often, industrial plantations are based on intensive genetic improvement programs producing tree populations with low levels of genetic variation. Neighboring populations notice losses on biodiversity and other environmental services and land availability. However, they also perceive the creation of new job opportunities and the movements towards sustainability. Those trade-offs depend on the characteristics of the area where the plantation has been established and how it has managed (Rodriguez et al., 2014).

The use of MCDM techniques are particularly useful for resolving conflicts of interest. It brings transparency to the processes of participation and negotiation because the trade-offs among objects of interests can be translated into graphs using quantifiable indicators. Moreover, MCDM in collaborative decision making can be a useful tool for implementing good governance (de Castro and Urios, 2016).

3. OBJECTIVES

Chapter 2 described the challenges faced by managers of industrial forest plantations to support their decisions scientifically. We showed how the expansion of the scientific and technological frontiers have contributed to meet the demands of these forest managers in their quest for the efficient use of available resources.

Brazilian forest plantations, mainly the industrial ones, require robust and flexible DSS to maintain them on track and at the same time to solve the conflicting interests that arise among different groups of stakeholders, such as investors, industry managers, forest managers, social representatives, and environmentalists.

Specifically, our review also presented how MDCA has been applied worldwide to support forest management decisions involving different forest types. The management of industrial plantations, though, best represents the case where not only criteria are conflictive, but also the case in which managers and different stakeholders would greatly benefit if they could operate as a team in search for common grounds. Therefore, this research focuses on the management of industrial forest plantations as the target for MCDM and GDM hybridization techniques, as they provide sound theoretical fundamentals to handle conflict resolution.

We propose the development of a FMDSS based on MCDM to support GDM in the diversified context of forest plantations in Brazil. Accordingly, the general objective of this thesis can be written as follows:

To propose and to develop a set of models to optimize forest management embedded in a DDS to meet the needs of the decision-makers of the different types of forest plantation organization that operate in Brazil. This set of models encompasses multicriteria mathematical programming models, processes and data models structured in such a way to be versatile enough to support interactive group decision-making.

The following subsections present four specific objectives that will build the necessary background to achieve the general objective.

3.1.Characterize the FMDSS globally to identify the main current demands.

As outlined in **Section 2.1**, in order to understand how DSS were being applied to Forest Management problems, we chose a representative case study that could contribute to the understanding of the use of Forest Management worldwide. FORSYS, a FP0804 European COST action, while more than a hundred researchers, from 26 countries, from 2013 and 2016, was considered adequate because its objective meets the needs of this research work. FORSYS objective was precisely “develop a procedural framework, information standards and guidelines for the development, testing and evaluation as well as the application of Decision Support Systems for forest management problems in multifunctional forestry” (FORSYS, 2014). The results contained in the extensive dossier of FORSYS Country Reports are summarized to reveal the contemporary use of FMDSS. More precisely, we have sought to answer the following questions:

- What proportion of the countries in our sample was using all the available research results?
- What types of problems do they have to solve?
- What kind of technology do they use to solve them?
- What are the main concerns and needs of the practitioners?

The first step to answer the questions above is to create a structured description of the problem’s decision-makers usually faced. The second step is to identify (i) the models they used to represent those problems, (ii) which methods and techniques each country implemented to support forestry management decisions, and (iii) identify the most important lessons from the perspective of practitioners were expressed by the authors of the Country Reports

3.2.Processes modeling to support information management

Section 2.2 delineated the role of knowledge management to support a FMDSS. It highlighted that processes and data models define the structure of the information and how information flows from the user to the mathematical model and vice versa. As well as in the first specific objective, we chose a case study that could represent a complex case of plantation in Brazil. We select an active restoration project that intends to supply a forest industry hub with wood and non-wood products in the state of Sao Paulo-Brazil (Zakia, 2013). With the additional

intent of contributing to the development of an effective and accountable active restoration project, this specific objective is to create a conceptual monitoring model that can be applied to the monitoring restoration program and can be embedded in a planning tool. Moreover, the referred monitoring model shall allow generalization to address similar monitoring programs.

3.3.Embedding multicriteria model into a forest management team decision support system (FMTDSS)

The third specific objective of this thesis is to develop a generalizable mathematical programming model embedded in a Forest Management Group Decision Support System, which from this point on will be called *Romero*[®].

Regarding the structure of the system, *Romero*[®] shall be developed according to the results of the first two objectives of this research, and the most important finds of the literature review, which generate three sub-objectives under this third objective:

- (i) Mitigate the main concerns raised by the practitioners of modern FMDSS.
- (ii) Meet the requirements of data integration and support different processes of parameters attainment.
- (iii) Have minimum scenario analysis features to allow interactive group decision making (GDM).

Regarding the models embedded in the system, according to the literature review presented in **Chapter 2**, *Romero*[®] shall be developed considering:

- (i) The principles of the multicriteria decision theory.
- (ii) The general world trends in strategic forest planning applicable to the context of industrial forest plantations in Brazil
- (iii) Enough flexibility to encompass the diversity of Brazilian situations

3.4.Application of the proposed FMTDSS in case studies

The fourth specific objective of this thesis is to apply *Romero*[®] to a case study that could represent the challenges that industrial plantations in Brazil usually faces. Actually, we choose

a situation to capture characteristics from reality that could demand flexibility and robustness from *Romero*®.

The case simulates a vertically integrated pulp company with internal conflicts regarding the quality of wood that is delivered to the mill. Economic and environmental variables, indicators and constraints were included. The ambition is to have a model that can be flexible allowing different kinds of flexibility such as (i) criteria selection, (ii) turning on/off constraints, (iii) changing the level of constraints, and (iv) all area and production parameters. Meanwhile, *Romero*®, to attend the requirements of GDM, needs to present an interface that supports scenario analysis and interactions with the stakeholders.

The case study aims to provide a realistic environment to guarantee the development a DSS able to meet the needs of situations in the industrial plantations in Brazil and fill a research gap in FMDSS application.

4. PRACTITIONERS NEEDS ON FOREST MANAGEMENT DECISION SUPPORT SYSTEM

4.1. Introduction

Much research work has been done on developing the models, techniques, and methods necessary to build computerised FMDSS. This research has been evaluated by reviewers from various standpoints (Baskent and Keles, 2005; Diaz-Balteiro and Romero, 2008; Gratzner et al., 2004; Vacik and Lexer, 2014). However, our knowledge about the FMDSS which have been implemented, and how they are utilised, is limited. Statistics on the computer programmes used or available for use by practitioners have not previously been collected. Thus, we still do not know how much of the available technology has been applied to the needs of forest managers. The aim of the FORSYS (FORSYS, 2014) project has been precisely to collect this information. FORSYS was a natural expression of the curiosity of the FMDSS research community to understand how the available research, produced over the last five decades, was being applied.

In order to understand how decision support systems were being applied to Forest Management problems, more than a hundred researchers—organised under a COST (European Cooperation in Science and Technology) Action, number FP0804, funded by the European Union, from 2009 and 2013—studied the use of FMDSS in forest management worldwide (Eriksson et al., 2014). Among other activities, a committee prepared a template to guide data collection, which was conducted in 26 countries, 18 European and eight from the Americas, Africa and Asia. In the first step, the template defined how to identify and classify a forest problem type. After that, for each problem type, researchers were provided with a guideline on how to describe the use of a DSS. In a concluding section, the uses of FMDSS were commented upon and discussed in more general terms.

Following a template guideline, local researchers prepared Country Reports producing one of the most significant results of the FORSYS project. Due to standardisation, data from the Country Reports could be compiled and analysed (Heaton, 1998) to answer questions related to the use of FMDSS in different countries. Therefore, analysis of the FORSYS project results provides a source of information to perceive how FMDSS research was being applied in contemporary forestry management around the world, which is the main contribution of this section of the thesis. I wish to stress that the data sources for the analysis were reports

documenting actual instances of FMDSS use across 26 countries in Europe, Asia, the Americas, and Africa, and not the many scientific publications on techniques and methods for FMDSS. The results contained in the large dossier of Country Reports are being analysed in this thesis to reveal the contemporary use of FMDSS, and the extent to which FMDSS has been adopted by forestry managers.

4.2. Case Study Description

The FORSYS Country Reports analysis comprise evaluations of two sources of information from the Country Reports (CRs) presented by Borges *et al.* (2014): a quantitative analysis of existing FMDSS applications, and an interpretation of the discussion and conclusion sections of the CRs to derive lessons learned from FMDSS use. In total, reports were obtained from 26 countries involved in the FORSYS cooperation (**Table 1**). A typical CR included an introductory section, a section on forest management planning problems, a section on FMDSS, and a section with discussion and conclusions (FORSYS, 2014). The CRs were produced based on template guidelines (**Figure 4**) standardized and prepared by the FORSYS scientific committee. Local researchers prepared CRs producing one of the most significant results of the FORSYS project (Borges *et al.*, 2014b).

Figure 4 - Country Report production Process

Table 1 - The number of problem types, their corresponding dimensions, and occurrences.

Country	Number of Problem Types	Distribution of Problem Types												
		Temporal Scale			Spatial Scale			Spatial Context [†]			Decision Makers		Objectives	
		Strategic	Tactical	Operational	Regional	Forest	Stand	Spatial, with NI	Spatial, with no NI	Non-Spatial	Single	> 1	Single	Multiple
Austria	5	1	3	1	2	0	3	3	2	0	2	3	0	5
Brazil	4	4	0	0	0	4	0	1	3	0	0	4	1	3
Canada	4	3	0	1	1	3	0	1	1	2	1	3	0	4
Chile	7	2	2	3	0	3	4	1	6	0	7	0	7	0
China	5	3	2	0	0	3	2	0	5	0	0	5	0	5
Denmark	6	3	2	1	1	5	0	4	1	1	4	2	0	6
Estonia	7	3	1	3	0	4	3	4	0	3	5	2	5	2
Finland	5	2	1	2	3	1	1	1	3	1	2	3	1	4
Germany	7	2	2	3	2	2	3	2	3	2	3	4	3	4
Greece	3	1	1	1	1	2	0	2	1	0	3	0	0	3
Hungary	16	6	6	4	6	6	4	0	7	9	9	7	9	7
Ireland	9	3	2	4	1	5	3	2	3	4	6	3	3	6
Italy	4	2	1	1	1	2	1	1	0	3	2	2	0	4
Morocco	5	3	1	1	1	1	3	0	5	0	5	0	0	5
Norway	6	6	0	0	1	2	3	1	4	1	4	2	2	4
Portugal	16	11	2	3	2	9	5	3	10	3	12	4	2	14
Russia	6	1	4	1	2	2	2	3	3	0	1	5	1	5
Slovenia	10	4	5	1	2	3	5	7	1	2	1	9	2	8
South Africa	7	2	2	3	2	4	1	6	1	0	0	7	2	5
Spain	14	8	5	1	1	9	4	5	4	5	9	5	1	13
Sweden	5	3	1	1	1	3	1	4	1	0	4	1	1	4
Switzer-land	9	5	2	2	2	5	2	3	4	2	6	3	0	9
Turkey	1	0	1	0	0	1	0	0	0	1	1	0	1	0

Country	Number of Problem Types	Distribution of Problem Types												
		Temporal Scale			Spatial Scale			Spatial Context [†]			Decision Makers		Objectives	
		Strategic	Tactical	Operational	Regional	Forest	Stand	Spatial, with NI	Spatial, with no NI	Non-Spatial	Single	> 1	Single	Multiple
United Kingdom	9	4	5	0	2	3	4	4	3	2	2	7	4	5
United States	5	3	2	0	2	3	0	0	3	2	2	3	1	4
Sum	175	85	53	37	36	85	54	58	74	43	91	84	46	129
Occurrence (%) [*]		96	88	76	80	96	76	80	88	64	88	84	68	92

[†] NI = neighbourhood interrelations; * Occurrence over all countries = $[N - n(0)]/N$, where N = total number of analysed country reports (25 countries), and $n(0)$ = number of countries reporting no problem types corresponding to the specified dimension.

4.3. Methodology

The method may best be characterised as that of secondary analysts, for we have taken multiple qualitative data sets and conducted additional in-depth analyses (Heaton, 1998). Because our primary objective is summarizing the results, it was necessary for us to go through the CRs, categorizing and analysing the information. Two aspects of our work are important and should be emphasized: (i) standardisation of the CRs was necessary in order to produce data compatible with a secondary analysis, and (ii) our secondary analysis has given us the opportunity to produce summarised answers to the original questions posed by the FORSYS committee to CR authors.

The quantitative analysis was based on counts of FMDSS instances in which a specific method, model, tool, or technique was used. To investigate the link between the features of FMDSS and their target decision problems, a classification of forest management planning problems into problem types was applied. In some cases, the country or group of countries was used as an additional variable to shed light on regional differences.

Section 1 presents the scheme used for the classification of forest management planning problems into problem types. To obtain a characterisation of the FMDSS in a specific category, standardisation was needed for the kinds of models, methods, tools, and techniques that were utilised. **Section 4.3.2** outlines the standards by which the FMDSS categories were described.

The analysis of the FORSYS CRs may be considered a qualitative research study conducted according to Chenail (2011) recommendations which establish that such studies need to adopt simple and pragmatically methods, especially when they are exploratory in their scope. We sought to discover and explore the basic patterns present in the conclusions, so as to describe in a structured manner how local practitioners understood their experiences regarding their use of FMDSS. This last part of the adopted method intends to answer one of the specific questions of this study that is about the main concerns of the practitioners. The results of this exploratory analysis may be expected to provide valuable guidelines for further FMDSS research. How the interpretation was made and what themes were followed are outlined in **Section 4.3.3**.

4.3.1. Classification of Forest Problem Types

The problem type dimensions were temporal scale (strategic, tactical, or operational), spatial scale (regional, forest, or stand), spatial context (spatial with or without neighbourhood interrelations, or non-spatial), number of decision makers (one or more than one), number of objectives (single or multiple), and scope (wood, non-wood products and services). The definitions can be found in **Table 2**, based on Eriksson *et al.* (2014).

A problem type was thus defined by the set of values for the six planning problem dimensions. In total, 175 problem types from 25 countries (one of the countries had to be excluded, as their CR did not follow the specifications provided with the report template) associated with FMDSS use were described, *i.e.*, on average seven problem types per country. A total of 119 distinct problem types were found in the material.

Table 2 - Forest management problem type dimensions, based on Eriksson *et al.* (2014).

Temporal Scale

Strategic (long-term) planning: planning horizon extending more than 10 years.

Tactical (medium-term) planning: planning horizon extending from 2 to 10 years.

Operational (short-term) planning: planning horizon extending to 1 year or less, typically including planning horizons of one month or less.

Spatial Scale

Regional/national level: focused on sets of landscapes that may be managed for different objectives.

Forest level: focused on forest landscapes with several stands managed for common purpose(s).

Stand level: focused on units with homogeneous ecological, physiographic, and development features.

Spatial Context

Spatial with neighbourhood interrelations: the interactions of decisions made for neighbouring stands (or other areal units) are of importance, *i.e.*, a decision made for one stand may: (i) constrain decisions for neighbouring stands or (ii) influence the outcome of decisions made for neighbouring stands.

Spatial with no neighbourhood interrelations: locations of forest operations are of importance, but it is assumed that a decision made for one stand does not constrain decisions for neighbouring stands or influence the outcome of decisions made for neighbouring stands.

Non-spatial: stands may be aggregated into strata or analysis units without considering their mutual locations. There is no concern with locational specificity or neighbourhood interrelations.

Decision-Making

A single decision-maker makes the decision on his/her own, e.g. the forest owner.

More than one decision-maker has the power to decide. In addition, there can be other parties (stakeholders) with no formal decision-making power who influence or may influence the decision.

Objectives

Single: problem addresses one and only one objective.

Multiple: problem addresses two or more objectives, any pair of which could be conflicting, complementary, or neutral with respect to each other.

Scope: Goods and Services

Wood products: problem addresses the supply of wood products that are traded in the market (roundwood, pulpwood, or biomass).

Non-wood products: problem addresses the supply of non-wood products that are traded in the market (fruits, cork, essential oils, etc.).

Services: problem addresses the supply of services that may be traded in the market (recreation, hunting, fishing ...).

4.3.2. Categorization of FMDSS Instances by Models and Methods

The following features of FMDSS were covered by the CRs: (i) Models and Methods (M & M), (ii) Knowledge Management tools and techniques (KM), and (iii) Participatory Planning tools and techniques (PP). M & M covered the models used as representations of the target systems of the FMDSS as well as the optimization and search methods used for solving management problems. KM and PP included both tools built into the FMDSS as well as techniques used together with the FMDSS to address forest management problems.

To go along with quantitative analyses, information related to topics mentioned in the previous paragraph had to be extracted from the reports and assembled in a form suitable for query. In a preliminary analysis, we realized that the descriptions of the FMDSS (M & M, KM, and PP) were heterogeneous, despite efforts towards a standardisation of the reports. Creating lists of categories by simple enumeration of the terms mentioned in the reports led to a large number of redundant categories. It became clear that a systematic classification of the reported categories or coding of the descriptions was needed.

Figure 5 - Methodology Description.

To render the material suitable for further analysis, we subjected the verbal descriptions of the FMDSS to two rounds of analysis and classification (**Figure 5**). The first round was a “raw classification”. Its main objective was eliminating redundancy. This classification resulted in 40 instances under a supra-category “models”, nine instances under a supra-category “method”, 59 instances under a supra-category “sub method”, 31 instances under a supra-category “knowledge management techniques”, and 18 instances under a supra-category “participatory planning method”. The second round of the classification was tailored according to the specific research questions, which were focussed on models and methods. We merged many categories and changed the names of some of the supra-categories to reflect better the character of the new, merged categories. This second round of classification resulted in two instances under a supra-category “Model type”, three instances under a supra-category “Methods group”, and four instances under a supra-category “Participatory planning techniques”. For the “Methods group”, simulation, optimization, and multiple criteria decision making (MCDM) were used as the main basis for classification of the problem-solving method employed to approach different planning problems. This allowed discrimination between (i) the ways that planning problems were dealt with, (ii) the kind of information required, and (iii) the kinds of decision-making processes that were involved. Simulation should here be

understood as “what if” methods, *i.e.*, rules for forest management activities were specified and the outcome of those rules represented the solution. Optimization means that an optimization algorithm of some sort generates a set of plans from which the best, according to criteria, is then identified. MCDM means that some multiple criteria technique was applied. A complication with this scheme for method classification was that either simulation or optimization must be used in order to produce a set of plans upon which an MCDM method may subsequently operate. In order to avoid double counting, a method was classified as MCDM if it was applied regardless of the underlying technique (simulation or optimization) employed to produce the plans.

Table 3 - Categories of FMDSS by model and method, and the number of instances *.

Supra-Category	Number	Category	Number	Methods
Model type	277	Timber; Ecological	253 24	-
Methods group	334	Simulation; Optimization; MCDM	126 158 50	LP; MIP; DP; NLP; Heuristics; Other AHP; Outranking; Simple ranking; MAUT; Voting; Other
Participatory planning techniques	103	Meetings; Survey & interviews; System & process; MCDM	54 15 21 13	-

* FMDSS = forest management decision support systems; MCDM = multiple criteria decision making; LP = linear programming; MIP = mixed integer programming; DP = dynamic programming; NLP = non-linear programming; AHP = analytical hierarchy process; MAUT = multiple attribute utility theory.

These supra-categories and their instances are listed in **Table 3**. This processed material enabled us to summarise the number of FMDSS or country instances by any (combination) of the named categories.

KM were not subject to any quantitative analysis since it was possible to establish only 31 instances from eight countries and almost half of the instances did not specify the technique.

Although researchers typically recognize the need for a significant amount of data, it is not clearly described how practitioners and modelers deal with them. This finding matches the same conclusions of a similar assessment done in 2013 over 17 Ecosystem Services DSS

(Bagstad et al., 2013), in which the author considered how to deal with data; one of the barriers to lower to improve the use of the considered DSS. Also, the author reports that it would take a considerable effort.

4.3.3. Standard for Lessons Learned

The standardisation that local researchers had to follow to make their reports did not include the conclusion section of the reports. As there was a lot of non-standardized information in the conclusion sections, we used a “lesson-learned” (LL) approach to provide a kind of structure to this information, which permitted subsequent analysis. An LL comprised, at least, three basic statements: (i) the lesson learned itself, (ii) the evidence for the lesson learned, and (iii) a recommendation to the community related to the lesson learned. Assuming that in preparing the conclusion sections the local researchers would freely express their own impressions regarding the use of FMDSS in their countries, the LL approach could give an overall idea of the status of FMDSS use and development in each reporting country.

Using this methodology (**Figure 5**), we analysed the conclusion sections of each CR. This work resulted in 77 lessons learned. In order to facilitate the analysis, the LL were grouped according to the following list: (i) KM Techniques; (ii) Participatory Process; (iii) Modelling; (iv) Expertise; and (v) Involvement of Academia. The strength of this methodology is in its ability to identify and group issues mentioned by the CR authors.

However, the imposition of structure limits the detail in the impressions offered by the local researchers that could be carried forward into the analysis that was commissioned by the FORSYS project committee. Once the LL had been grouped, it became possible to group the countries by the areas of concern the CR authors expressed in the conclusion sections, under the hypothesis that similarity of concerns is an indication of similarities in problem types faced or similarities in how problems were addressed. To complete the evaluation of the conclusions of the CRs, we took the information revealed by consideration of the groups by LL and country to produce the analytical discussion that is presented in the **Sections 4.4**.

4.4. Results: Practitioners main concerns

4.4.1. Uses of FMDSS to Address Forest Management Problem Types

The review started by tracing the number of problem types to which FMDSS were applied in each of the reporting countries, and the classification of the problem types under each of the dimensions presented in **Table 2**. This main result is shown in **Table 1**, which provides the number of problem types and their distribution over the problem type dimensions for the participating countries. The number of problem types and the diversification across the dimensions (**Table 2**) in each country reveals the high degree of heterogeneity of the forest problems to which FMDSS are applied, and hence the potential need for flexible application of a variety of FMDSS.

As noted in **Table 1**, for every problem type in every country, there was one or more FMDSS. It was also true that there was no FMDSS that was not related to at least one problem type.

Examining the occurrences presented in the last row of **Table 1**, all but one country (Turkey) reported on the implementation of FMDSS to support long-term planning whereas fewer have support for short-term, operational planning. Considering the application of FMDSS to problems with different spatial scales, tools to address larger spatial scales—regional and forest level—were more represented than stand level analysis tools. There were fewer applications of FMDSS to solve or analyse non-spatial problems than applications with a spatial dimension. However, this does not mean that there was a lack of tools for non-spatial problems (indeed non-spatial problems are generally simpler than spatial problems because they usually do not have integer variables), rather that there were fewer planning problems without a spatial dimension to which FMDSS were applied, than problems with spatial aspects. Single and multiple decision maker situations were equally well represented. Single objective problems were less frequent objects of FMDSS analysis than multiple objective problems.

Occurrences over all countries provided the simplest way to summarize the problem types since the requirements of the research were organised this way. Local researchers, however, reported few instances of problem types in each subgroup. Further, each problem is described by values for each of the six dimensions of **Table 2**, and it may be anticipated that certain combinations of dimension values will have a higher frequency than others. In order to obtain greater insight into the types of problems that the pool of 25 reporting countries were addressing using FMDSS, it was useful to group the problems according to combinations of the values for several dimensions, and determine the frequency of each combination, expressed as

a percentage of all problems, across the pool of countries. **Table 4** shows the results of an analysis of this type, where the values for temporal scale, spatial scale, and number of decision makers were selected to categorise the problem type. A quarter of all problem types was strategic, large scale (forest or regional), and participative in nature. The most frequent tactical problem, corresponding to 10% of all problem types, was linked to the forest spatial scale and a single decision maker, indicating a company planning situation. The next two problem types by frequency were stand based problems, indicative of a private forest owner situation; one type was strategic and the other operational. Operational problems were always associated with a single decision maker, whereas strategic and tactical problems were prevalent in both decision maker situations. Stand based problems were in all cases but one linked with a single decision maker, but were associated to all three temporal scales, strategic, tactical, and operational.

Table 4 - The most frequent problem types, based on temporal and spatial scales and the number of decision makers, ordered by decreasing frequency

Accumulated Frequency (% by Problems)	Temporal Scale			Spatial Scale			Decision Makers	
	Strategic	Tactical	Operational	Regional	Forest	Stand	Single	>1
14%	1				1			1
25%	1			1				1
35%		1			1		1	
44%	1					1	1	
53%			1			1	1	
61%	1				1		1	
67%			1		1		1	
73%		1			1			1
78%		1				1	1	
82%		1				1		1

4.4.2. Categorization of the FMDSS

Having presented our analysis of the problem types to which FMDSS were applied in the reporting countries, we moved on to consider the information extracted from the CRs regarding the categorisation of the FMDSS instances according to the scheme of **Table 3**. Importantly, the CRs did not mention the intensity of use of each FMDSS, or even how many people or entities were using a specific FMDSS at the time of the research. Thus, as for the analysis of problem types, we began by examining the occurrences over the reporting

countries for each category, within the three supra-categories enumerated in **Table 3**. In addition, numbers of instances by category and problem type were retrieved from the CRs and are reported here.

Table 5 - Type of model in FMDSS

Type of Model	Occurrence (%) *	Total Instances
Production	96%	256
Ecological	44%	24

* Occurrence over all countries = $[N - n(0)]/N$, where N = total number of analysed country reports (25 countries), and $n(0)$ = number of countries reporting no use of models of the specified type.

Under the supra-category of model type (**Table 5**), models for timber production existed in all countries but one. There was a total of 256 instances where a timber production model was used, of which 128 referred to strategic problems, 83 to tactical problems, 44 to operational problems, and one was unspecified. The most frequent strategic planning problem for the application of timber production models was harvest scheduling with 44 instances, followed by general landscape development with 26 instances, and stand development with 16 instances.

Table 6 - Type of method in FMDSS.

Method	Occurrence (%) *	Total Instances
Simulation	92%	126
Optimization	88%	158
MCDM	48%	50

* Occurrence over all countries = $[N - n(0)]/N$, where N = total number of analysed country reports (25 countries), and $n(0)$ = number of countries reporting no use of a method of the specified type.

There were fewer FMDSS that utilised ecological models (**Table 5**). Of the 24 total instances, there were 10 related to fire, five regarding storage or flux of elements like carbon and nitrogen, two for wind, and the remaining seven instances related to the protection of water, habitats, or against erosion and pests.

Table 6 shows that optimization and simulation techniques were frequently applied, whereas MCDM was less common. By classifying the problem types corresponding to the instances according to the temporal and spatial scale (**Table 2**), **Table 7** provides more insight into the

kind of method applied to specific problem types. There was a tendency for strategic and tactical problems to be approached with simulation rather than optimization when linked to the regional level, whereas forest level problems tended to be approached with optimization rather than simulation. MCDM methods were most common for forest level problems. The operational level had rather few instances overall, with simulation dominant for forest scale problems, but optimization was more common for stand level problems.

Table 7 - Breakdown of method group instances by problem type (temporal and spatial scale).

Method	Temporal Scale	Spatial Scale		
		Regional	Forest	Stand
Simulation	Strategic	24	20	13
	Tactical	8	19	15
	Operational	0	14	13
Optimization	Strategic	13	57	15
	Tactical	3	29	11
	Operational	6	8	16
MCDM	Strategic	6	16	2
	Tactical	5	13	5
	Operational	0	0	3

For problems where an FMDSS method employing optimization was adopted, it is interesting to explore the complexity of the problems, which can be inferred by considering the spatial scale and context of the problems addressed, and how this affected the selection of the optimization method. The highest level of complexity corresponded to regional and forest level problems, in which neighbour interrelations were incorporated. A characteristic of such multi-stand problems is that they comprise a great number, sometimes thousands of different forest units. At the other end of the spectrum are spatial problems with no neighbourhood interactions and non-spatial problems. In the problems within these latter categories actions in one forest unit did not affect the costs, output or growth conditions of another unit.

Table 8 - Instances of optimization methods used for problems with different spatial scales and contexts.

Spatial Scale	Spatial Context	Optimization Method					
		LP	MIP	DP	NLP	Heuristics	Other
regional & forest (multi-stand)	no neighbourhood interrelations	30	12	0	5	16	11
	with neighbourhood interrelations	7	7	3	4	7	15
stand	no neighbourhood interrelations	7	1	5	9	8	5
	with neighbourhood interrelations	0	0	0	0	0	0

Figure 6 - The use of MCDM methods for strategic and tactical problems

Table 8 shows that LP was the most common optimization method for dealing with problems at the multi-stand level in which the system did not incorporate interrelations between neighbouring stands. For regional and forest problems which demanded the consideration of neighbourhood interrelations, optimization through more advanced methods such as heuristics and MIP formulations were as common as LP. The majority of the stand level problems in which there were no neighbourhood interrelations were approached with non-linear optimization methods. There were no instances of spatial problems at the stand level with neighbourhood relations which were solved by optimization techniques. It happens because when problems are related to only one stand, usually, there are no neighbourhood relations and the spatial problems involving tree level decision were classified under “no neighbourhood relations”.

Fifty problems were approached by MCDM-based FMDSS. The principle distinguishing factor among the problems addressed was their temporal scale. Reports of the use of MCDM methods covered 24 strategic problems and 23 tactical problems, with just three instances of their use in operational problems. The distribution of MCDM methods over the strategic and tactical problems is presented in **Figure 6**; the most commonly applied methods for both strategic and tactical problems were found to be Voting and MAUT, followed by AHP.

Participatory planning, the final supra-category of **Table 3**, was not found to be widely used in addressing forestry management problems, with only 16 countries reporting instances of its use. The distribution over the types of techniques used in Participatory Planning is presented in **Table 9**. Participatory planning can be formulated as an MCDM technique, which provides a relatively rigorous framework for problem solving, but only four countries reported instances of participatory planning by MCDM. The most common approach to participatory planning was through meetings, five countries reported the use of techniques based on surveys and interviews, and five pointed to the utilisation of specific systems or processes (like cognitive mapping and group decision making).

Table 9 - Techniques for handling participatory planning problems.

Technique	Occurrence (%) *
Meetings	52%
Surveys and interviews	20%
Specific system or process	20%
MCDM	16%

* Occurrence over all countries = $[N - n(0)]/N$, where N = total number of analysed country reports (25 countries), and $n(0)$ = number of countries reporting no use of a participatory planning technique of the specified type.

A total of 10 countries reported instances of the use MCDM techniques in FMDSS, with four counties reporting on their specific use within participatory planning processes. This implies that MCDM was also sometimes being applied within non-participatory planning environments.

The processing of the raw responses to the structured questions in the template provided to the CR authors has provided a database of successful implementations of FMDSS, which may

be queried. We have probed this resource to gain insight into the types of problems which are most widely tackled with FMDSS, and also to look for links between problem types and features of the selected FMDSS solutions. An area with many implementations, which continues to be a long-term focus of FMDSS, is large-scale spatial problems (forest and regional level) in combination with multiple decision makers; the nature of these problems are indicative of applications for policy analysis. At the other end of the scale were a range of FMDSS implementations that, while addressing the strategic time scale, were directed to supporting a single decision maker. The spatial scale of these problems was typically stand or forest level, rather than regional. From these characteristics, we identified FMDSS implementations for stand and forest level problems with a single decision maker as mainly designed to serve the requirements of a forest owner.

Moving forward from the probable target users associated with different problem types, we can start to interpret the types of methods applied within the FMDSS. The objective in examining regional level problems will likely be the investigation of how different strategies affect forest owners and other stakeholders of the region (multiple decision makers), and accordingly simulation (or “what-if analyses”) dominated over optimization techniques. In contrast, forest level problems with a single decision maker were oriented towards the requirements of a forest owner, which would account for the dominance of optimization over simulation for these cases. However, there were a significant number of instances of regional level problems being addressed through optimization and uses of simulation methods for forest level problems. These observations pertain to both the strategic and tactical temporal scales. In contrast, at the shorter operational time scale, optimization dominated at the regional level and simulation at the forest level. More in depth analysis, through a specifically targeted survey, would be valuable to better understand exactly when and why different techniques are used.

Stand level problems had similar instance frequencies for simulation and optimization across all three temporal scale dimensions. This ran counter to our initial expectations: since most stand problems were oriented towards a single decision maker, optimization should dominate. When stand problems were tackled by optimization, the methods adopted showed a relatively high incidence of more exotic methods like dynamic programming (DP), non-linear programming (NLP), and heuristics (**Table 8**). We concluded that practitioners opted to use simpler, simulation-based methods because stand optimization contained within it technical challenges, some of which evidently remained to be overcome. Further research into

optimization methods to solve stand level problems will be profitable and allow optimization to replace simulation.

Another area where we recorded the implementation of a variety of methods was spatially constrained problems, which is an active frontier in FMDSS research. These problems are often rather difficult to solve, involving integer variables and being combinatorial in nature. There were a number of responses indicating the use of LP for spatially constrained problems. However, since LP is not considered an appropriate method because of the integer variables, this may indicate a confusion of terminology. Many of the methods that have been implemented did not fall into any of the standard categories and could only be labelled as “other”.

4.4.3. Lessons Learned on the Construction and Use of FMDSS

The original instructions for the preparation of the CRs directed local researchers to present their findings under three headings: Models and Methods, Knowledge Management, and Participatory Planning Processes, with no particular emphasis applied among the headings. We anticipated that the conclusions section of the reports would give equal weight to these three aspects of the survey. However, this did not happen; some issues and lessons learned were mentioned far more frequently among the CR conclusions than others. In addition, the local researchers used the conclusions sections to open topics which lay beyond the originally intended scope of the survey. Several of these topics were recurrent, appearing in the conclusion sections of the reports from multiple countries, which served to identify them as significant lessons learned (LL).

Table 10 - Number of lessons learned by group and occurrences by country.

Group of Lessons Learned	Instances	Countries (<i>n</i>)	Occurrence (%) *
Expertise	8	8	31%
Involvement of Academia	14	13	54%
Modelling	11	8	31%
KM Techniques	17	15	58%
Participatory Processes	26	19	73%

* Occurrence = n/N , where N = total number of countries who submitted conclusions (26).

The processing of the LL contained within the conclusion's sections began with their grouping, under the three original themes, supplemented by groups corresponding to the additional issues raised in the CRs. Typically, the CR authors gave their opinion of the relative importance of the issues mentioned and the different LL. These opinions were incorporated into the grouping process, so that it discerned topics that were rated as of high importance by the local researchers across multiple countries.

Table 10 enumerates the groups used to classify the LL and reports the number of LL by group and countries. The groups are: (i) Expertise: every LL that expresses any kind of concern about education or technical knowledge needed to develop or use the FMDSS; (ii) Involvement of Academia: groups every LL that is related to participation of researchers in FMDSS use or development; (iii) Modelling: every LL that expresses any issue about the need of modelling improvement; (iv) KM Techniques: regards the LL that mentions anything about how they deal with data, information or knowledge; (v) Participatory Processes: any LL that expresses needs or concerns related to how they are involving all stakeholders over the planning process. Expertise and the Involvement of Academia were the additional topic groups beyond the three surveyed topics that attracted wide attention within the conclusions section of the CRs and merited detailed further consideration.

We have conducted a separate analysis of the issues underlying each group of LL to probe in greater depth their implications for current and future applications of FMDSS. Expertise was mentioned by eight countries (**Table 10**), two of which had an education index (from United Nations HDI) of less than 0.96, and the other six were among the top twenty countries in terms of education. In the first two (educationally underdeveloped) countries, the LL were related to forest general education, with the authors expressing the opinion that formal education is an important pre-requisite for the effective use of FMDSS, while a lack of education imposes limitations on FMDSS use. Five, among the second group of six, reported the importance of training so that forest managers receive adequate preparation to apply ever more complex DSS to forestry problems. Given these opinions, it might be imagined that there would be differentiation among the types of forestry problems addressed and the FMDSS methods applied to solve them between the countries. However, this proved not to be the case; all eight countries that identified Expertise as an important LL were making use of complex models, were applying modern methods to their solution, and had access to the necessary technology. The information in the CRs allowed assessments only of problem types and solution methods. While the infrastructure was known from the CRs to be in place in all eight countries, the extent to which FMDSS were in active use in the countries could not be

determined. The lesson learned from the opinions of the local researchers, that more training will make the use of FMDSS more widespread and open new possibilities, is considered valid, regardless the size of the country, the resources available, and the forest area managed with DSS.

The advancement and efficient use of FMDSS have depended upon mutually fruitful relationships between researchers in academia and practitioners. In the literature analysed in **Section 2.1**, many authors have demonstrated how real needs and contemporary challenges have been the stimuli for scientific development (Baskent and Keles, 2005; Diaz-Balteiro and Romero, 2008; Eriksson et al., 2013, 2014). In the **Section 4.4.2**, data analysis from the CRs provided valuable information about how much of the available research has been applied to real forest management problems. Although the survey did not ask opinions on the Involvement of Academia, the many and tough responses from local researchers place it centre stage as a driver for and a relevant issue in FMDSS use. In thirteen CRs, the authors reported that not only did local academic institutions prepare users to use the DSS, but also participated in the development of the tools. Of the fourteen LL that referenced Involvement of Academia, four attributed the successful use of FMDSS in the government and/or private sector due to the influence of academia, two claimed that the involvement of academia was rising and promoting FMDSS, and another two reported that they were in the early stages of learning how to use FMDSS, and that they had successfully turned to academia to promote the introduction of FMDSS.

To test for the possible influence of local academia on the forestry management problems addressed in particular countries, we divided the countries into two mutually exclusive groups, A and B. Group A comprised the countries who mentioned the importance of the involvement of academia and Group B comprised the rest. The pattern of forest management problem types was the same for the two groups, from which we concluded that the involvement of local academia does not seem to drive the implementation of FMDSS directed at problems of high complexity.

Not all the lessons learned under the Involvement of Academia group were positive. There were seven lessons that together and similarly pointed to a concerning distance between FMDSS practitioners and researchers in academia. Further analysis of these opinions brought forward two causes for this distance. Users were demanding solutions of lower complexity than those under development in academia. The output available from academia in the form of research results was highly technical, making it difficult for practitioners to perceive how it

could be applied to their needs for FMDSS. These LL statements suggest that the current relationship between practitioners and researchers may not be optimal for the advancement of FMDSS. Some adjustment so that research challenge and system complexity, on the one hand, and real-world needs on the other are brought into better balance is required, although the point of balance is still unknown.

Reports from eight countries highlighted Modelling among LL. This is many fewer than the 19 who mentioned participatory planning processes, and while it may appear to tell us that M & M is no longer among the major concerns, it should not be taken to mean that major advances are not seen as required. The basic solutions to the main production problems were found some decades ago, and it is tempting to view the eleven LL related to Modelling as simple requests for improvements in the existing set of M & M. Four highlighted the need for tools to address problem types which have not previously received attention, and another seven pointed to improvements in M & M required to address better some existing problem types. Responding to these needs as well as new challenges is an integral part of the continuing evolution of FMDSS (Vacik and Lexer, 2014), which brings with it constant demands for new models and improvements in the methods employed to solve them. The eleven Modelling LL are among areas which, according to the literature, are under current and active development (Başkent et al., 2014; Baskent and Keles, 2005; Vauhkonen et al., 2014; Wei et al., 2014). Among the necessary improvements, one prominent recurrence was methods that can handle risk and uncertainty. This is a challenging endeavour and delineates a clear scientific frontier: the application of stochastic programming to forest management problems. Six CRs focused on improvements required so that FMDSS can address the difficult problems related to operational issues at the regional scale, when there are spatial constraints with multiple objectives and products. According to Eriksson *et al.* (Eriksson et al., 2014), the scientific community has successfully applied operational research knowledge to forestry problems of this type. Our analysis has shown that while small in number the M & M LL contained many major challenges whose resolution will require advances at the frontiers of current research in FMDSS.

Our main finding in relation to Knowledge Management technology in FMDSS is that there is no common understanding about its terms and concepts across the reporting countries. This emerged through both the standardisation and two-round classification of the answers to the structured questions designed to probe KM usage and tools (it is noteworthy that KM concepts do not figure explicitly within the supra-categories and categories enumerated in **Table 3**), and the lack of any consistent themes within the conclusion sections of the CRs. Despite the

ethereal nature of the topic of KM, the authors of 17 CRs did offer comments that could be viewed as LL. The general consensus was that large amounts of data are required for FMDSS, and that such systems also generate a large amount of information. This appreciation was expressed in fourteen LL insisting that “special technology” was required to manage the large amount of data required for FMDSS and that “knowledge-based systems” were needed to process the large amount of information generated from such systems. Some said KM technology, according to their understanding, was one of the keys to the success of the use of FMDSS, and others expressed much the same opinion by citing the need for more technology in this area because it was critical for success. Therefore, even though understandings concerning KM technologies were very heterogeneous, FMDSS users perceived a strong dependence between information technology and the successful use of FMDSS. In this sense, the authors of the CRs have reached the same recommendation as found in a number of studies of previously developed applications: forest management has reached a scientific frontier, which may only be breached through the application of advanced knowledge management techniques (Bagstad et al., 2013; Reynolds, 1999).

Participatory Planning was mentioned in nineteen CRs, and in many, there was more than one statement emphasising different aspects of this theme (**Table 10**). Participatory Planning was the most emphasized of the five topics, with more than twice as many instances as for Modelling. The issues raised in the LL statements fell into two categories: there were thirteen LL statements about the potentially contentious relevance of participatory planning processes, and six LL statements about how FMDSS could support participatory planning processes. This parallels the perception that the introduction of participatory planning into forestry management is a two-stage process. The first stage is reached when decision makers accept the need for the involvement of a community of stakeholders in forestry decisions, and perceive that early involvement brings better solutions. Having accepted the participation of a wider community of stakeholders, the second stage is the introduction of technology into participatory planning to support the efforts of all the contributors to find a best solution. An obvious application of technology would be to run “what if” simulations to explore the consequences of proposals from stakeholders and use the results to inform the decision making. Thus, in the first group, comprising 13 statements, the LL pointed to the importance of the involvement of stakeholders, the sharing of responsibility, the legitimacy of the planning process, and the participation of users in all phases. While in the second group of seven LL statements, the emphasis was on the development of technologies that could support the participatory process.

Participatory planning was not considered a relevant issue when publications on forest modelling started to appear in the 1970s. A recent review of the literature (Buchy and Hoverman, 2000) found that the first publication mentioning the application of participatory planning to FMDSS was presented in the 1990s. Examining current trends in FMDSS, participatory planning is the most recent addition into the conceptual framework of FMDSS (Diaz-Balteiro and Romero, 2008; Tindall et al., 2010; Vacik and Lexer, 2014; Yumin and Tianhe, 2004).

4.4.4. FORSYS case study – methodological considerations

The FORSYS case study has focused on the information given by local researchers in 26 countries organised in a survey over the existing FMDSS, their features, and the problem types to which they were applied, supplemented by conclusions in which the country authors were asked to present their opinions as LL. Before discussing, I should issue the disclaimer that the results presented here are no more certain than the data originally provided in the CRs. Difficulties were encountered in processing the information, even from the structured questions which were provided in the form of a common template designed to return key information under the three headings of Modelling and Methods, Knowledge Management, and Participatory Planning. Standardisation and classification processes, which can introduce elements of subjectivity into the analysis, had to be applied by ourselves. The rigour with which the template guidelines were followed may also be questioned, and different interpretations of what, for instance, distinguishes a forest level problem from a regional problem will impact on the count of problem type instances. Similarly, counts of instances of specific methods and comparisons between countries will only be correct if the local researchers all adopted the same interpretation of phrases such as linear programming and heuristics. The assessment unit was the country; no attempt was made to weight the instances extracted from the CRs according to the size of the forest sector or any measure of the intensity of FMDSS activity. In consequence, major players had fewer opportunities to project their influence and experience onto the results. Thus, while it is of great interest to ask questions such as how was LP used for stand problems, and why were heuristics so common for non-spatial large-scale problems, it needs to be recognised that these questions may arise as much from the processing of the reports and the interpretation given by the CR authors to the terms, as from how FMDSS were being applied across the globe. The results presented in the **Section 4.4** are a rich source of such questions, but definitive answers should not be

sought there. This study could only initiate and guide the asking of these questions. Obtaining answers will require the collecting of new data, subject to more rigorous guidelines than could reasonably be devised at the time we formulated our survey template. We embarked upon a very open exploration of an enormous, topical, and developing field. We have returned with highly relevant data, pertinent questions, and mainly guidelines which set the basis of the FMDSS development, object of this thesis.

5. PROCESSES MODELS TO SUPPORT INFORMATION MANAGEMENT

5.1. Introduction

Examples of large-scale restoration programs to recover essential ecosystem services are now common in many countries. Governments are assuming ambitious targets outlined in regional and national forest restoration policies (e.g., Sao Paulo State Resolution SMA 32/2014, Brazil; Environmental Protection Law, China) as well as global commitments (Benini & Adeodato, 2017; Ray *et al.*, 2017; Gatica-Saavedra, Echeverría, & Nelson, 2017). Additionally, an increasing interest in forest restoration can be seen in scientific literature in recent years (Gatica-Saavedra *et al.*, 2017).

Among other methods to reverse degradation and destruction, active forest restoration is increasingly being used. A great amount has been invested throughout the world on landscape restoration programs, and the *New Climate Economy Report*¹ estimates that the total expenditure on these activities amounts to \$50 billion USD per year, half of this coming from developing countries (Benini and Adeodato, 2017).

Demand for active restoration in Brazil is increasing strongly (Benini and Adeodato, 2017). Federal and State governments, NGOs, and the private sector have organized themselves in different types of coalitions after realizing the urgent need for the restoration of ecosystem services such water supply, soil, and biodiversity conservation (Viani *et al.*, 2017). Among other initiatives, a national multi-stakeholder coalition (the Atlantic Forest Pact) was created with the goal of promoting the restoration of 15 million hectare in the Atlantic Forest biome by 2050 (Viani *et al.*, 2017).

It is important to highlight that active restoration in Brazil, mainly in Atlantic Forest biome where there are only 12,4% of the original forest cover (SOS-Mata-Atlantica and INPE, 2017), means restore native vegetation cover through silviculture activities of species-mixtures such as planting, fertilization, thinning, and weeds and grass control (Durigan and Ramos, 2013).

Given the increasing investment of time, effort, and money in restoration, there is an urgent need to develop monitoring programs to assess restoration effectiveness (Durigan, Sukanuma, & Galv, 2016; Gatica-Saavedra, Echeverría, & Nelson, 2017; Watson *et al.*, 2017). Long-term

¹ The New Climate Economy was commissioned in 2013 by the governments of seven countries: Colombia, Ethiopia, Indonesia, Norway, South Korea, Sweden and the United Kingdom. The Commission has operated as an independent body and has been given full freedom to reach its own conclusions.

monitoring programs at larger spatial scales are especially growing in importance and have specific challenges to overcome such as consistency, standardization, repeatability, affordability, and continuity (White *et al.*, 2017; Reynolds, Knutson, Newman, Silverman, & Thompson, 2016; Gatica-Saavedra *et al.*, 2017).

Gatica-Saavedra *et al.* (2017) conducted a literature review covering a total of 94 publications, between 1990 and 2015 that were filtered in their analysis. They found forest restoration assessments in 25 different countries and concluded that the effectiveness of most restoration programs remains mostly unknown, limiting the ability to determine the overall impact of current investments in restoration.

The most considerable number of assessments, according to Gatica-Saavedra *et al.* (2017), was conducted in tropical forests. Published assessments increased considerably between 2010 and 2015 in all regions of the world. Forest composition and ecosystem functions were the most frequently cited attributes, found in 79% and 68% of the publications.

Although the number of assessments has increased over time in all regions, South America was the region with the most evident increase. The number of assessments was particularly high in Brazil, which leads South America in public policies and legislation aimed at increasing the effectiveness of forest restoration. Moreover, according to Durigan *et al.* (2016), forest restoration projects have grown not only in number but also in extension in Brazil over the recent years.

One of the most significant findings of the literature review conducted by Gatica-Saavedra *et al.* (2017) was the need for the use of a greater number of indicators of the effects of forest restoration. Unless a greater number is used, investigators might not be able to understand the extent to which management activities are contributing to restoring ecological complexity and integrity in forest ecosystems and contributing to achieving global conservation goals.

Restoration evaluation often entails significant difficulties such as the lack of harmonized monitoring data, lack of reference sites, and vague and imprecise information available about project goals and implementation (Ocampo-Melgar *et al.*, 2016).

Therefore, despite the growing demand for data collected consistently across space and time, monitoring efforts fail frequently (Reynolds *et al.*, 2016). Interestingly, one of the main failures simultaneously pointed at by Albert *et al.* (2015) and Reynolds *et al.* (2015) is that effective monitoring requires a remarkable plan phase and designed model to guarantee the link between the outcomes of the initiatives with the restoration objectives. The key benefits of

following a planning framework lie in providing a better basis for accounting and subsequent decision-making (Albert et al., 2015).

As a method for planning assessment programs, Reynolds *et al.* (2016) proposed a roadmap for designing and implementing successful biological monitoring programs. Their intended to address any monitoring program aims better natural resources management. The roadmap emphasizes linkages among core decisions to ensure alignment of all components, from problem framing through technical details of data collection and analysis (Reynolds et al., 2016).

The first phase of the roadmap is dedicated to clarifying the objectives and developing a conceptual model of the system. More specifically, the first phase comprises four steps (define the problem; state the objectives; design a conceptual model and specify management actions); the second and the third ones describe how a conceptual model should be designed. Reynolds et al. (2016) also define a conceptual model as the intellectual foundation upon which a monitoring program rests.

To accomplish the second specific objective of this theses, that is to create a conceptual monitoring model, we intend to follow the first phase of Reynolds et al. (2016), that will generate sufficient information to design the monitoring process model in the context of the São Paulo forest restoration program. Subsequently, the applicability of the model to more general cases is explained through references to other authors' experiences.

Watson et al. (2017) developed a conceptual model that represents the many hypothesized links from two groups of facts: (1) on-ground connectivity management to organismal movement and (2) the demographic parameters that define population processes and conservation outcomes intended. Then they embedded this model within an adaptive management framework to provide a decision-support tool that linked objectives to achievable monitoring goals, advising on the most appropriate methods to use for understanding, managing and reporting effects of connectivity restoration.

As in Watson et al. (2017), we are going to propose a conceptual model that can be embeddable as an adaptive management framework into Forest Management Decision Support Systems (FMDSS). Moreover, the proposal follows the fifth step of the Reynolds *et al.* (2016) roadmap, which classifies monitoring into different types and offers guidelines to conceptual model developers. Specifically, effectiveness monitoring is one of the types Reynolds *et al.* (2016) define. This type of monitoring focuses on the effects of management

actions. It assesses the effect of specific action by explicitly documenting the response in the system and noting the degree to which desired outcomes are attained.

5.2. Case Study

In this **Section 5.2**, a large forest restoration program is presented, in which monitoring takes an essential role to guarantee the success of the initiative. It is an appropriate case study sufficiently extensive, diverse and real to allow and test the generalization of the conceptual model proposed in this work.

The Brazilian Federal Law 2012/12651 determines that every rural private property has to set aside from 20 to 80% percent of its total area for forest management. This area is legally defined under the regulation as Legal Reserve (LR), and its aim is to ensure some economic and sustainable use of the rural property's natural resources and simultaneously promote its biodiversity conservation. The delimitation of the LR area is set forth in articles 12 and 13 of the law. Property owners have to plant only native forest species to compose the vegetation cover in the LR area.

The mandatory percentage of the total area on rural properties in the state of São Paulo to be maintained as LR is 20% (Zakia and Pinto, 2014). Most of the rural properties in the state do not have enough vegetation to fulfil this obligation. For these cases, the law establishes that the property owner must conduct some form of induced restoration, natural regeneration, or a combination of both until 20% of the property is covered with a legally reserved forested area (Zakia and Pinto, 2014). The LR area can be used for commercial purposes subject to some constraints monitored by key indicators established by state regulations.

Table 11 - Land Distribution in State of São Paulo

Area classes in hectares	[0 - 20]	[20 - 50]	[50 - 100]	[100 - 200]	[200+]	Total
Number of properties in each area class	174,352	77,720	32,888	19,722	19,640	324,322
Total area per Class (ha)	1,743,520	2,720,200	2,466,600	2,958,300	10,571,695	20,460,315

The restoration of LR areas with Brazilian native tree species for commercial purposes is still incipient in the country. There is a lack of silvicultural techniques and information, and the uncertainty about markets for forest products and services is high (Zakia, 2013). These problems make proper economic evaluations very difficult and inhibit the supply and demand of adequate credit lines.

In the state of São Paulo, a restoration target was set to reach 300,000 ha in the next ten years (Barretto and Assunção, 2015). There are 20 million hectares in the hands of private farm owners (**Table 11**), and the legal reserve deficit is estimated at 1,7 million hectares (Barretto and Assunção, 2015). Half of the area is in hands of 19,000 property owners, and the other half has 304,000 land units. The São Paulo State Department of Environment (SMA) expects that 30,000 to 40,000 landowners will present LR forest restoration projects to be analysed and approved during the upcoming years.

Table 12 - List of Policies

Group of policies	Policy
1: Regulations	
Priority Areas	Create areas according to the state priorities, like water supply, biodiversity distribution, and soil protection urgencies.
	Through regulations, facilitate the restoration on those areas.
Regulation Adjustments	Adjust all it is needed to promote restoration, number of species, restoration rules, and performance indicators to control.
2: Technical Assistance	
Technical Recommendation	Encourage the state research institutes and consulting companies to study native species silviculture to find:
	<ul style="list-style-type: none"> - Suitable species to the state and their correct combination - Species mix with economic return. - Species distribution in the area to allow economic exploitation.
	Training program to technical assistance public staff and amplifying the tech team through public-private partnership (PPP).
Processes support	Develop system to do the recommendation to the entire state.
	Develop web-portal to publish the technical recommendations.
	Develop monitoring system to feed planning systems.

Group of policies	Policy
	Integrate the recommendation web-portal to the State Environmental Control System (SIGAM) already developed.
Demonstration Units	Research areas in several regions to demonstrate silviculture techniques: private and public land.
3: Infra-Structure	
Funding	Negotiate with funding institutions.
Forestry-base Industry Clusters	Finding priority micro-regions to incentive forestry-base Industry clusters.
Continuous Research	Institutional agreements and research priorities to the state research.

Therefore, a new set of policies has been planned to mitigate eventual barriers that prevent landowners in this state from restoring their LR based in three fundaments: regulations, technical assistance, and infrastructure. **Table 12** shows the set of policies per fundament. The São Paulo State Department of Environment (SMA) leads a mobilization of research institutes, universities, NGOs, and consulting companies to support the development and implementation of the new policies.

Many of these policies are in the implementation phase, and restoration has already begun. In Fundament 2, a “Legal Reserve” technical recommendation module has already been developed. This system is integrated into other systems that control licensing processes and the general registration of a property named “SIGAM – State Environmental Control System”².

The set of policies listed essentially relies on the existence of a DSS named “Restoration Scenario Simulator”. This tool determines all possible alternatives of forest restoration available to each landowner depending on where the property is located. This DSS supports the policy formulation as it turns possible the simulation of forest restoration alternatives under different hypothesis.

² (<http://www.sigam.ambiente.sp.gov.br/>)

Table 13 - Simulator Database overview

Data Type	Quantity	Data available, used by the Simulator
Number of property units	324,000	Maps
Number of Municipalities	646	Maps, Total Area, Priority area, Land prices Climate data as Temperatures, Rain, Evapotranspiration etc.
Phito-ecology units	1597	Maps, Area, Species adaptation Wood technical data, Growth models, Taper models, BDH
Species	250	Distribution models, etc Species combination rules
Wood products	4	Diameters, prices, markets
Non wood products	10	Production curves, prices
Silviculture Operations	50	Costs, inputs, labour hours, machinery needed, etc.
Insurance data	1	Interest rates, payment conditions, etc.
Funding options	20	Interest rates, payment conditions, etc.
Available Nurseries	208	Location, Capacity, Seedlings of each species
Available Sawmills	156	Location, Capacity
Number of tables in the database	80	

The “Restoration Scenario Simulator” needs a large set of parameters to allow the simulations. A group of researchers, mobilized by SMA, from different knowledge areas carefully prepared these parameters (**Table 13**). They are based on research data and a few restoration experiences we have in the country. All of them must be updated as soon as we have data from reality to support it.

A monitoring system is under development to complete the knowledge they need to update the parameters and support the entire restoration process (Rodrigues et al., 2013). The aim of the system is to gather data and interpret them to (i) get feedback for the *Legal Reserve Technical Recommendation Module* and (ii) recommend adaptive actions (Adaptive Management System). In addition, the state needs to verify the effectiveness of the plan to adjust the policies.

The monitoring model in the case study aims to check what has been actually done and verify whether forest restoration policies are stimulating changes and how effectively they have promoted forest restoration. The monitoring parameters will be iteratively recalculated to set new scenarios for the analysis of the subsequent cycles predicted in the environmental and forest policy DSS and to prescribe the need for policy revisions.

5.3. Methodology

5.3.1. The components of the model

Fundamentally, the conceptual model is developed following an action learning approach. The action learning approach was idealized by Professor Reginald Revans during the 1940s (Revans, 2014). According to Waddill and Marquart (2003), who conducted an extensive review of the theme, the power of action learning is its wide-ranging application to both learning and action. Practitioners and theorists from diverse disciplines, including science, embrace its practical effectiveness.

Revans (2014) proposed a very basic equation to express learning (L):

$$L = P + Q$$

where P is the acquisition of programmed knowledge and Q is insightful questions.

Action learning offers a useful starting point to treat problems in the real world when no solutions have yet been envisioned (Revans, 2014). Action learning recognizes that in the absence of any insight (Q), programmed knowledge (P) is not sufficient to solve the described problem. Therefore, good propositions cannot be applied to the problem until insightful questions are asked. That is to say, P is necessary but, in the absence of Q, is not sufficient.

In the context of this work, the theoretical content described in **Section 2.2** could be referred to as programmed or predisposing knowledge (P). The insightful questions (Q) could be stated as (i) 'what information is essential and sufficient to monitor?' And (ii) 'how is the monitoring process organized to become effective?' During the designing process, we detailed the original question about data to define precisely what variables we should measure to calculate the ecological indicators. Similarly, we detailed the question about processes to determine when, why, and how each variable would be measured.

The action of learning essential concept provides the foundations for building the conceptual model presented in this work. The development process guarantees the building of a conceptual model that is simultaneously useful for the case study and generalization.

Figure 7 shows the main forest restoration phases predicted in the case study. It essentially resembles the planning process depicted by McDill (2014) in **Figure 3** except for the need to detour after the monitoring evaluation component to either correct on-going activities or reset planning parameters.

Figure 7 – Essentials of the case study.

The presentation of the conceptual model shows fundamental components, with their corresponding breakdowns and generalization. For the sake of clarity, the breakdown of each fundamental component splits into two parts, planning and monitoring, with the precise identification of the many planning actions and events involved.

5.3.2. Planning and monitoring processes

Figure 8 shows a diagram for the policy implementation of the case study. The monitoring process gathers data from the fundraising phase until final operational activities in the field. The system translates data received from the inspection team and other controlling processes into interpreted outputs that are then stored in a knowledge base.

The next step involves evaluation of the monitoring iteration. The evaluation checks for (i) goal achievement, (ii) acceptability of intermediate results, and (iii) adherence to recommendations by landowners. The assessment of the goals triggers the reformulation of the policies. Plantation inspection triggers the review of technical recommendations, and intermediate results trigger the “Adaptive Management System” to recover or improve actual plantations. These actions are identified as “Evaluate the monitoring iteration” in **Figure 8**.

The success of this first phase relies on:

- (i) Organized gathering of each iteration data
- (ii) Adequate interpretation of data gathered
- (iii) Prioritization of resources to trigger immediate adaptive management action
- (iv) Continuous revision and reformulation of policies for next planning cycle

At this stage, the main stakeholders are individuals involved in the process as system developers, system users (landowners and technical assistants) and forest experts.

Figure 8 – Planning and Monitoring processes

5.3.3. Breakdown of the planning component

A breakdown of the planning component allows a proper design of an integrated monitoring. It is important to see in **Figure 9** that there are two distinct subdivisions in the planning process separated by an intermediate sub-process, “Policies: review guidelines.” The first subdivision regards the “scenario analyses” and the second relates to “revisions of a set of policies”.

The first subdivision, “scenario analyses” has two important components before the first simulation cycle:

- Gather new parameters. Many of them come from internal systems, and others come from external sources.
- Update parameters, such as priority areas, possible costs, prices, market information, and production models (update production equations using updated data from monitoring process).

The intermediate sub process, “Policies: Review Guidelines,” focuses on results and reports coming from the critical IT-based sub process, “Scenario Analyses” and “Simulation”. Policy

makers reach mutual consensus on guidelines for the next steps during public hearings and workshops.

Figure 9 - Breakdown of the monitoring component

In the first iteration of planning, parameters come from a database organized by the best estimations the experts' team of the State Department of Environment could get. From the second iteration on, the database is updated accordingly to adjustments produced by the monitoring module. In the **Section 5.3.4**, a breakdown of the monitoring module is presented to provide the details that will guarantee the proper updating of the database.

The second subdivision, “revisions of a set of policies”, comprises the policies’ definitions, which are independent of each other, even though the same parameters are used to support all of them. From what we observed during research, typically, in the region, those definitions are prepared in consensus meetings and tend to be not based on the information. From the first iteration on, data will start constituting a first knowledge base that must be done according to the specifications to gain the confidence of São Paulo State leadership.

5.3.4. Breakdown of the monitoring component

In the case study, landowners are required by law to perform a sequence of steps to unlock the restoration process itself and its operations. Firstly, the landowner has to register the property with the "CAR – Cadastro Ambiental Rural" (Rural and Environment Register), in which a geo-referenced map of its property is required. The landowner declares the Legal Reserve (LR) area portion inside the boundaries of the property.

Secondly, landowners have to access the - Legal Reserve Technical Recommendation Module to perform a small series of choices, according to their preferences, and to generate the pre-approved restoration project. Landowners can make adjustments in this project according to their local needs and submit them for SMA approval.

Once approved, a restoration project in accordance with the nature of the landowner’s property is ready to be issued. Called *PRA – Environment Restoration Plan*, this project complies with Brazilian laws 12.651/12 and 7.830/12 which will be submitted with the support of another SIGAM module.

Thirdly, the landowner has to seek alternatives to fund the operation. Landowners can use their funds or request them from state or private banks. No IT module supports this subprocess completely.

Finally, according to the *PRA - Environment Restoration Plan* module, a report gives a schedule of restoration to produce an “Inspection Plan” that meets the inspection teams’ availability. The inspection team visits the properties and measures what was planned to be measured.

Table 14 - Examples of Adaptive Management: Atlantic Forest Restoration according to Zakia (2013)

KPI – Key Performance Indicators (2)	Verifiers: minimum values	Adaptive Management
percentage of invasive grasses	25%	Grass Control (chemical or biological control depending on other KPI values)
invasive tree species	absent	Invasive species control (mechanical methods)
invasive shrub species	absent	Invasive species control (mechanical or chemical methods depending on other KPI values)
land cover with native species	75%	Replantation
tree species basal area (DBH >5cm) 200m2 plots	18,75m2	Thinning or re-planting depending on other KPI values.
tree species diversity	20	Enrichment or seeds bank transposition depending on others KPI values.

The subprocess, “Trigger Report,” produces reports describing how landowners performed each action (**Figure 10**). The answers from landowners about the reasons for non-performed actions can come through by sample gathering or by census according to the available resources. After reading the response, the Data-Treatment subprocess must process and save them in a structured format in a knowledge base.

The “Inspect area” subprocess should produce a diagnostic of each land property according to at least KPI (key performance indicators) required by forest regulations, such as (i) sapling quality, (ii) the amount of sapling, and (iii) basal area. Additionally, the technical support team will measure more variables to feed the rule calculations of the adaptive management, such as the sequence of silvicultural operations the landowners made and corresponded inputs they applied.

Figure 10 - Breakdown of the monitoring component

The rules are based on barriers the ecosystem must overcome to achieve the predefined levels of restoration (Durigan and Ramos, 2013; Rodrigues et al., 2013). For each set of values of the indicators, the system recommends one sequence of actions to correct the regeneration course. **Table 14** contains some examples of these adaptive management rules.

From the “Report on funding” subprocess on, there are no IT resources to support the process. SMA is projecting the further modules of the system. In this first version of the monitoring application, the system will follow the rules and provide a recommendation. However, the system is not going to change the rules automatically according to the results because there is no enough knowledge to do it yet. It will be a user subprocess performed by local researchers to analyse the results and propose revisions to the rules.

Figure 11 describes the details of the adaptive management subprocess showing how researchers follow and review rules. Each inspection of each land property, which happens in a monitoring iteration, admits an adaptive management subprocess. When it is completed, i.e., when all land properties are properly inspected in the actual iteration, the system is ready to check the goals.

According to the actual view of the policy makers, the main KPIs are as follows:

- the sum of the area implanted in the year;
- the sum of the area stopped in each step of the process and the stop reasons;
- the sum of the area has surpassed each barrier of restoration per age of planting;
- an average of restoration performance indicators (basal area, the amount of sapling, and quality of sapling).

All ecological indicators should be available per region and other dimensions present in the knowledge base, including at least sub-regions, counties, municipalities, types of funding, and the technical support team. This information is going to be used to review the set of state policies as **Figure 10** demonstrates. Depending on which dimension group the available indicators is, policymakers can also have the effectiveness of (i) technical support teams, (ii) the funding process and (iii) IT resources used in the process.

Figure 11 - Adaptive Management

5.4. Results: Data and Parameters integration

The model described in the **Section 5.3** serve as a framework to conduct the monitoring component of the forest restoration program fostered by the government of the state of Sao Paulo in Brazil. To describe the generalizable model, we use some terms defined according to **Table 15**.

We can describe the generalizable model (**Figure 12**) by using previous definitions as follows:

Firstly, the system recovers all *GeoUnits* and separates the units in which status has changed since the last analysis. Each *GeoUnit* brings the information on which *step* of the whole forest process it has stopped. There are two types of steps:

- (1) an operational step when a technical visit is needed;
- (2) a report step when only a set of questions must be answered online or offline, entirely IT-supported or not.

If for a specific *GeoUnit*, the next *step* required is an operational one, the “Optimized Visiting Plan” process is triggered; if not, a reporting procedure for that step is triggered. A reporting procedure can be a query in other modules of the same system, or a query over external systems, even an email or a list of telephone calls or any other types of manual tasks. The aim of each reporting procedure is to report the status of each unit in a step that is being analysed.

Table 15 - Terms and definitions

Terms	Definitions
Forest process	A sequence of events related to forestry or the environment that happens in the field or an IT system context involving stakeholders, such as policy makers, IT resources, technical teams, landowners, or researchers.
Iteration	Each repetition of a piece of a process is called “iteration,” and the results of one iteration are used as the starting point for the next iteration.
<i>GeoUnit</i>	A forest process happens upon a set of forest geographic units - <i>GeoUnits</i> . This can be farms, regions, stands, watersheds and so forth. In our generalizable model, we consider we have <i>U</i> units from 1 to <i>u</i> .
Steps	The responsibility for each unit should be to perform a sequence of different steps; this sequence constitutes an iteration. In our generalizable model, we consider we have 5 steps, from 1 to 5 .

In the side of operational steps, each visit will produce data that should be input into the database. On the other hand, a *report step* should produce an answer for each *GeoUnit*, which also should be input into the database. This data constitutes the “operational database”. On both sides, the next step is “Data Treatment” to transform data into structured knowledge to further use as planning parameters.

In the operational side, after “Data Treatment”, “Adaptive Management” is the next subprocess, which comprises a technical recommendation to correct the progress of the analysed *GeoUnit*, if needed. Treated visiting information and stored rules are the foundation for the recommendation.

When all units are analysed, the system can proceed to *Policies Revisions*. This subprocess cannot be fully automated, but IT tools can actively support it. Over the time, the data treatment process might be improved based on experience. Data, after being treated, is transformed into information knowledge upon which *Policies Revisions* will be done.

Figure 12 - Generalizable Process Model

Throughout the design of the model process, we used a set of checkpoints extracted from the literature review and presented in the previous **Section 2.2**. In this **section (5.4)**, we discuss whether the resulting model meets the recommendations claimed in the literature review.

The fundamental components (**Figure 7**) and the breakdown of the planning component (**Figure 9**) set the basis for the formulation of a generalizable model. The diagram for the breakdown of the planning component indicates that the planning parameters must come from the knowledge base. Accordingly, the diagram for the breakdown of the monitoring component (**Figure 10**) shows that data derived from monitoring processes should be entered

into the knowledge base only after it has been arranged and checked properly. This sequence guarantees that the policies can rely on real-world knowledge as recommended by Rist et al. (2016) and Vacik and Lexer (2013) (**Table 16** – recommendation 01).

Table 16 – Checking points of literature recommendation

01	Planning and Policies rely on knowledge	08	Gathering knowledge during the monitoring process
02	Consider activities or interventions	09	Translated into a user-friendly DSS
03	Data interpretation component must be integrative	10	Computerized tools can be developed
04	Continuous intelligent monitoring	11	Systemic model that represents the real systems
05	Can maximize the performance of a process and minimize the impacts of faults	12	Clarify the uncertainties
06	Has critical trigger points to ensure that corrective actions	13	Has a limited number of indicators that are repeatable, sensitive to change, and affordable
07	Organizing data from previous processes		

The breakdown of the monitoring component (**Figure 10**) shows that the model considers which interventions have been implemented in each land unit (Reynolds et al., 2016). It is crucial to have interventions and correlated outcomes precisely registered for the purposes of adaptive management (Bodini, 2012). Hence, the system can suggest changes regarding technological recommendations for the next planning cycle (Bagstad et al., 2013; Hujala et al., 2013; Tyndale, 2002). Also, urgent actions to fix problems affecting the growth of the plantation can be triggered (Cortés et al., 2001; Durigan and Ramos, 2013; Gatica-Saavedra et al., 2017; Plunkett, 2001) (**Table 16** – recommendations 2, 3, 4, 5, and 6). However, fixing silvicultural operations of fast-growing species once plantations have been established in Brazilian restoration projects can be challenging. The effectiveness of the adaptive management approach will also depend on the allocation of sufficient amounts of resources.

It is important to emphasize that the knowledge base is a central entity in both the planning and monitoring processes (Dickinson et al., 2016; Ekbja and Reynolds, 2007; McElroy, 2000; Vacik et al., 2013). The two most critical activities in the whole process are data treatment, one of the activities pertaining to the monitoring component (**Figure 10**), and prepare parameters, another activity in the planning component (**Figure 9**), listed as recommendations 7 and 8 of a conceptual model (**Table 16**).

The continuity of the cycle, which guarantees the improvement of the forest operations, depends on the integration between monitoring and planning. In the proposed conceptual model, integration is ensured if planning updates come from the monitoring process itself as the knowledge base evolves (Blount et al., 2016; McDill, 2014; Rauscher et al., 2007; Vacik and Lexer, 2014).

The inclusion of the monitoring component in the conceptual model became a principle proposed by Rauscher et al. (2007) and was embedded in a FMDSS following the guidelines established by Albert *et al.* (2015) and Reynolds *et al.* (2016). The resulting DSS allows decision-makers to rely on a knowledge base supported by real-world information, which implements recommendations 1, 9, and 10 **Table 16** as described by Rist *et al.* (2016) and Vacik and Lexer (2013).

Naturally, not all available knowledge becomes stored in the knowledge base, and there will always be non-internalized knowledge guiding decision-makers in different directions (Nemati et al., 2002). Additionally, in a forest restoration context, the long-term accumulation of contradictory knowledge can misguide the knowledge creation process. Therefore, the conceptual model proposed here emphasizes the need for a continuous update of the data treatment and parameters preparation rules.

Bodini (2012) recommends the development of FMDSS supported by information technologies (IT) tools. The case study considers the existence of more than 40,000 restoration projects, and the use of IT tools becomes the only viable way of dealing with a large amount of input data, the complexity of the data treatment, the territory extension, and the long duration of the project (**Table 16** - recommendations 10 and 11).

When it comes to reducing uncertainties associated with the decision-making process, as required by Reynolds *et al.* (2016), we argue that our conceptual model overcomes this challenge by interpreting the results of previous management cycles and updating the knowledge base to reduce future uncertainties in the next management cycle (**Table 16**, recommendations 13 and 14). Furthermore, the inclusion of ecological indicators in the monitoring component proposed by Chaves *et al.* (2015) becomes a source of risk reduction and precautionary action.

The conceptual model described here is generalizable and applicable beyond the realms of FMDSS. Its development, as described here, reveals guidelines that can be followed when dealing with similar situations. Even though cases are always different one from another in

some particularities, as stated by Rohde, Brödner, and Stevens *et al.* (2016), the generalizable principles used to develop the conceptual model result in continuous intelligent monitoring processes that make the systems adaptable to apparently dissimilar situations.

As seen in the discussion above, each subprocess and each aspect imposes specific challenges, leading to situations where the development of information system projects still fails to deliver sufficient benefits (Rohde et al., 2016). Conceptual models that integrate adaptive planning and monitoring processes, supported by an auto-updatable knowledge base, mitigate the risk of such failures, especially when the comprehensive gathering of well-established references for the initial knowledge base is well conducted at the beginning.

6. MATHEMATICAL MODELLING OF THE FMTDSS

To accomplish the third specific objective of this thesis, which is to develop a generalizable mathematical programming model embedded in an FMTDSS, Chapter 6 describes the model and the FMTDSS. **Section 6.1** describes the methodology and the theoretical principles that guided the development. **Sections 6.2** and **6.3** describe the entire model from the definitions that support the model until the complete model with all its details.

The model follows the most common techniques used to address the situation described as strategic planning of forest plantations according to the discussions of **Chapters 0** and **4**. Moreover, continuous methods such as LP - linear programming, GP - goal programming, and Compromise Programming are the most popular methods to resolve problems about the management of natural resources. These techniques are continuous models using optimization techniques to select the best possible alternative. (Greco et al., 2005).

Also, the FMTDSS, described in **Sections 6.4** and **6.4.7**, follows the most accepted principles of a DSS design discussed in **Chapters 0** and **0**. It is important to stress that *Romero*[©] embeds the model described in **Sections 6.2** and **6.3** and guarantees the application of the Multicriteria decision theory and the interactive group decision making principles.

6.1. Models and Methods

6.1.1. Harvest Scheduling Model

Since the beginning of the 1960-decade, forest researchers have been using Mathematical Programming to address forest planning problems. The *harvest scheduling model* is one of the most appropriate models used to solve long-term strategic forest planning world-wide (Borges et al., 2014a, 2014b, 2017; Eriksson et al., 2014; Garcia-Gonzalo et al., 2013, 2014, 2015; McDill, 2014). It consists in looking for the best alternative to intervene in a forest growth; decision variables are related to when, where and how interventions would be made to maximize profits, ecosystem services or production (Ware and Clutter, 1971). Moreover, the application of a harvest scheduling model demands constraints on production goals, infrastructure limits, and environmental concerns (Hujala et al., 2013; Nobre et al., 2016; Reynolds et al., 2008). In those models, interventions are often linked to several types of forest

establishments, restoration, silvicultural treatments, cuts, thinning, and non-wood products pickups.

Johnson and Scheurman (1977) and Clutter *et al.* (1983) offered two alternatives for linear programming formulations to address a harvest scheduling model. Besides the generation of optimal management plans, these formulations also aim to promote forest regulation. These authors presented concepts that have been often used to formulate a harvest scheduling problem since then. The minimum set of equations first formulation model, called *Model I*, can be written as follows:

$$\text{Max } Q = \sum_{i=1}^I \sum_{k=1}^K D_{uk} X_{uk}$$

subject to :

$$\text{Initial Area) } \sum_{r=1}^R X_{ur} = A_u \quad \forall u, u=1,2,\dots,U$$

$$\text{Production) } \sum_{u=1}^U \sum_{r=1}^R V_{upr} X_{ur} \geq vMin_p \quad \forall p, p=1,2,\dots,P$$

Where X_{ur} is an amount of area of the unit u assigned to regime r
 D_{ur} is a per – hectare NPV resulted from regime r in unit u
 A_i is the size (ha) of the unit u
 V_{upr} is a per – hectare volume harvested from unit u
in period p if regime r is assigned
 $vMin_p$ is a volume restriction, minimum accepted for period p (1)

In *Model I* formulation, the decision variable X_{ur} is a management prescription, that is to say, a sequence of interventions in the same unit u that can happen inside the planning horizon. However, we must decompose the entire regime in interventions to control productions and other outcomes that occur throughout the regime because the schedule and outcomes should be calculated by period.

One variation of the *Model I*, called *Model II*, proposed by the same authors, uses a different decision variable (Clutter et al., 1983; Johnson and Scheurman, 1977). This time, the decision variable is each intervention that happens upon a forest. The minimum set of equations for the formulation of *Model II* can be written as follows:

$$\text{Max } Q = \sum_{u=1}^U \sum_{j=1}^J D_{uj} Y_{uj} + \sum_{j=1}^{J-n} \sum_{k=j+n}^K E_{jk} X_{jk} + \sum_{u=1}^U T_u W_u + \sum_{j=1}^J Z_j B_j$$

subject to :

$$\text{Initial Area)} \quad \sum_{j=1}^J Y_{uj} + W_u = A_u \quad \forall u, u=1,2,\dots,U$$

$$\text{Area)} \quad \sum_{k=j+n}^K X_{jk} + B_j - \sum_{u=1}^U Y_{uj} = 0 \quad \forall j, j=1,2,\dots,J$$

$$\text{Production)} \quad \sum_{u=1}^U V_{up} Y_{up} + \sum_{j=1}^{J-n} H_{jp} X_{jp} \geq v \text{Min}_p \quad \forall p, p=1,2,\dots,P$$

- Where:
- Y_{uj} is area (ha) of unit u harvested in period j
 - X_{jk} is area (ha) regenerated in period j and harvested in period k
 - W_u is area (ha) of unit u that are left unharvested through the planning period
 - B_j is area (ha) regenerated in period j and left unharvested until the end planning period
 - D_{uj} is NPV per ha of all costs and incomes associated to the unit u that are harvested in period j
 - E_{jk} is NPV per ha of all costs and incomes associated to the stands that are regenerated in period j and harvested in period k
 - T_u is NPV per ha of leaving a stand from unit u unharvested at the end of the planning period
 - Z_j is NPV per ha of leaving a stand that was regenerated in period j unharvested at the end of the planning period
 - A_u is the size (ha) of the unit u
 - V_{up} is a per – ha volume harvested in period p from unit u
 - H_{jp} is a per – ha volume harvested in period p regenerated in period j
 - n is the minimum number of periods between two harvest operations
- (2)

There are two concerns among forest researchers (Clutter et al., 1983; Davis et al., 2001) about the *Model II*, which are:

- ✓ The decision variable X_{jk} and B_j are no longer associated to any management unit u . That means that from the first intervention the model loses geographic reference. Accordingly, parameters E_{jk} , Z_j , and H_{jp} cannot be related to a specific geographic area such as a management unit u .
- ✓ *Model II* has fewer variables than *Model I* formulation, but requires many more constraints than *Model I*. In *Model I*, area constraints (**Initial Area**) are defined by means of a single mathematical sentence for each forest management unit. In *Model II*, the definition of

area constraints (*Area*) requires one mathematical sentence for each possible intervention throughout the planning horizon.

The model proposed in this thesis solves the first concern making variables X_{jk} and B_j refer to the management unit u .

- ✓ Variables X_{jk} and B_j shall be changed to X_{ujk} and B_{uj}
- ✓ the *Area* constraints in the **statement (2)** shall be altered to:

$$\begin{aligned} \text{Area)} \quad \sum_{k=j+n}^K X_{ujk} + B_{uj} - Y_{uj} &= 0 \quad \forall j, j=1, 2, \dots, J \\ &\quad \forall u, u=1, 2, \dots, U \end{aligned} \quad (3)$$

- ✓ Parameter H_{jp} shall be changed to H_{ujp}
- ✓ the *Production* constraints written in the **statement (2)** shall be altered to:

$$\text{Production)} \quad \sum_{u=1}^U V_{up} Y_{up} + \sum_{u=1}^U \sum_{j=1}^{J-n} H_{ujp} X_{ujp} \geq vMin_p \quad \forall p, p=1, 2, \dots, P \quad (4)$$

- ✓ Parameter E_{jk} shall be changed to E_{ujk}
- ✓ the *Objective function* written in the **statement (2)** shall be altered to:

$$\text{Max } Q = \sum_{u=1}^U \sum_{j=1}^J D_{uj} Y_{uj} + \sum_{u=1}^U \sum_{j=1}^{J-n} \sum_{k=j+n}^K E_{ujk} X_{ujk} + \sum_{u=1}^U T_u W_u + \sum_{j=1}^J Z_j B_j \quad (5)$$

It is essential to stress that doing this is like having one *Model II* for each management unit u . If only the first change is done, the model becomes a merge of several similar models. However, it seems that the second issue (more constraints than *Model I*) would worsen. We could argue that, nowadays, within certain bounds, there is no need to worry about the size of the models because of the extended capacity of our computers.

To expand the use of the model, we should consider that there are other types of interventions besides harvesting. One important type could be, for example, “do nothing.” Therefore, if there are I types of intervention, then:

- ✓ Variable Y_{uj} becomes Y_{iuj} , and there is no need for variable W_u

✓ the **Initial Area** constraints that are written in the **statement (2)** becomes:

$$\text{Initial Area)} \quad \sum_{i=1}^I \sum_{j=1}^J Y_{iuj} = A_u \quad \forall u, u=1,2,\dots,U \quad (6)$$

✓ Variables X_{ujk} becomes X_{iujk} , and there is no need for variable B_{uj}

✓ the **Area** constraints in the **statement (2)** shall be altered to:

$$\text{Area)} \quad \sum_{i=1}^I \sum_{k=j+n}^K X_{iujk} - \sum_{i=1}^I Y_{iuj} = 0 \quad \forall j, j=1,2,\dots,J \\ \forall u, u=1,2,\dots,U \quad (7)$$

✓ Parameter V_{up} and H_{uijp} shall be changed to V_{iup} and H_{iuijp}

✓ the **Production** constraints in the **statement (2)** shall be altered because production may also depends on the type of intervention:

$$\text{Production)} \quad \sum_{i=1}^I \sum_{u=1}^U V_{iup} Y_{iup} + \sum_{i=1}^I \sum_{u=1}^U \sum_{j=1}^{J-n} H_{iuijp} X_{iuijp} \geq vMin_p \quad \forall p, p=1,2,\dots,P \quad (8)$$

✓ Parameter D_{uj} and E_{ujk} become to D_{iuj} and E_{iujk}

✓ the **Objective function** that is written in the **statement (2)** shall be altered because per-ha NPV may also depends on the type of intervention:

$$\text{Max } Q = \sum_{i=1}^I \sum_{u=1}^U \sum_{j=1}^J D_{iuj} Y_{iuj} + \sum_{i=1}^I \sum_{u=1}^U \sum_{j=1}^{J-n} \sum_{k=j+n}^K E_{iujk} X_{iujk} \quad (9)$$

It is essential to emphasize that to substitute T_u and Z_j , that were in the **statement (2)** and are not in the **statement (9)** any more, we have to treat the final intervention in the planning horizon differently. The final intervention must be followed by a “do nothing” intervention that must have the per-ha NPV of “do nothing”, or, at least, add a “do nothing” intervention value to the last intervention of all possible alternatives that happen inside the planning horizon.

For the sake of generalization, we still have one more crucial change to do. For **statements ((2) to (9))**, we have only one possibility of intervention in each unit u happening in period j . We must generalize to allow any number of interventions needed inside the planning horizon

without having to control if we are in the first or second intervention from the initial situation of the management unit.

To generalize the number of interventions inside the planning horizon, only one decision variable X_{iujk} is needed and Y_{iuj} can be considered a particular case of X_{iujk} when $k=0$. In X_{iujk} , j is the period when the intervention occurs, and k is the period when the last intervention in that unit had happened before. Therefore, the *Area* constraint becomes:

$$\begin{aligned} \text{Area)} \quad \sum_{i=1}^I \sum_{j=p+n}^J X_{iujp} - \sum_{i=1}^I \sum_{k=1}^K X_{iupk} &= 0 \quad \forall p, p=1, 2, \dots, P \\ &\quad \forall u, u=1, 2, \dots, U \end{aligned} \quad (10)$$

Accordingly, the *Initial Area* constraints in **statement (2)** will again be rewritten to:

$$\begin{aligned} \text{Initial Area)} \quad \sum_{i=1}^I \sum_{j=1}^J X_{iujk} &= A_u \quad \forall u, u=1, 2, \dots, U \\ &\quad \text{when } k = 0 \end{aligned} \quad (11)$$

If there are different types of interventions and each of them may occur in a different range of periods after the previous intervention, then the parameter n , displayed in **statements (2)** to **(11)**, can vary.

Furthermore, there is a logical sequence of interventions in terms of silvicultural and management possibilities that must be considered before creating a tree of alternative interventions. Moreover, the possibility of occurrence of each type of intervention may depend on management units' attributes. The (i) logic sequence, (ii) when each intervention can or cannot occur, and (iii) in which conditions they are allowed define a process we name in this thesis as "*interventions generator*" – *IGen*.

Thereby, this described generalization of *Model II* formulation is only possible to implement if there is an associated generation of possible interventions of each management unit u . This generation shall produce a set of interventions that cannot be represented by a one-dimension index such as i , a sequence of integer numbers, as presented in the previous statements. An intervention i must carry a set of attributes to feed the sequencing rules. Considering the complete generalization, of the *Model II* could be written as follows:

$$\text{Max } Q = \sum_{i=1}^I \sum_{u=1}^U \sum_{p=1}^P \sum_{k=j+n}^K E_{iupk} X_{iupk}$$

subject to :

$$\text{Initial Area) } \sum_{i=1}^I \sum_{p=1}^P X_{iupk} = A_u \quad \forall u, u=1,2,\dots,U$$

when $k = 0$

$$\text{Area) } \sum_{i=1}^I \sum_{j=p+n}^J X_{iujp} - \sum_{i=1}^I \sum_{k=1}^K X_{iupk} = 0 \quad \forall p, p=1,2,\dots,P$$

$\forall u, u=1,2,\dots,U$

$$\text{Production) } \sum_{i=1}^I \sum_{u=1}^U \sum_{k=1}^K V_{iupk} X_{iupk} \geq vMin_p \quad \forall p, p=1,2,\dots,P$$

Where: X_{iupk} is the area (ha) of the unit u , in which intervention i has occurred in period p , linked to the last intervention (i_k) that happened in period k

E_{iupk} is a per – ha NPV of all costs and incomes associated to the intervention i that has occurred in period p linked to the last intervention (i_k) happened in period k

A_u is the size (ha) of the unit u

V_{iupk} is a per – ha outcome obtained from unit u

in which intervention i has occurred in period p linked to the last intervention (i_k) happened in period k

n is the number of periods between interventions i and (i_k), n assumes different values depending on the type of i

K and J assume different values depending on the type of i

I can assume different values depending on u

P will be the higher value of p for each unit u , that is, when it the latest alternative intervention

(12)

The “interventions generator” (*IGen*) plays a crucial role in the context of *Romero*® because it is responsible for the translation of the forest guidelines into a mathematical language. Actually, it generates a set of indexes i (interventions) for the model; it interprets formal rules based on silviculture and management and creates a vector of 10 dimensions for the case implemented in this thesis. From this point on, the adjustments proposed provide a consistently and adequately generalizable mathematical model.

The selection of the *Model II* formulation instead of the apparent simplicity of the *Model I* still need to be further explained. *Model II* formulation becomes less complicated to formulate due to the efficient routines programmed inside the *IGen* module. The rules become more

straightforward when they refer to only one decision: which, when and how each intervention can or cannot be implemented after the other. Information technology experts (Gacto et al., 2011; Minutolo et al., 2017) argue that the simpler the rules, the easier becomes the interpretation of the algorithms, their creation and maintenance. Moreover, since *IGen* will deal with complex real cases, it will be, probably, the most maintenance demanding function inside *Romero*®.

The more accurate the alternatives represent the reality, the more the results will meet the stakeholder's expectations. Besides accuracy, *IGen* must be flexible because it needs to address different situations in an industrial forest plantation. Accuracy and flexibility are difficult to achieve at the same time in an IT procedure (Dias et al., 2017; Funk et al., 2019); one method to try both is to build a function based on rules where new rules can be added as different situations arise.

Sections 6.2 and 6.3 will describe the complete model as an extension of the generalized *Model II* with a multicriteria approach. **Section 6.4** will show the System Architecture of *Romero*®, including the explanation of *IGen* in **Section 6.4.3**. Finally, **Section 6.4.7** will explain the technology used to develop the entire system.

6.1.2. Multicriteria and Pareto frontier

There are some essential concepts, within the multicriteria scope, that are needed to be highlighted because they are the foundation of the mathematical model and the *Romero*® development. The way Ballester and Romero's (1998) approach was added to the model presented in the previous section is the focus of this section.

Attribute refers to a value related to a decision-making reality. These values can be measured independently from any stakeholder desire. They are expressed as mathematical functions of the decision variables. As an example, in the **statement (12)**, in the line "*Production*," the

expression $\sum_{i=1}^I \sum_{u=1}^U \sum_{k=1}^K V_{iupk} X_{iupk}$ is the total production within the planning horizon. It will be the

first attribute we are going to define in our model, and it will be called **TotalProd**.

Objectives represent directions of attribute improvement. We can maximize or minimize an attribute. Due to the desired flexibility to our model, the more attributes we calculate, the better. We make them available to be selected by the user to constitute the objectives. In our

example, if the user selects the attribute **TotalProd** to form his objective, the model will be changed to:

$$\begin{aligned}
 & \text{Max } Q = \sum_{p=1}^P \text{TotalProd}_p \\
 & \text{subject to :} \\
 & \text{.....} \\
 & \text{Production) } \sum_{i=1}^I \sum_{u=1}^U \sum_{k=1}^K V_{iupk} X_{iupk} - \text{TotalProd}_p = 0 \quad \forall p, p=1, 2, \dots, P
 \end{aligned} \tag{13}$$

A **target** is an acceptable level of achievement for an attribute, that means a figure for which a decision-maker feels satisfied. Again, in the **statement (12)**, in the line “*Production*”, the value $vMin_p$ is a target; decision-makers want at least $vMin_p$ of production in period p . In our implementation, targets will be parameters saved in a database ready to be updated by the decision-makers.

The combination of a target and an attribute generate a **goal**. In our example, in the **statement (12)**, in the line “*Production*”, the goal could be written as following.

$$\begin{aligned}
 & \text{Production) } \sum_{i=1}^I \sum_{u=1}^U \sum_{k=1}^K V_{iupk} X_{iupk} - \text{TotalProd}_p = 0 \quad \forall p, p=1, 2, \dots, P \\
 & \text{Goal) } \text{TotalProd}_p \geq vMin_p \quad \forall p, p=1, 2, \dots, P
 \end{aligned} \tag{14}$$

Moreover, deviation variables can be included in the “*Goal*” constraint line to capture how far the production is from the target $vMin_p$. The “*Goal*” constraint line would be defined as follows. However, the objective function should be modified to minimize the sum of the deviation variables to turn the model into a Goal Programming model, which is not the case when compromise programming is the selected multicriteria technique.

$$\text{Goal) } \text{TotalProd}_p + Ndev_p - Pdev_p = vMin_p \quad \forall p, p=1, 2, \dots, P \tag{15}$$

How *Romero*® deal with these attributes, objectives, targets, and goals within the system is relevant. There are dozens of attributes that are always calculated as in the line *Production* of the **statement (14)**. Depending on the choices of the decision makers, the attributes will be used in goals or objectives. For the sake of flexibility, *Romero*® builds the model in such a way

to smooth the maintenance process in adding other attributes and relating them to objectives, targets, and goals.

Finally, a **criterion** is a general concept that comprises the former concepts; thereby, **criteria** are attributes, objective, and goals considered relevant for a given decision-making problem. Again, in the example, *Production* criterion means that the attribute *TotalProd* will be used to calculate the objective *Max TotalProd*.

Having exposed the basic multicriteria concepts and how they are used in the model that is embedded in *Romero*[®] context, we can emphasize further concepts that are related to the way the criteria should be managed.

When decision-makers need to consider multiple objectives, one acceptable technique is **multiobjective mathematical programming** (MOLP). After having described the generalization of *Model II* formulation to address a long-term scenario analysis, next step is to use it within a MOLP approach.

The first step of a MOLP consists in optimizing one criterion at a time, using exactly the same scenario, and in calculating all attributes related to the other criteria (the ones that are not being optimized). After calculations, an essential instrument named **Pay-off matrix** shows the objectives on the rows and the values of the attributes in the columns. This instrument is the first step of the analysis, where it is possible to identify the level of conflicts among criteria. The second step is to figure out what happens among the extreme points presented in the Pay-off matrix, which are optimal of each criterion. The best methodology to do so is the **Pareto optimality**.

One feasible solution to a problem, as we are going to calculate, is considered **Pareto-optimal** or **efficient solution** when there no other feasible solution improves one criterion without worsen one of the other criteria. From this definition, it can be concluded that there is a frontier of the feasible solutions that are Pareto-optimal. This optimality or this frontier of the feasible solutions is crucial to guarantee the rationality of the decision-making; that is, the decision should be one solution in this frontier.

At this point, it is possible to introduce the mathematical notation of a MOLP proposed by (Romero, 1993), that means that the model seeks a set of efficient solutions that satisfy the objective functions $f^1, f^2, \dots, f^n$. And are subject to a set of constraints represented by a vector of functions $Q(x)$.

$$Eff\ f(x) = [f^1(x), f^2(x), \dots, f^n(x)]$$

subject to :

$$Q(x)$$

(16)

The concept of **Pareto frontier** leads to another concept that is the **trade-offs** between two criteria. If along the Pareto frontier, when we improve one criterion, necessarily we worsen another, we can calculate the trade-offs between the criteria. As we can see, trade-offs are the best way to measure the opportunity costs, that is, how many units we lose of one criterion when we want to gain one unit of another. Trade-offs may also be used to calculate substitution and transformation rates between criteria. Most importantly, trade-offs are the basis of all interactive methodology which intends to support decision-makers negotiation (Romero, 1993).

There are some methodologies to calculate the set of Pareto-optimal solutions, also named, efficient solutions (Ballesteros and Romero, 1998; Romero, 1993). The most common method is the **constraint method** because it is the easiest to implement, and it has a low computational cost. This method consists in optimizing one of the objectives while the others are placed as parametric equality constraints. For each vector of values to be used as a right-hand-side in the parametric constraints, we generate one Pareto-optimal solution.

Romero® shows the Pay-off matrix and the Pareto frontier as described above of every scenario built upon the user selections on constraints, objectives, goals, and targets. However, the decisional process needs to go further. After knowing the extreme efficient solutions presented as a matrix (pay-off matrix), the set of the efficient solutions presented as a graph, the next phase is select, along the Pareto Frontier, a small set of solutions that could best fit a specific group of decision-makers. One of the most productive ways to accomplish this task was proposed in 1973 by Yu and Zeleny under the name of Compromising Programming (Ballesteros and Romero, 1998; Romero, 1993).

Next **Section (6.1.3)** will present a brief description of the Compromising Programming principles and how we implemented it in *Romero*®.

6.1.3. Compromise programming

The **ideal point** is the point where all criteria have their best level. This point is never achievable because all criteria cannot assume the best level at the same time in a context of conflict. Efficient solutions that are closer to the ideal point would be preferred to those that are farther, this is what says the *Zeleny axiom*, the fundamental concept of compromise programming. Moreover, to be as close as possible to the ideal point is the rationale of human choice (Romero, 1993; Steuer, 1986).

Therefore, to go further in defining a compromise, there are questions to answer, such as (a) how to calculate the **distance** to the ideal point (Diaz-Balteiro et al., 2018), and (b) what if the decision-makers have **preferences** regarding stay closer to one attribute best level than to another. Additionally, to avoid meaningless comparisons between attribute values due to their different measurement units, the attribute values must be **normalized** (Diaz-Balteiro et al., 2018). These concepts will be defined in the following (Romero, 1993; Steuer, 1986).

The normalized distance from an efficient point along the Pareto frontier to the ideal point can be determined as follows:

$$N_a(x) = \frac{|f_a^* - f_a(x)|}{|f_a^* - f_{*a}|}$$

where :

$N_a(x)$ a normalized distance of the attribute a

f_a^* the best value of the attribute a when the objective a is optimized

f_{*a} the worse value of the attribute a when other objectives are optimized

$f_a(x)$ the attribute a value in a specific Pareto – efficient point (17)

The set of techniques to measure this distance, inside the CP context, is called “a family of distance functions” L_p . This text do not intend to go deep into the L_p definitions; however, it is crucial to have a clear understanding of the distance concepts (Romero, 1993) to sanction the use of the two limits of the compromise set: $Min(L_1)$ and $Min(L_\infty)$.

The starting point is the geometric distance defined by Pythagoras theorem that is the minimum distance between two points in two-dimensional space named “*Euclidean distance*”. It is easy to generalize the “*Euclidean distance*” to an n-dimensional space where the distance between two points $x^1 = (x_1^1, x_2^1, \dots, x_n^1)$ and $x^2 = (x_1^2, x_2^2, \dots, x_n^2)$ can be written as follows:

$$d = \sqrt{\sum_{j=1}^n (x_j^1 - x_j^2)^2} \quad (18)$$

However, the most acceptable generalization of the n-dimensional “*Euclidean distance*” (Romero, 1993) is given by the following expression:

$$L_p = \left[\sum_{j=1}^n |x_j^1 - x_j^2|^p \right]^{1/p} \quad (19)$$

Where L_p represents the family of distance functions. For each value of p , there is a different distance value L_p for the same pair of points x^1 and x^2 . A particular case of L_p is for $p=2$ when the two-dimensional “*Euclidean distance*” is obtained. A second particular case of L_p is for $p=1$, called “*Manhattan distance*”, which, in a two-dimensional space, is the sum of the cathets lengths. Therefore, L_1 is the largest distance between x^1 and x^2 , while L_2 is the shortest one according to Pythagoras theorem.

$$L_1 = \sum_{j=1}^n |x_j^1 - x_j^2| \quad (20)$$

When the metrics p tends to ∞ , L_∞ is called “*Chebysev distance*” and tends to the value that can be calculated as follows:

$$L_\infty = \text{Max}_{j=1}^n \left(|x_1^1 - x_1^2|, |x_2^1 - x_2^2|, \dots, |x_n^1 - x_n^2| \right) \quad (21)$$

The **Statement (21)** means that the L_∞ is given by only one deviation of the set of n deviations: the larger one. If L_1 and L_∞ are calculated for each point along the Pareto frontier, it is possible to determine two shorter distances, the $\text{Min}(L_1)$ and $\text{Min}(L_\infty)$.

The *Yu theorem*, presented in the literature in 1974 (Romero, 1993) demonstrated that for a two-criterion problem, the compromise solutions calculated with L_p (**Statement (19)**) are contained in a “compromise set”, which is a subset of the efficient solutions set (Pareto frontier). In addition, the limits of this subset are given by L_1 and L_∞ (**Statements (20)** and **(21)**). Two years later, Freimer and Yu demonstrated similar conditions to a more than two-criterion problem. Moreover, according to the traditional economic analysis and the theorems

of Yu, the utility functions intercept a Pareto frontier in one of the points of the “compromise set”.

L_1 is a summation of the deviations between each attribute value from this ideal value (**Statement (20)**). The minimum L_1 is the maximum efficiency point, where the best point is achieved considering the value of the attributes. However, this point may be unbalanced, that is to say, in that point; one attribute can have much more value than others. Moreover, if the decision-makers have different **preferences** that can be translated into **weights** (from 0 to 1), L_1 could be mathematically represented as follows using previous definitions of **Statements (17)** and **(20)**:

$$L_1 = \sum_{a=1}^A w_a N_a(x)$$

where :

w_a is the weight of the attribute a

$N_a(x)$ is the normalized distance (22)

On the other hand, to obtain L_∞ , it is necessary to select the maximum deviation between attribute individual deviations. That is, only the largest deviation of each attribute from its best value is considered. Considering all previous definitions, L_∞ could be mathematically represented as follows:

$$L_\infty = \text{Max}_a (w_a N_a(x)) \quad (23)$$

A linear programming model to calculate $\text{Min}(L_1)$ is presented by Romero (1993) and can be written as follows, based on **Statements (17)** and **(22)**.

$$\text{Min } L_1 = \sum_{a=1}^A w_a \left(\frac{|f_a^* - f_a(x)|}{|f_a^* - f_{*a}|} \right)$$

Subject to :

$$x \in F \quad (24)$$

And to calculate $\text{Min}(L_\infty)$ a linear programming model can be written as follows:

$$\begin{aligned}
& \text{Min } L_{\infty} = d \\
& \text{Subject to :} \\
& \quad x \in F \\
& \quad w_a \left(\frac{|f_a^* - f_a(x)|}{|f_a^* - f_{*a}|} \right) \leq d \quad \forall a
\end{aligned} \tag{25}$$

In the context of *Romero*[®], due to the fact that all attribute values of each efficient solution along the Pareto frontier is saved in a database, there is no need to build and run the linear models of the **Statements (24)** and **(25)**.

To locate the two points **Min(L₁)** and **Min(L_∞)** along the Pareto Frontier, *Romero*[®] implemented the following sequence of steps:

- ✓ The user inputs how many points he wants to calculate of the Pareto-efficient set. The user should set as many points as possible depending on the time each run (to obtain one point) takes; dozens of times if we have time enough.
- ✓ The system distributes those points between the best and worse value of each attribute
- ✓ *Romero*[®] run the MOLP model to calculate the efficient point using the constraint methodology.
- ✓ *Romero*[®] saves the results (attribute values, decision variables and deviation variables) of all points into the database.
- ✓ The user updates the decision-makers preferences weights for each criterion, according to the preferences of the decision-makers.
- ✓ *Romero*[®] calculates **L₁** and **L_∞** for each efficient point
- ✓ *Romero*[®] finds the minimum **L₁** and minimum **L_∞** using as SQL model (**Statement (26)**) to implement and find a proxy of the linear programming models of the **Statements (22)** and **(23)**.

```

Select G2.idSimulation,
      G1b.PlotPoint L1Point,   G2.L1,
      G1c.PlotPoint LInfPoint, G2.Linf
from
  (Select G1a.idSimulation,
    min(G1a.L1) L1, min(G1a.Linf) Linf
    from (select D.idSimulation, D.PlotPoint,
      Sum(0.01*Weight*Distance) L1,

```

(26)

```

        Max(0.01*Weight*Distance) Linf
    from v_CalcCompromise2 D
    group by D.idSimulation, D.PlotPoint
) G1a
    group by G1a.idSimulation
)G2
inner join
    (select D.idSimulation, D.PlotPoint,
        Sum(0.01*Weight*Distance) L1,
        Max(0.01*Weight*Distance) Linf
        from v_CalcCompromise2 D
        group by D.idSimulation, D.PlotPoint
    )G1b on G1b.idSimulation = G2.idsimulation and
        G2.L1 = G1b.L1
inner join
    (select D.idSimulation, D.PlotPoint,
        Sum(0.01*Weight*Distance) L1,
        Max(0.01*Weight*Distance) Linf
        from v_CalcCompromise2 D
        group by D.idSimulation, D.PlotPoint
    )G1c on G1c.idSimulation = G2.idsimulation and
        G2.Linf = G1c.Linf

```

Statement (26) has `v_CalcCompromise2` as source of information, which has the distances from the `PlotPoint` to the Ideal Point for each attribute ($\forall a$ of **Statements (22)** and **(23)**). The set of data named **G1a** gets the values of L_1 and L_∞ ; the set of data **G1b** seeks the `PlotPoint` that has the L_1 value; and the set of data **G1c** seeks the `PlotPoint` that has the L_∞ value. **Annex 1** describes how `v_CalcCompromise2` calculates the distances and the normalization.

6.1.4. Interactive Group Decision Making (GDM)

According to the literature review presented in **Chapter 2**, the more participatory the process is, the better the decision-making process will be. Moreover, the authors go deep on the participatory process characterization. According to them, the best methods are those that allow conveying, and debating opinions and responsibilities.

On the other hand, there is one crucial point to be considered that is the complexity of the decisions to be made in a group that needs to have a good understanding of the topic. The literature analyzed in **Chapter 2** also pointed out the importance of the interpretation and discussions of the results to address those complex decisions.

Considering those two raised points, the interactive structure proposed by Romero (1993) and Steuer (1986) is suitable for the system we are developing in this research work. These authors suggest a discussions cycle that involves the multicriteria elements cited in the **Sections 6.1.2** and **6.1.3**. *Romero*® was developed to allow the decision-making group to go through the process presented in **Figure 13**.

Figure 13 - Interactive Multicriteria Structure

From the first parameterization, the analyst presents a preliminary solution. The first scenario presentation should comprise at least: *(i)* the pay-off matrix with all attributes, *(ii)* trade-offs curves between two criteria at a time, *(iii)* compromise solution considering equal weights for the criteria involved, and *(iv)* details about any Pareto-efficient solution. Moreover, regarding the chosen criteria, the first scenario would be according to the preliminary discussions with the decision-makers. After analyzing the solution, the analyst and *Romero*® should be prepared for changes in *(i)* set of criteria, *(ii)* criteria weights, *(iii)* constraints, and *(iv)* parameters.

6.2. Problem Formulation

This **Section (6.2)** describes the elements of the model which is embedded in *Romero*® according to the principles set in **Section 6.1**. In **subsection 6.2.1** we start with the definition of the primary forest concepts that support the model. From the sets (**subsection 6.2.3**) to the

complete model (**subsection 6.3**), we describe the problem formulation and how we prepared the model to ease the participatory decision process.

6.2.1. Definitions

Land unit

Forest managers usually divide the forest area in compartments called stands. Silvicultural treatments and interventions are executed at a stand. What a forest manager expects from a harvesting scheduling model is when which intervention should be done in each stand considering a defined planning horizon.

Interventions & Transitions

An intervention is a specific event that happens upon a land unit, in a specific period, when the forest has a specific age. The index of an intervention should describe how the forest was before a specific type of transition, and how the forest becomes after that transition. In our example a type of transition can be a clear-cut followed by renewal; a clear-cut followed by sprouting from stumps, a final cut and so forth. To allow the flexibility, interventions and transitions require multi-dimensional indexes.

Therefore, an intervention is defined by:

$i \in \mathcal{I}$, $\mathcal{I}$ is generated by a module outside the model and it is not a sequence of numbers, it is a set of vectors like:

$$i = [last_t, last_p, last_a, ttype, t, p, a]$$

where :

$last_t$	<i>last transition that happened in the forest before this transition t</i>
$last_p$	<i>period when the last transition $last_t$ happened.</i>
$last_a$	<i>age the forest had when the transition $last_t$ happened.</i>
$ttype$	<i>type of the transition t</i>
t	<i>transition t is happening now</i>
p	<i>period when the transition t is happening</i>
a	<i>age the forest has when transition t is happening</i>

(27)

The complexity of the transitions is encapsulated inside the *LP Model*, which was implemented using the Pyomo Python library (described in **Section 6.4.7**). Forest transitions were identified by one single index, which suffices in terms of the *LP Model*. Each forest project has its particularities regarding what can happen in the forest, and the *LP Model* does not need to change because of it. With this approach, the model becomes independent of the forest.

Outside the *LP Model*, other modules of *Romero*® deal with the transitions, generating them (*IGen*) and interpreting them to make the results easy to understand by the decision-makers. The set of possible interventions is the link between *IGen* and *LP Model*, whereas the set of chosen interventions is the link between the *LP Model* and the *Results Presentation Module*.

A transition is a possibility of change in a specific forest unit *u*. Transitions are defined by two stages of a forest that happen successively. In other words, a transition interrupts the course of the forest and establishes another set of characteristics. *IGen* module applies a transition to a pre-defined set of ages and attributes values (rules). Therefore, a transition can originate more than one intervention. In the current implementation of this concept, embedded in *Romero*®, a ten-dimension index defines a transition (**Statement (28)**).

Due to the above methodology, *IGen* module only has to follow a list of rules. Those rules describe which type of transition can happen after another and which characteristics it changes in the forest. As shown in the **Statement (28)**, a transition does not refer to a specific period. They can happen in any period; they depend on forest transition types and project problem specifications conveyed into the rules.

$$t = [last_t, last_u, last_c, last_r, last_sp, ttype, u, c, r, sp]$$

Where:

<i>last_t</i>	transition that happened before the transition in the land unit <i>last_u</i>
<i>last_u</i>	land unit in which <i>last_t</i> happened
<i>last_c</i>	in which cycle unit <i>last_u</i> was before transition <i>t</i>
<i>last_r</i>	in which rotation unit <i>last_u</i> was before transition <i>t</i>
<i>last_sp</i>	which species as growing in unit <i>last_u</i> before transition <i>t</i>
<i>ttype</i>	type of transition <i>t</i>
<i>u</i>	land unit upon which transition <i>t</i> happens
<i>c</i>	to which cycle unit <i>u</i> goes after transition <i>t</i>
<i>r</i>	to which rotation unit <i>u</i> goes after transition <i>t</i>
<i>sp</i>	which species will grow in unit <i>u</i> after transition <i>t</i>

(28)

Each project will have its database, with its data about the forest units, possible transition types, and rules. Due to the independence between the *LP Model* and transition index components, it is possible to use *Romero*® with diverse types of forest plantations.

The better representation of the possible interventions is a decision-tree showed in **Figure 14**. In this tree of alternatives, the root is the initial status of a land unit. That is the reason why we consider the InitialArea the first transition that happens upon a land unit, and it occurs in the period Zero. This pre-defined intervention has the *tttype* value *ina* (initial area).

From this point on, the transition rules guide the generation process. Each transition type has its own rules of behavior. Those rules establish which forest attributes will change, and how they will change. They also define the possible sequence of transition types.

A tree of interventions has the following characteristics:

- Each land unit has its independent tree of alternative regimes. This independence guarantees the event track; the aim is not to lose the reference of where the forest events happen as explained in **Section 6.1.1**.
- Nodes of interventions compose the tree of alternatives to interventions.
- Each intervention has a unique identification; it appears in a tree just once.
- **Figure 14** shows an example of a management unit that enters in the planning horizon with two years old. There is only one type of interventions that can happen when the forest is 5 or 6 years old.
- The rules regarding the finalization of a tree of the alternative are:
 - Selection of a period $p' < P - (A/2)$. In **Figure 14** is $p' = 18$;
 - During the tree of alternatives generation, when there is an intervention that finishes a forest cycle happens in a period $p \leq p'$, and the next intervention will happen in period $p > p'$, the generation of this branch is ended.
 - During the tree of alternatives generation, when there is an intervention that does not finish a forest cycle happens in a period $p \leq p'$, and the next intervention will happen in period $p > p'$, the generation continues until finding a node that finishes a forest cycle.

- Every final node receives distinguished treatments while calculating the indicators values to make the branches comparable among them because they do not end at the same period.

Figure 14 - Alternatives to interventions upon a unit u

6.2.2. Schematic representation of the model

$$Eff \ f(x_i, x_{Market_{p,sp,prd,m}}) = [Maximize \ NPV, \\ Maximize \ Production, \\ ..., Maximize \ Mill \ Production]$$

Subject to

Required lines :

Area Control

Forest Regulation

AccountingVariablesCalculations

production, costs, revenues, areas, conversions...

GeneticMaterialSecurity

Multicriteria Attribute Calculations

Deviations Calculations

Elegible lines :

Production Flow

MinimumProductionRequirements

Maximum Production Requirements

NDY – Non Declining Yields

Quality and Regularity Control

(29)

6.2.3. Sets and Indexes

Given the definitions, and beyond the multi-dimensional intervention and transitions index, the model uses the following indexes and sets:

- $a \in \mathcal{A} = \{1, 2, 3, 4, \dots, A\}$ the set of ages that a land unit can be immediately before the forest being clear-cut. Typically, $A \leq 10$ for eucalyptus plantations, A is around 20 for pine, teak, acacia, and paricá plantations.
- $m \in \mathcal{M} = \{1, 2, \dots, M\}$ the set of marketplaces the forest products can be sold. Typically, forest managers do not operate in more than three marketplaces.
- $p \in \mathcal{P} = \{0, 1, 2, \dots, P\}$ the set of periods, from period = 0 that is the current period before the planning horizon starts, to P the last period of the horizon. In fast-growing plantations, often $P = 21$ for eucalyptus and $P = 30$ for pine, teak, acacia, and paricá.
- $prd \in \mathcal{D} = \{0, 1, 2, \dots, Prd\}$ the set of possible products that can be obtained from the forest interventions. They can be wood or non-wood products. Typically, in multiple-use fast-growing plantations, there is a maximum of five different products.
- $millprd \in \mathcal{M} = \{0, 1, 2, \dots, MillPrd\}$ the set of possible products that can be obtained after processing the wood. They can be pulp, round wood, essential oils, pellets, charcoal, or assortments.
- $rg \in \mathcal{G} = \{0, 1, 2, \dots, RG\}$ the set of regions where the area of the project is geographically distributed.
- $sp \in \mathcal{S} = \{0, 1, 2, \dots, SP\}$ the set of species or genetic materials are already planted and can be planted during the horizon in the considered area of the project.
- $ttype \in \mathcal{T} = \{'ina', 'th1', 'ccr', 'ccs', \dots\}$ the set of possible types of transitions that can happen upon the area of the project.
- $u \in \mathcal{U} = \{1, 2, 3, 4, \dots, U\}$ the set of land units (stands or farms) as described in **Section 6.2.1**.
- $t \in \mathcal{T} = \{1, 2, 3, 4, \dots, T\}$ the set of all possible transitions that can happen upon the considered area of the project.

6.2.4. Data and Parameters

The model requires data on the status of the area, productivity, market information, prices, and costs. Specifically, this data includes:

- $pIniArea_u$: the initial area (in ha) of each unit u .
- $pProductivity_{ttype, rg, sp, a, prd}$: how much (in m^3/ha) a piece of area in region rg , which is growing the species sp , produces of product prd , if it is in age a , when if a $ttype$ transition is occurring.
- $pDemand_{p, sp, prd, m}$: how much (in m^3) a market m demands of a products prd , of a species sp , in period p .
- $pMinContract_{p, sp, prd, m}$: there is a minimum (in m^3) by contract that the forest project should supply the market m of a products prd , of a species sp , in period p .
- $pPrice_{p, sp, prd, m}$: how much (in $R\$/m^3$) the market m , will pay to the forest managers for product prd , of a species sp , in period p .
- $pMktCst_m$: how much (in $R\$/m^3$) it will cost to forest managers to deliver their products to the market m .
- $pHrvCst_{ttype, sp, prd}$: how much (in $R\$/m^3$) it costs to harvest the product prd of species sp when managers are performing the transition type $ttype$.
- $pSlvCst_{ttype, rg, sp, a}$: how much (in $R\$/ha$) the silvicultural operations cost in the region rg , when forest has age a , since a transition $ttype$ occurred in a forest that the species sp is growing.
- $pLEV_u$: each land unit u has its Land Expectation Value which is calculated outside the model regarding the best way to use that piece of land. The final nodes revenue calculation gets this value. The system has to recalculate it every time the discount rate changes (Brazeel, 2018; Clutter et al., 1983; Ware and Clutter, 1971).
- $pDiscRate_p$: the rate to turn the silvicultural costs compatible with a different period that it occurs where p is the number of periods between two periods.
- $pPrdConversion_{r, sp, a, prd, millprd, m}$: it is the rate of conversion from forest products into mill products.
- $pMillDemand_{p, millprd, m}$: It is the maximum that the mill can sell of the product $millprd$ to the market m in period p .
- $pMillContract_{p, millprd, m}$: It is the minimum that the mill must deliver of the product $millprd$ to the market m in period p .

- **$pMixMatGen_{sp}$** : It is the best (or the desirable) rate between the total volume each species sp and total volume of in period p .
- **$pRegControl$** : It is a parameter that establishes a rate between age class area from one period and the next one.
- **$pGenMatMax$** : It is the maximum percentage of the total area that can be growing of each genetic material.
- **$pGenMatMin$** : It is the minimum percentage of the total area that can be growing of each genetic material.
- **$pIgor$** : It is the maximum rate allowed to the delivery of products out of the desirable quality.

6.2.5. Decision variables

The first set of decision variables express the intervention area. In other words, for the set of variables x_i , i is a possible intervention and x is an area (expressed in hectares) where the intervention i will be performed.

The second set is regarding the market; it expresses how much of each forest product will be delivered to each available market. The definition of this variable is: $xMarket_{p, sp, prd, m}$ where $xMarket$ is an amount (in m³ or other similar unit) of the product prd , of the species sp , that will be delivered to the market m .

6.2.6. Accounting variables

$xProd_{p, sp, prd}$ is the sum of production (in m³) of the product prd , obtained by harvesting every x_i that happened in period p , in units that species sp was growing.

$$xProd_{p, sp, prd} = \sum_i pProductivity_{ttype, rg, sp, a, prd} \cdot x_i \quad \forall p, \forall sp, \forall prd$$

where

$ttype, rg, sp, a$ are subindex of i

(30)

$xTotalPrdPSP_{p, sp}$ is the sum of forest production (in m³) that occurred in period p , where species sp was growing.

$$xTotalProdPSP_{p,sp} = \sum_{prd} xProd_{p,sp,prd} \quad \forall p, \forall sp \quad (31)$$

$xTotalPrdP_p$ is the sum of forest production (in m³) that occurred in period p .

$$xTotalProdP_p = \sum_{sp} \sum_{prd} xProd_{p,sp,prd} \quad \forall p \quad (32)$$

$xPrdRev_{p,sp,prd,m}$ is the sum of revenue (in R\$) obtained by the delivery of product prd , of species sp , to the market m , in period p .

$$xPrdRev_{p,sp,prd,m} = pDiscRate_p \cdot pPrice_{p,sp,prd,m} \cdot xMarket_{p,sp,prd,m} \quad \forall p, \forall sp, \forall prd, \forall m \quad (33)$$

$xTotalPrdRev$ is the sum of revenue (in R\$) obtained by the delivery of all products to all markets, in all periods.

$$xTotalPrdRev = \sum_p \sum_{sp} \sum_{prd} \sum_m xPrdRev_{p,sp,prd,m} \quad (34)$$

$xMillPrd_{p,millprd,m}$ is the sum of mill production of the product $millprd$, in the period p , market m , obtained by the delivery of wood product to the market m , in period p .

$$xMillPrd_{p,millprd,m} = \sum_{prd} \sum_i pProductivity_{ttype,rg,sp,a,prd} \cdot pPrdConversion_{rg,sp,a,prd,millprd,m} \cdot x_i \quad \forall p, \forall millprd, \forall m$$

where

$$ttype, rg, sp, a \text{ are subindex of } i \quad (35)$$

$xTotalMillPrd$ is the sum of mill production obtained by the delivery of the first product to all markets, in all periods.

$$xTotalMillPrd = \sum_p \sum_{millprd} \sum_m xMillPrd_{p,millprd,m} \quad (36)$$

$xMktCst_{p,sp,prd,m}$ is a set of market costs, which are the costs (in R\$) caused by the delivery of the product prd , of the species sp , to the market m , in period p .

$$xMktCst_{p,sp,prd,m} = pDiscRate_p \cdot pMktCst_m \cdot xMarket_{p,sp,prd,m} \quad \forall p, \forall sp, \forall prd, \forall m \quad (37)$$

$xTotalMktCst$ The sum of all market costs.

$$xTotalMktCst = \sum_p \sum_{sp} \sum_{prd} \sum_m xMktCst_{p,sp,prd,m} \quad (38)$$

$xHrvCst_i$ is the sum of the cost (in R\$) related to the harvesting activities of the intervention i .

$$xHrvCst_i = \sum_{prd} (pDiscRate_p \cdot pHrvCst_{ttype,sp,prd} \cdot pProductivity_{ttype,rg,sp,a,prd} \cdot x_i) \quad \forall i$$

where
 i is a $ttype$ intervention, that happens in a region rg when forest is in age a . (39)

$xTotalHrvCst$ is the sum of all costs (in R\$) related to harvesting activities.

$$xTotalHrvCst = \sum_i xHrvCst_i \quad (40)$$

$xSlvCst_i$ is the sum of the cost (in R\$) that come about due to the silvicultural activities that happen to make possible the intervention i . Most of the silvicultural activities do not occur in the same period of the intervention i , so, we use the parameter $pDiscRate_p$ to make the value compatible with the period that the intervention occurs.

$$xSlvCst_i = \sum_{prd} (pDiscRate_p \cdot pSlvCst_{ttype,sp,prd} \cdot x_i) \quad \forall i$$

where
 i occurs over a species sp , has the type of the last intervention = $ttype$
 p is a number of periods between $SlvCst$ occurrence and intervention period. (41)

$xTotalSlvCst$ is the sum of the cost (in R\$) that come about due to the silvicultural activities.

$$xTotalSlvCst = \sum_i xSlvCst_i \quad (42)$$

$xAreaSP_{p,sp}$ is the sum of the area that species sp is growing by the end of a given period p .

$$xAreaSP_{p,sp} = xAreaSP_{p-1,sp} - \sum_{i'} x_{i'} + \sum_{i''} x_{i''} \quad \forall p > 0, \forall sp$$

where
i' are the interventions that cut species *sp*
i'' are the interventions that plant species *sp*

(43)

$xAgeClass_a$ is the sum of the area of the forest that are in age $a \in \mathcal{A}$, in a particular period p' , chosen by the user.

$$xAgeClass_a = \sum_{i'} x_{i'} + \sum_{i''} x_{i''} \quad \forall a$$

where
p' is a given period
i' are interventions that happen after *p'* and forest had age *a* in *p'*
i'' are final – nodes that happen before *p'* and forest would have age *a* in *p'*

(44)

$xAgeClassVol_a$ is the sum of the standing volume of the forest that are in age $a \in \mathcal{A}$, in a particular period p' , chosen by the user.

$$xAgeClassVol_a = \sum_{i'} \sum_{ttype} \sum_{rg} \sum_a pProductivity_{ttype,rg,sp,a,prd} \cdot x_{i'} + \sum_{i''} \sum_{ttype} \sum_{rg} \sum_a pProductivity_{ttype,rg,sp,a,prd} \cdot x_{i''} \quad \forall a$$

where
p' is a given period
i' are interventions that happen after *p'* and forest had age *a* in *p'*
i'' are final – nodes that happen before *p'* and forest would have age *a* in *p'*

(45)

$xLEV_p$ is the sum of all LEV (land expectation value) of the final nodes that occur in period *p*.

$$xLEV_p = \sum_{i'} (x_{i'} \cdot pLev_u) \quad \forall p$$

where
final – node intervention i' happens on the unit u

(46)

$xTotalLEV$ is the sum of all LEV of the all final nodes.

$$xTotalLev = \sum_p xLEV_p$$

(47)

6.2.7. Attributes and Objectives

Attributes as defined in **Section 6.1.2**, are particular accounting variables. The model assigned each attribute to its associated objective. The system will always calculate and save their values, even in scenarios that the users do not choose their associated objectives. **Table 17** shows all attributes, their related objective, and which accounting variables are aggregated to obtain them.

Table 17 – Attributes and Objectives

Description Accounting variables		Related Objectives
1	Total Area of all interventions $xTotalArea = \sum_i x_i$	MaxArea
2	Total production from all interventions $xTotalProd = \sum_p \sum_{sp} \sum_{prd} xProd_{p,sp,prd}$	MaxProduction
3	Total mill production of the first mill product to all markets, in all periods. $xTotalMillPrd = \sum_p \sum_{millprd} \sum_m xMillPrd_{p,millprd,m}$	MaxMillPrd
4	Total Revenue from all interventions and logistics to all markets $xTotalRev = xTotalPrdRev + xTotalLEV$	MaxRevenue
5	Total Costs from interventions and logistics to all markets $xTotalCst = xTotalMktCst + xTotalSlvCst + xTotalHrvCst$	MinCost
6	Total Net Present Value (NPV) of all project $xTotalNPV = xTotalRev + xTotalLEV - xTotalCst$	MaxNPV
7	Total of the attribute IGOR $xTotalIgor = \sum_{sp} xTotalDevMixPrd_{sp}$	MinIgor
8	Total Standing Wood Stock by the end of horizon (period p' - Figure 14) $xTotalStock = \sum_a xAgeClassVol_a$	MaxStck

The only attribute in **Table 17** that needs additional explanation is **IGOR** - General index of regularity, that is a kind of measure of deviation from a desirable level of production. The variable $xTotalDevMixPrd$ sum all deviations between the period production per species and a desirable production per species per period. It will better understand in next section when deviation variables will be defined.

The most common objective function used in harvest scheduling models is the Net Present Value (NPV) that expresses the maximum profit forest managers can obtain from a forest activity (Diaz-Balteiro et al., 2014; Packalen et al., 2013; Pastorella et al., 2016). However, over the last decades many other objectives have been used to address new needs related to modern view about forest functions and ecosystem services (Borges et al., 2017, 2014b; Garcia-Gonzalo et al., 2015, 2014; Orazio et al., 2017) as a step forward to the multi-criteria approach.

Romero® was developed to allow criteria selection. Users can choose how many objectives they want in the available list showed in the second column in **Table 17**. Until now, *Romero*® has all the objects needed to address forest plantations in Brazil; however, the model is prepared to accept, when required, other attributes and assign them to their respective objectives.

For each objective selected, the system will maximize or minimize the value of the corresponded attribute using the statements showed in the first column of **Table 17**. *Romero*® optimizes one at a time, save all results from attributes and decision variables into the database, save key data to build the pay-off, and by the end, show the complete pay-off matrix in the “Results window.”

For each optimization, *Romero*® guarantees that the vector of decision variables is the same, as well as all the constraints. Raising the problem in these terms, the general structure of a multiobjective program can be schematically represented in the following way (Romero, 1993; Steuer, 1986):

$$\begin{aligned}
& \text{Eff } f(x) = [f_1(x), f_2(x), \dots, f_n(x), \dots, f_N] \\
& \text{subject to :} \\
& \quad X \in C \\
& \text{where :} \\
& \quad \text{Eff} \quad \text{means the search for Pareto - efficient solutions} \\
& \quad f_n(x) \quad \text{mathematical expression of the attribute } n \\
& \quad X \quad \text{vector of decision variables} \\
& \quad C \quad \text{set of Constraints that defines the possible solutions}
\end{aligned} \tag{48}$$

The vector X in **Statement (48)**, in the problem defined in this **Section 6.2**, is the set of decision variables defined in **subsections 6.2.5** and **6.2.6**. The vector $f(x)$ is the set of chosen attributes available in **Table 17**. The set of constraints C will be defined in next **Sections 6.2.8, 6.2.8** and **6.2.10**.

The formulation presented in **Statement (48)** implies that beyond the Pay-off matrix, which is only the set of extreme solutions; a multiobjective program must also find the set of Pareto-efficient solutions. The process of obtaining them will be explained in **Subsection 6.4**.

6.2.8. Deviation variables.

Usually, mills demand uniformity or regularity on their raw material supply. Also, accordingly to the type of client, and technical characteristics of their processes, mill managers may demand final product quality indicators to remain between certain limits. Uniformity and quality thresholds are a significant source of conflict along the forest supply chain due to the manner forest managers and mill managers shall handle planning horizons. In the implementation of this thesis, genetic material supply, and the attribute IGOR – General index of regularity will characterize such conflicts. IGOR, labeled $xTotalIgor$, is defined similarly to how deviations are calculated in goal programming formulations.

- $xDevPMixPrd_{p,sp}$ is the sum of all positive deviations from a desirable level of production of each species sp in each period p .
- $xDevNMixPrd_{p,sp}$ is the sum of all negative deviations from a desirable level of production of each species sp in each period p .
- $xTotalDevMixPrd_{sp}$ is the sum of all deviations from a desirable level of production of each species.

- $xTotalIgor$ is the total deviation from a desirable level of production.

These variables are defined in a set of constraints, named deviation constraints, as shown in **Statement (49)**.

$$\begin{aligned}
 xTotalPrdPSP_{p,sp} - xDevPMixPrd_{p,sp} + xDevPMixPrd_{p,sp} \\
 - pMixMatGen_p \cdot xTotalPrdP_p &= 0 \quad \forall p, sp \\
 \sum_p xDevPMixPrd_{p,sp} + \sum_p xDevNMixPrd_{p,sp} \\
 - xTotalDevMixPrd_{sp} &= 0 \quad \forall sp \\
 \sum_{sp} xTotalDevMixPrd_{sp} - xTotalIgor &= 0 \quad (49)
 \end{aligned}$$

6.2.9. Required constraints:

Besides the calculation of the accounting variables and multicriteria attributes, there are some required constraints. The area balance is part of the *Model II* as described in **Section 6.1.1**. Moreover, forest regulation and genetic material security must be added to the model due to sustainability and ecological limits (Kaya et al., 2016).

6.2.9.1. Area control

The following constraints established the links between interventions that can happen at the same unit u lengthwise the horizon.

$$\begin{aligned}
\text{Initial Area)} \quad & x_i = pIniArea_u \quad \forall u \\
& \text{where } i = [last_t, last_p, last_a, ttype, t, p, a] \\
& last_t, last_p, last_a = null \\
& t \text{ happens at unit } u \\
& p = 0 \\
& ttype = 'ina' \\
\text{Area Balance)} \quad & \sum_{i_b} x_{i_b} = \sum_{i_a} x_{i_a} \\
& \text{for each set of } i_a \\
& \text{where } last_t_a = t_b \\
& last_p_a = p_b \\
& i_a = [last_t_a, last_p_a, last_a_a, ttype_a, t_a, p_a, a_a] \\
& i_b = [last_t_b, last_p_b, last_a_b, ttype_b, t_b, p_b, a_b] \tag{50}
\end{aligned}$$

6.2.9.2. Forest regulation

The forest regulation was implemented using the accounting variables $xAgeClass_a$ and the parameter $pRegControl$. The following constraints turn the forest regulation more flexible, as shown in **Statement (51)**. Even though the constraint is required, the user can change the value of the parameter $pRegControl$ to make the constraint regulation more or less unbending.

$$\begin{aligned}
\text{RegulationMin)} \quad & (1 - pRegControl) \cdot xAgeClass_{a-1} \leq xAgeClass_a \quad \forall a \\
\text{RegulationMax)} \quad & (1 + pRegControl) \cdot xAgeClass_{a-1} \geq xAgeClass_a \quad \forall a \tag{51}
\end{aligned}$$

6.2.9.3. Genetic material security

Parameters $pGenMatMin$ and $pGenMatMax$ control the genetic material security through the constraint lines showed in **Statement (52)**.

$$\begin{aligned}
\text{GenMatCtrlMin)} \quad & xAreaSP_{p,sp} - pGenMatMin \cdot xTotalAreaPlt \geq 0 \quad \forall p, sp \\
\text{GenMatCtrlMax)} \quad & xAreaSP_{p,sp} - pGenMatMax \cdot xTotalAreaPlt \leq 0 \quad \forall p, sp \tag{52}
\end{aligned}$$

6.2.10. Eligible Constraints

The user defines which constraints to include in the model by setting eligible constraints at the beginning of the problem definition. The *Romero*® interface provides a checkbox to do so. Eligible constraints are set at the beginning of the multicriteria analysis in order to guarantee that the optimization of each criterion is done under the same assumptions.

6.2.10.1. Production flow control

Similar to **Statement (51)**, the production flow is controlled by parameters *pFlowIncrease* and *pFlowDecrease* which can be changed by the user. Again, the user can change the value of the parameters to make the production flow more or less unbending. The following constraints control the flow separately for each species only for the mains product.

$$\begin{aligned} PrdFlowMin) \quad (1 - pFlowDecrease) \ xProd_{p-1,sp,1} &\leq xProd_{p,sp,1} \quad \forall a \\ PrdFlowMax) \quad (1 + pFlowIncrease) \ xProd_{p-1,sp,1} &\geq xProd_{p,sp,1} \quad \forall a \end{aligned} \quad (53)$$

6.2.10.2. Minimum and maximum production requirements

There are minimum and maximum production requirements for the forest and mill production. Parameters *pDemand* and *pMinContract* control the forest production while *pMillDemand* and *pMillContract* control mill production. Parameters *pDemand* and *pMillDemand* represent the maximum forest and mill can produce; *pMinContract* and *pMillContract* express the minimum forest and mill must provide to accomplish their clients' contracts. As **Section 6.2.4** describes, *pPrdConversion* converts forest production into mill production. **Statement (54)** presents these constraint lines.

$$\begin{aligned} ForestPrdMin) \quad xMarket_{p,sp,prd,m} &\geq pMinContract_{p,sp,prd,m} \quad \forall p, sp, prd, m \\ ForestPrdMax) \quad xMarket_{p,sp,prd,m} &\leq pDemand_{p,sp,prd,m} \quad \forall p, sp, prd, m \\ MillPrdMin) \quad xMillPrd_{p,1,m} &\geq pMillContract_{p,1,m} \quad \forall p, m \\ MillPrdMax) \quad xMillPrd_{p,1,m} &\leq pMillDemand_{p,1,m} \quad \forall p, m \end{aligned} \quad (54)$$

6.2.10.3. NDY – non declining yield

Beyond the selection of an NDY constraint to take part in the model, the user can set the period from which the NDY will start. NDY controls the production of the first product, where $prd = 1$. **Statement (55)** shows the constraint line as it was implemented.

$$NDY) \quad xProd_{p,sp,1} \leq xProd_{p+1,sp,1} \quad \forall p > p_{ndy}, sp \quad (55)$$

6.2.10.4. Regularity control

The user can choose if he wants to control the IGOR, that is to say, the user can set the maximum deviation from desirable quality, giving value to the parameter $pIgor$. **Statement (56)** shows how it was implemented.

$$MaxIgor) \quad xTotalIgor - pIgor . xTotalProd \leq 0 \quad (56)$$

6.3. Complete multiobjective model

The full multiobjective model that has been used in a multicriteria context is presented in the following. Only three objectives constitute the objective function as an example. The user can choose any objectives presented in **Table 17** to compose the multiobjective function. All the constraint lines with names starting with “*Acctv_*” are the lines that calculate the accounting variables. The ones beginning with “*Devv_*” calculate the deviation variables, while the ones beginning with “*Attr_*” calculates the multicriteria attributes. All the constraint lines with names followed by a * are the eligible constraints; they will only integrate the model if the user chooses them.

$$Eff \ f(x_i, xMarket_{p,sp,prd,m}) = [MaxNPV(x_i, xMarket_{p,sp,prd,m}), \\ MaxMillPrd(x_i, xMarket_{p,sp,prd,m}), \\ MaxStock(x_i, xMarket_{p,sp,prd,m})]$$

Subject to :

$$Initial \ Area) \quad x_i = pIniArea_u \quad \forall u \\ \text{where } i = [last_t, last_p, last_a, ttype, t, p, a] \\ last_t, last_p, last_a = null \\ t \text{ happens at unit } u \\ p=0 \\ ttype='ina'$$

$$Area \ Balance) \quad \sum_{i_b} x_{i_b} - \sum_{i_a} x_{i_a} = 0 \quad \text{for each set of } i_a \\ \text{where } last_t_a = t_b \\ last_p_a = p_b \\ i_a = [last_t_a, last_p_a, last_a_a, ttype_a, t_a, p_a, a_a] \\ i_b = [last_t_b, last_p_b, last_a_b, ttype_b, t_b, p_b, a_b]$$

$$Acctv_Prod) \quad \sum_i pProductivity_{ttype,rg,sp,a,prd} \cdot x_i - xProd_{p,sp,prd} = 0 \quad \forall p, \forall sp, \forall prd \\ \text{where} \\ ttype, rg, sp, a \text{ are subindex of } i$$

$$Acctv_TotalPrdPsp) \quad \sum_{prd} xProd_{p,sp,prd} - xTotalProdPSP_{p,sp} = 0 \quad \forall p, \forall sp$$

$$Acctv_TotalProdP) \quad \sum_{sp} \sum_{prd} xProd_{p,sp,prd} - xTotalProdP_p = 0 \quad \forall p$$

$$Acctv_PrdRev) \quad pDiscRate_p \cdot pPrice_{p,sp,prd,m} \cdot xMarket_{p,sp,prd,m} - xPrdRev_{p,sp,prd,m} = 0 \quad \forall p, \forall sp, \forall prd, \forall m$$

$$Acctv_TotalPrdRev) \quad \sum_p \sum_{sp} \sum_{prd} \sum_m xPrdRev_{p,sp,prd,m} - xTotalPrdRev = 0$$

$$Acctv_MktCst) \quad pDiscRate_p \cdot pMktCst_m \cdot xMarket_{p,sp,prd,m} - xMktCst_{p,sp,prd,m} = 0 \quad \forall p, \forall sp, \forall prd, \forall m$$

$$Acctv_TotalMktCst) \quad \sum_p \sum_{sp} \sum_{prd} \sum_m xMktCst_{p,sp,prd,m} - xTotalMktCst = 0$$

$$Acctv_HrvCst) \quad \sum_{prd} (pDiscRate_p \cdot pHrvCst_{ttype,sp,prd} \cdot pProductivity_{ttype,rg,sp,a,prd} \cdot x_i) - xHrvCst_i = 0 \quad \forall i$$

where

i is a $ttype$ intervention, that happens in a region rg when forest is in age a

$$Acctv_TotalHrvCst) \quad \sum_i xHrvCst_i - xTotalHrvCst = 0$$

$$Acctv_SlvCst) \sum_{prd} (pDiscRate_p \cdot pSlvCst_{ttype,sp,prd} \cdot x_i) - xSlvCst_i = 0 \quad \forall i$$

where

i occurs over a species sp , has the type of the last intervention $= ttype$

p is a number of periods between $SlvCst$ occurrence and intervention period

$$Acctv_TotalSlvCst) \sum_i xSlvCst_i - xTotalSlvCst = 0$$

$$Acctv_AreaSP) \sum_{i'} x_{i'} + \sum_{i''} x_{i''} - xAreaSP_{p-1,sp} = 0 \quad \forall p > 0, \forall sp$$

where

i' are the interventions that cut species sp

i'' are the interventions that plant species sp

$$Acctv_AgeClass) \sum_{i'} x_{i'} + \sum_{i''} x_{i''} - xAgeClass_a = 0 \quad \forall a$$

$$Acctv_AgeClassVol) \sum_{i'} \sum_{ttype} \sum_{rg} \sum_a pProductivity_{ttype,rg,sp,a,prd} \cdot x_{i'} + \sum_{i''} \sum_{ttype} \sum_{rg} \sum_a pProductivity_{ttype,rg,sp,a,prd} \cdot x_{i''} - xAgeClassVol_a = 0 \quad \forall a$$

where

p' is a given period

i' : interventions that happen after p' and forest had age a in p'

i'' : finalNodes that happen before p' and forest would have age a in p'

$$Acctv_LEV) \sum_{i'} (x_{i'} \cdot pLev_u) - xLEV_p = 0 \quad \forall p$$

where

i' is final – node intervention that happens on the unit u

$$Acctv_TotalLEV) \sum_p xLEV_p - xTotalLev = 0$$

$$Acctv_MillPrd) \sum_{prd} \sum_i pProductivity_{ttype,rg,sp,a,prd} \cdot pPrdConversion_{rg,sp,a,prd,millprd,m} \cdot x_i - xMillPrd_{p,millprd,m} = 0 \quad \forall p, \forall millprd, \forall m$$

$$Devv_MixPrd) xTotalPrdPSP_{p,sp} - pMixMatGen_p \cdot xTotalPrdP_p - xDevPMixPrd_{p,sp} + xDevPMixPrd_{p,sp} = 0 \quad \forall p, sp$$

$$Devv_TotalMixPrd) \sum_p xDevPMixPrd_{p,sp} + \sum_p xDevNMixPrd_{p,sp} - xTotalDevMixPrd_{sp} = 0 \quad \forall sp$$

$$\begin{aligned}
Attr_TotalArea) \quad & \sum_i x_i - xTotalArea = 0 \\
Attr_TotalPrd) \quad & \sum_p \sum_{sp} \sum_{prd} xProd_{p,sp,prd} - xTotalProd = 0 \\
Attr_TotalMillPrd) \quad & \sum_p \sum_{millprd} \sum_m xMillPrd_{p,millprd,m} - xTotalMillPrd = 0 \\
Attr_TotalRev) \quad & xTotalPrdRev + xTotalLEV - xTotalRev = 0 \\
Attr_TotalCst) \quad & xTotalMktCst + xTotalSlvCst + xTotalHrvCst - xTotalCst = 0 \\
Attr_TotalNPV) \quad & xTotalRev + xTotalLEV - xTotalCst - xTotalNPV = 0 \\
Attr_TotalIgor) \quad & \sum_{sp} xTotalDevMixPrd_{sp} - xTotalIgor = 0 \\
Attr_TotalStock) \quad & \sum_a xAgeClassVol_a - xTotalStock = 0 \\
\\
PrdFlowMin)* \quad & (1 - pFlowControl).xProd_{p-1,sp,1} - xProd_{p,sp,1} \leq 0 \quad \forall a \\
PrdFlowMax)* \quad & (1 + pFlowControl).xProd_{p-1,sp,1} - xProd_{p,sp,1} \geq 0 \quad \forall a \\
\\
ForestPrdMin)* \quad & xMarket_{p,sp,prd,m} \geq pMinContract_{p,sp,prd,m} \\
& \quad \quad \quad \forall p, sp, prd, m \\
ForestPrdMax)* \quad & xMarket_{p,sp,prd,m} \leq pDemand_{p,sp,prd,m} \\
& \quad \quad \quad \forall p, sp, prd, m \\
MillPrdMin)* \quad & xMillPrd_{p,1,m} \geq pMillContract_{p,1,m} \\
& \quad \quad \quad \forall p, m \\
MillPrdMax)* \quad & xMillPrd_{p,1,m} \leq pMillDemand_{p,1,m} \\
& \quad \quad \quad \forall p, m \\
\\
NDY)* \quad & xProd_{p,sp,1} - xProd_{p+1,sp,1} \leq 0 \quad \forall p > p_{ndy}, sp \\
\\
MaxIgor)* \quad & xTotalIgor - pIgor . xTotalProd \leq 0
\end{aligned}$$

6.4. Romero©Architecture

This section describes the FMTDSS processes and how the mathematical programming model, presented in previous sections, was embedded into it. Most importantly, this section focuses on how the system guarantees the interactive MCDM principles, described in the methodology section, are followed during the system processes.

6.4.1. *Romero*® main components

According to Kanojiya and Nagori (2018) guidelines, a DSS, and any other type of model-driven system, should include, at least, these general components: (i) a user interface, (ii) a database, knowledge base or data repository to handle with inputs and outputs (iii) model base, and (iv) a rule engine. To follow the guidelines of the cited authors and the interactive MCDM principles, *Romero*® comprises the general components showed in **Figure 1****Figure 15**.

Figure 15 – *Romero*® main components

Romero® has four independent components. The first and central one is the database to deal with all types of information. Database, in its turn, has the most of information (parameters, results, and rules) are stored and controlled by a SQL Database. User's choices related to the optimization process and set-up information are stored in xml files, and the model described in **Sections 6.2** and **6.3** is saved in Pyomo® source files. The second component, the user interface, comprises a set of screens to communicate with users. The third component includes the optimization modules written in Pyomo®, Python®, and its libraries to read parameters, generate forest interventions, run the model, and save results. Finally, the fourth component, the inference engine named *IGen*, covers the generation of the possible forest interventions. The following sections present all the processes focusing on the application of the interactive MCDM principles.

6.4.2. Romero® general processes

Figure 16 shows the general processes of Romero® which were developed to implement an interactive MCDM applied to a forest MOLP model. In the very beginning, *Romero®* needs to know where the setup xml file is. Among other information, the database to connect is the most important one. Each database is an independent forest project with its area information, rules about interventions, and planning parameters that are supposed to come from a sequence of treatments after monitoring activities as described in **Chapter 0**. *Romero®* provides screens to query, check, and update all the planning parameters, including the intervention rules.

Figure 16 – Romero® General Processes

Since the intervention rules are stored in the database linked to the project, the shape and size of the model depend on the forest project. On the other hand, the degree of flexibility

depends on the evolution of the inference engine. Moreover, the planning parameters generates more or less complex models depending on how the forest managers build the database. The problem can have one or more markets, one or more products, one or more species, periods, and units without limits, and, most importantly, a variety of intervention types. Therefore, the complexity is decided when the database is chosen.

The screenshot shows the 'Romero - Forest Plantation Multicriteria Analysis Framework' window with the 'Optimization' tab selected. The 'Optimization Parameters' section contains a list of criteria to be optimized: MaxArea, MaxVolume, MaxPeriod, MaxFinalStock, MaxRevenue, and MinIgor. A 'Discount Rate' of 0.070 and 'Monte Carlo Iterations' of 1 are specified. The 'Forest Regulation' section includes a 'Regulation Period' of 17, 'Perc% from previous class' of 0.01, and 'Last Age Class' of 6. The 'Regulate on' section has radio buttons for 'Area' (selected), 'TotProd', and 'Prod1'. The 'Goal Programming' section shows a value of 1.000 'from each criteria range'. The 'Optional Constraints' section includes checkboxes for 'NDY Non-Declining Yield from period: 1', 'Forest Demand and Supply Control', and 'Forest Production Flow Control from period: 2'. It also features a 'Genetic Material Security' section with 'Min of each Genetic Material' at 0.200 and 'Max of each Genetic Material' at 0.600. Other constraints include 'Forest Production Range Constraint' with 'Decrease Percentage from previous period' at 0.100 and 'Increase Percentage from previous period' at 0.250, and 'IGOR - General Index of Regularity - Genetic Material Regularity Cont' with a 'Last IGOR Value' of 0.00.

Figure 17 - Optimization parameters

In the next step, *Romero*[®] provides the means to prepare the optimization scenario (**Figure 17**); it shows the criteria available and a list of eligible constraints to select. At this moment, the model is completely defined, and the scenario can be built. The building process starts from the *IGen* (described in **Section 6.4.3**), that generates the primary set of indexes of the model – transitions and interventions. For each run, *Romero* changes only the objective and

save all the results. By the end, the payoff matrix and Pareto frontier can be calculated as **Figure 16** shows.

Figure 18 - Payoff matrix view

There is an independent screen that can be called anytime to present all the scenario results: payoff, Pareto frontier, and decision variables and accounting variables (**Figure 18**). Each scenario has a number and a description to facilitate scenario analysis testing various levels of constraints, different constraints, and intervention rules.

6.4.3. IGen – Interventions generator

The main objective of this engine is to generate the indexes i (interventions) and t (transitions) of the model described in **Sections 6.2** and **6.3**. These indexes were defined explicitly in **statements (27)** and **(28)** and used in the entire model. **Figure 19** illustrates the engine.

Figure 19 - Inference Engine

The initial area information and rules regarding the changes that can happen in a specific forest project feed the engine. The first step is to create a structure according to the initial area of the attributes of the forest project that is being considered. The possible transitions are generated based on the rules and the initial situation of the forest. The last step schedules the possible transitions along the horizon using the information about periods and ages. Scheduled transitions get the name of intervention.

After the formal generation of the multi-dimension indexes (transition and intervention), to improve the performance, it was necessary to create an optimized set of matrices to support the AML (Algebraic Modeling Language) in which the model was developed.

The rules are written in terms of the attributes of the forest. The *Romero*® implementation used the attributes *u*, *c*, *r*, and *sp* – land unit, cycle, rotation, and species, respectively. **Figure 20** shows two examples of rules written schematically.

Figure 20 - Rule Examples

The first rule says that after a “ccr” intervention, it can happen another “ccr” or an “ccs” (clear-cut + sprout from stumps) if the attribute *r* is less than 1. The rule also says that if a “ccr” (clear cut + renew) happens in a specific area of a forest, the forest attribute will change:

- attribute *u* (land unit) will remain the same,
- attribute *c* (cycle) will be added of 1 unit,
- attribute *r* (rotation) will change to 1,
- attribute *sp* (species) will remain the same.

The second rule says that after a “ccs” (clear- cut + sprout from stumps) intervention, it can happen only a “ccr”. Also, the forest attributes will change according to the rule: *u1=u*; *c1=c*; *r1=r+1*; *sp1=sp*.

6.4.4. Calculation processes' details

Figure 21 focus on how *Romero*© proceed with the calculations. While each optimization for each one of the criteria is running, *Romero*© prepares the results to calculate the pay-off matrix and automatically sets the parameters to Pareto frontier. To use the constraint method, two steps are needed: (1) the creation of intervals from the minimum and maximum value of all attributes; (2) the used of these intervals' values as constraints to optimize one of the criteria at a time. In other words, to create a frontier it is necessary to optimize one criterion using the others as constraints. For each point of the Pareto frontier, *Romero*© saves all decision variables and accounting variables in the database to allow the recreation of a solution when decision-makers choose a point along the frontier.

Figure 21 - Romero© calculations

To calculate the two points L_1 and L_∞ (Compromise Programming) of each Pareto Frontier, Romero doesn't need to optimize anymore, only query the results stored in the database and calculate the distance function as described in **Section 6.1.3 and Annex 1**.

6.4.5. AML resources and multicriteria calculations.

The technology used to implement the MOLP described in **Sections 6.2 and 6.3** was an implementation of AML (Algebraic Modeling Language) as a Python library named Pyomo – Python optimization modeling objects (Hart et al., 2017, 2011). Some authors have already used Pyomo to implement forest models (Huang and Martin, 2010; Veliz et al., 2015) and many others have developed Pyomo models to address other's engineering problems (Andersson et al., 2019; Chen and Grossmann, 2019; Eason and Biegler, 2018; Legg et al., 2013, 2012; Lozano Santamaria and Gomez, 2016; Nguyen and Byrne, 2017; Nicholson and Sirola, 2018).

Figure 22 - Run MOLP: Multi Objective Linear Programming

Figure 23 – Legend of **Figure 22**

Python and Pyomo are object-oriented and makes the model into an object; and makes objectives, constraints, and parameters into properties of this object. Moreover, Pyomo builds the model in two steps: first, it creates the abstract model and then creates a concrete model with specific numerical parameters. *Romero*® uses these features to make the multi-criteria process efficient and accurate.

The creation of an abstract model must happen after every *IGen* run due to the change of the shape of the model. On the other hand, every time that the parameters structure change, the concrete model must be built again. The most time-consuming function, individually, is the creation of the concrete model. To make this procedure efficient, the indexes needed during the process were reorganized in new structures to optimize the time consumption of the concrete-model creation.

At this point, Pyomo offers the opportunity to instance the model as many times as necessary. In each instance, the value of the properties can be changed. At this moment, the value of the parameters can be changed; the objectives and constraints can be activated and deactivated. Due to this powerful feature, regarding time-consumption, two functions are relevant to the entire process: (1) the solver time; and (2) the time to save the results into the database.

6.4.6. Decision makers interaction

The process described in **Figure 24** was used to interact with the decision makers. Comparing to the process suggested in the methodology section (**Figure 13**), the interactive process had to be improved; one important agent was added into the process: the information manager, which is the expert responsible for the planning process. Even when *Romero*® is fully integrated into the information environment of an organization, maybe this agent will be still

necessary for the process due to the complexity of the planning process in a large plantation company.

The main result that could be observed during the process is that each iteration brings new needs in terms of modeling and information. It seems to indicate that the most important result is the understanding enhancement of the company operations more than the decision itself. The results of the interaction can be better understood in the case discussion in further sections.

Figure 24 – MCDM applied to an interactive GDM Processes

6.4.7. Technology Description

Romero[®] combines and integrates a set of technology. Due to its flexibility to build mathematical programming models, an AML was an essential element that determined the subsequent choices. AML are high-level computer programming languages for describing and solving high complexity problems for large scale mathematical computation (Kallrath, 2004). One advantage of an AML is the similarity of their syntax to the mathematical notation of optimization problems. This similarity allows for a very concise and readable definition of problems in the domain of optimization (Hart et al., 2011). Among AML options, LINGO, AIMMS, GAMS, and AMPL, **Pyomo** (Python-based, open-source optimization modeling language) was chosen because it was developed to be used in research projects that require a flexible framework for customizing the formulation and direct integration with a high-level programming language – Python - to ensure cross-platform portability and access a broad range of functionality.

Due to Python flexibility, the other choices were easy to make. SQLite was chosen as a relational database management system (RDBMS) because it is easy to deal with and light, open access and also easily exchangeable to other power RDBMS like SQL Server, MySQL, PostGres and others. Regarding the solver, a choice was not needed because Pyomo code is independent of the solver chosen to calculate, and it accepts many open access and commercial ones with no need to change any code.

In a perspective of Romero components (**Figure 15**), the latest version uses SQLite3 to support the SQL Database, Pyomo to support the Model Base, Pyomo + Python to support the Optimization Procedures, and Python and Python libraries to support *IGen* and the user interface.

7. FMTDSS APPLICATION

7.1.Introduction

Environmental concerns bring challenges and opportunities to the forest industry. Sustainable production processes of timber and fibers have become increasingly demanded. South America has continued the expansion of wood pulp production with an increasing number of new pulp mills being built in Brazil, Chile and Uruguay. These three countries in 2016 accounted for 15 percent of global wood pulp production and 33 percent of exports. (FAO, 2017). Fiber furnish³ production (and exports) has been increasing consistently in Brazil, where fast-growing planted forests give the country a competitive advantage in the manufacturing of wood pulp exports in 2016 (FAO, 2017). Pulp and paper demand is expected to grow by 2.7% a year, reaching 747 million tons by 2030 (FAO, 2008). Following this trend, the Brazilian pulp industry has increased by 5.9% a year in the last 15 years, guaranteeing its position in the international market scenario (IBÁ, 2017). Meanwhile, eucalyptus timber became more expensive; sectoral inflation was 1.5 times higher than average Brazilian inflation over the last ten years; and forest plantations' productivity stabilized in the 2000s after 30 years of cumulative growth (IBÁ, 2017).

Since the 1970s, the Brazilian pulp industry has invested in the quality of its plantations, which means investments in technology such as photosynthetic capacity and higher wood density. One of the remarkable results of these efforts is the availability of a variety of suitable genetic materials for plantations. Genetic variability may now contribute to further productivity growth (Ferreira et al., 2018; Gomide et al., 2006; Queiroz et al., 2004).

In this scenario, forest managers want to maximize their profits by looking for operational efficiency and more productive genetic materials (Gomide et al., 2010). Otherwise, industry managers want to receive a regular and suitable mix of raw material concerning wood density to maximize their pulp productivity (Mokfienski et al., 2008). Both sides must operate under strong environmental constraints, which brings one more group of stakeholders to the conflict scenario.

An optimized forest planning may contribute to the efficiency in the use of forest resources regarding tons of pulp per ha per year. To demonstrate the applicability of *Romero*[©], the

³ In FAO's forest products statistics, the fiber used to manufacture paper and paperboard is referred to as "fiber furnish". This includes recovered paper (wastepaper), other fiber pulp and the wood pulp used to make paper.

following sections will present a case study based on Brazilian pulp industry reality and calculate trade-offs and a compromise among the three groups of stakeholders: forest managers, industrial managers, and those responsible for environmental constraints.

7.2. Case study

Brazil had 19 pulp mills distributed throughout the country in 2016. However, they are concentrated in the south and southeast regions, as shown in **Figure 25**, which yearly production range from 200,000 to 2 million tons of pulp per mill. In 2016, Brazil produced 18.8 million tons, 16.2 of short fiber, which wood is 100% from Eucalyptus planted forests. Logs harvested from around one third of the 5,7 million hectares of Eucalyptus plantations are the main source of fiber for these pulp mills. Mean annual increment in these plantations varies from 30 to 50 m³/ha.year, averaging 35,7 m³/ha.year (IBÁ, 2017).

Figure 25 - Pulp mills geographic distribution

According to FAOSTAT (FAO, 2019), in 2016, Brazil produced 69.136 million m³ of pulp non-coniferous wood, which means the industrial short fiber average consumption was 4.34 m³ of wood to produce one ton of pulp. While the literature mentions industrial productivities from 3.5 to 5.1 m³ per ton of dry pulp (Mokfienski et al., 2008). To sustain their high level of industrial productivity, Brazilian pulp mills' main concerns in terms of wood quality are (i) the wood density (Mokfienski et al., 2008), (ii) the size uniformity of the chips (Camargo et al., 2015), and (iii) chemical composition (Alves et al., 2011).

Moreover, while forest managers in Brazil tend to shorten the rotations due to the usually high interest rates practiced in the Brazilian banking system, the industrial managers tend to ask for larger ones due to the positive correlation between age and wood density (Andrade, 2006; Ribeiro and Filho, 1993).

Forest managers have pushed for high volumes of wood, prescribing rotations in which trees are cut at ages 6 to 7 years old when MAI (mean annual increment) generally reaches its peak. That generally leads to wood being delivered in the mill with low wood density averages. Mill managers complain about these low averages, as they usually lead to a lower content of fibers of cellulose in a per ton of dry wood basis.

Long term strategic planning that balances forest managers desire to deliver large volumes of wood, and mill managers aspiration to get good quality wood into their industrial processes, requires the application of MCDM techniques. The MCDM based on MOLP (multi-objective linear programming) principles shall not only account for economic performance and a steady and regulated annual supply of good quality wood delivered to the mill but also evaluate the consequences of moving towards longer rotations of eucalyptus plantations. Romero's flexibility to apply MCDM techniques and to serve as a platform for conflicting stakeholders to reach consensus is tested in a case study.

The case prepared for the applicability test refers to a hypothetical pulp mill. The main aspects of the plantation supplying wood to the mill are presented in **Table 18**. Due to the short rotation plantation cycle of approximately 6 years, the length of the planning horizon was set to 19 years to guarantee the completion of at least three entire rotations.

The total area is 21,400 hectares distributed in 18 forest management units planted with *Eucalyptus spp* to supply the mill. The smallest unit has 550 hectares, and the largest one has 1900 hectares. Each forest management unit is homogeneous in terms of region, species, cycle, rotation, and age. The silvicultural total costs sum R\$9500 over the years to complete

one full *Eucalyptus spp* plantation cycle, pulpwood price is R\$50/m³, and the annual interest rate is 7% (Brasil Ministerio da Economia, 2019). Also, due to the short rotation plantation cycle of approximately 6 years, the length of the planning horizon was set to 19 years to guarantee the completion of at least three entire rotations.

Table 18 – Plantation case study

Area	21,400 ha		
Management Units	18		
Area of each unit	From 500 to 1,900ha		
Allowable harvest ages	6 and 7 years old		
Silvicultural Costs	R\$ 9,500.00/ha		
Pulpwood price	R\$50/m ³		
Discount rate	7%		
Groups		Average Productivity (m ³ /ha.year at 7 years old)	Average Wood Density (Kg/m ³ at 7 years old)
Species	MatGen1	42	580
<i>Eucalyptus spp</i>	MatGen2	48	500
	MatGen3	52	420

Wood density was the variable used to classify clones into three groups. Group GenMat3 considers clones classified in the lower density class (average 420 kg/m³). The other two groups, GenMat2, and GenMat1 classify clones into mid-density (500 kg/m³) and high density (580 kg/m³), respectively. The productivity varies from 42 to 52 m³/ha.year, at 7 years old. The business as usual scenario considers that forest managers limit the choice of harvesting ages to only two alternatives, 6 and 7 years old.

; Wood density, pulp production, and trees age

Lopes and Garcia (2002) isolated the effect of age into the density of some species of eucalyptus. Foekel (1974) also found a good correlation between wood density and pulp production efficiency. **Figure 26** and **Figure 27** show how these two concepts were applied to the three groups of genetic material. The hypothetical curves for wood density as a function of age shown in these figures were created fixing the slope coefficient and varying the intercept.

Figure 26 - Wood Density

Figure 27 - Industrial Efficiency

The GenMat3 group has a density of 420 Kg/m³ at the age 7; it is equivalent of the *Eucalyptus grandis* average (Lopes and Garcia, 2002). GenMat2 (500 kg/m³) group and GenMat1 (580 kg/m³) density are equivalent to *E. grandis* x *E. urophilla* hybrids and *E. urophilla*, respectively. These species are widely used in genetic improvement programs in Brazil to boost volume productivity and to obtain highly productive clones (Binkley et al., 2017; Stape et al., 2010).

The **after digester efficiency** has a positive correlation with wood density and a negative correlation with size regularity of the chips (Foekel, 1974). The size regularity of the chips does not correlate with any forest management variable, though. Therefore, for simplicity, the same average regularity was used for all groups. Average wood density values per age of MatGen1, MatGen2, and MatGen3 groups were used to build the curves showed in **Figure 27**.

The initial situation of the plantation reflects the characteristics of the three groups of genetic material. This situation is represented by the distribution of hectares among age classes, also considering how density classes distribute within each age class. The initial situation can be depicted in **Figure 28**. Group GenMat3 with highly productive clones in terms of volume, but lower quality in terms of wood density, prevails in most age classes. Group GenMat1, the most desirable by mill managers due to its high density, is relatively less represented in each age class.

Figure 28 - Initial Area

Due to the high productivity plantations in terms of volume, and general low wood densities, the case study considers that pulp mill managers are requiring higher densities and want to evaluate the hypothesis that larger rotations would increase mill productivity. Therefore, *Romero*® was configured as a DSS simulator to evaluate the consequences of harvesting the Eucalyptus plantations at older ages.

Before setting older ages, new rules were also set to allow for genetic material change after clear-cuts, as shown in **Figure 29**. The transition types *c/1*, *c/2*, and *c/3*, represent clear-cuts; the *c/1* clear-cuts and re-establishes the plantation with GenMat1, *c/2* with GenMat2, and *c/3* with GenMat3. After an intervention of type *c/1*, it will be alternatively possible to have interventions of all three types (*c/1*, *c/2*, *c/3*). **Figure 29** also shows the *ina* transition type, which represents the initial status of the forest. After an intervention of type *ina*, interventions *c/1*, *c/2*, or *c/3* may follow; and *ina* does not change the value of any forest attribute.

Figure 29 - Intervention rules

Figure 30 shows that transition types *cl1*, *cl2* and *cl3* are all possible in this scenario. All of them end a forest cycle, reset the age to zero when they happen, renew the plantations, and define the productive transition according to the production parameter associated with it. Each one of the transition types, *cl1*, *cl2*, and *cl3* triggers a change in the values of attributes *c*, *r*, *sp* for the forest plantation (**Figure 29**). Attribute *u* (management unit) remains the same *u*, but attribute *c* (cycle) turns into *c+1*, attribute *r* (rotation) turns to *1*, and attribute *sp* (species) turns to *cl1*, *cl2* or *cl3* depending on the transition type.

Transition Type	Possible	CycleEnd	ReStartAge	Plantation	Production
cl1 cut plant gen mat 1	✓	✓	✓	✓	✓
cl2 cut plant gen mat 2	✓	✓	✓	✓	✓
cl3 cut plant gen mat 3	✓	✓	✓	✓	✓
ina Initial Area	✓	✗	✗	✓	✗

Figure 30 - Transition Types

Furthermore, interventions of the types *cl1*, *cl2*, and *cl3* may be repeated for a set of possible harvesting ages. This case study considers three scenarios (**Table 19**), each one for a distinct set of ages. Scenario 216 considers rules that allow harvesting at ages 5, 6, and 7 years old. Scenario 217 allows ages 6, 7, and 8; and scenario 218 considers ages from 6 to 9 years.

Table 19 - Allowable harvesting ages

Scenarios	Allowable ages
216	5, 6, 7
217	6, 7, 8
218	6, 7, 8, 9

*I*Gen, described in **Chapter 6**, uses the rules described in previous paragraphs to generate alternative forest prescriptions that can potentially meet mill requirements regarding higher wood density. Besides wood quality, the mill also imposes further requirements such as:

- regulated wood flow,
- genetic diversification to mitigate risk exposure to plagues and diseases,
- and production sustainability.

A regular wood flow is imposed from period 2 on, in the form of a 10% max declining and 25% max increase to the amounts of two consecutive years. For safety reasons related to plagues and diseases, the total area planted to supply the mill must have simultaneously (i) less than 60% of the planted area covered by one single genetic material type and (ii) each one of the three genetic material types must represent at least 20% of the planted area. In other words, the mill wants to guarantee that they will always have at least three distinct genetic material groups producing pulpwood.

Regarding production sustainability, the age class constraints were included in the model to guarantee a reasonably well-regulated plantation forest at the end of the planning horizon. Therefore, age class constraints allowing for up to 10% variation in between age classes were set, which means that one age class can have up to 10% more or less area than the adjacent age class. **Table 20** summarizes the mill requirements.

Table 20 - Mill requirements

Requirements	Implementation
regulated wood flow	From period 2 on
	No decrease above 10%
	No increase above 25%
genetic material safety	60% maximum area for any MatGen type
	20% minimum area for any MatGen type
and production sustainability	Age Class control
	10% flexibility

The initial situation of the forest plantations, all forest managers' demands, as well as previously described mill requirements were applied by setting the *Romero*®s parameters defined in **Section 6.2.4**, and *Romero*®s constraints defined in **Sections 6.2.9** and **6.2.10**. **Table 21** summarizes the correspondence between model and case study for the plantations and pulp mill parameters. **Table 22** does the same for the constraints.

Table 21 - Parameters implementation

Parameter	Application
$pIniArea_u$	area (in ha) of each of the 18 units u , with a total of 21,400 ha
$pProductivity_{ttype, rg, sp, a, prd}$	the productivity (in m ³ /ha) of only one region $rg=1$, which is growing the species $sp=1, 2$ and 3 , of the product $prd=1$ (pulpwood), for ages a between 5 to 9, for all transition types $ttype = cl1, cl2$ and $cl3$.
$pPrice_{p, sp, prd, m}$	50 R\$/m ³) in only one market $m=1$, will pay to the product $prd=1$ (pulpwood), for all species $sp=1, 2$ and 3 in all periods $p=1$ to 19.
$pSlvCst_{ttype, rg, sp, a}$	R\$9,500/ha of silvicultural operations distributed from age 0 to 9, for the region $rg=1$, since a transition $ttype = cl1, cl2, cl3$ occurred in a forest that the species $sp = 1, 2$ or 3 are growing.
$pDiscRate_p$	7% a year.
$pPrdConversion_{r, sp, a, prd, millprd, m}$	has the values of the graph “After Digester Efficiency” shown in Figure 27 , which is the rate of conversion from pulpwood in m ³ , into ton of dry pulp, for the production region $r=1$, forest product $prd=1$ (pulpwood), $millprd=1$ (dry pulp), market $m=1$.

The values of **Table 21** are all saved into the database because they belong to the forest project, and they remain available during the calculation process. The values that compose the constraints presented in **Table 21** are stored in XML files and are available at the beginning of the process while *Romero*® is building the model. These last ones are not considered data from a forest project, but preferences regarding the optimization scenario.

Table 22 - Constraints implementation

Statement	Constraint Name	Application
Initial Area Statement(50)	<i>Initial Area</i>	Initial area of the 18 forest management units.
Production flow control Statement (53)	<i>PrdFlowMin</i> <i>PrdFlowMax</i>	regulated wood flow <i>pFlowIncrease</i> = 25% <i>pFlowDecrease</i> = 10%
Genetic material security Statement (52)	<i>GenMatCtrlMin</i> <i>GenMatCtrlMax</i>	genetic material security <i>pGenMatMin</i> = 20% <i>pGenMatMax</i> = 60%
Forest Regulation: AgeClass Control Statement (51)	<i>RegulationMin</i> <i>RegulationMax</i>	production sustainability, <i>pRegControl</i> = 10% age ranges from 1 to 6

After setting the initial situation, requirements, and acceptable prescriptions to the future management of the forest, it is possible to return to the original conflicts and define them as needed. *MaxNPV*, listed as objective number 6 in **Table 17** was chosen to represent forest managers' aspiration; *MaxNPV* is the amount to be maximized as it expresses forest profits by means of the accounting variable *xTotalNPV* defined in **Section 6.2.6**.

MaxMillPrd, listed as objective number 3 in **Table 17** was chosen to represent the pulp mill managers' aspiration; *MaxMillPrd* is the amount to be maximized as it expresses mill production by means of the accounting variable *xTotalMillPrd* defined in **Section 6.2.6**. Additionally, one more criterion will be chosen to represent the environmental concerns due to the facts that environmental issues pressure both sides. So, *MaxStck*, listed as objective number 8 in **Table 17**, was chosen to express the environmental concern of maintaining an adequately well-regulated and well stocked standing forest by the end of the planning horizon; *MaxStck* is the amount to be maximized as it expresses wood stock at the end of the planning horizon by means of the accounting variable *xTotalStock*.

The objective functions built to calculate the three chosen objectives (*MaxNPV*, *MaxMillPrd*, *MaxStck*) depends on two sets of decision variables x_i and $xMarket_{p,sp,prd,m}$ defined in **Section 6.2.5**. x_i refers to the amount of area in which will occur the intervention *i*. while $xMarket_{p,sp,prd,m}$ refers to the amount of product *prd*, produced with the wood of species *sp*, will be delivered to the market *m* in period *p*.

Finally, once agreements have been reached upon the definitions mentioned in previous paragraphs, it is possible to schematically summarize the model that represents the case

study. *Romero*[©] was used to precisely set up flexible sets for the parameters, run different scenarios adequately handling possible combinations of the sets of parameters, and report the results. **Statement (57)** shows the multiobjective linear programming (MOLP) model.

$$\begin{aligned}
 \text{Eff } f(x_i, x\text{Market}_{p,sp,prd,m}) = & [\text{MaxNPV}(x_i, x\text{Market}_{p,sp,prd,m}), \\
 & \text{MaxMillPrd}(x_i, x\text{Market}_{p,sp,prd,m}), \\
 & \text{MaxStck}(x_i, x\text{Market}_{p,sp,prd,m})] \\
 \text{Subject to :} \\
 & \text{InitialArea} \\
 & \text{AreaBalance} \\
 & \dots \\
 & \text{all accounting variables} \\
 & \dots \\
 & \text{RegulationMin} \\
 & \text{RegulationMax} \\
 & \text{GenMatCtrlMin} \\
 & \text{GenMatCtrlMax} \\
 & \text{PrdFlowMin} \\
 & \text{PrdFlowMax} \\
 & \dots \\
 & \text{all deviation variables} \\
 & \text{all attribute variables}
 \end{aligned} \tag{57}$$

The first sentence of the MOLP in **Statement (57)**, states that this model seeks efficient solutions that satisfy three objectives: *MaxNPV*, *MaxMillPrd*, *MaxStck*, which, on its turn, depends on the set of decision variables x and $x\text{Market}$. Likewise, the feasibility set of these decision variables is defined by the list of the constraints, which also depends on the same decision variables x and $x\text{Market}$.

The model in Statement 55 also shows that all accounting variables and deviation variables will be calculated and will have the result values saved into the database. As explained in **Chapter 6**, this procedure is made to guarantee analyses related to attributes defined in **Table 17**, even though they do not belong to the chosen criteria set.

7.3.Results

This section presents initially a subset of results obtained for the many scenarios that could be created as described in the previous section. Three scenarios were created by *iGen* module combining different harvest ages, limiting the choice of ages allowed for the creation of scenarios considering only short, medium, or long rotations as forest management prescriptions.

Table 23 shows the main results for the three strategies limiting the interventions generator (*iGen*) to shorter rotations (harvesting at ages 5, 6, and 7 years), mid-range rotations (harvesting at ages 6, 7, and 8 years), and longer rotations (harvesting at ages 6, 7, 8 and 9 years). For each scenario, the corresponding MOLP (multiobjective linear programming) problem optimized all criteria, one at a time, with the other unconstrained.

Table 23 - Case study main results

Scenario	Ages (years)	Highest NPV (R\$)	Lowest NPV (R\$)	Forest NPV reduction	Highest Pulp Production(t)	Lowest Pulp Production(t)	Mill Production Reduction
216	5,6,7	262,293,353	224,246,933	16.97%	5,149,727	4,845,076	6.29%
217	6,7,8	266,445,003	232,677,252	14.51%	5,022,290	4,671,327	7.51%
218	6,7,8,9	266,612,275	232,677,252	14.58%	5,022,290	4,656,634	7.85%

The maximization of NPV, with pulp unconstrained, resulted in maximum NPV values reported as Highest NPV and pulp production values presented as Lowest Pulp Production. Likewise, the maximization of pulp production, with NPV unconstrained, resulted in maximum pulp production values reported as Highest Pulp Production and NPV values as Lowest NPV. Due to the conflicting nature of these two criteria, as one increases, the other decreases. The differences observed between the highest and lowest NPV are reported in **Table 23** as “*Forest NPV Reduction*”. The differences observed between the highest and the lowest Pulp Production are reported as “*Pulp Production Reduction*.”

All three scenarios show that, from the perspective of the forest managers, the differences between the best and worse outcomes causes reductions varying from 14.6% to close to 17% in NPV if the mill manager criteria (max pulp) prevails. On the opposite side, from the perspective of the mill manager, the differences between the best and worse outcomes cause reductions varying from 6.3% to close to 8% in pulp quality if the forest manager criteria (max NPV) prevails.

Table 23 presents interesting and unexpected results. One is that the most significant reduction on NPV occurs in the shorter-rotations scenario 216, precisely the ones prevailing currently in Brazil. Another interesting result is that the optimal and non-optimal value of total NPV increases when mid-range and longer rotation scenarios are compared to shorter rotation scenarios. That seems counterintuitive to the current preferences for shorter rotations expressed by Brazilian forest managers, and leverage for mill managers in favor of optimizing pulp production.

The reported results demonstrate how conflicting interests expressed by the two groups of stakeholders, forest managers, and industrial managers, can create fairly different outcomes. Consequently, multi-criteria analysis becomes adequate to evaluate the tools provided by *Romero*®. The use of *Romero*® framework to support the multi-stakeholder team of managers would start by defining the minimum and maximum age that foresters would be allowed to harvest the eucalyptus plantations.

Considering the three scenarios presented in **Table 23**, and as described in **Section 7.2**, the simulation would start by confirming the parameter values in a window like the one presented in **Figure 17** and asking *Romero*® to run. The simulation finishes when *Romero*® shows the results window like **Figure 18**. **Table 24** summarizes the time performance of *Romero*® when running each scenario.

Table 24 - *Romero*® Performance

		Scenarios		
		216	217	218
number of constraints		53,304	23,280	38,049
number of variables		76,588	33,145	55,096
time consumption (min:sec)				
<i>IGen</i>		00:01.0	00:01.0	00:02.0
Mem structure optimization		00:01.0	00:00.0	00:00.0
Building abstract model		00:01.0	00:00.0	00:00.0
Building concrete model		21:21.0	03:44.0	12:33.0
Solving 1st criteria & save results	<i>MaxNPV</i>	00:19.0	00:07.0	00:11.0
Solving 2nd criteria & save results	<i>MaxStck</i>	00:18.0	00:06.0	00:12.0
Solving 3rd criteria & save results	<i>MaxMillPrd</i>	00:19.0	00:07.0	00:12.0

The number of decision variables and constraints in each scenario varies from 33,145 and 23,280, respectively, in the mid-rotation scenario 217, up to 76,588 variables and 53,304 constraints in the short-rotation scenario 216. Obviously, the more variables and constraints

Romero® had to deal with, the most time-consuming becomes the data processing. The most time-consuming step is the concrete model building routine when the abstract model is populated with numerical data. The larger the model, naturally, the longer it took for building the full populated model.

As observed in **Table 24**, the short-rotation scenario took 21 minutes and 21 seconds to be fully populated with data, and the smallest model took only 3 minutes and 44 seconds. It is worth noting that although lengthy, this is not relevant when it gets to the phase when stakeholders seek a consensus. At that point, with the model fully specified, *Romero*® will be cycling through solving, changing the values of the few parameters defining the next objective, and solving again. As seen in **Table 24**, these steps run relatively faster than the concrete model building step (6 to 7 seconds for the smallest problem, and 18 to 19 seconds for the largest problem).

Scenario number 217 is now used to illustrate the most important features of the analysis provided by *Romero*® framework to facilitate the search for consensus between stakeholders. A third aspiration was included to add more substance to the analysis. It considers the consequences of regulating the annual mill wood demand at the same time that the standing wood stock at the end of the planning horizon is maximized. NPV and pulp parameters were only accounted and left unconstrained.

A pay-off matrix was built to evaluate the scenario and to allow us to see in more details the conflicting results in terms of NPV (MaxNPV), pulp production (MaxMillPrd) and (MaxStck). **Table 25** shows the resulting pay-off matrix. The test was done using the mid-range rotations scenario because it was considered as a good starting point due to its conciliatory nature of not tending to any of the other two opposites (very short and very large rotations). It allows for harvests to happen in 6, 7, and 8-year-old stands.

The simulation test invites forest managers and mill managers to explore the uncompromised solutions and to debate relaxations on expectations and commitments to find a path towards an agreement. *Romero*®'s capacity to support the two groups of managers on this task starts with discussions around the payoff matrix (**Table 25**).

The first column of Table 25, "Clear-cut area" refers to a summation of all area harvested during the planning horizon, while the column "Production" reports the total volume produced in these cuts. So, from this two information, it is possible to get the average of productivity along with the horizon.

Table 25 - Scenario 217 Payoff matrix

Criteria	Clear-cut Area (ha)	Production (m ³)	Productivity (m ³ /ha)	%Max Stock	Forest NPV (R\$)	Pulp Production (t)	Final Stock (m ³)
MaxNPV	82,992	19,708,408	237	88.42%	266,445,003	4,671,327	624,349
MaxMillPrd	84,622	18,856,363	223	91.79%	232,677,252	5,022,290	648,120
MaxStck	81,695	18,335,678	224		239,414,189	4,801,415	706,102

The payoff matrix expresses with numbers the consequences of emphasizing conflicting aspirations. The search for a consensus starts with a discussion among stakeholders about the first round of values found for the payoff matrix. It is assumed that the two groups of conflicting managers, foresters and mill, come into an agreement on how far they would like to be from the final stock constraint. Therefore, for simplicity, the results from this point on are shown considering only the two original groups of stakeholders.

Figure 31 shows the resulting annual flow of pulpwood when each criterion is maximized separately. It is worth noting the striking differences in how the eucalyptus plantations evolve along with planning horizon in terms of how MatGen groups of hectares distribute annually. Visibly, the **MaxNPV** criterion manages the stands in favor of relatively larger participation of GenMat3 (the lower density set of clones). The **MaxMillPrd** criterion gradually replaces GenMat3 with GenMat1 and manages the plantations leading to relatively more significant participation of GenMat1 in the future.

Figure 31 - Pulpwood supply per genetic material

Figure 32 shows the relative quality of the delivered pulpwood in terms of what age classes the logs were harvested from. Relatively larger participation of logs from older trees seem to

be a trend in the future but is not so evident at the beginning and midterm planning horizon. Conversion rates were expressing more intensively how density increases with age and the use of logs from longer rotations would be more significant. Anyhow, maximizing pulp changes effectively the annual composition of logs in terms of age classes they were cut from.

Figure 32 - Pulpwood supply per age

An agreement would not be in any of the extreme points, and the two stakeholders would be willing to verify the trade-offs between the two criteria. Twenty points were calculated between the two extreme ones using the constraint method. **Figure 33** shows the Pareto frontier that is the trade-off curves between the two criteria.

Figure 33 - Pareto Frontier

Further support to reach a consensus can be obtained with the help of the Pareto frontier graph. It visually expresses the tendency of the consensual solution towards one stakeholder or the other. It may also help as a tool during the discussion to mitigate eventual tendencies of

one part become more influential or powerful than the other and help both sides chose a consensual solution.

In this stage of the analysis, compromise programming leads one step more towards the consensus. **Figure 34** shows the Compromise interval considering that the relative importance between forest and industrial managers are even. **Table 26** demonstrate how the distances were calculated.

Figure 34 - Compromise Programming

The theoretical optimum point is where the best for both stakeholders would be simultaneous. In this point, reported as “**Optimum**” in **Figure 34**, NPV assumes its higher value R\$ 266,445,003; also, Pulp production assumes its higher value 5,022,290. The distance function calculates the distance from any point over the Pareto frontier to this theoretical optimum point.

Line segment **a** (**Figure 34**) is the distance between the point L_{∞} and the industrial managers’ best value, and **c** (**Figure 34**) is the distance between the point L_1 and the industrial managers’ best value. Likewise, **b** and **d** are distances from L_{∞} and L_1 to forest managers’ best value. The sum of the distances from point L_{∞} to the Optimum point is **a+b**, and a sum of the distances from point L_1 to the Optimum point is **c+d**. Herein this distance from the optimum point is called a loss.

As explained in **Section 6.1.3**, L_1 corresponds to the point in which the distance from the Optimum point is the minimum of the sum of both losses (line segments **c+d** in **Figure 34**). In

other words, it is the point where they lose less together. On the other hand, L_∞ is the minimum of the max between them, which corresponds to the line segment **a** in **Figure 34**. This L_∞ point means where there are no noteworthy losses for none of the stakeholders.

Table 26 presents the calculations. It shows details of only three points of the Pareto frontier. The 9th point of the L_∞ point and the 11th point is the L_1 one. The columns “Best Value” and “Worst Value” repeat optimum point’s values. The column “Interval” refers to the difference between the best and the worse values. “Distance” column presents the distance between the point and the line that cross the optimum point and it is calculated according to the **Statement (58)**.

Table 26 - Compromise Programming

Point	Criterion	Value	Best Value	Worst Value	Interval	Distance	Sum	Max
9	MaxMillPrd	4,879,406	5,022,290	4,671,327	350,963	a 0.4071		
9	MaxNPV	254,004,253	266,445,003	232,677,252	33,767,751	b 0.3684	0.7755	0.4071 L_∞
10	MaxMillPrd	4,900,167	5,022,290	4,671,327	350,963	0.3479		
10	MaxNPV	252,227,003	266,445,003	232,677,252	33,767,751	0.4210	0.7690	0.4210
11	MaxMillPrd	4,919,484	5,022,290	4,671,327	350,963	c 0.2929		
11	MaxNPV	250,449,753	266,445,003	232,677,252	33,767,751	d 0.4736	0.7666	0.4736 L_1

$$Distance = \left| \frac{(BestValue - Value)}{(BestValue - WorstValue)} \right| \quad (58)$$

As explained in **Section 6.1.3**, according to Yu theorem, the utility curve touches the Pareto frontier at some point between L_∞ and L_1 . Point 10 of **Table 26**, which is located between L_∞ and L_1 (**Figure 34**), for the purpose of this exercise, can be taken as a good compromise.

Even if the decision makers agree on selecting point 10, within the compromise interval, they may need a more in-depth understanding of this particular solution. Therefore, to illustrate how *Romero*® can be useful on supporting a multi-stockholder team of decision makers, point 10 was selected to be investigated if it converges to meet decision-makers’ needs.

The same graphs showed in **Figure 31** and **Figure 32** are rebuilt now using data from the solution of the Pareto Frontier point 10. While previous figures showed the extreme solutions, now, in **Figure 35** and **Figure 36**, it is possible to see a balanced solution that might be taken as a compromise.

Figure 35 - Genetic Material distribution

In this particular solution, the solution strategy chose to emphasize the adoption of GenMat2, which is the intermediate group of genetic material in terms of forest productivity in volume, wood density, and industry efficiency. Gradually, the plantations with GenMat3 and GenMat1 were substituted by GenMat2 until it reaches the maximum possible for a group of genetic material, which is 60%. Meanwhile, the other two groups, GenMat1 and GenMat2, achieve the lowest level for each group that is 20%.

Figure 36 - Clear-cut ages distribution

Likewise, the solution strategy chooses younger ages at the beginning of the planning horizon, and gradually changes the standard to 7 years old until achieve 100% of the harvest of this intermediate age.

The results shown in this section for one case study illustrates how *Romero*[®] can support large-scale multi-stakeholder's decision processes and, at the same time, comply with the assumptions established in this thesis for the development of consistent decision support systems. Larger problems, either in terms of total number of decision variables or stakeholders and conflicting aspirations, can be handled by *Romero*[®]. In fact, any problem involving a large number of decision variables and stakeholders can be addressed by the *Romero*[®] framework, provided that the parties involved in the negotiation are willing to seek consensus guided by the compromise programming principle. Next section discusses the results summarized in this session, points to some of the strengths of the methodology suggested in this thesis and stipulates some improvements still needed as the approaches suggested here evolve.

8. DISCUSSION

It is essential to start the discussion retrieving the FORSYS study findings described in **Chapter 4**, as they summarize current main concerns of forest decision-makers. One of the most critical concerns, which is the need for using different approaches to promote participatory planning processes and stakeholder's involvement is addressed in this thesis. **Chapter 2** points out that DSSs developed to manage industrial forest plantations in Brazil have not promoted multi-stakeholders' participation. The essential features and an overview of how FMDSS could integrate models and methods to deal with a team of decision makers involving multi-stakeholders were described in **Chapters 6** and **7**.

An equally important concern, raised by the FORSYS study, regards knowledge management. End-users and decision-makers argue that current IT approaches on knowledge management have not been applied in a forest management context. The thesis addresses this critical issue in **Chapter 5**, showing how it has influenced the development of the *Romero*[®] framework.

A third crucial issue, also raised by the FORSYS study, deals with the relationship among academia, complexity, and usability. This issue is discussed in the following sections in the context of the case study presented in **Chapter 7**. The final part of the discussion presented in this chapter focuses on the observed outcomes of integrating the suggested model and methods into the *Romero*[®] framework, as observed in the case study.

For the sake of coherence, the discussion follows the same order of presentation of results observed in previous chapters, also bridging eventual relationships among chapters and subsections. **Section 8.1** focuses on discussions about the outcomes of **Chapters 4** and **5**, and their relation to the components and features of the *Romero*[®] framework. **Section 8.2** summarizes a discussion about the performance of the *Romero*[®] system when applied to the case study.

8.1. FMDSS in Brazilian Plantations and globally

8.1.1. Demands for Participatory Planning and Multicriteria Analysis

FORSYS case study findings will be discussed in the order of importance implied by the instance, and country occurrence counts of LL by theme contained in **Table 10**, which were

derived from the opinions of the CRs authors. Participatory processes, and hence also technologies to support participatory planning stood out above the other topics. The perception is that there is a substantial collection of models and methods available, enough to address a broad spectrum of contemporary forest management problems. This discernment accord to the literature review presented in **Chapter 2** that says current FMDSS include models, methods to address aspects related to production and environmental management (Fontes et al., 2010; Marques et al., 2013; Rammer et al., 2014; Vescoukis et al., 2012; Wei et al., 2014).

The issue raised through the LL would appear to be how to use models and methods effectively within the context of participatory planning, which aims to provide further legitimacy to planning decisions by involving a community of stakeholders. However, digging into the data from the structured survey, MCDM, a critical technology that could support participatory planning, was not frequently employed in FMDSS. The use of MCDM methods was limited to a few countries, and when applied, involved fairly sophisticated methods. Stakeholder involvement was more commonly through archaic techniques such as meetings, surveys, and interviews.

Belavenutti et al. (2018) are in accordance with FORSYS findings regarding the limited use of MCDM techniques in countries like Brazil. Acosta and Corral (2017), as well as Esmail and Geneletti (2018), also detected on their review that the most MCDM techniques applied to FM are not the ones that allow conveying, and debating opinions and responsibilities. Moreover, Bruña-García and Marey-Perez (2014) concluded in their work that there is a lack of training which prevents people from facing the participative processes which are in line with FORSYS researchers' complaint about the sophistication of the DSS. *Romero*®

Therefore, these FORSYS outcomes, reinforced by recent literature, led this research work to apply MCDM techniques to an FMDSS focused in industrial forest plantations. Besides MCDM, *Romero*® was prepared to address interaction among stakeholders. The case study results presented in **Chapter 7** shows the capability of *Romero*® to support active involvement. It can promote conveys and debates about alternative solutions. Furthermore, due to the transparency of the attribute values and information on possible impacts of the solution, as demonstrated in the case study, *Romero*® can guide to a compromise solution where stakeholders assume responsibilities regarding the decision.

8.1.2. Demands for Knowledge Management

KM may be seen by few as a confusing area. Some participants in the FORSYS study struggled to grasp the concepts and implications. Nevertheless, the literature review points out to the need of KM integration to the FMDSS (Bagstad et al., 2013; Gordon et al., 2013; Vacik et al., 2013), and to the relatively few specific KM implementations documented by members of the FMDSS community. It seems like the forestry community is at the beginning of a learning process: there was a realization that KM is required to harness the full power of FMDSS, which draw on a large amount of knowledge that needs to be curated and generate large amounts of information for analysis within decision making. However, a lack of understanding of the basic concepts and the processes through which analyses can convert information into knowledge is hampering the implementation of KM. At this stage, KM may be considered as a frontier ready for development in FMDSS and will likely be the focus of future technology improvements.

The lack of understanding how data, information, and knowledge interconnects in forestry points to the necessity of further research in this area. It is the reason why this thesis embraced this topic, in search of a method to incorporate KM concepts into an FMDSS. **Chapter 5** presented a generalizable conceptual model that builds upon an initial knowledge base that evolves "by learning." Two specific mechanisms that collect and treat data from ecological indicators in each of the two planning and monitoring component phases considerably reduce the design effort.

Moreover, the design proposed in **Chapter 5** promotes the maintenance of an auto-updatable knowledge base that internalizes creativity into the planning and monitoring of integrated processes. The integration of the two main building blocks, planning, and monitoring, into a single conceptual model supported by a knowledge base that learns as it evolves, expands the benefits of working with knowledge bases solely built upon scientific information. The result was a conceptual model that incorporates many of the desirable characteristics published by experts in the related literature (Blount et al., 2016; McDill, 2014; Rauscher et al., 2007).

An intelligent monitoring process is achievable as the continuously updatable knowledge base adapts itself, maximizing performance, minimizing the negative impacts of failures, and gradually increasing the beneficial effects of the outcomes. Basically, the DSS relies on a continuous improvement loop: (i) read and treat data from processes; (ii) transform data into knowledge by checking indicators and updating the knowledge base; (iii) use knowledge to update policy guidelines; (iv) update recommendations; and (v) read and treat data from processes again.

The development and implementation of the monitoring component of the conceptual model in the case study presented In **Chapter 5** is a large and multifaceted project still under development. Currently, the implementation of the monitoring component is being expanded gradually by IT resources that will allow for the participation of the many stakeholders, including landowners, agricultural extension professionals, and others. Limited to a region in the state of São Paulo, the exercise was conducted with the expectation to have its use expanded to the rest of the state and even to other states in Brazil.

Consequently, it is essential to highlight how **Chapter 5** results have constructively guided *Romero®* architecture. Firstly, the possibility to include new alternative prescriptions without having to redesign the data structure of the parameters, given by *IGen* module, is the main contribution of the conceptual monitoring models. Monitoring information treatment usually indicates changes in the way the forest is managed, and *Romero®* allows prescription updates naturally. **Chapter 7**, through the age rotation case study, gave an example of this kind of dynamics when stakeholders ask for new forest management shape. Not to mention that the attributes calculated under the multicriteria conceptual framework provide the stakeholders with the means to test their hypothesis and achieve their aims.

Secondly, the independence of the mathematical model from the structure of the parameters, described in **Sections 6.4.1** and **6.4.2** allows the creation of new attributes and the easy inclusion in the math model. When stakeholders need to create new attributes to test their hypothesis, after updating the math model, this new attribute is a new item in variables table in the database, and all the results will accordingly be integrated.

So thirdly, initial area and costs information are results of a summarization of the detailed monitoring data about forest operations. This summarization is precisely the “*data treatment*” process proposed by **Chapter 5** models. “*Data treatment*” procedures should generate initial area and costs information in a flexible structure of *Romero®*; the “*planning processes*” would naturally work.

The on-going tests of the proposed monitoring generalizable model in other case studies and situations are triggering further research and evaluations. As prescribed by the proposed process itself, these tests are producing new references potentially useful for the improvement of the current knowledge base used by the conceptual model in the state of São Paulo. Given the adaptive nature of the proposed conceptual model and its high level of resilience, the expectation is that the system will survive the implementation phase and

become an efficient way to help the Brazilian government achieve its forest restoration targets and commitments.

Similarly, against the background of generalization, data from different situations of plantations were used to hasten the model and architecture improvement of *Romero*® and presented to experts and forest managers to be criticized. Regarding the evolution of the system, the expectation is that *Romero*® would achieve its aim of being a reference to the industrial forest plantation due to its flexibility as well as in the case of São Paulo monitoring model.

However, considering KM issues, the “data treatment” subprocess that could generate ready-to-use planning parameters related to costs, prices, and productivity still should be developed to integrate *Romero*®. The structure of these parameters should be improved according to further research efforts. Likewise, further development has to be done to connect the attributes of the management plan and future monitoring indicators. Comparing the planning attribute values and future outcomes are crucial to feeding the adaptive management and intelligent monitoring as proposed by **Chapter 5** results. Meanwhile, planning attributes are already structured and stored in the database ready to be queried.

8.1.3. Academia, complexity and usability

Next, in order of importance came the involvement of academia. Authors’ opinions taken from the FORSYS country reports were multi-faceted. Training provided from academia was highlighted as the primary route through which forest managers could gain expertise on FMDSS, and very much taken as a definite positive. Academia as a repository of expertise for the development FMDSS for subsequent deployment was also viewed positively. However, the tendency for academia to add complexity to applications did elicit some negative comments. It may lie behind the view that MCDM techniques are rather complicated and indicate that academia has sometimes contributed with too much sophistication. How these issues of complexity and sophistication as blocks to technology transfer from academia can be addressed remains uncertain, and should be an area of concern, as moves to introduce KM techniques and tools, which were poorly understood in the wider forestry community, into FMDSS appear to be the next frontier for development.

Romero® is a response to the demand described in the previous paragraph. It creates a unique platform where MCDM techniques were applied to an FM problem upon a SQL database

prepared to be integrated into monitoring systems. However, the sophistication could not be avoided due to the complexity of the problem itself. The flexibility cannot be achieved without a good grade of sophistication and the use of recent available IT resources. According to Lutowsky (Rick Lutowski, 2005), what should be done in this kind of situations is encapsulate the complexity inside a user-friendly interface.

Therefore, *Romero*[©] has made the first steps towards this encapsulation. A user-interface was created to update planning parameters, and to query decision, accounting, and attribute variables values. It is also possible to inform the solver about the optimization preferences and criteria, as well as to see the main graph results like the Pay-off matrix, Pareto frontier, and production graphs of any scenario. However, there is much more to be done to improve the user experience and achieve what FORSYS CRs authors required.

The right balance between complexity and the necessary inclusion of features to fully support the decisions of those involved in the planning is unreachable. However, nearness must be pursued. The use of the available technology with creativity and involvement of the stakeholders can lead us to better approaches to a reasonable FMDSS. The challenge is to find a fair balance between flexibility, complexity, and usefulness.

8.1.4. Demands for up to date models and methods

“Models and Methods” are the next; various areas for improvement were evident in this field from the responses of the CRs. Quantitative models associated with timber production have a long history and were well represented in the survey, specific applications within larger FMDSS were growth prediction, harvest operations, and logistics. In contrast, the modeling LL reflected the lack of both ecological models, which are required for the prediction of phenomena beyond tree growth, and descriptive models. As more functions of the forest ecosystem are recognized, we need to make improvements and advances within “Models and Methods” domain to solve new types of forest management problems.

Those findings related to models reinforce the idea of having flexible models that allow easy inclusion of new criteria, variables, and constraints demanded by the latest environmental and political challenges. However, enlightened by the discussions in **Section 8.1.3**, one could argue that the more flexibility it is given to the system, the more complicated it will become. This paradox might be solved by choosing a flexible tool to design mathematical programming models that could be embedded in a FMDSS.

Therefore, **Pyomo** (Python-based, open-source optimization modeling language), an AML (Algebraic modeling language), was chosen to take part of the *Romero*®'s technology set due to its flexibility to maintain and add new variables and constraints to the model. Pyomo proved its flexibility by allowing the creation of several attributes representing alternative needs of the stakeholders.

The structure of the model, precisely the systematic way to build the groups of constraints and variables such as decision, accounting, deviation, and attributes, allows the adding of new needs easily. Additionally, Pyomo, through this systematic organization, made it possible choosing desirable criteria, as shown in **Figure 17** and adding criteria in the list.

However, since the model is specialized in forest plantations, the proposed model can deal only with variables related to production and forest operations, or those that can be calculated using production values and additional parameters. Nevertheless, if it is possible to represent ecosystem services as a function of the area, it will be possible to include them into the model due to the *Romero*® possibility to deal with multiple products.

8.1.5. *Romero*®'s practical applicability to industrial forest plantations

FORSYS CRs reported 96% of the described forest problems related to production, and they occur in all countries but one. Therefore, considering the discussions of the previous section, *Romero*® is appropriated to the forest community needs. However, only 28% are similar to problems that *Romero*® is prepared to solve, which are “*strategic problems*” that address “*forest level*”⁴ situations. Nevertheless, in Brazil CR, 100% are “*strategic problems*” that address “*forest level*” situations (Rodriguez and Nobre, 2014).

Moreover, according to FORSYS country reports, 34% of the problem types reported by FORSYS CRs involves more than one decision maker, potentially they could be approached with MCDM. However, only 50 of the DSSs reported in the FORSYS study use MCDM techniques. Most importantly, they are not in Brazil (Rodriguez and Nobre, 2014). Regarding problems to address, *Romero*® has broad applicability to Brazilian production problems. Further case studies should be conducted to evaluate their capabilities in different situations.

⁴ In FORSYS context, “*forest level*” means problems focused on landscapes with several stands managed for common purpose(s).

Considering participatory planning, only 16 of the 26 FORSYS country reports mention this approach on their planning processes, and only ten countries reported instances of the use of MCDM techniques in FMDSS. Moreover, four countries report on their specific application within participatory planning processes. Even though the literature recommendation (Acosta and Corral, 2017; Bruña-García and Marey-Pérez, 2014; Diaz-Balteiro et al., 2016b; Ezquerro et al., 2016a; Segura et al., 2015), only 16% of the participatory planning processes reported by FORSYS CRs are supported by MCDM techniques. So, regarding the application of MCDM techniques, *Romero©* contributes to filling the gap that exists on the use of MCDM techniques into FMDSS capable of supporting participatory processes.

8.2. *Romero©* and its application

8.2.1. *Romero©*

A SWOT analysis, from business administration science, is designed to facilitate a realistic, fact-based, data-driven look at the strengths and weaknesses of an organization, its initiatives, or an industry. It is still used to analyze products, frameworks, and information systems (Grošelj et al., 2016; Marttunen et al., 2017; Vahidi et al., 2018). This section will take advantage of this technique to guide the discussions on *Romero©* and its embedded model.

The main weakness of the framework is the need to write pieces of code to create new variables and attributes. Even though the systematic organization of the variables is robust, a specialist in modeling is always required. Besides, **Figure 13** in **Section 6.1.4** describes the recommend (Romero, 1993; Steuer, 1986) that active participation of a modeling specialist can grantee the interaction; therefore, *Romero©* was developed following this recommendation. However, it would be more convenient for this specialist if he could create new variables and constraints with no risks to damage the model code.

Moreover, after creating new constraints and variables, the specialist has to insert new records into the variables and attributes table to allow the integration and the perfect functioning of the “save results” sub-process. It is a significant risk of malfunctioning of the system; *Romero©* should interpret the code and automatically update the variables and attributes table. Pyomo, as an object-oriented library, has specific objects that could be used for this purpose.

The main threat of *Romero©* is also its main strength. The intervention defined in **Section 6.2.1** as “a specific event that happens upon a land unit” is a critical index of the model

because it is the index of the core decision variable set, which is x_i , where i is the intervention. All calculations of accounting variables and consequently, all criteria attributes depend on them. Also, interventions are generated by *iGen*, and they are implemented as a multi-dimensional index. Theoretically, *Romero*® was developed to support different structures of this index. So, *iGen* and the model should support different structures of these dimensions.

Therefore, the model should use only i and never need to get access to i sub-indexes. However, it was not possible to get. Parameters like productivity and costs depend on some sub-indexes. So, it can bring instability to the software and difficulties to achieve the complete independence of i . Moreover, most of the tests, including the case study presented in **Chapter 7** used a composition of this index that might comprise the most common factors that could influence on the generation of the interventions in industrial plantations Brazil.

Regarding *iGen* capabilities, probably there will not be difficulties to achieve complete independence from the structure of i . Actually, it seems to be close to independency already, due to the way the rules are written: the user only can input rules that use the current intervention sub-indexes. Only time, new case studies and further evaluations can bring new elements to promote the improvements of *Romero*® related to this issue.

One potential threat was evident in **Table 24**, which describes *Romero*® performance during the case study runs. *Romero*® log-registration function saved the time consumption of all functions during the process. Clearly, “*Building a concrete model*” is the most time-consuming function of the process. There is no need to compare this time to the performance of other DSSs to realize that this is not an acceptable time considering that a group of stakeholders could be waiting for a result.

Moreover, the correlation of time consumption and number of variables seems to be exponential, which is a relevant problem to any information system. “*Building a concrete model*” is a Pyomo built-in function, that modelers don’t have easy access to it. Great research effort has already been done to reduce this time. A function called “*Memory Structure Optimization*” optimizes the structure of the matrixes that will be input to the “*Building concrete model*” function. It was possible to reduce the time-consuming more than 20 times. However, much more has to be done to guarantee an acceptable time consumption.

There are other characteristics of *Romero*® that could be taken as essential strengths: Solver flexibility and Database management system (DBMS) flexibility. Gurobi and Glpk were used during the development and tests phases. Many others, like CPLEX, Mosek, Xpress, and many

others could be used with Pyomo. A user has to say in the first configuration window his preferences regarding the solver.

It is also true to the DBMS, *Romero*® SQL statements were written using the basic of the language to allow the use of any DBMS. The user has to say where is the database of the project in the first configuration screen.

IGen is the next strength. During the case study analysis and development tests, IGen proved itself to be extremely fast and flexible. While other prescription writers are one of the most complex and time-consuming of the FMDSS, IGen never took more than 2 seconds to generate any set of interventions until now, not to mention how easy it is to create new rules.

A final distinguished strength is the capacity to save the results of all solutions in a SQL database. The values obtained by the solver are saved in tables linked to the variable, scenario, criterion that was being used to optimize and the number of the point when the solution is related to a plot along the Pareto frontier.

A relevant opportunity that *Romero*® development brings to the forest management community, comprised of researchers and practitioners, is its potential use to address other cases of plantations involving production. Theoretically, there are no limitations to its use in any strategic problem focused on production, or anyone that could be solved by model 1 or 2 formulations. However, evaluations should be conducted.

Next set of opportunities is related to the expansion of *Romero*® to use other MCDM techniques but Compromising Programming, like Goal Programming and Lexicographic Method. Actually, Goal Programming is still implemented, but it needs refining in its interface management and the presentation of results. Lexicographic Method, due to the need to optimize one criterion at a time modifying constraints, it would be easy to implement due to the similarity with the already-implemented functions.

A final set of opportunities is related to risk analysis inclusion. Monte Carlo simulation, due to the looping characteristics, has a great potential to be implemented in *Romero*®. Moreover, the integration to a database is an essential function to calculate Monte Carlo simulations due to the need for storage a large amount of data during the calculation process. Preliminary tests have been already made using a MOLP inside a Monte Carlo loop, and they were successful.

Regarding Stochastic programming, the model would be prepared to use Pyomo ready-to-use functions specialized in stochastic programming. To accommodate stochastic models,

Romero© should be expanded to support the selection of a model as a user preference. It would be an interesting expansion that could be used for other purposes.

8.2.2. Case Study

We have proposed to apply MCDM techniques in a new FMDSS to address conflicting situations faced by Industrial forest plantation sector in Brazil. A framework named *Romero©* was developed with this purpose. A case study was used to illustrate an application of *Romero©*; it simulates a vertically integrated pulp company with internal conflicts regarding the quality of wood that is delivered to the mill. **Chapter 7** presented the context, the case study details, and the results of the application. This section discusses the findings obtained by this application.

Table 23 presents an interesting and unexpected result. The most significant reduction on NPV occurs in the shorter-rotations scenario 216, precisely the scenario prevailing currently in Brazil. This reduction from 262 million R\$ to 224 million R\$ would happen if instead of maximizing the forest profits (the NPV), managers decided to maximize mill production. It is interesting to note that this (216) is the best scenario for the mill. The model can find a better value for the mill production (5,144,727 tons) than for the other two scenarios (5,022,290 tons). The best solution for the mill does not come from longer-rotations, but from the possibility to cut at 5 years old and change from GenMat3 to GenMat1 as soon as possible. The second graph of **Figure 31**, which is for scenario 217 shows this effect clearly. It is assumed that in scenario 216, this effect was more intense because the model allowed cutting at 5-years-old.

The second interesting result is that the optimal and non-optimal value of total NPV increases when mid-range and longer rotation scenarios are compared to shorter rotation scenarios. That seems counterintuitive to the current preferences for shorter rotations expressed by Brazilian forest managers, and leverage for mill managers in favor of optimizing pulp production. These results seem to indicate that 5-year-old cuts are good, paradoxically, only for the mill due to the opportunity to replace GenMat3. An in-depth analysis of forest yield curves might show that the maximum MAI is closer to 7 years old than to 5 years old.

Interesting to notice that, also in **Table 23**, no improvements happen when age 9 is added to the set of alternative cut ages. One of the reasons might be the same that explains the mill production apparently illogical improvements with age 5. However, there is one more

significant reason in this context. The graph of **Figure 28** shows that there are 2000 ha of age 5 and 2000 ha of age 6. To accomplish the mill requirements regarding flow production it would not be possible to cut at ages 8 or 9 in the beginning of the planning horizon. Cuts in older ages can only be possible from fourth period on. **Figure 32** confirms this hypothesis.

For the same reason, **Table 24** reports much more variables and constraints for scenario 216, even having the same number of alternative ages as scenario 217. Due to the younger ages, IGen generates more alternatives inside the planning horizon. In model II formulation, the one that has been used in this model, each possible intervention is one variable. Moreover, to link the variables in a tree of alternatives, each node is a constraint.

In an extreme solution, when mill production is maximized, the model conducts to cut in younger ages in the beginning of the planning horizon to replace genetic material group 1 demonstrating that, in this scenario, there are more gains on changing the genetic material than cutting in older ages given the industrial efficiency curves shown in **Figure 27**. Both extreme solutions show that the model led to having the maximum possible of the best group of genetic material for the perspective of the criterion that is being maximized. Even in the compromise solution, the model led to the maximum possible, which is 60% of the area, of the intermediate genetic material group.

From this discussion we can conclude important things: (i) that the initial hypothesis that cutting in older ages could improve the mill production was not confirmed; (ii) this is a long-term process, mill managers cannot ask for changes in a short-term, changes in rotation size and in genetic material takes time and decisions has to be made involving both interests: forest and mill managers'; and (iii) *Romero's* support was essential to consider and inspect all aspects of the solution, it was an information-based decision making process as preconized by literature.

9.

9. CONCLUSIONS

According to the opinion of many experts summarized in a study called FORSYS that was presented in **Chapter 4**, the improvement of forest management decision support systems requires the incorporation of multi-criteria decision making (MDCM) techniques, adequate knowledge management and the possibility of group decision making (GDM). This thesis aimed to the development of a framework that could simultaneously consider these three recommendations. Named *Romero*®, the resulting forest management team-decision support system (FMTDSS) proved to be suitable to deal with cases in which different stakeholders have conflictive views on how to manage production forests. Furthermore, *Romero*® has shown capable of promoting interaction among stakeholders while seeking consensual decisions.

The FORSYS country reports enlightened the path for the development of *Romero*® point to the main structural features that the system should address, more specifically, participatory planning, knowledge management support, and a well-balanced framework to deal with complexity and usability. Hence, the MDCM and GDM techniques encompassed by *Romero*® could be successfully applied to a framework that promotes the dynamic interaction of stakeholders. It was also developed offering in its core the power of a SQL database specially designed to support integration and monitoring of the system elements. Although complete in terms of the main inner core routines that encapsulates good part of the needed complexity to generate comprehensive compromise programming models and all its dependencies, the user interface is still opened for further improvements and development.

São Paulo monitoring case study contributed to a generalizable monitoring model to be embedded in similar monitoring systems. Also, it brought to the *Romero*® context essential requirements to be accomplished. The most critical requirement regards the integration of a SQL database that allows the link of the planning parameters to the latest monitoring indicators. Also, *Romero*® fulfilled the need regarding the storage of all planning attributes to be followed up in the future and checked out against real accomplishments.

Concerning the models embedded in the system, they followed the multicriteria decision theory rigorously. A multiobjective linear programming model (MOLP), based on forest model II formulation, was specially designed and addresses world trends in terms of strategic forest planning applicable in the context of industrial forest plantations in Brazil. Furthermore, the MOLP integrated into the MCDM framework produced the necessary elements for a

comprehensive multicriteria analysis, such as efficiently reporting (i) pay-off matrices, (ii) the efficient solutions of the Pareto frontier, and (iii) the compromise interval.

The case study illustrated how Romero© was able to support large-scale multi-stakeholder's decision processes. A vertically integrated pulp company situation was simulated to provide a real scenario. *Romero©* demonstrated its capacity to support the interaction among stakeholders with different expectations regarding forest management. Specifically, the hypothesis proposed in the study case that longer rotations could improve mill production, as expected by the mill managers, could not be confirmed. Nevertheless, *Romero©* led the compromise to an unexpected point where the possibility of harvesting in younger ages allowed a sooner replacement of less efficient genetic material.

The overall conclusion is that the *Romero©* system can potentially function as a more realistic tool to support groups of managers that seek apparently conflictive aspirations, by means of an interface that promotes compromise and consensual planning. Furthermore, through the case study application, *Romero©* demonstrated that strategic scenario analysis is still a key tool to evaluate future impacts of short-term decisions.

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ANNEX

Annex 1: SQL statements to calculate Compromise L_1 and L_∞

A1.1 Calculation of Normalized values of the attributes:

```
View v_CalcCompromise1:
select rcb.idsimulation, obj.Sense, rcb.Objective,
       obj.Variable ObjVar, rcb.Variable,
       obj.weight, rcb.Value BestValue, rcw.WorseValue,
       abs(rcb.Value - rcw.WorseValue) Interval
from ResCriteria rcb
  inner join Objective obj on obj.Objective = rcb.Objective
  inner join (select c.idSimulation, c.variable,
                    case when ob.sense = 'Max'
                        then Min(c.Value)
                        else Max(c.Value)
                    end WorseValue
               from ResCriteria c
                 inner join Objective ob
                     on ob.Variable = c.Variable
               group by c.idSimulation, c.variable
             ) rcw on rcw.idSimulation = rcb.idSimulation
                  and rcw.Variable = rcb.Variable
where obj.Variable = rcb.Variable
```

A1.2 Calculation of the Distances from the Ideal Point:

```
View v_CalcCompromise2:
Select rp.idSimulation, rp.idResult, rp.PlotPoint,
       rp.Variable, rp.Value,
       vcc.BestValue, vcc.WorseValue, vcc.Interval, vcc.Weight,
       (abs(vcc.BestValue - rp.Value)/vcc.Interval) Distance
from ResPareto rp
  inner join v_CalcCompromise1 vcc
      on vcc.idSimulation = rp.idSimulation and
         vcc.Variable = rp.Variable
order by rp.idSimulation, rp.idResult
```

A1.3 Determine what are L_l and L_∞ Points:

View [v_CalcCompromise3](#):

```
Select G2.idSimulation,
       G1b.PlotPoint L1Point,   G2.L1,
       G1c.PlotPoint LInfPoint, G2.Linf
from
  (Select Gla.idSimulation,
        min(Gla.L1) L1, min(Gla.Linf) Linf
   from (select D.idSimulation, D.PlotPoint,
              Sum(Distance) L1, Max(Distance) Linf
        from v\_CalcCompromise2 D
        group by D.idSimulation, D.PlotPoint
       ) Gla
   group by Gla.idSimulation
  )G2
inner join
  (select D.idSimulation, D.PlotPoint,
        Sum(Distance) L1, Max(Distance) Linf
   from v\_CalcCompromise2 D
   group by D.idSimulation, D.PlotPoint
  )G1b on G1b.idSimulation = G2.idsimulation and
        G2.L1              = G1b.L1
inner join
  (select D.idSimulation, D.PlotPoint,
        Sum(Distance) L1, Max(Distance) Linf
   from v\_CalcCompromise2 D
   group by D.idSimulation, D.PlotPoint
  )G1c on G1c.idSimulation = G2.idsimulation and
        G2.Linf           = G1c.Linf
```


Annex 2: Data Model of the parameters and results

A2.1 Parameters

A2.2 Results