Forest management-consideration of multiple objectives

by

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FOREWORD

This thesis is prepared as an article insertion thesis comprising of five chapters starting with the introduction, Chapter 1, Chapter 2 and Chapter 3 ending with a conclusion. Chapters 1, 2 and 3 regroup published and submitted book chapter and articles. Here is the information on the mentioned book chapter and articles:

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This Ph.D. thesis has been realized under the co-direction of Professor Mustapha Ouhimmou from École de technologie supérieure, Professor Mikael Ronnqvist from Université Laval and Professor Marc Paquet from École de technologie supérieure. All the research was funded by the Natural Science and Engineering Research Council of Canada (NSERC) through its Strategic Research Network on Value Chain Optimization (VCO) and the FORAC research consortium. The thesis includes one published book chapter for which I am the second author, one published paper and one paper submitted to a scientific journal, for these two papers I am the first author. The book chapter was co-authored by Prof. Jean-

Francois Audy from Université du Québec à Trois-Rivières, Prof. Mustapha Ouhimmou, Dr. Alexandra Marques from Centre for Enterprise Systems Engineering INESC TEC in Portugal and Prof. Mikael Ronnqvist. In this work Prof. Audy was the lead and coordinated the relevant tasks related to writing this chapter. He provided the relevant papers, directions on the scope and limitation of the review, a template on what information of each paper needs to be summarized. Each co-author was designated to write one or more sections of the book chapter; I wrote the following sections: “Generic Mathematical Model for Tactical Planning”, “Biorefinery Value Chain” and “Bioenergy Value Chain”; in addition, I was responsible to respond to the reviewers’ comments during the review process.

I have acted as the principal researcher in the two articles. The first published article was co-authored by Prof. Mustapha Ouhimmou, Prof. Mikael Ronnqvist and Prof. Marc Paquet. For this paper as the first author, I have developed all the mathematical models, the solution approach, and performed all data collection, analysis and results validation, as well as writing the first draft of the article. The second paper submitted to a journal is co-authored by Dr. Julio Montecinos from École de technologie supérieure, Prof. Mustapha Ouhimmou, Prof. Mikael Ronnqvist and Prof. Marc Paquet. For this paper as the first author, I have developed all the mathematical models, the solution approach, and performed the data collection, analysis and results validation, as well as writing the first draft of the article. For this paper, the implementation of the clustering algorithm in MATLAB and the relevant experiments to generate clusters is done by Dr. Montecinos; he also provided the text related to explanation of the clustering algorithm that was then integrated in the paper. Regarding these two articles, my supervisors have directed and guided me throughout the projects starting from defining and understanding the problems under study, choosing and developing solution methodologies, analyzing and interpreting results and they have also provided constructive comments on improving the earlier versions of the papers.

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My heartfelt thanks are to my family for their constant support and encouragement in the pursuit of this work, especially my brother Zurvan who has always been the source of wisdom and strength for me.

PLANIFICATION FORESTIÈRE - CONSIDÉRATION DE PLUSIEURS OBJECTIFS

Azadeh MOBTAKER

RÉSUMÉ

Au Canada, en tant que grand pays forestier, les ressources forestières fournissent des bénéfices environnementaux, sociaux et économiques importantes. Par conséquent, la prise en compte de multiples critères souvent contradictoires dans la planification de la gestion forestière est devenue une nécessité plutôt qu'un cas particulier. Depuis 2013, un nouveau régime de gestion forestière est entré en vigueur au Québec, où le ministère des Forêts, de la Faune et des Parcs (MFFP) est devenu responsable de la préparation et de la mise en œuvre des plans de développement forestier intégré. Pour que le MFFP prenne en compte les besoins et les interêts locaux, plusieurs objectifs doivent être ciblés. Ainsi, l'objectif principal de cette thèse est d'analyser et de proposer de nouveaux modèles d'affaires pour la planification de la gestion forestière en tenant compte de plusieurs facteurs clés.

La première partie de la thèse comprend un examen d'un certain nombre de méthodes de planification et de systèmes d'aide à la décision pour les décisions tactiques dans le réseau de création de valeur dans le secteur forestier. Dans la deuxième partie de la thèse, nous avons proposé un modèle d'optimisation multi-objectif pour le problème de la sélection des zones de récolte et de l'allocation du bois aux usines de transformation du bois sur un horizon de planification de 5 ans. Ce modèle a été utilisé pour analyser un plan de gestion forestière tactique au Québec. Une unité d'aménagement forestier à l'intérieur de la région de l'Outaouais, dans l'ouest du Québec, a été considérée comme notre étude de cas. La solution du modèle multi-objectif proposé a été comparée à la stratégie traditionnelle de minimisation des coûts. De plus, les impacts des contraintes logistiques ont été évalués. Enfin, dans la troisième partie de la thèse, nous avons proposé un outil d'aide à la planification pour regrouper les zones de récolte de manière à réduire la dispersion spatiale des grappes, ce qui signifie que la logistique de déplacement de la machinerie entre les zones de chaque groupe devient plus efficace. Les résultats des trois parties de la thèse ont démontré que la prise en compte simultanée de certains objectifs importants dans la gestion tactique des forêts pourrait aboutir à un plan plus équilibré et économiquement durable. En outre, la formation des grappes systématique des zones de récolte réduirait la dispersion spatiale des zones de récolte qu'une équipe de récolte typique doit couper, ce qui réduit par conséquent le temps et le coût de déplacement des machines de récolte entre les zones. En général, les travaux de cette thèse peuvent soutenir un plan d'aménagement forestier efficace tenant compte de multiples objectifs et minimisant la dispersion spatiale des zones de récolte. Les modèles et les approches d'optimisation proposés dans cette thèse sont nouveaux et pratiques pour les problèmes de planification de l'aménagement forestier.

Mots-clés: Planification forestière, optimisation multi-objectif, minimisation de la dispersion spatiale, la formation des grappes

FOREST MANAGEMENT-CONSIDERATION OF MULTIPLE OBJECTIVES

Azadeh MOBTAKER

ABSTRACT

In Canada, as a major forested country, forest resources provide significant environmental, social, and economic values. Hence, consideration of multiple often-conflicting criteria in forest management planning has become a necessity rather than a special case. Since 2013, a new forest management regime came to effect in the province of Quebec, Canada where the Ministry of Forests, Fauna, and Parks (MFFP) became responsible for preparing and implementing integrated forest development plans. In order for the MFFP to take local needs and goals into account usually multiple objectives need to be targeted. So, the main objective of this thesis is to analyze and to propose new business models for forest management planning addressing several key factors.

The first part of the thesis includes a review of a number of planning methods and decision support systems for tactical decisions in the forest-based value creation network. In the second part of the thesis, we have proposed a multi-objective optimization model for the problem of selection of harvest areas and allocation of timber to wood-processing mills over 5-year planning horizon. This model has been used to analyze a tactical forest management plan in Quebec. The forest management unit 07451 inside region 7, Outaouais in western Québec was considered as our case study. The solution of the proposed multi-objective model was compared with the traditional cost minimization strategy. Also, the impacts of logistics constraints were assessed. Finally, in the third part of the thesis we have proposed a planning support tool to group the harvest areas in a way that the spatial dispersion of the clusters is reduced, meaning the logistics of moving the machinery between areas in each cluster becomes more efficient. The results from the three parts of the thesis have demonstrated that simultaneous consideration of some important objectives in the tactical forest management could lead to a more balanced and economically sustainable plan, in addition systematical cluterization of harvest areas will reduce the spatial dispersion of the harvest areas that a typical harvesting team has to cut, which consequently reduce the time and cost of movement of harvesting machineries among the areas for the team. In general, the work in this thesis can support an efficient forest management plan considering multiple objectives and minimizing the spatial dispersion of harvest areas that a harvesting team would cut. The optimization models and approaches proposed in this thesis are novel and practical for the forest management planning problems.

Keywords: Forest management, multi-objective optimization, spatial dispersion minimization, clusterization

TABLE OF CONTENTS

Page

INTRODUCTION 22
CHAPTER 1 TACTICAL PLANNING AND DECISION SUPPORT SYSTEMS IN THE FOREST-BASED VALUE CREATION NETWORK....................34
1.1 Introduction..34
1.2 Value chains in the FVCN 36
1.3 Planning of the value chains in the FVCN...36
  1.3.1 Value chain planning matrix... 36
  1.3.2 Value chain planning support 40
  1.3.3 Generic mathematical model for tactical planning 42
1.4 Decision support in the value chains of the FVCN..45
  1.4.1 Forest value chain 45
  1.4.2 Lumber, panel and engineered wood products value chain........................ 53
  1.4.3 Pulp and paper products value chain 60
  1.4.4 Biorefinery value chain... 64
  1.4.5 Bioenergy value chain... 68
  1.4.6 Integrated value chains 76
1.5 Discussion..80
  1.5.1 Gaps and trends in DSS development.. 80
  1.5.2 Issues and challenges in implementation... 81
  1.5.3 Future research paths forward... 82
1.6 Conclusion 85
CHAPTER 2 DEVELOPMENT OF AN ECONOMICALLY SUSTAINABLE AND BALANCED TACTICAL FOREST MANAGEMENT PLAN: A CASE STUDY IN QUÉBEC 87
2.1 Introduction and literature review...88
2.2 Problem description 93
2.3 Solution approach 95
2.4 Model formulation 97
2.6 Results and discussion 111
2.7 Conclusions and future works...115
CHAPTER 3 MINIMIZING SPATIAL DISPERSION OF FOREST HARVEST AREAS USING SPECTRAL CLUSTERING AND SET COVERING MODELLING..119
3.1 Introduction...120
3.2 Problem statement..122
3.3 Modelling and solution methodology 125
3.4 Case study description 133
3.5 Results and discussion 135
3.6 Conclusions and future works..142
CONCLUSION… 145

FUTURE RESEARCH 146
BIBLIOGRAPHY 153

LIST OF TABLES

Page

Table 1.1 Scope along the forest value chain addressed by the reviewed literature. 48

Table 1.2 Scope along the lumber, panel and engineered wood products value chain addressed by the reviewed literature 54

Table 1.3 Scope along the pulp and paper products value chain addressed by the reviewed literature 61

Table 1.4 Scope along the Biorefinery Value Chain Addressed by the Reviewed Literature 65

Table 1.5 Scope along the Bioenergy Value Chain Addressed by the Reviewed Literature 69

Table 1.6 Scope and value chains of the FVCN addressed by the reviewed literature 77

Table 2.1 List of indices, sets, parameters and decision variables of the model 100

Table 2.2 Information on the cases A and B regarding the dimension of the planning problem and some other relevant data 110

Table 2.3 Summary of harvest areas' properties for Case A 110

Table 2.4 Comparison among single-objective models, MOO and MinCost strategies for Case A 112

Table 2.5 Solution comparison between MOO (linearization method) and MinCost for Case A 113

Table 2.6 Comparing MOO and MinCost strategies for Case B solved by BARON & linearization approach 114

Table 3.1 List of indices, sets, parameters and decision variables of the model 131

Table 3.2 Results of the 4 models for $h = 6$ 137

Table 3.3 Comparing the scenarios: $h = 5, 6, 7$ 138

Table 3.4 Another comparison of the scenarios: $h = 5, 6, 7$ 139

LIST OF FIGURES

Page

Figure 0.1 Map of forest management regions and units in the province of Québec (period 2013-2018)…………………………………………………..…..25

Figure 0.2 Forest supply chain including the main activities………..………………………………….……..…...…26

Figure 0.3 The main contributions of the thesis……………………………….…….28

Figure 0.4 Geographical location of the case under study……………………..…29

Figure 0.5 Research organization in the first contribution……………………..…31

Figure 0.6 Research organization in the second contribution……………………..32

Figure 0.7 Research organization in the third contribution………………………..33

Figure 1.1 Five main value chains composing the forest-based value creation network 38

Figure 2.1 Geographical location of the case under study 109

Figure 3.1 An example of the defined problem: Spectral Clustering ((b) and (d)) and the N-Node Diameter Clustering ((a) and (c)), considering 3 (upper) and 4 clusters (lower) for 16 sites 124

Figure 3.2 Network plot and similarity matrix visualization 127

Figure 3.3 Eigenvectors scatter plot 130

Figure 3.4 Map of forest management regions in the province of Québec, Canada; 134

Figure 3.5 Geographical setup of the 107 harvest areas and their timber volume considered in the case under study in the bar plot below (in $10^5\ m3$) ... 135

Figure 3.6 Spatial representation of the clusters chosen by Min-MST for $h = 6$.... 140

Figure 3.7 Spatial representation of the clusters chosen by Min-Slacks for $h = 6$. 140

Figure 3.8 Spatial representation of the clusters chosen by Bi-O for $h = 6$........... 141

Figure 3.9 Spatial representation of the clusters chosen by Min-MST_2 for $h = 6$ 141

LIST OF ABREVIATIONS

AHP	Analytic Hierarchical Process
BIOLOGICS	BIOmass LOGIstics Computer Simulation
CHP	Combined Heat and Power
DM	Decision-Maker
DSS	Decision Support System
Eq	Equation
ERP	Enterprise Resource Planning
FAO	Food and Agriculture Organization
FMU	Forest Management Unit
FVCN	Forest-based Value Creation Network
GDP	Gross Domestic Product
GIS	Geographical Information System
GP	Goal Programming
GVA	Gross Value Added

ICE	Internal Combustion Engine
IDEAS	Integral Decision Effect Analysis System
IoT	Internet of Things
IP	Integer Programming
KPI	Key Performance Indicator
LP	Linear Programming
MFFP	Ministry of Forests, Fauna, and Parks
MILP	Mixed-Integer Linear Programming
MINLP	Mixed-Integer Nonlinear Programming
MIP	Mixed Integer Programming
MOO	Multi-Objective Optimization
MST	Minimum Spanning Tree
NRC	Natural Resources Canada
NSERC	Natural Sciences and Engineering Research Council of Canada
OP	Open Problems

OR	Operations Research
ORC	Organic Rankine Cycle
OSB	Oriented Strand Board
P&P	Pulp and Paper
PSC	Pellet Supply Chain
STD	Standard Deviation
S&OP	Sales and Operations Planning
TL	Timber License
TSP	Travelling Salesman Problem
VMI	Vendor-Managed Inventory

INTRODUCTION

Canada has 348 million hectares of forest land, which represents 9% of the world's forests and 24% of the world's boreal forest (Natural Resource Canada (NRC)-Annual Report 2014). Most of Canada's forests (about 90%) are publicly owned and are managed by the provinces and territories. The province of Quebec's forests account for 20% of the total Canadian forests and 2% of the world's forests. The dense forests have an area of 761,100km^2, equivalent in size to the territories of Norway and Sweden combined. The forestry sector, consisting of forest management, timber products and pulp and paper production, is a pillar of the Québec economy. There are over 400 wood processing plants throughout the Québec regions and about 80,000 direct jobs in the forestry and wood processing sectors. The forest creates one out of every six jobs in Québec and 1.6 indirect jobs in the other sectors. More than 250 Québec municipalities depend directly on forest-related activities (https://www.mern.gouv.qc.ca/english/international/forests.jsp).

However, due to globalization of the market, increased competition over traditional forest commodities and substantial decrease in newsprint paper demand and in Canadian softwood lumber exportation to the United States, the Canadian forest industry needs to deliberately revise its current business strategies and policies and implement new business models capturing new opportunities to stay competitive in the international market. So in order to exploit the significant environmental, social and economic values provided by the forest products industry it is usually organized in a complex industrial system known as a value chain, starting from the forest up to markets (Audy *et al.*, 2016). Fleischmann *et al.* (2008) structured a two-dimensional matrix for categorization of supply chain planning problems from two perspectives: the main processes along the supply chain (i.e., procurement, production, distribution and sales) and the planning horizon (i.e., strategic, tactical and operational). Different stages of planning based on the time-perspective planning horizon could involve substantially different planning tasks. For instance, strategic forest planning normally covers a horizon of a few decades to hundreds of years and may involve decisions about the design and structure of forest value chain network, development of forest management strategies/policies, silviculture treatments, selection of conservation areas, etc. Tactical planning often addresses a full seasonal cycle (from 1 to 5 years) and decisions about how to treat standing timber and allocate them to specific mills to fulfill certain demands made at this level. Finally, at the operational level, planners deal with day-to-day issues of harvesting and transportation; see e.g., the review by D'Amours *et al.* (2011).

Moreover, both the federal and provincial governments have an important responsibility to legislate up-to-date rules and regulations to support the forest industry as one of the major economic poles in Canada. In the province of Quebec, the legislators at the National Assembly of Quebec unanimously agreed on the Sustainable Forest Development Act in effect since April 2013. This Act gives the Ministry of Forests, Fauna and Parks (MFFP) responsibility for preparing and implementing integrated forest development plans, and for executing checks in the forest, so the MFFP will have the power to take local needs and goals into consideration (Légis Québec, 2016). In order for an effective implementation of such new regulations and strategies, advanced decision support systems are subsumed to be substantially beneficial. Operations research (OR) specialists and computer scientists have been for many years contributing in the design and implementation of intelligent decision support systems. This can be done through deep understanding of the industry structure and its urgent need for new business models to deal with the challenging decisions and the optimization of various value chains shaping this industry.

In this thesis, we decided to study the situation of the forest industry in Canada and provide OR-based decision support tools to be used by planners at the MFFP to facilitate their decision making in the forest management context. For this purpose, the three main research questions that were designed in the framework of the project are as follows:

1. At the tactical level of planning, what are the latest researches for the development of decision support systems for planning the forest-based value creation network?
2. How can we support the MFFP to simultaneously consider multiple objectives in its tactical forest management planning?

3. How can we employ clustering methods to control the spatial dispersion of harvest areas that a harvesting team would cut at forest management unit (FMU) level?

Answering the above questions would help the forest industry and the MFFP to plan for a more efficient and sustainable consumption of wood resources and savings in the time and the costs spent for the movement of harvesting machineries between harvest areas. Therefore, in what follows, we describe the research problem regarding the tactical forest management planning and the clusterization of harvest areas. Moreover, we explain some aspects of the region Outaouais in Quebec that is considered as our case study. The outline and organization of the thesis are given at the end of this chapter.

Problem description

An FMU can be defined as a geographic area covered by forests (Fig. 0.1), each includes a number of harvest areas managed to achieve the objectives of forest management strategies. Historically, these management units were managed by either one or a number of forest products companies who hold supply guarantee agreements with the government where commonly coordination conflicts arose. Since April 2013 a new forest management regime in the province of Québec has been put in place where the government is responsible for forest management planning including harvest area selection and stem allocation to wood-processing mills.

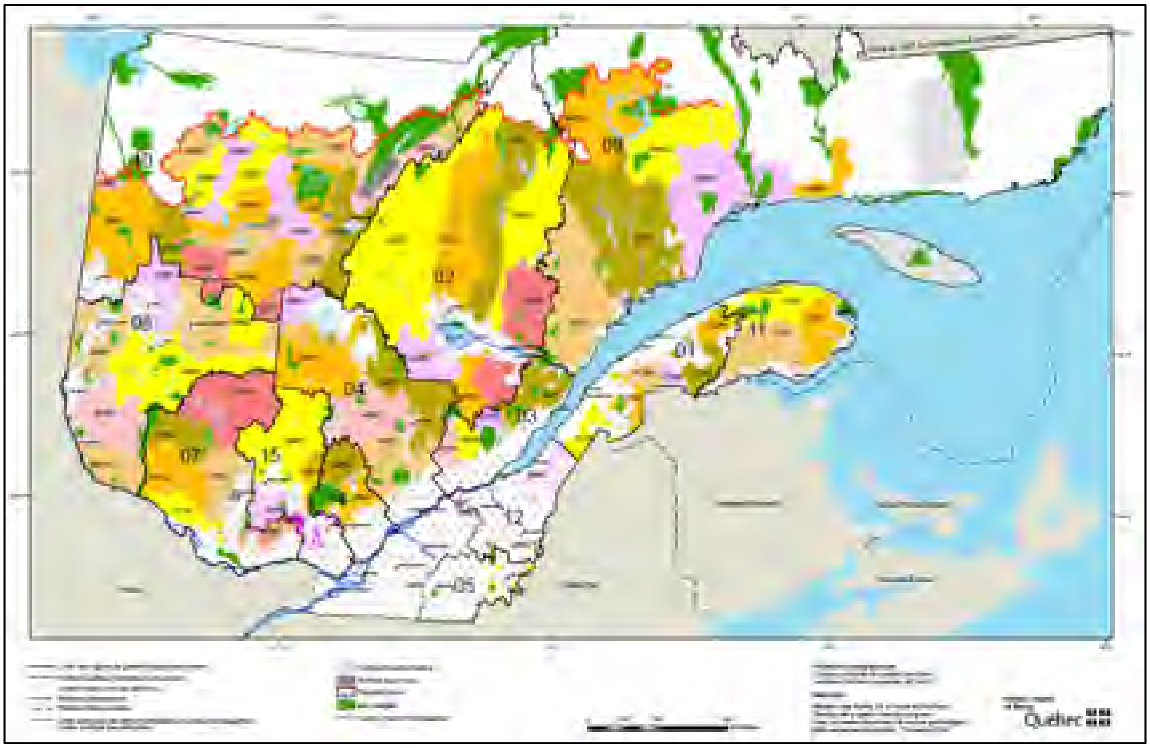
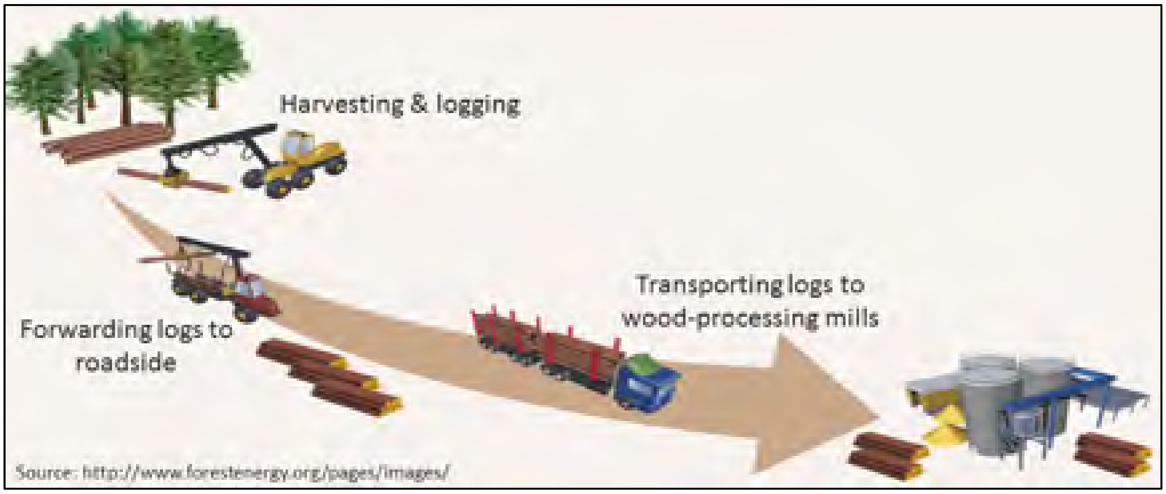


Figure 0.1 Map of forest management regions and units in the province of Québec (period 2013-2018)

Forest management planning involves various activities starting from cutting the trees at the stands selected to be harvested in the planning year and then the fallen timber will be categorized into different assortments based on their species, dimension, etc. and stored at roadside of forest. Finally, specific assortment of stems will be delivered to the wood-processing mills according to their demand for that year (Fig. 0.2).



Source: http://www.forestenergy.org/pages/images/

Figure 0.2 Forest supply chain including the main activities

In the context of forest management, we have proposed three contributions. First, we have conducted a review of a number of planning methods and decision support systems (DSS) for tactical decisions (i.e., mid-term decisions ranging from a couple of months to a few years) in the forest-based value creation network (FVCN) since the 1990s that have been published in the literature. The solution methodologies and decision-making frameworks behind these methods/DSS were discussed. This review summarizes what has been done worldwide, highlighting the most successful DSS developments by reporting their most significant applications and benefits, present trends and gaps in planning methods/DSS, and future research directions. Second, we have proposed a multi-objective tactical optimization model for the forest management planning at the FMU level. The developed model and solution method are addressing one of the recognized research paths in the first contribution. It is also aimed to support the MFFP for a more efficient implementation of the new forest management regime in Quebec and the applicability of the model and solution approach is demonstrated for a case study of FMU Outaouais in western Québec. The proposed linearization method and the impact of logistics constraints were assessed for the considered case. The proposed multi-objective model was compared with the conventional cost minimization alternative and it was observed that the multi-objective model leads to much less deviation of the studied objectives from their respective target values, hence providing a more stable plan in terms of those objectives over longer periods.

Another important aspect in forest management highlighted in our first contribution is the spatial aspect of a management plan. Particularly, in the process of developing the second contribution we recognized that the spatial dispersion of harvest areas that a typical harvesting team will get to cut is a major factor in reducing the time and cost of moving the harvesting machineries among the harvest areas. Hence, the third contribution of this thesis has been defined to develop a two-phase decision support tool including the Spectral clustering method to systematically generate many alternative clusters and a set covering model to select the most suitable clusters of harvest areas in a FMU (i.e. one cluster for each harvesting team working in that territory). A bi-objective set covering model was proposed to simultaneously minimize the overall spatial dispersion of the chosen clusters of harvest areas and to distribute approximately the same volume of timber among the teams. We compared the bi-objective model with a single-objective variation.

Figure 0.3 demonstrates the accomplished work in each contribution. The presented research in this thesis has started with questions about: What are the planning methods and DSS for tactical decisions (i.e., mid-term decisions) in the forest based value creation network since the 1990s that have been published in the literature? What are the most successful DSS developments with significant applications and benefits? A review of the literature on published articles within the above-mentioned scope has been conducted and trends and gaps in planning methods/DSS, and future research directions are presented. Afterwards, we have concentrated on the tactical forest management planning and we have raised the question about: How can multi-objective optimization improve the forest management decision making at the tactical level towards a more balanced and economically sustainable use of forest timber? The multi-objective programming method along with a normalization technique has been employed to answer this question. Finally, we have answered the questions including: how can a clustering technique be used to effectively reduce the spatial dispersion of harvest areas assigned to a typical harvesting team in a forest management unit? What is the efficient measure for the spatial dispersion? How to choose the most suitable clusters among a large pool of alternatives? A clustering algorithm is applied, combined with bi-objective and single-objective set covering models aimed to answer these questions.

Forest Management Planning – review of the literature, simultaneous consideration of multiple objectives, controlling spatial dispersion of harvest areas

Contribution 1: Conducting an extensive literature review on decision support systems in the forest-based value creation network at the tactical level of planning	* Studied and summarized the gathered relevant scientific papers * Developed a generic mathematical model to represent a vertically integrated company that manages a forest-to-customer value chain where all members coordinate their operations toward a common objective
Contribution 2: Proposing a decision support tool for simultaneous consideration of multiple objectives for tactical forest management planning	* Developed a tactical multi-objective optimization model for forest management over 5-year planning horizon * Collected and analyzed the information for the case study * Analyzed the results
Contribution 3: Proposing a decision support tool for controlling the spatial dispersion of harvest areas that a typical harvesting team gets to cut	* Employed Spectral Clustering algorithm to generate large number of clusters of harvest areas * Developed a bi-objective Set Covering model to choose the best clusters of harvest areas * Compared the bi-objective Set Covering model with a single-objective model * Tested the Clustering algorithm and Set Covering model for a case study

Figure 0.3 The main contributions of the thesis

Case study

The study is comprised of a real case of the FMU 07451 inside region 7, Outaouais in western Québec, Canada. This FMU has a large area of forest of various species and the mills that are expected to be supplied by the timber produced in this FMU have very complicated demand specifications in terms of for instance the average size of stems for each assortment that they require. This has made the defined problem to satisfy the mills' demand for which many constraints and goals need to be taken into account a very complex case to be solved. The geographical location of the case is shown in Figure 0.4. For this case, 107 harvest areas are available in a register that could be used for the planning of supply for 13 wood-processing mills (holders of timber supply guarantees) operating in the territory of this FMU. We have 10 sawmills, 2 pulp and paper mills and 1 veneer mill. Seventeen log types have been defined; each encompasses a few number of species and has one specific application. Also, six harvesting teams work in the territory of this FMU. All the required data for the case has been provided by the MFFP and some have particularly been extracted from the software FPInterface developed by FPInnovations, the research and development centre of the Canadian forest industry.

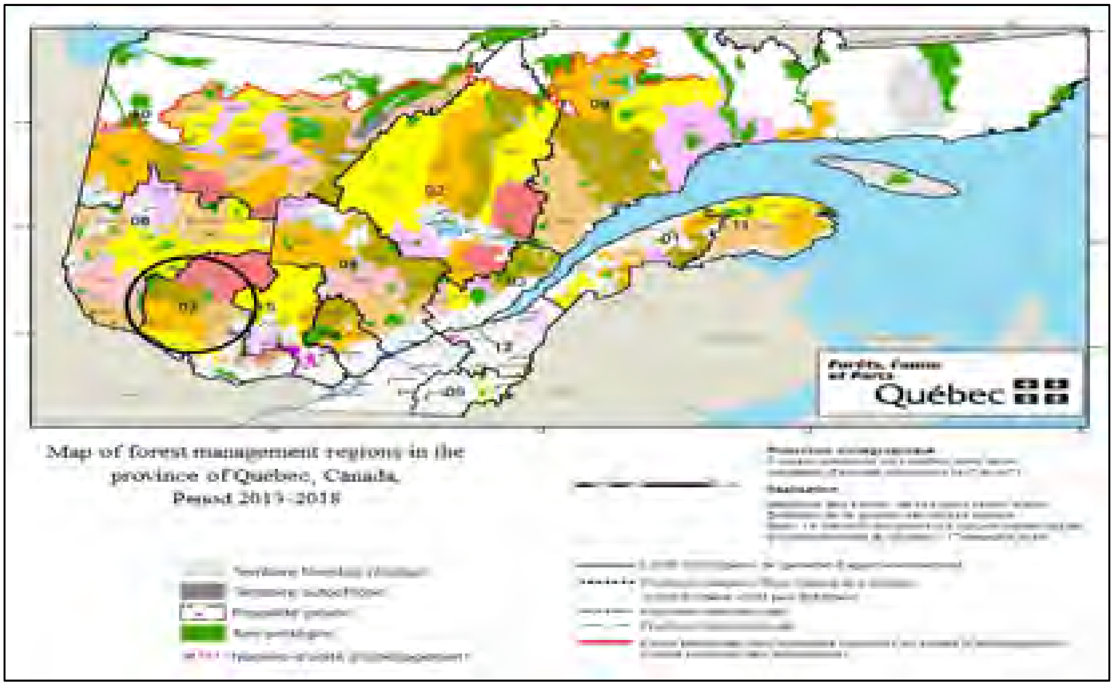


Figure 0.4 Geographical location of the case under study

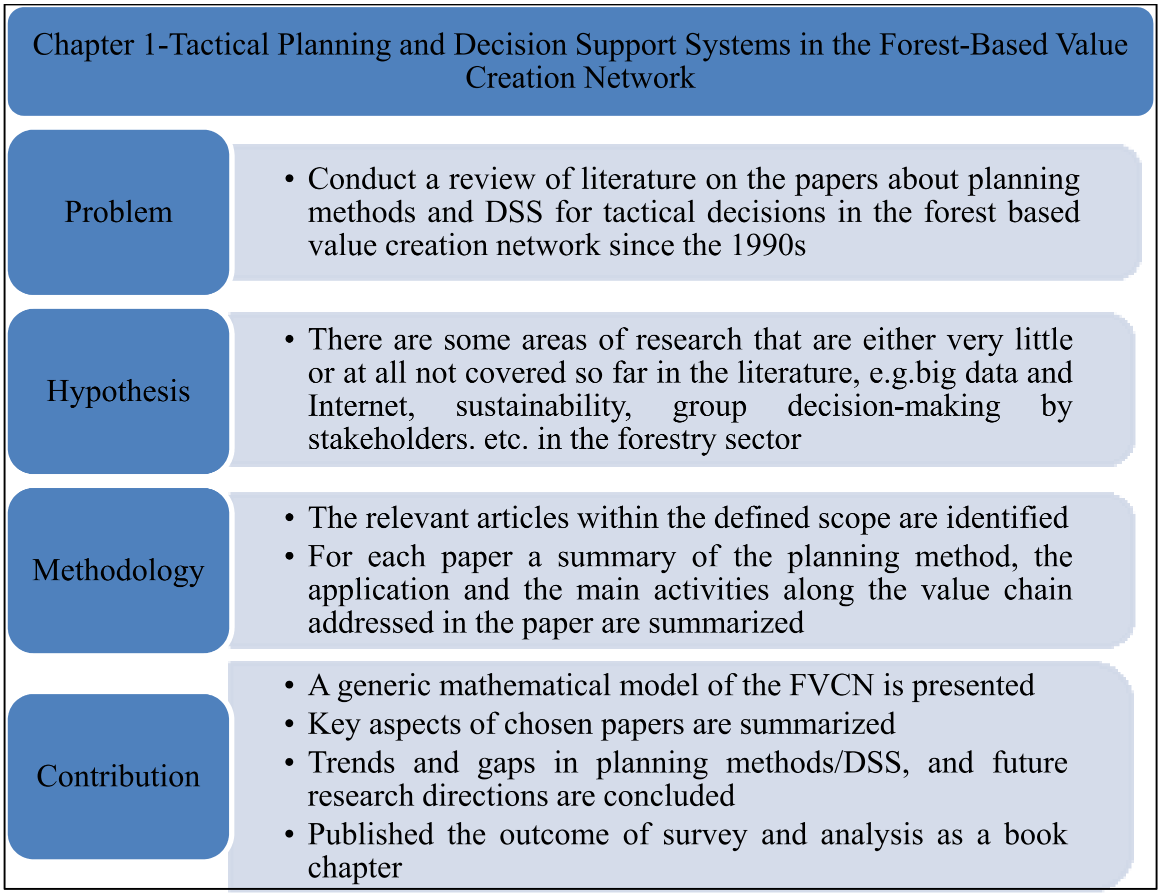
Thesis contributions and organization

As mentioned earlier, our first contribution is a review of the literature on a number of planning methods and DSSs for tactical decisions in the FVCN since the 1990s. This review, presented in the next chapter of the thesis, has defined the FVCN by its five main value chains; four of which produce sets of finished products (i.e., biorefinery value chains; pulp and paper products value chains; lumber, panel, and engineered wood products value chains; and bioenergy value chains). These four value chains are dependent on the forest value chain for their procurement. In this study, our focus is on the forest value chain, in particular.

According to the conducted review, we realized that very few studies have addressed the tactical forest management planning problem in the context of a multi-objective decision making. In addition, minimizing the spatial dispersion of a number of harvest areas that a typical harvesting team would cut was not addressed in the literature. So, this thesis presents models and solution approaches to plan the selection of harvest areas and allocation of stem to wood-processing mills over 5-year planning horizon in a multi-objective optimization context. Additionally, the spatial dispersion of harvest areas is modelled and reduced using an advanced clustering method named spectral technique combined with the set covering model. The concept development and the experimentation performed for this thesis represent different scientific contributions. The thesis includes three original contributions (presented as one book chapter and two articles), which have been provided throughout Chapters 1 to 3 as follows.

Chapter 1

In Chapter 1 we present the published literature review entitled "*Tactical planning and decision support systems in the forest-based value creation network*" as a book chapter in the book "Forest value chain optimization and sustainability". We presented a generic mathematical model to illustrate the typical tactical decisions to be made in a value chain. About 60 methods/DSS were discussed regarding which decisions (planning problems) were made, their applications (e.g., results reported, level of implementation), and the solution approach used. The contribution organization of the book chapter has been depicted in Figure 0.5 that summarizes the contents of chapter 1.

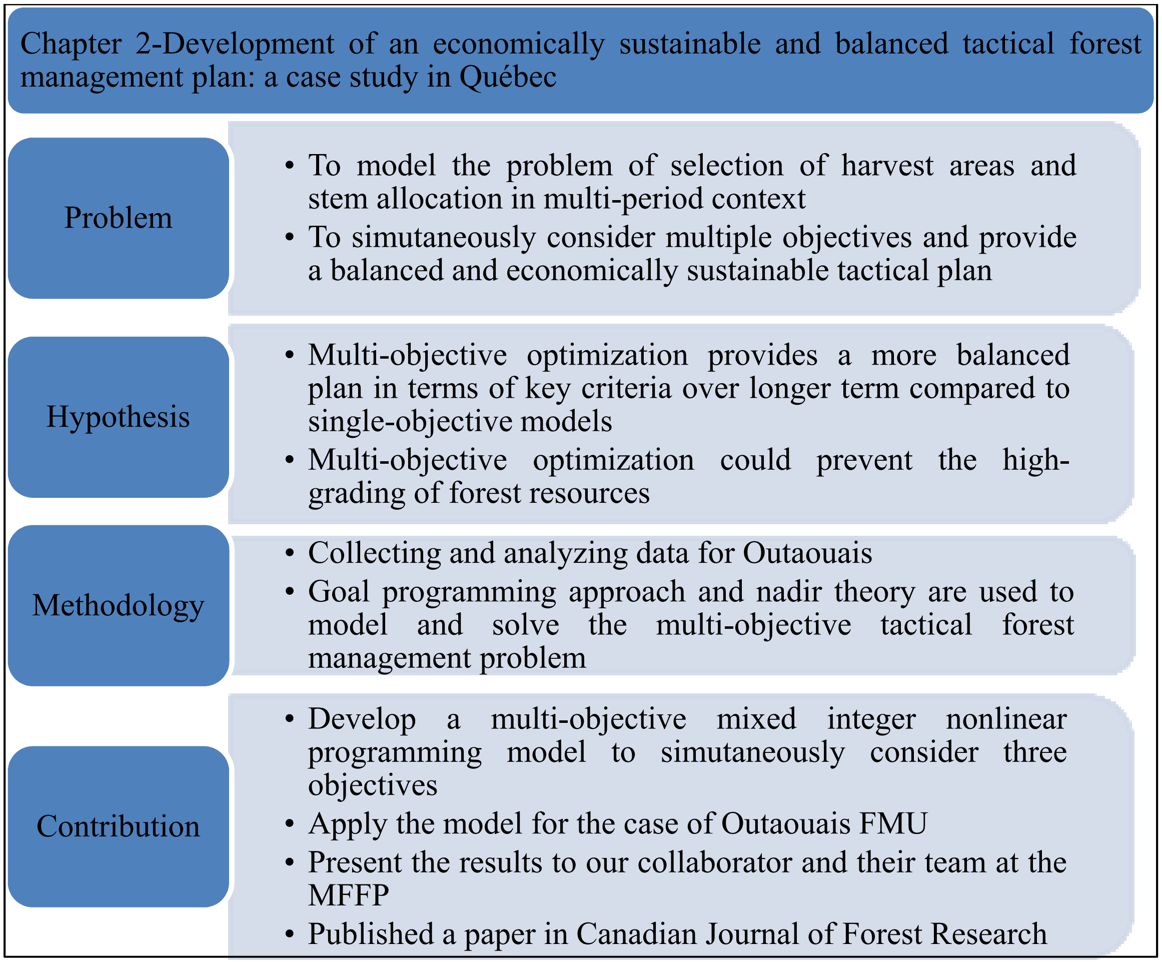


Chapter 1-Tactical Planning and Decision Support Systems in the Forest-Based Value Creation Network	
Problem	• Conduct a review of literature on the papers about planning methods and DSS for tactical decisions in the forest based value creation network since the 1990s
Hypothesis	• There are some areas of research that are either very little or at all not covered so far in the literature, e.g.big data and Internet, sustainability, group decision-making by stakeholders. etc. in the forestry sector
Methodology	• The relevant articles within the defined scope are identified • For each paper a summary of the planning method, the application and the main activities along the value chain addressed in the paper are summarized
Contribution	• A generic mathematical model of the FVCN is presented • Key aspects of chosen papers are summarized • Trends and gaps in planning methods/DSS, and future research directions are concluded • Published the outcome of survey and analysis as a book chapter

Figure 0.5 Research organization in the first contribution

Chapter 2

Following the identification of the research objective in the literature review regarding the multi-objective optimization planning of the forest value chain, we have presented the first paper entitled "*Development of an economically sustainable and balanced tactical forest management plan: a case study in Québec*". We have developed a new multi-objective optimization model that considers three key criteria in the decision making of selection of harvest areas and allocation of stem to mills with the goal of providing a balanced and sustainable plan over the years. The model ensures a stable level of cost, quality/size and availability of wood supply to forest products companies over five years of planning. We employed the idea of business and anticipation periods in the context of a rolling horizon re-planning strategy. The business decisions are the main decisions, which are going to be implemented while the anticipation decisions only allow us to control the impact of our business decisions over a longer period. This allowed us to accommodate in our model the means to prevent creaming in the use of wood supply over the planning horizon as well as overcoming the challenge of lack of demand information for the last four years of the considered planning horizon. Figure 0.6 depicts the contribution organization of the paper and summarizes the contents of chapter 2.



Chapter 2-Development of an economically sustainable and balanced tactical forest management plan: a case study in Québec

Problem

- To model the problem of selection of harvest areas and stem allocation in multi-period context
- To simutaneously consider multiple objectives and provide a balanced and economically sustainable tactical plan

Hypothesis

- Multi-objective optimization provides a more balanced plan in terms of key criteria over longer term compared to single-objective models
- Multi-objective optimization could prevent the high-grading of forest resources

Methodology

- Collecting and analyzing data for Outaouais
- Goal programming approach and nadir theory are used to model and solve the multi-objective tactical forest management problem

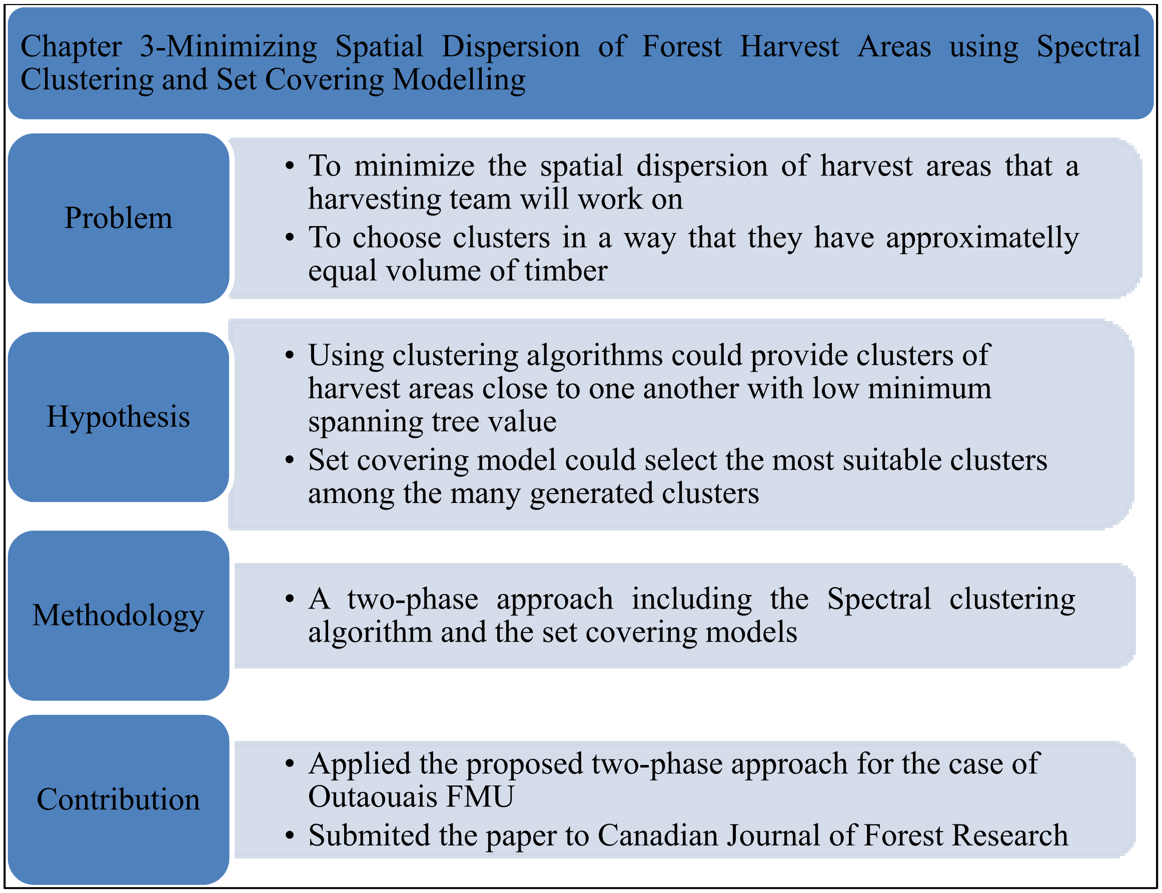
Contribution

- Develop a multi-objective mixed integer nonlinear programming model to simutaneously consider three objectives
- Apply the model for the case of Outaouais FMU
- Present the results to our collaborator and their team at the MFFP
- Published a paper in Canadian Journal of Forest Research

Figure 0.6 Research organization in the second contribution

Chapter 3

The second paper, entitled "*Minimizing Spatial Dispersion of Forest Harvest Areas using Spectral Clustering and Set Covering Modelling*", has proposed a two-phase approach to cluster harvest areas in a FMU with the goal of reducing the overall spatial dispersion and balancing out the available timber volume among the chosen clusters. The principal objective of this chapter is to enable MFFP to reduce the spatial dispersion of harvest areas that a specific team will work on over a specific period of time. The spatial dispersion has been measured in terms of the value of the minimum spanning tree of the clustered harvest areas and the set covering models in both bi- and single-objective forms have been proposed to select the best clusters among many alternatives. The contribution organization of the paper has been shown in Figure 0.7.



Chapter 3-Minimizing Spatial Dispersion of Forest Harvest Areas using Spectral Clustering and Set Covering Modelling

Problem
- To minimize the spatial dispersion of harvest areas that a harvesting team will work on
- To choose clusters in a way that they have approximatelly equal volume of timber

Hypothesis
- Using clustering algorithms could provide clusters of harvest areas close to one another with low minimum spanning tree value
- Set covering model could select the most suitable clusters among the many generated clusters

Methodology
- A two-phase approach including the Spectral clustering algorithm and the set covering models

Contribution
- Applied the proposed two-phase approach for the case of Outaouais FMU
- Submited the paper to Canadian Journal of Forest Research

Figure 0.7 Research organization in the third contribution

CHAPTER 1

TACTICAL PLANNING AND DECISION SUPPORT SYSTEMS IN THE FOREST-BASED VALUE CREATION NETWORK

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1.1 Introduction

Forests worldwide create environmental, social, and economic value. Focusing on the latter, the value of exports in forest products was estimated at US$231 billion in 2012 (FAO, 2014a), while the formal forest sector employs some 13.2 million people across the world (FAO, 2014b). For a major forested country such as Canada, the forest sector contributed to 1% of the nominal GDP and provided 200,000 direct jobs in 2013 (NRC, 2014). Similar figures are found in other countries where the forest industry is important. In Sweden (www.skogsindustrierna.se), the forest industry sector represents 2.5% of the gross domestic product (GDP), the number of direct jobs in 2013 was 55,000 (175,000 indirect jobs), revenues are about US$25 billion, and the export value is US$15 billion. In Portugal, the gross value added (GVA) of forest-based companies in 2012 was worth 1.746 million euros (about 1.2% of the national GVA), corresponding to 9.1% of the total exports and 1.7% of total employment (www.aiff.org). To create this value, the forest products industry is organized in a complex industrial system known as a value chain, starting from the forest and continuing to the delivery of products to end customers (markets) as well as recapturing the value (or disposal) of a product at the end of its use/life span. Planning such an extended industrial system, accounting for its distributed and dynamic nature, constitutes a challenging task. In past years, research in supply/value chain management has contributed to major improvements in the forest sector as well as in other industrial sectors. Among the most important outcomes are the advanced planning methods embedded in decision support systems (DSS) that are often modules of the overall business system of a company [i.e., enterprise resource planning (ERP) system]. This chapter aims to provide a broad overview of a number of planning methods and DSS for tactical decisions (i.e., mid-term decisions ranging from a couple of months to a few years) in the forest-based value creation network (FVCN) since the 1990s that have been published in the literature. The solution methodologies and decision-making frameworks behind these methods/DSS are discussed. The motivation is to furnish readers with an easy-to-read and pedagogical summary on what has been done worldwide, highlighting the most successful DSS developments by reporting their most significant applications and benefits, present trends and gaps in planning methods/DSS, and future research directions and links for further reading. As such, an exhaustive literature review is beyond the scope of this chapter, but throughout the chapter, we have identified a number of reviews focusing on specific value chains within the extended FVCN. Also, although there are many commercial software programs that have been developed and utilized, their methodology and models are not known in detail and are hence not included.

The chapter is organized as follows. In Section 1.2, the five main value chains of the FVCN are introduced. Then, Section 1.3 discusses the main planning problems encountered in the FVCN and presents a generic mathematical model to illustrate typical tactical decisions. Section 1.4 reviews a number of planning methods and DSS in each of the five main value chains and also reviews methods/DSS spanning over two or more value chains. A discussion about the gaps and trends in planning method/DSS development, the issues and challenges for their implementation, and future research directions are presented in Section 1.5. Concluding remarks end the chapter in Section 1.6.

1.2 Value chains in the FVCN

The transformation of raw materials from the forest into finished products involves several consecutive activities performed by a number of private and public organizations. The mixture and number of the involved organizations vary according to several country-to-entity features such as forestland ownership structure, level of vertical business integration, business models and practices in place, and so on. This complex set of entities that work together to perform the transformation activities via different types of relationships to create economic, environmental, and social values is known as a value chain or a value creation network (D'Amours et al. 2011). Thus, the FVCN could be illustrated according to its five main value chains (Figure 1.1). Four value chains produce sets of finished products sold over different market channels, that is, from left to right in Figure 1.1: biorefinery value chains; pulp and paper products value chains; lumber, panel, and engineered wood products value chains; and bioenergy value chains. All of these value chains are linked to a fifth value chain, the forest value chain (top of Figure 1.1), for their procurement, which also comes from flows in various raw materials (including by-products) between some of the value chains. To a certain extent, all these raw material flow links lead to interdependent value chains in constant adjustment to sustain the raw material flow equilibrium at the FVCN level. A description of each of these five value chains is provided in Sections 1.4.1 through 1.4.5, respectively.

1.3 Planning of the value chains in the FVCN

1.3.1 Value chain planning matrix

A supply chain can be subdivided into four main processes consisting of substantially different planning tasks (Fleischmann et al., 2008). Procurement involves the operations directed toward providing the raw material and resources necessary for production. Production is the next process in which the raw materials are converted into intermediary and/or finished products. Thereafter, distribution includes the logistics taking place to move the products either to companies further processing the product (e.g., value-added mills) or to ship for sales to distribution centers, and then to retailers. The sales process deals with all demand planning issues including customer or market selection, pricing strategy, forecasting, and order-promising policies. The planning within each process is typically managed according to three time-perspective planning horizons: strategic (long-term planning), tactical (mid-term planning), and operational (short-term planning). Strategic planning is related to the design and structure of the value chain while operational planning is related to the scheduling instructions for the execution of the operations in the value chain. Serving as a bridge between the strategic and operational level, tactical planning addresses the definition of rules and policies through a global analysis of the value chain, needed for guiding day-to-day operations. Often, the tactical planning horizon covers a full seasonal cycle and the decisions seek to balance demand forecast and facilities' capacities to avoid shortage and excess. In the FVCN, the tactical decisions play a key role in meeting the need to plan in advance and to address seasonal aspects such as the impacts of weather conditions on the operations such as thaws affecting transportation, frozen ground constraining harvesting blocks, forest fires affecting procurement, seasonal demand for lumber, and seasonal variation of biomass moisture content.

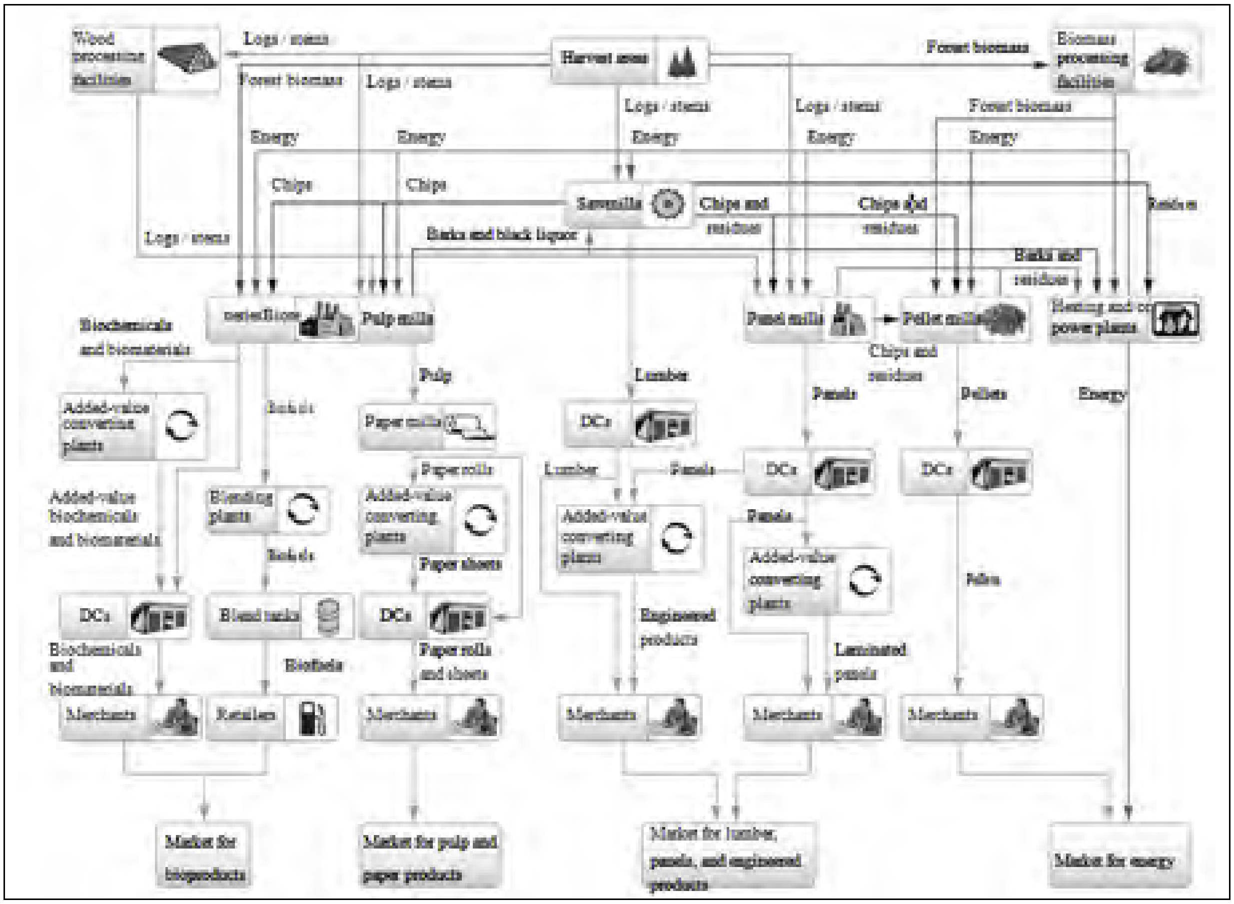

Figure 1.1 Five main value chains composing the forest-based value creation network

Fleischmann et al. (2008) present the typical planning problems in a supply chain using the form of a two-dimensional matrix structured according to the main processes along the supply chain (i.e., procurement, production, distribution, and sales) and the planning horizons (i.e., strategic, tactical, operational). At each intersection of these two dimensions, a number of planning problems, with associated decisions, are reported. A planning matrix for the forest value chain, lumber value chain, and pulp and paper value chain has been proposed by Rönnqvist (2003), Singer and Donosco (2007), and Carlsson et al. (2009), respectively. However, it is worth noting that depending on the country-to-company specificities and business context, some of the planning problems could be shifted up or down in the planning horizon, removed or added, combined or separated, and so on. In Tables 1.1 through 1.5, we present a non-exhaustive list of references addressing tactical level planning problems in a value chain of the FVCN and indicate (using a X mark) which of the main process(es) along the given value chain they cover. It should be noted that we considered the transportation decisions within the distribution process.

Different characteristics of the FVCN increase the complexity when it comes to planning. First, we must consider the divergent nature of the material flow where a different mix of products can be obtained from the harvesting of a single standing tree and where not all products have a demand. In addition, different markets ask for various quality attributes (e.g., dryness, moisture content, National Lumber Grades Authority's standards) and different dimensions, which lead to a manifold product basket. Second, the intrinsic variability of natural raw material characteristics, the diversity of orographic conditions in which the procurement operations need to be conducted in the forestland sites, and the external and not-controlled environment highly subject to changing weather conditions all affect the availability of the raw material and performance of forest operations. Some of the characteristics of the raw materials, such as the moisture content, also change over time depending on the storage duration and conditions. Thus, sources of uncertainty are introduced in the very early stage of the FVCN, requiring planning strategies to handle such uncertainties. One way to deal with those cases is to consider business and anticipation decisions in the modeling of the planning problem. Third, raw material can be used to fulfill demand of several value chains. In some contexts (e.g., pulpwood shortage is pulling saw-wood or high energy price on the market is increasing price paid for any wood quality), there is a competition for the raw material among and within the value chains (e.g., Kong et al. [2012] study the market interactions between the pulpwood and forest fuel biomass). Such competition changes the wood flow equilibrium in the FVCN, thus leading to temporary or even permanent restructuring of some value chains. Fourth, the usual wide geographic spread of the units involved in the FVCN, starting with the forest areas for supply in raw material to the international markets to sell final products, requires efficient management of transportation and inventory. Fifth, as mentioned by Marier et al. (2014), there are very different planning problems to be solved in each manufacturing facility. For instance, a softwood lumber sawmill involves a production process where one input leads to several outputs (one-to-many in the sawing and finishing) and also a one-to-one batch process (drying). At energy-producing units, there may be many-to-one as the demand (output) is for energy only and several assortments can be used as input. Sixth, there are typically very large volumes often transported with multimodal transportation options, including road, railway, and maritime transport. Seventh, there are many stakeholders involved in the value chains, for example, governments, companies, First Nations, carriers, entrepreneurs, and local communities (including hunters, campers, etc.). Each of these groups has its own objectives and agendas. Hence, there is a need to include multiobjective modeling as well as shared use of forest resources in many cases when several stakeholders are integrated.

1.3.2 Value chain planning support

The complexity of the tactical planning problems and the economic importance of their decisions have motivated research on computer-based planning support for several decades. Several techniques such as optimization, simulation, and hybrids of them (e.g., simulation and optimization combination, see Marques et al. [2014a]) can be found in the literature. For operational research (OR) techniques, the literature reports the use of linear, integer, mixed-integer, and nonlinear models. The solution method in use depends on the type of model used, required solution time, and includes dynamic programming and linear programming (LP) methods, branch and bound methods, column generation, multicriteria decision-making, heuristics, and metaheuristic approaches.

To allow decision-makers (DMs) to benefit from this computer-based planning support, DSS embedding the planning methods have been developed and deployed in the industry. To the best of the authors' knowledge, the earliest applications in the forest sector can be traced from the 1950s (see review by Bare et al. [1984]). At the present time, the contribution of the DSS on the improvement of the quality and transparency of decision-making in natural resources management is well established (Reynolds et al., 2007). As an example, the wiki page of the Forest DSS Community of Practice (www.forestDSS.org) reports 62 DSS for forest management developed in over 23 countries, covering a broad range of forest ecosystems, management goals, and organizational frameworks.

These DSS can either be focused on one specific problem or an attempt to combine more, either at the same planning level or from two consecutive planning levels in order to avoid suboptimization (Rönnqvist, 2003). In this context, Marques et al. (2014a, b) propose distinguishing between a fully integrated planning problem and a decoupled planning problem with the anticipation of related decisions. The fully integrated planning problem considers simultaneously various interrelated business decision variables. This means that obtaining the problem result ends the decision-making process and choices made in respect to each of the single decision variables will then be implemented in the course of processes that are often conducted separately. Even if this model is tractable, all decisions are not often implemented in practice. In contrast, the decoupled planning problem has a main set of business decisions but also includes other anticipation variables in order to anticipate the impact on/from other related planning problems. The anticipation variables improve the quality of the results of the main problem as the impact of the business decisions can be described in the model. The outcome of such problems ends the decision-making process but only for the business decisions. A new decision-making process will be conducted for the secondary problem, which will then provide the best choice to be implemented.

In a literature review on DSS in the transportation domain, Zak (2010) reports two definitions of transportation DSS that could be generalized to all DSS addressing any planning problem along a value chain in the FVCN. The first definition gives a broader meaning to DSS by including all computer-based tools supporting the decision-making processes in transportation. Thus, all information management systems, data analysis methods, and spreadsheets applied to solve transportation decision problems can be designated as transportation DSS according to this first definition. The second definition gives a narrower meaning to transportation DSS: it is "(…) an interactive computer-based system that supports the DM in solving a complex (…) transportation decision problem. (…) a [ideal] role of a 'computer-based assistant' that provides the DM [with] specific transportation-focused information, enhances his/her knowledge of a certain transportation decision problem and amplifies the DM's skills in solving the considered transportation decision problems." Therefore, a DSS must manage the information required for planning, execute the planning technique (e.g., the solution method set to address the planning problem), and display the arising plans using graphical user interfaces and, common in forest DSS, spatial maps. Moreover, to enable flexibility, the planning technique must allow solving several instances of different characteristics of a given planning problem that, of course, represent decision(s) to be made, in practice, by a DM. A DSS may even present the comparison among the results of the different instances in graphical user interfaces. In Section 1.4, we discuss a number of DSS that fall into the second definition by Zak (2010) and that address a tactical level planning problem in a value chain of the FVCN.

1.3.3 Generic mathematical model for tactical planning

To illustrate the typical decisions to be made in tactical planning of a value chain in the FVCN, we present a general mathematical model. This model assumes a vertically integrated company that manages a forest-to-customer value chain or a value chain where all members coordinate their operations toward a common objective. Also, we stress that the model is only one example of many possibilities depending on the required level of detail.

We allow for flows between manufacturing plants and a combination of direct flows from manufacturing plants to customers directly or via distribution centers. This model is a general LP model with some network structure. As we have process descriptions with general input/output values, it is not a network flow model. It is also a divergent value chain, that is, the number of products increases through the chain.

In this formulation, manufacturing mills represent any forest products manufacturing plant such as a sawmill, pulp and paper mill, lumber and engineered wood mill, and biorefinery and bioenergy mill.

Consider the following sets, parameters and variables:

Sets and Indices

$s \in S$: Set of suppliers

$m \in M$: Set of manufacturing mills

$d \in D$: Set of distribution centers

$c \in C$: Set of customers

$t \in T$: Set of time periods

$r \in R$: Set of recipes used in manufacturing mills

$p \in P$: Set of products (our definition of products includes raw material, semi-finished products, co-products and finished products)

Parameters

c_{pst}^{pur}: Purchasing cost per unit of product p from supplier s in time period t

c_{r}^{rec}: Production cost for each activity level when using recipe r

c_{pij}^{tr}: Transportation cost of each unit of product p from node i to node j

c_{np}^{inv}: Inventory holding cost of product p at node $n \in \{S \cup M \cup D\}$

b_{pst}^{pro}: Procurement capacity of supplier s for product p in time period t

b_{pmt}^{pc}: Production capacity of manufacturing mill m for product p in time period t

b_{mt}^{pm}: Production capacity of manufacturing mill m in terms of available machine hours at time period t

b_{dp}^{s}: Storage capacity of product p at the distribution center d

d_{r}^{rec}: Machine hours that processing recipe r takes, on a unit activity level

f_{rp}^{in}: The quantity of product p consumed when using recipe r on a unit activity level (Activity level can be interpreted as how many times a standard recipe is used.)

f_{rp}^{out}: The quantity of product p produced when using recipe r on a unit activity level

d_{cpt}: Demand quantity of product p by customer c at time period t

Decision Variables

X_{pijt}: Flow of product p from node i to node j at time period t

Y_{rmt}: Activity level of recipe r at manufacturing mill m at time period t

I_{pnt}: Inventory level of product p at node n at the end of time period t ($n \in \{S \cup M \cup D\}$)

Objective function

$$Min\ z = \sum_{s\in S}\sum_{m\in M}\sum_{p\in P}\sum_{t\in T} c_{pst}^{pur} X_{psmt} + \sum_{r\in R}\sum_{m\in M}\sum_{t\in T} c_r^{rec} Y_{rmt} + \sum_{i\in\{S,M,D\}}\sum_{j\in\{M,D,C\}}\sum_{p\in P}\sum_{t\in T} c_{pij}^{tr} X_{pijt}$$
$$+\sum_{p\in P}\sum_{n\in\{S\cup M\cup D\}}\sum_{t\in T} c_{np}^{inv} I_{pnt}$$

The objective is to minimize the total cost of a four-echelon value chain (suppliers, manufacturing mills, distribution centers and customers) with respect to the constraints mentioned below. The total cost includes purchasing costs from suppliers, processing costs, transportation costs throughout the value chain and inventory holding costs at suppliers, manufacturing mills and distribution centers.

Constraints

Procurement capacity constraints of suppliers

$$\sum_{m\in M} X_{psmt} \le b_{pst}^{pro}\ \forall\, s \in S, p \in P, t \in T$$

Production capacity constraints of manufacturing mills in terms of quantity of products produced

$$\sum_{r\in R} f_{rp}^{out} Y_{rmt} \le b_{pmt}^{pc}\ \forall\, m \in M, p \in P, t \in T$$

Production capacity constraints at mills in terms of machine hours

$$\sum_{r\in R} d_r^{rec} Y_{rmt} \le b_{mt}^{pm}\ \ \forall m \in M, t \in T$$

Storage capacity constraints of distribution centers

$$I_{pdt} \le b_{dp}^{s}\ \forall\, d \in D, p \in P, t \in T$$

Customers' demand constraints (including product flows from mills directly and via distribution centers)

$$\sum_{d\in D} X_{pdct} + \sum_{m\in M} X_{pmct} = d_{cpt}\ \forall\, c \in C, p \in P, t \in T$$

Flow conservation constraints of manufacturing mills

$$\sum_{r\in R} f_{rp}^{out} Y_{rmt} + \sum_{s\in S} X_{psmt} + \sum_{o\in M} X_{pomt} + I_{pm,t-1} = \sum_{r\in R} f_{rp}^{in} Y_{rmt} + \sum_{d\in D} X_{pmdt} + \sum_{o\in M} X_{pmot} + \sum_{c\in C} X_{pmct} + I_{pmt} \forall m \in M, p \in P, t \in T$$

Flow conservation constraints of products at distribution centers

$$\sum_{m\in M} X_{pmdt} + I_{pd,t-1} = \sum_{c\in C} X_{pdct} + I_{pdt} \ \forall \ d \in D, p \in P, t \in T$$

All decision variables must be non-negative.

1.4 Decision support in the value chains of the FVCN

In the following sections, we describe the main decisions and planning problems arising in tactical planning in each of the aforementioned value chains in the FVCN. We also review a number of models and solution methods proposed in the literature. Furthermore, we provide an overview of existing DSSs for tactical planning developed world-wide since the 1990s. These DSSs could be at different development stages, i.e., from a DSS proof-of-concept developed by researchers and tested on a real/realistic problem instance to an operating DSS in use by DMs in the industry or government. Each DSS is discussed according to the decision(s) made, the planning approach used, the quantitative and/or qualitative results obtained and to what extent the DSS is implemented in the industry (e.g., used by DMs, used for consulting analysis). Finally, for each reference, we also indicate in which of the main process(es) along the value chain the planning method/DSS is used.

1.4.1 Forest value chain

The forest value chain includes the entities responsible for managing forestlands, those handling forest harvesting and wood transportation up to the manufacturing mills. There are several articles that describe this value chain, see e.g. the review by D’Amours et al. (2008, 2011). In general terms, tactical forest planning is done by the forest manager (that may or may not be the forest owner) or by the entity that purchased the wood (still standing trees), which may be the mill or a wood-contractor that intermediates the wood supply to the mills. In most cases, harvesting and forwarding operations are outsourced to small-scale local entrepreneurs that manage the manpower and own or rent the machinery. Forest harvesting operations in a cut-to-length system includes tree felling (final felling or thinning operations), tree bucking into logs of different lengths and forwarding the logs to pick-up points (landing) adjacent to logging roads. Felling and bucking operations are done by specialized workers with manual chainsaws or mechanized harvesting systems depending on the characteristics of the stand and equipment availability. The forwarding can also be done with mechanized forwarders. Log processing and sorting can occur at the harvesting site. It involves removing the limbs and the tops of the trees and bucking them into merchantable log lengths. Each log is sorted into assortments according to grade, dimensions (length and diameter) and specie. The assortments are individually piled at the roadside. Log transportation is usually outsourced to a third company that manages a fleet of log trucks and drivers. Logs may be directly transported to an industrial transformation site (see e.g. the review on forest-to-mill transportation by Audy et al., 2012a) or to intermediate stockyards located at strategic logistic nodes (e.g. close to the railway network). There, the logs are temporarily stored. In a full/whole-tree harvesting system, the processes taking place at a stump in a cut-to-length system are postponed at one or several stages from the landing site to the industrial transformation site. In some regions, tower hauling is used for forwarding purposes. In very special cases, depending on road accessibility and site conditions, helicopters may be used to transport the logs.

The number and nature of the entities involved determines the way these forest operations are planned from strategic to operational level, across the forest value chain. Unlike strategic planning, the distinction between tactical and operational planning is sometimes narrow and greatly country-to-company-specific. In some pulp and paper industries, the term tactical is not used, therefore they designate as operational planning the entire process of scheduling forest operations on a 12-month basis (e.g. Murray and Church, 1995; Epstein et al., 1999b). In any case, it is commonly acknowledged in the literature that tactical harvest planning deals with decisions of selection of the harvesting stands and scheduling harvesting across a planning horizon that may vary from 1 to 5 years, depending on the complexity of the problem and the species composition, allocating available manpower and existing harvesting machinery systems to the stands to be harvested, determining allocation to customers (e.g. sawmills), as well as road engineering (building new roads or maintaining existing ones). Operational harvest planning relates to detailed scheduling decisions that precede and determine the real-world operations (D'Amours et al., 2008). The length of the planning time periods is generally such that in tactical planning several stands can be harvested in the same time period (months or years). In operational harvest planning, the harvesting of a stand covers several time periods (months or days). Another difference is that tactical planning often uses aggregated demand information on assortments without spatial data whereas operational planning includes location of industries and a more detailed description of the assortments needed. Detailed discussion of tactical and operational planning problems is provided in Marques et al. (2014).

The references on planning method/DSS in the forest value chain that are discussed in this section are listed in Table 1.1 with an indication of the main process(es) covered along the value chain. Please note that this is a non-exhaustive selection, aiming to capture the most relevant DSS found in the literature to support forest harvesting and/or raw material transportation-related decisions. In fact, in many DSSs (e.g. Optimed, Beaudoin et al. (2007), RoadOpt and FlowOpt) transportation and forest harvesting are jointly planned, with the goal to fulfill the demand at the mill that may encompass different types of product assortments. Few of such DSSs also address the production process. The DSSs discussed in this section rely on Linear Programming (LP), Integer Programming (IP) or Mixed Integer Programming (MIP) formulations. Binary (or continuous) decision variables state when each stand should be harvested. Integer or continuous wood flow decision variables relate to the amount of wood transported from a stand to the mill in a given period or a given product assortment. The solution methods include both exact and heuristic methods. Case-specific heuristics are used in some of the systems (e.g. FlowOpt) as a way to obtain good solutions in short computational time. All the DSSs also have in common a development tailored to a real industrial problem. Therefore, the time (months to 2-5 years) and spatial scales (group of stands to forest region) of planning are very diverse in adapting to the reality of the DM.

Table 1.1 Scope along the forest value chain addressed by the reviewed literature

References	**Main processes along the value chain**			
	Procurement	Production	Transportation /Distribution	Sales
Planex (Epstein et al., 1999a)		X	X	
Optimed (Epstein et al., 1999a)		X	X	
FlowOpt (Forsberg et al., 2005)	X		X	
Carlgren et al. (2006)	X	X	X	
RoadOpt (Karlsson et al., 2006; Flisberg et al., 2014)			X	
Beaudoin et al. (2007)	X	X	X	
MaxTour (Gingras et al., 2007)			X	
Bredström et al. (2010)	X	X		
FPInterface (Favreau, 2013)	X	X	X	

Optimed runs for two to five years divided into summer and winter seasons to support harvest and transportation planning, considering multiple types of assortments (including sawn timber and pulp logs), with the goal of maximizing the net present value of the forest management or minimizing the total harvesting costs across the planning period. Harvesting is driven by the forecasts of the demand at the mill over the planning period for different types of product assortments. The number of assortments impacts the price at the mill but also the harvesting cost. Harvesting is mainly constrained by the total volume available at the forest site, which is estimated by growth and yield models. Optimed also considers road network design and planning. This means that the decisions to upgrade a given road segment or to build a new one in a period are made according to when harvesting is expected to occur in the stands served by that road segment and its required accessibility conditions. DSSs for tactical forest value chain planning often acknowledges the seasonality of the harvesting operations that exists in some countries, conditioned by unfavorable soil conditions and difficult accessibility of the logging roads during part of the year. In Nordic countries, harvesting tends to be focused during the winter when the ground is frozen, thus reducing the risk of soil erosion when moving logs out of the forest, while in Chile and in the Mediterranean countries harvesting and transportation is forced to occur mainly during the summer to avoid the rainy season that has a negative impact on the quality of the road network. Moreover, in some countries, sawmills or harvest operations are closed during summer holidays whereas the pulp and paper mills work continuously during the year. This impacts the inventory planning of the assortments. Optimed encompasses a MIP model. Binary variables address where to harvest and whether to upgrade or build a certain road segment in a certain period. Continuous variables are related to the wood flow decisions. The model is solved by a combination of strengthening the LP formulation and heuristic rounding of variables. At least one industry in Chile has been using the DSS since 1994, running every few months and reporting relevant revenue gains.

Beaudoin et al. (2007) addresses harvest scheduling and wood transportation decisions in a demand-driven multi-facility environment. Specifically, the problem consists in maximizing a firm's profit while satisfying demand for end products and wood chips covered under agreements and demand for logs from other companies. The DSS also takes into consideration the movement of machinery from one harvested stand to the next. Equipment transportation is a non-profit operation that further contributes to the increase of harvesting costs whenever there is a need to hire specific equipment movers for traveling long distances between harvesting units. In some cases of disintegrated forest value chains, the decisions related to the efficient use of the harvesting resources are separated from harvest scheduling as these are the sole responsibility of the sub-contractors. The MIP model proposed by Beaudoin et al. (2007) was tailored to the case of productive forestland within the public domain, as in Canada, where the government allocates volumes of timber to mills through timber licenses (TL) in wood procurement areas. Procurement areas and TL may be shared among companies and wood exchanges between companies can also occur. The outcome of this model is a five-year development plan (tactical plan) that identifies blocks to be harvested in each year. It assumes that a strategic plan was produced before and also that an annual plan will follow, including more details on surrounding activities on the harvesting blocks for the first year of the tactical plan. The solution method makes use of Monte-Carlo methods to address uncertainty. This approach was successfully applied in a hypothetical case, suggesting an 8.8% increase in profitability when compared with a deterministic model.

FlowOpt addresses the allocation of catchment areas to demand points with the possibility of integrating multimodal transportation planning (truck, train and vessel) and back-haulage tours for reducing empty driving. The DSS further foresees the possibility of wood bartering between companies. The first version of the system was developed from 2002-2004 by the Forestry Research Institute of Sweden (Skogforsk) and was used by Skogforsk in analyses for many Swedish forest companies. The optimization model is based on a LP model with a lot of flexibility provided by many detailed input files. The software has been used to carry out case studies with savings from 5 to 15 % (Forsberg et al., 2005, Frisk et al., 2010). In addition, the use of the DSS has led to increased knowledge in the industry about optimization. FlowOpt is also used as an important educational tool in Swedish forest logistics education (Fjeld et al., 2014) and a slightly modified version was used to update the whole transportation and logistics planning of a Swedish forest company after its supply areas were hit by a major storm (Broman et al., 2009).

Carlgren et al. (2006) present an MIP model for harvesting and transportation planning considering alternative strategies for sorting the logs in the forest and the possibility of back-haulage tours. The solution method is based on column generation combined with branch-and-bound techniques. The method was applied in two case studies in Sweden including three pulpwood suppliers working with many pulp mills and sawmills. One case study showed that the introduction of specific demands on pulpwood from thinning by two of the region’s pulp mills would lead to a 6% increase in total sorting and haulage costs. By optimizing the use of back-haulage tours, the cost increase could, however, be reduced by 25%.

Similarly, RoadOpt (Karlsson et al., 2006; Flisberg et al., 2014) relies on a MIP formulation for demand-driven annual harvesting and transportation planning with several assortments and road opening decisions, considering variations in road accessibility conditions during the year due to the weather conditions. RoadOpt further addresses harvest team/machinery allocation to each harvesting area, considering skills, home base and production capacities as well as stands characteristics (e.g. terrain physiography, tree density, height and stand composition). The model was solved optimally with CPLEX. Alternatively, a heuristic approach was proposed for larger problem instances to mimic limited Branch-and-bound in CPLEX. This DSS has been applied in case studies for several Swedish companies and has led to promising results. Similarly, Bredström et al. (2010) solves an annual resource planning problem which includes decisions related to the assignment of the machine systems and teams to the harvesting stands minimizing the harvesting costs over time, taking into account the specific characteristics of the stands as well as home base location for the teams and production capacities, as well as varying weather and road conditions during the year. It also includes variables to decide the sequencing of teams during the seasons. This part is handled by solving the overall problem in two phases. The first phase allocates stands to teams and the second finds a sequencing solution. The system has been further developed to consider also a detailed demand description at mills. Here, variables for transportation flows are also included. The system has been used to support capacity planning in a number of case studies.

Planex combines these machinery assignment decisions with road design. Decisions include which areas to harvest by skidders and which by towers; where to locate the landings for towers, what area should be harvested by each tower, what road to build and what volume of timber to harvest and transport. The system is highly dependent on geographical data for the stands location and site characteristics. A graphical user interface enables the user to modify and visualize solutions as well as possible location of towers, relevant costs, technical parameters, maximum slope. The solution approach encompasses a series of heuristics rules for the minimum cost allocation of machinery to harvest sites. Priority is given to areas to be harvested with skidders and towers according to slopes. Then a shortest-path algorithm determines the best new roads to build to link the machinery location to existing roads. A local search routine looks for changes of machine locations to improve the solution. Planex has been in use by Chilean companies since 1996. Savings were 0.5 to 1.5 US dollars per cubic meter and the road network was reduced by as much as 50%.

There are a number of other technical, economic and ecological aspects affecting harvest scheduling decisions that may be included in the DSS, often as alternative constraints, including budget constraints or producing minimum levels of certain assortments.

It is noteworthy that none of the DSSs listed above takes into account spatial adjacency constraints. However, when the planning horizon extends up to five years, national regulation or silvicultural best practices may impose a maximum allowable size of the clearcut opening area in order to minimize the risk of soil erosion. This means that consecutive stands cannot be harvested in the same period if the sum of the areas is higher than the maximum allowed clearcut opening size (e.g. Clark et al., 2000; Richards and Gunn, 2000; Murray, 1999). Green-up constraints may also be used to assure that there is a minimum number of periods between harvesting two consecutive stands, in order to assure that the vegetation from the first harvested stand covers the bare ground before the neighboring stand can be clearcut. For additional information about adjacency constraints and spatial harvest scheduling please refer to Baskent and Keles (2005) and Weintraub and Murray (2006).

The level of utilization of the listed DSS is the most diverse. Some of the DSSs developed for the Chilean companies (Planex, Optimed, Opticort) have been in use since the 1990s. Some of the DSSs developed for the Swedish companies (RoadOpt, Carlgren et al. (2006) and FlowOpt) have also been in use since 2004. FlowOpt has been in use at two of the major Swedish forest companies for monthly transportation planning and in many case studies to support the forest industry with answers to ‘what if’ scenarios (e.g. location of new terminals). The software described in Carlgren et al. (2006) has been used internally in one company for analysis. RoadOpt has been used in several case studies to support the companies with selection of suitable roads for upgrading. This problem is receiving increasing interest due to deteriorating quality of roads and discussions to increase the truck load limit. In Canada, the FPSuite developed by FPInnovations includes a number of simulation/planning modules and we discuss two of them. Deployed to over 100 licences in government, industry and academics in Canada (Favreau, 2013), the DSS FPInterface is a simulation module allowing the results (e.g. costs, yield, products baskets) to be generated for a given procurement plan entered on the system by a DM. The system's first obvious benefit is the time saved for DM to assess the performance of their harvesting plan and Canadian industry has reported gains of over CAD\$0.25/m³ (Favreau, 2013) when using the system. To increase the benefits, the system could be linked to other planning modules supporting the DM such as the transportation module MaxTour (Gingras et al., 2007). This system computes the potential in back-haulage tours within the volume of one or several types of products usually managed by distinct DM (e.g. round timber/bulk fiber delivered/shipped to/from a sawmill). Its planning method was developed in partnership with researchers at HEC Montréal (Canada) and is based on an adaptation of the well-known savings heuristic of Clarke and Wright (1964). During recent years, a number of analyses have been conducted by FPInnovations on historical transportation data of Canadian forest companies and, in the six most exhaustive cases, potential cost savings (traveling time reduction) between 4-7% (5-9%) have been identified. Also, in a number of the analyses, the proposed back-haulage tours have been used by DMs in Canada to support their manual truck routing (Audy et al., 2012a). When several types of products are jointly planned, multi-product truck trailers (i.e. logs and bulk fiber trailers) are used in addition to classic (mono-product) truck trailers. By allowing the transportation of different types of products on the same truck trailer, a multi-use truck trailer increases the number of possibilities for back-haulage tours and thus, additional cost savings can be realized. For example, Gingras et al. (2007) report an additional savings of 1.1% with the addition of multi-use truck trailers in the transportation of timber and bulk fiber in a large network of forests and mills of a Canadian company.

1.4.2 Lumber, panel and engineered wood products value chain

A typical supply chain in the wood (softwood and hardwood) lumber industry includes sawlog suppliers, sawmills, kilns, added-value products mills, warehouses, retailers and end-customers. The combination of seasonality of supply, log quality variation, customer demand variation, the wood long cycle time (and relatively short transformation cycle time), the divergent production process with the lack of synchronization and integration between business units, makes the planning of the lumber and value-added products value chain a complex task. The planner faces the challenge of defining optimal procurement, sawing, drying, and transportation plans as well as seasonal stock levels for each product, in each location of the value chain, while taking into account all of the procurement, production, transportation and customer constraints.

This section covers the literature about lumber, panel, engineered wood, and value-added wood products value chain, respectively. There are several articles that describe these value chains, see e.g. Singer and Donosco (2007) and D'Amours et al. (2008, 2011). The references on planning method/DSSs in this value chain that are discussed in this section are listed in Table 1.2 with an indication of the main process(es) covered along the value chain.

Table 1.2 Scope along the lumber, panel and engineered wood products value chain addressed by the reviewed literature

	Main processes along the value chain			
References	Procurement	Production	Transportation /Distribution	Sales
Carino et al. (1998, 2001a, 2001b)	X	X		
Maness et al. (1993, 2002)	X	X	X	X
Reinders (1993)	X	X		
CustOpt (Liden and Rönnqvist, 2000)	X	X	X	X
Donald et al. (2001)	X	X	X	X
Farrell et al. (2005)	X	X	X	X
Optitek (Zhang and Tong, 2005; Favreau, 2013)	X	X	X	
FORAC's experimental platform (D'Amours et al., 2006; Frayret et al., 2007; Forget et al., 2008)	X	X	X	X
Ouhimmou et al. (2008, 2009)	X	X	X	X
Singer et al. (2007)	X	X	X	X
Feng et al. (2008, 2010)	X	X	X	X
Marier et al. (2014)	X	X	X	X

Maness and Adams (1993) proposed a model to integrate the processes of bucking and sawing to respond to expected changes in product value or market demand by changing policies with regard to sawing patterns and log consumption. They developed an iterative approach solution based on three models. The first model involves a cutting pattern optimizer which determines the optimal sawing pattern for each log including diameter, taper and length, according to lumber values. The log bucking model objective includes determining the optimal combination of logs to cut from the stem. The problem can be formulated as a knapsack problem and it can be solved using a dynamic programming approach. The log allocation model acts as the master problem and uses the cutting pattern optimizer and the stem bucking model. Its objective involves distributing logs to different sawmills and selecting optimal bucking and sawing strategies to maximize the profit. Maness and Adams reported that the computational results show between 26%-36% potential revenue gain due to the integration of the bucking and sawing processes for a large log mill in British Columbia producing export products. Maness and Norton (2002) developed an extension of the model to take into account several planning periods.

Donald et al. (2001) developed two linear programming models for tactical production planning in value-added lumber manufacturing facilities. The first model is designed for non-integrated value-added facilities (sells its entire lumber production to the market); the second is designed for value-added facilities integrated (resaw and molder) with a sawmill with the ability to produce their own raw materials from their primary operations (sawmill sells only the lumber that is not directed to the value-added facility for further processing). The authors compared the two models to explore the financial benefits for a real sawmill of integrating a value-added lumber manufacturing facility at the back end of the mill. The results showed that net revenue for integrated value-added sawmill exceeds the net revenue of non-integrated one by 10% and also the production decisions in the value-added facility had a significant influence on production decisions in the sawmill. The authors suggested that these results should be validated by practical testing of the model in field use and how easily they can be used and understood by mill personnel with little or no background in mathematical programming.

Liden and Rönnqvist (2003) introduced an integrated optimization system, CustOpt, which allows a wood supply chain to satisfy customer demand at minimum cost. The model considers bucking, sawing, planing, drying and the classification process. This integrated model aims to maximize the value of various products and secondary products while taking into account harvesting costs, transportation, external buying, production costs (drying, grading and planing) and internal flow. The system was tested and analyzed in a company using two to five harvesting districts, two sawmills and two planing mills and very detailed log breakdown information with many products. Key decisions at the mill were to decide the production of products for three main customer areas (Japan, Europe and US). From a similar perspective, Singer and Donoso (2007) presented a model for optimizing planning decisions in the sawmill industry. They modeled a supply chain composed of many sawmills and drying facilities, with storage capacities available after each process. In this problem, each sawmill is considered as an independent company, making it imperative to share both the profitable and unprofitable orders as equitably as possible. The model allows transfers, externalizations, production swaps and other collaborative arrangements. The proposed model was tested at AASA, a corporation that consists of 11 sawmilling plants located in southern Chile. Based on the results of the testing, the authors recommend using transfers, despite the explicit transportation costs incurred. They also recommended that some plants focus almost exclusively on the upstream production stages, leaving the final stages to other plants. The authors find an opportunity to increase profits by more than 15% through a higher utilization of the capacity and a better assignment of production orders.

Reinders (1993) developed a prototype for a decision-support system called IDEAS (for Integral Decision Effect Analysis System) for tactical and operational planning of centralized conversion site where bucking and sawing operations are performed. The model considers only one sawmill and does not take into account other processes such as planing and drying. IDEAS consists of a database, a model base (bucking process, sawing process, production planning models) and a user interface. The model base is an optimization based model, based on both dynamic programming and column generation. The author has validated the model in a real case study where a real-world plant in Germany served as test. The plant uses raw material both from company-owned forests, and purchased on the open market. The author simulated five different policies ranging from service level, profit maximization (production effectiveness), to value recovery (production efficiency) from wood, etc. the results show that a trade-off between profitability and value recovery can be made by manipulating stock out costs.

Farrell et al (2005) developed a relational database approach to create an integrated linear programming-based decision support system that can analyze short and mid-term production planning issues for a wide variety of secondary wood product manufacturers. The mathematical model takes into account generic constraints related to the secondary wood products industry such as raw material, material balance, recovery, machine capacity and marketing considerations. They aimed to maximize the profits of the secondary manufacturing operation over a planning horizon. They generated specific reports related to the financial aspect, procurement strategies, machine yield, sales, etc. The authors did not report any results of the implementation of the DSS on real industrial cases but conclude that due to its generic design, the system can determine product mix, raw material sourcing, production strategies, pricing strategies and resource evaluation for different configurations of companies in the secondary wood industry.

A DSS called Optitek has been developed by FPInnovations to simulate the whole softwood sawmilling process (bucking, sawing, trimming, and edging) in Canada. The system allows analyzing the impacts on the yield (value or volume) and baskets products (including by-products) of modifications to the sawmilling process or in the input log characteristics (Zhang and Tong, 2005). Since the tool required advanced expertise and direct use by industry is often an impediment to gaining the full potential from the system, most sawmills use external resources to conduct such studies. Over 75 Canadian sawmills have been modeled on the system over the last decade and case studies often indicate potential improvement of more than CAD\$2/m^3 (Favreau, 2013). Optitek has been integrated with FPInterface (FPInnovations) to anticipate the economic value of each harvest area (net value of each bloc) by simulating trees of each harvest bloc in Optitek and allocating them to the right sawmill. On the other hand, D'Amours et al. (2006), Frayret et al. (2007), and Forget et al. (2008) have together proposed an agent-based experimental platform for modeling different lumber supply chain configurations and assessing the impact of different planning approaches. This model represents the sawmilling, drying and finishing processes as alternative one-to-many processes constrained by bottleneck capacity. The authors used different business case studies to validate the simulation platform and the specific planning models proposed (e.g. linear programming, constraints programming and heuristics). In addition, simulations were done to evaluate different strategies for the lumber industry, given different business contexts. During the simulation, wood procurement was set as a constraint, and demand patterns were stochastically generated according to different spot market and contract-based customer behaviors. The authors did not report any real implementation of the simulation platform in real mill.

Carino and Lenoir (1988) developed a mathematical model to successfully optimize wood procurement for an integrated cabinet-manufacturing company that owns one sawmill and one kiln. The authors used regressions equations based on a sample of 25 logs to determine the volume and grade and furniture components yielded from each log diameter and length. They found an optimal wood procurement policy where raw material input should be limited to #2 grade hardwood logs and #2 common green lumber purchased directly from outside suppliers. The model was not used by the company even if the authors estimate the potential savings could reach 32% for raw material purchases.

Carino and Willis (2001a, 2001b) presented a LP model to solve the production-inventory problem inherent in vertically integrated wood products manufacturing operations (hardwood lumber-cabinet). The model aims to maximize mill profitability and provides valuable information for making management decisions related to desired level of production and end-of-period inventories, desired quantity of products to be sold, level of resource utilization at each stage and impact of changes in input/output and operating conditions on system profitability. The authors presented the results of a real case study to demonstrate the ability of this model in solving a complex set of production-inventory problems. The objective of the analysis was to determine the optimal sawlog and lumber production-inventory program for the study mill over a specified planning horizon. Their results indicate that mill profit could be maximized by adopting a specific log procurement policy (log volume, sawing patterns and inventory level). Such a policy could result in profit improvement of up to 156% over the result from the minimum 1-month log inventory policy used by the sawmill. They have also performed a parametric analysis and showed that mill profitability is very sensitive to changes in kiln-dried lumber prices, sawmill conversion efficiency, and lumber drying degrade; moderately sensitive to changes in log supply and prices and processing costs.

Ouhimmou et al. (2008, 2009) presented a MIP model for planning the wood supply for furniture assembly mills. Their model addresses multi-site and multi-period planning for procurement, sawing, drying, and transportation operations. Assuming a known demand that is dynamic over a certain planning horizon, the model was solved optimally using CPLEX and approximately using time decomposition heuristics. The model was then applied to an industrial case with a high cost-reduction potential (22%), with the objective of obtaining procurement contracts, setting inventory targets for the entire year for all products in all mills, and establishing mill-to-mill relations, outsourcing contracts and sawing policies. These results have convinced the company to use the tool for the future configuration of its supply chain network. This research project has been extended to develop the DSS called LogiLab (see Section 1.4.6).

Feng et al. (2008) applied the concept of sales and operations planning (S&OP) to oriented strand board (OSB) supply chain. They used sales decisions to investigate the opportunities of profitably matching and satisfying the demands of a given supply chain, given the chain’s production, distribution, and procurement capabilities. They proposed three MIP-based planning approaches of the four processes within the value chain of an oriented strand board (OSB) company using a make-to-order strategy: fully integrated planning, fully decoupled planning and integrated sales and production with decoupled distribution and procurement planning. The MIP models were simulated, for a real OSB manufacturing supply chain, with deterministic demand (Feng et al., 2008) and with a stochastic demand in a rolling horizon planning (Feng et al., 2010). In both cases, the fully integrated planning approach outperformed (e.g. up to 4.5% revenue increase with perfect demand forecasting) the fully decoupled and partially integrated planning approaches. In a similar way, Marier et al. (2014) proposed a linear program for the integrated annual planning of the sales and operations of a network of sawmills. Simulated over the historical data of twelve years, a two-sawmill case study showed that the model would have increased the gross margin by an average of 1.47% of sales revenue. This potential increase is due to adapting production and inventory decisions to market price fluctuations. The authors reported that these results convinced the company to explore ways of implementing sales and operations planning even though they were very skeptical about the benefits of such approach before the start of the study.

1.4.3 Pulp and paper products value chain

The main activities of the pulp and paper value chain are harvesting and transportation, pulp making, papermaking, sales and distribution. There are several articles that describe this value chain, see e.g. Carlsson et al. (2009) or more recently D'Amours et al. (2014). Harvesting is of course also a part of other value chains. However, in some cases harvesting is driven by one main value chain. For example, in thinning operations a vast majority is focused on pulpwood. In others, the focus is on sawmills, and pulpwood is a secondary co-product. Moreover, in other situations there is no harvesting. This happens often in Québec (Canada) where virtually all logs flow through sawmills and hence the raw material (wood chips) come directly from sawmills. Pulp making converts pulp logs unless chips are directly transported as mentioned above. Chips of different species are mixed in recipes to get pulp with desired properties. The chips are boiled and washed to separate fibers from lignin in a number of steps. To get the correct brightness level the fibers are blended with different chemicals in a bleaching process. The pulp process is often a continuous process where some parts may be batched, for example, the cooking. Paper making is to produce so-called jumbo rolls that are typically 5-8 meters wide and many kilometers long. It is also possible to put some coating on the paper depending on the end use of the products. The jumbo rolls are later cut in shorter lengths and smaller widths according to specific customer demand. This cutting is done in order to minimize waste or maximize value in case quality can be considered. Some of the typical tactical planning decisions made in P&P value chain are wood fiber procurement alternatives (chips vs. pulplogs), defining appropriate pulp recipes with mix of species, sequence of recipes for pulp production, allocating right wood fiber grade to processes and end-products and optimal lot sizing in paper machine. The references on planning method/DSS in this value chain that are discussed in this section are listed in Table 1.3 with an indication of the main process(es) covered along the value chain.

Table 1.3 Scope along the pulp and paper products value chain addressed by the reviewed literature

	Main processes along the value chain			
References	Procurement	Production	Transportation /Distribution	Sales
Bredström et al. (2004)	X	X	X	X
Carlsson and Rönnqvist (2005)	X	X	X	X
Bouchriha et al. (2007)		X		
Carlsson and Rönnqvist (2007)	X			
Chauhan et al. (2008)		X	X	X
Rizk et al. (2008)		X	X	
Everett et al. (2010)	X	X	X	X
Dansereau (2013)	X	X	X	X
Carlsson et al. (2014)			X	X

There are many computerized tools in use for operational and process control at the pulp and paper mills. Yet, the number of tactical decision support tools is much lower. One reason is the uncertainty in the production processes and the fact that there is a limited number of pulp products produced. One system is PIVOT developed for Norske Skog to optimize manufacturing, distribution, and sourcing of raw materials in Australia and New Zealand (Everett et al., 2010). It is based on a MIP model and the application was an INFORMS Franz Edelman Award finalist in 2009. Even though the main decisions are on a strategic level, the model considers a tactical decision level. The system has been developed over many years but has been used actively by the company to make both strategic and tactical decisions. The potential savings by the system evaluated at the Franz Edelman competition was evaluated at US$ 100 million each year. This includes operations for all pulp and paper mills at the company.

Södra Cell is a large pulp company that mainly produces pulp for European customers from pulp and paper mills in Sweden and Norway. A number of planning problems is outlined and described in Carlsson and Rönnqvist (2005). This company has tested a number of different tactical planning tools based on OR for their operations. In Bredström et al. (2004) a system for combining procurement, production planning and sales is tested. It is based on a detailed production planning model where column generation is an important part of the solution process. Large savings are reported by making integrated decisions instead of using a sequential planning process. This paper received the EURO Excellence in Practice Award in 2004. The DSS is at the prototype development stage, but nevertheless it has been used in some rounds of the production planning. Here, it helped the planners to change their behavior even if the DSS was not integrated with the company ERP system. The same company has introduced a vendor-managed inventory (VMI) system. This has put high stress on making sure that the right products are available to customers at all times. A prototype DSS system using robust optimization has been tested to better plan the routing and inventory handling (Carlsson et al., 2014). The VMI system is implemented and in full use but the optimization system has only been used on a case study basis.

Chauhan et al (2008) describes a DSS to optimize the roll cutting of tambours at the paper mills. It takes customer demand into account in order to decide how to manage the cutting, including which parent roll should be kept in inventory before the cutting operations once customer orders are known. The model is a MIP model and a column generation approach has been used to solve the problem. The case study provided the company with many insights and the network structure was redesigned. The DSS has been used as a case study but is not implemented for continuous planning. Rizk et al. (2008) expand the model for multiple distribution centers and propose an efficient heuristic sequential solution approach to solve large problem instances. Bouchriha et al. (2007) developed a model for production planning at a single paper machine where the campaigns are fixed in duration.

A tactical planning problem for the wood procurement stage of the supply chain is dealt with in Carlsson and Rönnqvist (2007). The problem was to decide sorting strategies at different catchment areas to best satisfy the demand at paper mills. The model is a MIP model where the alternatives are pregenerated. The system is implemented at one company and used for case studies within the company, in particular when there are larger changes made for the production planning and a change in the need or mix of species. Collaboration between a paper mill and its customers has been analyzed by Lehoux et al. (2007). Different contract agreements are simulated and optimized. One result was that depending on the different players, they may prefer different alternatives and this must be considered in the agreements. The study led to some changes in the way business was conducted between the paper company and certain key customers.

Dansereau (2013) proposes a margins-based approach for the profit maximization of a pulp and paper value chain. The framework involves five main components: profit maximization, revenue management, manufacturing flexibility, activity-based cost accounting, and integrated tactical planning optimization. The author has justified the inclusion of each of these components as follows. First, a company should aim to maximize its profitability and not just minimize costs. Second, a company should use revenue management concepts to manage its sales and produce the most profitable product portfolio. Third, manufacturing flexibility should be exploited in order to be able to deal with market volatility and manufacture the most profitable product combination. In order to analyze the trade-offs between different manufacturing modes, the company should access reliable operating cost estimations for each manufacturing mode. Then the fourth aspect of the proposed planning framework would be about activity-based accounting, which makes it possible to accurately quantify the cost trade-offs between different manufacturing modes. Finally, all these four concepts have been included in an integrated tactical planning model which optimizes the whole supply chain from procurement to production, distribution and sales. The proposed margins-based planning approach proved to be effective especially in difficult market scenarios; it provides a robust planning approach through exploiting manufacturing flexibility. The model was tested in a real case study of a newsprint manufacturer in North America with overcapacity in its thermomechanical and deinking pulping lines, and which also faces varying wood chips and recycled paper prices. In this case study, the author ran the model under two different process and flexibility configurations. The first configuration represents the current case in the pulp and paper mill. In this configuration, the mill managers select the thermomechanical pulping lines and paper machines recipes based on a heuristic which is believed to minimize production costs. In the second configuration, the margins-based approach was used to optimize the recipe selection and throughput of pulping lines and paper machines in order to maximize profitability. These two instances were run in different market scenarios. Utilizing the proposed margins-based planning model showed the mill's earnings before interests, taxes, depreciation and amortization can be increased by up to 35% in some scenarios by adopting pulping production to changing market conditions.

1.4.4 Biorefinery value chain

As discussed by Dansereau et al. (2012a), the biorefinery concept appears to be a promising business opportunity for the forest products industry, especially the pulp and paper sector, to diversify its revenue stream and improve its environmental profile. Specifically, the diversification of the traditional product baskets will involve the production of value-added biochemicals and biomaterials as well as biofuels from the renewable forest biomass. This supply will come from traditionally unused biomass such as forest residues (directly from harvest areas or through an intermediate processing site) but also compete for biomass with current customers including bioenergy producers. Because existing pulp and paper mills have been using woody biomass for decades, these facilities represent natural sites to implement biorefineries (as illustrated in Figure 1.1) but selecting the most profitable biorefinery configurations to install in an operating P&P mill is a challenging decision (Dansereau et al., 2012a). The typical tactical planning decisions made in the biorefinery value chain can be summarized as biomass procurement quantities from each supplier, amount of each biomass feedstock used for producing different products through different processes, which recipe to use in each process unit, inventory levels of biomass feedstock and production level in each period, and distribution and transportation mode use and sales to different customers.

We refer to Feng et al. (2012) and Dansereau et al. (2012a) for a description of this value chain. The references on planning method in this value chain that are discussed in this section are listed in Table 1.4 with an indication of the main process(es) covered along the value chain.

Table 1.4 Scope along the Biorefinery Value Chain Addressed by the Reviewed Literature

References	Main processes along the value chain			
	Procurement	Production	Transportation/ Distribution	Sales
Eksioglu et al. (2009)	X	X	X	
Eksioglu et al. (2010)	X	X	X	
Santibañez et al. (2011)	X	X		
Faulkner (2012)	X	X	X	X
Dansereau (2013)	X	X	X	X
Meléndez (2015)	X			

These papers have modeled the biorefinery value chain planning problem mostly as a mixed-integer linear programming (MILP)/LP problem. Some papers combined MILP models with simulation modeling while another paper developed a multiobjective optimization model. We have also observed that the sales process has been covered by only two papers due to the lack/nonexistence of data (price, volume, etc.) for new bioproducts. None of these papers reported implementation in the industry, except the one by Dansereau (2013).

Ekşiogğlu et al. (2009) proposed a MIP model addressing both the strategic and tactical decisions about the design and management of a regional network of biorefineries producing biofuels. They test their model over the entire state of Mississippi, USA, using corn stover and woody biomass including pulpwood and sawtimber. They show that transportation cost and biomass availability are the two main factors affecting value chain design and therefore suggest operating multiple small-size biorefineries instead of one centralized mega-biorefinery. Ekşiogğlu et al. (2010) extended the previous model by considering different modes of transportation including intermodal and exploring how the existence of an intermodal facility affects the biofuel value chain design. Because of the bulky and low-density nature of biomass feedstock, the quantity and volume of a biorefinery's outgoing product (i.e., ethanol) are smaller in comparison to the incoming biomass. This fact justifies the result of testing the MIP model on the same case study, which encourages locating the biorefinery closer to the source of biomass than the market and leads to a 5% reduction in the biofuel delivery cost. Moreover, the case demonstrated that a biorefinery consuming a much larger amount of biomass than is available locally must be located close to a transportation hub (i.e., an intermodal facility) to be economically sustainable. Indeed, this reduces the biofuel delivery cost by as much as by 4.6 times the number of incoming truck shipments when using barges.

Santibañez et al. (2011) proposed a multiobjective optimization approach maximizing the annual profit while minimizing the environmental impact (measured through an indicator based on a life cycle analysis) of the procurement, production, and sales decisions of a biorefinery. A constraint approach is used to find a set of optimal solutions of these two conflictual objectives and thus construct a Pareto curve. Several sources of supply in agricultural biomass and woodchips are available for the production of different biofuels according to specific processing recipes. The proposed methodology was tested to study different scenarios for a biofuel mill located in Mexico.

Dansereau (2013) extended its model presented in Section 1.4.3 (i.e., profit maximization of a pulp and paper value chain) with the addition of a biorefinery within the same industrial complex. Using the same case study, the author studied several configurations of running a P&P mill and biorefinery in parallel and showed that using the proposed margin-based approach can lead to higher revenues and more savings in both P&P and biorefinery product lines. The benefit of feedstock flexibility on the biorefinery operations and of manufacturing flexibility on the integrated P&P and biorefinery operations is also demonstrated in the case. For instance, a biorefinery line with feedstock flexibility allows increasing the operational profitability by 12%. Also, as a general conclusion, they demonstrated that biorefinery lines have to consider flexibility in their process in order to be able to deal with market volatility and maintain profitability. The proposed model has been used by a newsprint mill in North America that was implementing a parallel biomass fractionation line producing various biochemicals.

Some studies have combined simulation and MILP modeling to solve a biorefinery value chain planning problem. Faulkner (2012) proposed a MILP model that addresses both the strategic and tactical decisions about the value chain design and management of one biorefinery. The author used a simulation model to generate baskets of products using all available biomass in the case study located in Kentucky, USA. The output of the simulation was the input for the MILP model. Despite biomass abundance (including forest residue) and existence of a robust chemical industry (i.e., potential market), testing the model for three different sizes of integrated biorefinery reports no profitable instance. To improve performance of the value chain, two options are proposed: first, using a less expensive mode of transportation (i.e., via pipeline) instead of truck for delivery of the most profitable product, and second, shutting down the mill in the nonprofitable months to negate the truck transportation cost. Meléndez (2015) analyzed the feedstock procurement costs and feasibility of 10 biorefinery scenarios involving two biorefinery technologies and a cogeneration plant. These were deployed at different times and scales of production at an existing P&P mill with the partial or complete shutdown of the paper machines. They also studied the potential savings on procurement costs by changing the forest harvesting technologies. The scenarios focused on fulfilling feedstock demand according to available resources while minimizing procurement costs over the whole scenario lifespan for a financially feasible biorefinery implementation strategy. A MILP optimization model for strategic decision-making along with a forest harvesting techno-economic simulation model for tactical decision-making were proposed and run over a 20-year planning horizon on a case study in Eastern Canada. Each scenario's procurement costs were compared with current practices and amongst themselves to determine which led to the best procurement strategy both for the P&P mill and interacting forest industry during and beyond the transition period.

1.4.5 Bioenergy value chain

Forest residues are by-products of conventional harvesting operations and production of traditional forest products. In recent years, the conversion of forest residues to bioenergy has gained great interest for two main reasons: (1) it gives communities in forest-based regions access to new sources of revenue, and (2) it provides the opportunity to diversify their energy sources and/or dependency while reducing greenhouse gas emissions, as forest residues are renewable materials with the potential to replace fossil fuels. As discussed by Cambero et al. (2015a), there are several operational and economic challenges that hinder the intensified use of forest residues for energy production such as challenges related to capital investment, feedstock availability, quality, and cost. Since capital costs of energy-producing technologies are high, success of bioenergy projects relies heavily on achieving the economies of scale. This would lead to an increase in the demand for forest residues, which are scattered over vast regions and whose availability varies over time. Also, different quality attributes of different types of biomass influence their procurement, preprocessing, and transportation cost as well as their conversion efficiency. Additionally, due to the low-energy density of forest biomass, collecting, processing, and transporting large amounts of forest biomass over the operational cycle of a bioenergy facility is required. To do so, several types of specialized equipment and logistics strategies are available. Consequently, to install a profitable bioenergy facility, it is necessary to address the optimal design and management of the value chain. Particularly, the main strategic–tactical decisions that affect the overall profitability of the bioenergy value chain are: the sources and types of forest residues, the location of bioenergy plant(s), the type and capacity of technologies, the material flows per period within the value chain and, in the case of uncertain feedstock supply and market conditions, the plant(s) installation period must be determined. We refer to Hughes et al. (2014) for a review on the pellet value chain and Shabani et al. (2013) for a review on the forest biomass energy production value chain. The references on planning method/ DSS in this value chain that are discussed in this section are listed in Table 1.5 with an indication of the main process(es) covered along the value chain.

Table 1.5 Scope along the Bioenergy Value Chain Addressed by the Reviewed Literature

References	**Main processes along the value chain**			
	Procurement	Production	Transportation/ Distribution	Sales
Eriksson and Björheden (1989)	X		X	
De Mol et al. (1997)			X	
Freppaz et al. (2004)	X	X		
Gunnarsson et al. (2006)	X	X		
Alam et al. (2009)	X			
Kanzian et al (2009)	X		X	
Mäkelä et al (2011)		X		
FuelOpt (Flisberg et al., 2012)	X	X	X	
Keirstead et al (2012)	X	X		
Shabani and Sowlati (2013)	X	X		
Akhtari et al. (2014)			X	
Hughes (2014)	X	X	X	X
Mobini et al. (2014)	X	X	X	X
Shabani et al. (2014)	X	X		
Flisberg et al. (2015)	X		X	

These papers have modeled the bioenergy value chain planning problem mostly as a MILP/LP problem; a few used simulation, multiobjective modeling, and nonlinear formulation, while only one paper integrated the proposed DSS with a geographical information system (GIS)–based interface. We have also observed that the sales process has not been considered in most of the studies mainly because of the lack/ nonexistence of data (price, volume, etc.) for the bioenergy market. Another reason is that the mills themselves are in fact the final customers. Nevertheless, two papers studied the entire value chain and in order to generate sales (e.g., demand) information they used simulation and forecasting techniques. Furthermore, only Eriksson and Björheden (1989) and Flisberg et al. (2012) reported implementation of the proposed DSS in the industry.

De Mol et al. (1997) developed a simulation model called BIOLOGICS (BIOmass LOGIstics Computer Simulation) and a MIP optimization model to analyze the logistics costs of biomass fuel collection. The optimization model determines the optimal network structure (i.e., inclusion/exclusion of possible nodes and situation of pretreatment) as well as the mixture of biomass types supplied to the energy plant, given the available quantities as a restriction. The simulation model, on the other hand, calculates costs and flows for a given network structure. Testing the proposed models in an energy plant fed with biomass in the Netherlands showed that both models are useful to gain insight into the logistics cost of biomass fuel collection. Indeed, the latter is typically the main cost component when evaluating the feasibility of a biomass conversion energy plant(s) project. That is why many other research projects in different countries are also focused on the logistics cost of the bioenergy value chain; in that respect the next paragraph summarizes three such studies.

Eriksson and Björheden (1989) presented an LP formulation to model the energy value chain of a forest fuel supplier. The model determines optimal annual planning decisions about procurement, processing, and storing of raw material while minimizing the sum of acquisition, processing, and transportation costs of raw material and fuel chips. The proposed DSS was implemented on the energy value chain of Jämtlandsbränslen AB (a subsidiary of the Swedish Cellulose Company), which includes several forest supply regions (consisting of four different types of raw material: chip wood, logging waste, tree sections, and sawmill waste), one central processing site, and one heating plant. The result of this analysis showed that using mobile chippers to produce chips at forest supply regions is more cost efficient than using stationary chipping equipment at the terminals. In fact, when the chips are stored at the terminals an additional transhipment cost would occur, and the results indicate these additional costs would not be paid off by the better quality (better moisture content) of stored biomass at the terminals. Accordingly, the optimal solution of the model recommended chipping 92% of the fuel by mobile chippers and transporting them directly to the heating plant while only 8% of the forest fuel should be chipped and stored at terminals. This problem is also studied by Kanzian et al. (2009) and the authors proposed a model consisting of two submodels (LP and MIP) solved sequentially. The proposed solution method is applied on a case study for a value chain of 16 combined heat and power plants and eight terminal storages in Austria. Results similar to Eriksson and Björheden (1989) were obtained; specifically, direct flow of biomass from forest area to plants proved less expensive than indirect flow via terminals. For instance, supply cost increased by 10% when half of the fuel and by 26% when all the fuel was sent via terminals. The same problem is studied by Akhtari et al. (2014) in Canada; an LP formulation is proposed and tested on a potential district heating plant in Williams Lake, British Columbia. The results of this case study do not refute those of Eriksson and Björheden (1989) and Kanzian et al. (2009) in general. Particularly, the optimal solution emphasizes that all chipping processes should be done at the forest sites and suggests transporting 90% of annual woodchip demand directly to plants and sending the remaining 10% via storage terminals.

Gunnarsson et al. (2006) developed an integrated MIP model to handle forest fuel for a Swedish forest fuel company. This model includes transportation, comminution (or conversion to wood chips) at terminals, and inventory. The aforementioned DSS FlowOpt has recently been extended to address the procurement logistics of forest biomass, in particular comminution and selection of areas for production of forest fuel (Flisberg et al., 2012). Named FuelOpt, the DSS relies on a MIP model because there is a need to select harvest areas as well as a machine system. The FuelOpt system is implemented at the Forestry Research Institute of Sweden (Skogforsk) in Sweden and has been used in several large case studies at Swedish forest companies. The savings are about 5%–15% compared with existing manual planning. One of the case studies for Stora Enso Bioenergi included 86 heating plants, six assortments, six truck types and five chipping systems, 12 periods (months), 72 terminals of which 8 have train transport possibilities, and 1,256 supply areas. The energy consumption was 3.6 TWh corresponding to 1.5 million metric tons of wood chips. The initial model had 16.4 million variables and 4.6 million constraints. Some aggregation of supply areas reduced the size to 5.9 million variables and 0.5 million constraints. The total cost of using the executed system was SEK 508.8 million (US$ 62.5 million) and with optimization it was reduced to SEK 477 million (US$ 58.7 million).

To make an optimal biomass exploitation plan for thermal and electrical energy conversion plants, Freppaz et al. (2004) developed a mathematical model accompanied with a GIS-based interface and tested the proposed tool in a consortium of municipalities in an Italian mountain region. The objective was to optimize costs and benefits of the energy value chain including collection, transportation, harvesting, and plant installation and maintenance costs together with benefits from the sale of thermal and electrical energy. The local authority of the region under study set a target of satisfying at least 10% of the overall energy needs of the area with biomass exploitation and in that regard, the optimal result made use of only 1.9% of the total biomass available in the region, which provided about 14% of the whole energy demand. More importantly, the optimum cost was 63% higher than the cost for receiving the same amount of energy from combustibles other than forest biomass. The authors analyzed this extra contribution of cost according to the environmental impact of the proposed solution. The same problem of optimization of an urban energy supply system was addressed in Keirstead et al. (2012); specifically, it assessed various biomass conversion technologies. A MIP model is developed based on a resource-technology network where resources are materials involved in provision of energy for a city and technologies represent processes converting a set of input resources to a set of output resources. The model was tested on a case study in an eco-town in UK, evaluating five scenarios of different types of conversion technologies [i.e., grid fuels, biomass boilers, biomass combined heat and power (CHP) plants with internal combustion engine (ICE), or organic Rankine cycle (ORC) and all technologies]. Results showed that, since finished wood chips have higher energy density than forest residues, importing them is economically more beneficial than importing forest residues to be converted into chips within the eco-town. The results also confirmed that using biomass domestic boilers alone is more expensive than the traditional gas-fired systems, whereas biomass CHP systems offer up to 15% cost savings over the gas-fired boiler scenario. Moreover, since the CHP systems make full use of the biomass fuel, these technologies are recognized as the most energy-efficient scenarios; for instance, compared to the gas boiler scenario, the CHP technologies consume 15%–19% less energy per capita. Also, from the environmental point of view, CHP scenarios had 80%–87% fewer emissions compared with the gas boiler scenario, meeting the regulation of the eco-town for 80% reduction in CO2.

Shabani and Sowlati (2013) modeled the value chain optimization problem of a forest biomass power plant as a mixed-integer nonlinear programming problem. The proposed model calculates a monthly amount of biomass to buy from each supplier, burn, and store, and it determines whether or not to produce extra electricity to maximize the total profit. The model is solved by the AIMMS Outer Approximation algorithm. Testing the proposed tool on a real case study in Canada reduced the biomass procurement cost by 15%, when compared with the current situation where the company managers conduct tactical planning based solely on their own experience. Biomass procurement cost and transportation cost contributed to 63% and 33% of the total cost of the power plant, respectively. Additionally, evaluating various scenarios of biomass supply availability and investment in a new ash recovery system showed investing in a new ash recovery system is beneficial from both the environmental and economic aspects. Shabani et al. (2014) reformulated the mixed-integer nonlinear programming model developed by Shabani and Sowlati (2013) into a MIP model which determines the monthly consumption and storage variables of biomass as well as monthly generated electricity in a one-year planning horizon. The authors integrated procurement, storage, production, and ash management decisions in a single framework, maximizing profitability while considering uncertainty in the amount of available biomass. First, the proposed model was solved by means of a two-stage stochastic programming approach; then the authors developed a weighted bi-objective model to balance risk and profit within the value chain. Profit variability index and downside risk (the probability that the real profit is less than a certain threshold) are the two risk measures considered. Testing the model in the case of a Canadian power plant resulted in an annual profit of CAD$16.2 million, calculated based on perfect information about suppliers' monthly available biomass. However, in reality, the amount of available biomass varies and implementing the average scenario, while other scenarios occur, led to a CAD$0.4 million reduction in the expected profit. This amount could be improved by CAD$0.2 million if uncertainty in biomass availability was taken into account in the model and the stochastic programing approach was used to solve it. Moreover, when downside risk was reduced, the probability of having high profit in the range of CAD$17–18 million or low profit between CAD$12–12.9 million became zero and the total expected profit of the power plant decreased.

Procuring wood biomass for bioenergy production in a sustainable and economical way is by itself a complex task. Alam et al. (2009) specifically focused on procurement activities involved in bioenergy production, modeled this problem as a multiobjective optimization problem, and solved it with a pre-emptive goal programming technique. The three objectives considered were minimizing the total biomass procurement cost, minimizing the total distance for biomass procurement, and maximizing biomass quality in terms of its moisture content. The authors demonstrated the application of the model in a biomass power plant consuming harvesting residues and poplar trees collected from three forest management zones (FMU) in northwestern Ontario, Canada. The problem is solved sequentially based on the DM's prioritization of the three objectives and the solution includes optimal weekly quantities of wood biomass to be collected from each FMU.

Alternatively, forest industry profitability can be improved by producing value-added products, that is, by more efficient utilization of by-products in energy application such as wood pellets. Mäkelä et al. (2011) addressed the problem of maximizing profit for Finnish sawmills with a fixed production capacity aiming at pellet production. The authors developed a static partial equilibrium model as a mixed complementarity problem. The proposed model optimizes the use of wood and by-products, which determines the optimal output mix (i.e., sawnwood, heat and power, and pellet) as well as decisions about investments in increasing the production capacity of sawnwood, heat, CHP, and pellet. Testing the model on 30 large-scale Finnish sawmills revealed the fact that with the pellet price at the time of study in the Finland sawmill industry, pellet production would not be profitable. It suggests slightly increasing pellet price or applying modest political support can make pellet production in sawmills a financially feasible business. In that respect the authors studied the application of input, investment, and production subsidies where the last two proved to be the most efficient policy instruments in promoting pellet production. Recently, in Canada, Hughes (2014) studied the pellet value chain planning problem under uncertain demand conditions over a 1-year planning horizon with the objective of gross margin maximization. The author generated stochastic demand information by means of the exponential smoothing forecasting method and proposed three optimization models based on different operating conditions (i.e., with/ without an inventory management system and with variable/fixed production rate). The models have been tested on a case study of a wood pellet producer in northern Ontario, Canada. Results show the model with an inventory management system and variable production rate outperforms the other models and this is because it enables the pellet producer to account for deviation in demand according to its operational environment. In addition, the result of a sensitivity analysis indicates fluctuations in supply and demand have the highest influence on the gross margin.

In another recent work by Mobini et al. (2014), the integration of torrefaction into wood pellet production is evaluated; the authors used a simulation model called the pellet supply chain (PSC) proposed by Mobini et al. (2013). The outputs of PSC are the amount of energy consumed in each process, its related CO2 emissions, and the cost components of delivered wood pellets to customers. The underlying model combines discrete event and discrete rate simulation approaches and has taken into account uncertainties, interdependencies, and resource constraints along the value chain. More precisely, uncertainty in parameters such as quality and availability of raw materials, processing rates and equipment failure, and electricity/fuel consumption is taken into account. The model was tested in an existing wood pellet value chain, located in British Columbia, Canada, to assess the cost of delivered torrefied pellets to different markets. Also, energy consumption and carbon dioxide emissions along the supply chain were compared with those of regular pellets. The result of this case study shows, due to increased energy density and reduced distribution costs compared with regular pellets, the delivered cost of torrefied pellets ($/GJ) to Northwest Europe decreases by about 9%. Moreover, in terms of energy consumption and CO2 emissions along the value chain, the result of this study indicates that torrefied pellets are superior to regular pellets. Hence, the success of integration of torrefaction into wood pellet production depends on trade-offs between the increased capital and operating costs and the decreased transportation cost. For example, when long transportation distance is involved, torrefied wood pellets are more economical in terms of lower cost of delivered energy content.

Flisberg et al. (2015) analyzed all transport of forest biomass in Sweden for a year. There are 200,000 transports of eight assortments from 58,000 harvest areas to 647 heating plants included in the case study. The authors use the FlowOpt system for the analysis, which also includes 61 companies. Of these companies, 28 have volumes exceeding 10,000 tons and are treated as single companies whereas the others are aggregated. The largest model includes 100 million variables and 1.2 million constraints. Some cost allocation methods are proposed and analyzed. One of the problems with cost allocation is that the number of coalitions is 536 million, which means that many standard game theoretical models based on core stability are not practical. The actual transports are registered and by changing delivery time, changing assortments, and collaborating, different levels of savings can be obtained. Collaboration in itself can save 12% and together with the other options up to 22%.

1.4.6 Integrated value chains

Some planning methods/DSS are designed to combine two or more value chains in an attempt to avoid suboptimization. The references discussed in this section are listed in Table 1.6 with an indication of the main process(es) covered along the value chain, as well as which value chains they address.

Table 1.6 Scope and value chains of the FVCN addressed by the reviewed literature

	Main processes along the value chain				**Value chain**				
References	Procurement	Production	Transportation/Distribution	Sales	Forest	Lumber, panel and engineered wood products	Pulp and paper products	Biorefinery	Bioenergy
Kong et al. (2012)	X	X	X	X	X		X		X
Kong et al. (2015)	X	X	X	X	X		X		X
FPInterface- Optitek-LogiLab (Morneau-Pereira et al., 2013, 2014)	X	X	X		X	X			
FPInterface- Optitek-ForestPlan (Kryzanowski, 2014)	X	X	X		X	X			X
Kong and Rönnqvist (2014)	X	X	X	X	X	X	X		X
LogiLab-SilviLab (Simard, 2014)	X	X	X		X	X	X	X	X
Troncoso et al. (2015)	X	X	X	X	X	X	X		X

The DSS LogiLab has been under development by researchers at the FORAC Research Consortium, Université Laval, since 2009 (Lemieux, 2014). The system enables the tactical modeling and optimization of a FVCN from the supply areas up to the final customers. The user-friendly modeling is done through either the fulfillment of an Excel spreadsheet (that will be imported on the system by the user) or a schematic/geographical representation where the user adds the different locations of its network one by one, and defines for each a set of mandatory/optional parameters (e.g., geographical location, inputs and outputs according to the transformation process involved, processing capacity, demand, etc.). The current material flow between the locations and the traveling distances are also defined. Then the DSS optimizes the value creation of the network by maximizing the profit of the whole network while reducing transportation, inventory, and production costs. Therefore, the DSS allows answering two main questions: (1) what is the most profitable wood fiber allocation among the FVCN entities? (2) can we increase profitability of as-is VCN with a given what-if scenario? A number of case studies have been conducted with the DSS LogiLab; we discuss one of them and also report its combinations with other DSS.

Elleuch et al. (2012) used the system to compute the potential profitability of implementing three interfirm collaboration approaches (i.e., regular replenishment, VMI, and collaborative planning, forecasting, and replenishment) in a FVCN of five sawmills and one pulp and paper mill in Eastern Canada. Each approach was computed according to four what-if scenarios (e.g., opening of two shutdown mills, consideration of chip freshness and sorting rules, external chip supplier) and for a base case scenario. Through a column generation method, the optimization model of the DSS LogiLab (master problem) has been combined with the optimization model of SilviLab (subproblem), a strategic forest management DSS also developed by the FORAC Research Consortium. Through an iterative process, this tactical–strategic combination allows the tactical planning to ask for modifications to the forest management plan (strategic planning) to increase FVCN profitability. A case study of an FVCN (i.e., six sawmills and one pulp and paper mill in Eastern Canada) demonstrated the potential gains of such an integrated approach from forest management to production and sales decisions. For instance, an increase from 23% to 92% of a sawmill production capacity utilization rate (while still respecting the annual allowable cut) leads to a lumber demand satisfaction increase of 13% and whole network profit increase (Simard, 2014). A case study involving an FVCN of three sawmills is presented by Morneau-Pereira et al. (2013) to demonstrate the combination of the aforementioned simulation tools FPInterface and Optitek with the DSS LogiLab. The two simulation tools allow generating the required data on different harvesting and sawing scenarios (e.g., costs, yield, product baskets) that is the input for optimization. Assuming no limit on the assortment sorting at the forestland, the potential profitability of the annual optimized plan is on average 55.6% better than the ones generated by a heuristic rule that mimics a typical DM planning behavior. This impressive gain comes from a better selection of the harvesting blocks and a better allocation of the wood to the sawmills but again, supposes no restriction on the assortment sorting rule in the forest. The simulation tools FPInterface and Optitek were also combined with the ForestPlan, which uses

LP to maximize the annual plan profitability of a company-wide forest value chain. Developed in 2013 by FPInnovations and Dalhousie University, the DSS was tested on two industrial cases in Western Canada (Kryzanowski, 2014). The application case involved eight sawmills with a wide range of domestic and international customers (lumber, logs, chips, hog fuel, shavings, sawdust). Results show a potential to increase profit by 13% by selecting a different mix of harvesting blocks to meet the demand in comparison to the 691 harvesting blocks (spanning over 16,000 hectares) in the current annual harvest plan (Ristea, 2015).

Troncoso et al. (2015) studied how sequential planning tools for harvesting, transportation, production, and sales can be integrated to find better solutions in comparison with using a sequential planning process. They report savings of between 5% and 8.5% with integrated planning. This is due to the fact that better log types are connected to appropriate sawmills and final prices are implicitly integrated already in the harvesting planning. Kong and Rönnqvist (2014) took the same models and proposed strategies to establish coordination prizes between the sequential planning steps so that the DSS can be operated in a sequential approach but achieve an overall integrated solution. The strategies to find efficient coordination prizes are based on various dual and Lagrangian dual schemes.

Kong et al. (2012) combined the forest, pulp and paper, and bioenergy value chains. In Sweden, the roundwood (sawlogs and pulpwood) chains are integrated but the forest fuel for energy production is planned independently. However, as there is more and more pulpwood used directly for energy production, it is interesting to study how they impact each other depending on, for example, the supply situation and relative prices for lumber, paper, and energy. The problem becomes nonlinear as the demand from the customer follows a demand based on the purchasing cost. In the paper, the authors study an industrial case from a major Swedish forest company and conduct an analysis based on a number of scenarios. Substantial benefits and savings from integration are reported. Kong et al. (2015) expands the previous work where the selection of harvest areas also is included as decision variables. In addition, different settings of market prices are tested.

1.5 Discussion

1.5.1 Gaps and trends in DSS development

The scientific community worldwide has been developing DSS for the forest value chain for many years. The wiki page of the Forest DSS Community of Practice (www.forestDSS.org) reports 62 DSS for forest management developed in over 23 countries, covering a wide range of forest systems, management goals, and organizational frameworks. Yet, only 18 of them addressed medium- and/or short-term decisions; some of them originated from internal development of forest companies. In fact, we observe that on one hand, DSS for tactical/operational planning are more recent developments and still more rare than DSS for strategic planning. On the other hand, DSS for tactical planning are often tailored to the needs of a specific industry and country, which makes them unique, flexible, and scalable and also more likely to be utilized outside the scientific publications. We can argue that DSS are usually research-driven proofs-of-concept, developed by researchers and gradually introduced to the end user in practice. This may explain the way they are developed as prototypes rather than real commercial software where the focus is on the modeling/optimization rather than DSS features such as a friendly graphical user interface, support, maintenance, and upgrades. This jeopardizes the implementation and is most of the time the main reason behind the failure and also why forest companies do not adopt such DSS in practice. The lack of scalability and flexibility of such DSS to meet new needs of the end user can be another issue. This mismatch between DSS features and the needs of the end users leads them to cease using such DSS. This mismatch is also due to the long cycle time of developing a DSS where a large gap arises between the original user's needs at the development phase and his current needs at the implementation phase. Also, end users use the DSS for other purposes completely different from the initial ones for which the DSS has been designed, which leads to another mismatch. We should also note that we limit our comments to the DSS that are published in the scientific literature. There are software programs used by many companies, but their solution methodologies are not known.

Despite the large number of DSS developed in forest planning, some studies (e.g., Reynolds et al. 2007; Menzel et al., 2012) emphasized the need for a clear focus on the target users, therefore acknowledging the human dimension in information systems. Stakeholders' participation may be instrumental in developing a DSS that might effectively address the business specificities (Sousa and Pereira 2005). This is a critical success factor for DSS (Arnott and Dodson 2008).

Most of the research addresses the forest-to-mill part of the FVCN or from the mill to the market in each respective value chain (decoupled). There is a need to better integrate the forest value chain with the following value chains of the FVCN and in this way, to better use the information flow from the different markets in the earlier stages of the FVCN. Also, there is a lack of integration between the tactical planning with upper and lower levels (strategic and operational) that leads to misalignment between the three planning levels. We state that current DSS that cover the full FVCN are still rare, with the exception of biomass where recent DSS have been developed. No forest value chain planning methods/DSS discuss the sales process. Other issues typically included in logistics such as stockyard management and inventory management are also poorly addressed. We refer to Rönnqvist et al. (2015) for a review of research challenges (open problems) related to the application of OR in the FVCN, mainly on the forest-to-mill part.

1.5.2 Issues and challenges in implementation

Different issues related to DSS adoption are discussed by Audy et al. (2012a) and Rönnqvist (2012). To implement a DSS there are many practical questions that arise. In the article, a number of seemingly easy questions become difficult in implementing full DSS.

DSS are data intensive and are not always integrated with GIS and ERP systems; they also require a lot of data and connections with other systems to be fully utilized. These missing connections and gateways are expensive and complex due to lack of expertise, time, or funding to perform them in an appropriate way. Sometimes, end users do not see the value to justify such investments and efforts to replace their current practices with the new alternatives. Also, end users view DSS as black boxes and cannot follow the reasoning behind them; consequently, they are hesitant to accept and trust the results/outcomes of such DSS. Requiring high competencies (e.g., in OR, analytics, databases) to be used at their full potential (and thus provide the highest benefits), several DMs give confidential mandates to specialized resources for conducting advanced analysis using the DSS to help them in their tactical decisions. The DM will then be free to decide whether or not to use the recommendations derived from these studies. Such time-consuming support for the DMs would not be conceivable with DSS designed for operational level decisions.

The individual competencies and training of the end user are often neglected during the implementation process of DSS where he is expected to be capable, ready to use, and understand the reasoning behind the DSS, and finally interpret the results and outcomes of the DSS. The lack of support and continuous improvement of DSS after implementation is another factor that leads to failure due to the disconnection between the development and implementation teams that belong to university and industry, respectively.

Expectations are very high regarding what DSS can deliver. Most people expect that DSS can solve problems for them which a DSS is not aimed to do: DSS by itself does not solve the problem. One reason could be that DSS are presented as game changers and very sophisticated tools based on advanced optimization techniques combined with technology, which may lead end users to think that they can really solve problems and are more than just systems aiming to help them. There is a need to draw business models built on collaboration between companies (or departments within the same company) which may be supported in the DSS (Audy et al., 2012b).

1.5.3 Future research paths forward

Stakeholders including the public are paying ever more attention to how forest resources are managed and utilized, which poses new challenges for the new generation of DSS in respect to its comprehensiveness but also simplicity. Economic performance is no longer the ultimate goal as other environmental and social aspects gain greater importance. Among the key drivers that will influence the research in DSS in tactical planning in forestry are big data and Internet, sustainability, group decision-making by stakeholders, uncertainty, interfirm collaboration, integrated planning, and multidisciplinary research approaches.

The rapid development of the Internet and the use of advanced technologies have led to the explosive growth of data in the forest industry. Currently, data sources include large spatial data sets, GIS information, ERP systems, ecological information, social and environment-related data sets, government regulations, GPS-based solutions and sensors to track products/machines in real time, and so on. These sources generate a huge amount of data across the value chain ready to be used by DSS. An illustrative example for such a platform is being developed in the EU project FOCUS—Advances in Forestry Control and Automation Systems in Europe (www.focusnet.eu). The next generation of DSS must be able to handle and process these raw data and turn them into valuable information and pertinent decisions. The Internet of Things (IoT), where all devices will be connected to the Web, will enable DSS to be web-based applications and available on new mobile platforms such as smartphones, tablets, and so on. Big data and IoT will be key drivers in the development of the next generation of DSS and this requires research in new methodologies to fill the gap between existing DSS and these new technologies (Bettinger et al., 2011; Vacik and Lexer, 2014).

The social acceptability and environmental impact of the forest industry should be integrated in tactical planning in the next generation of DSS for a truly sustainable forest value chain. For instance, the development of new bioenergy and biorefinery products in the last decade, in conjunction with new regulations and policies, requires the combination of existing and new assessment methods such as life-cycle assessment and multiobjective optimization that must be integrated in DSS (Boukherroub et al., 2015; Cambero et al., 2015b).

Forest planning affects and involves many stakeholders (industry, governments, landowners, communities, etc.) with different goals and objectives. The Internet has contributed and facilitated interactions between groups, including the public, making them more active in forest planning and problem solving. This shows the limitations of current DSS to support this interactive planning approach and raises the need to propose new frameworks to design a new decision theater to support coordination and interactions among stakeholders and integrate them into new group DSS (Kangas, 1992; Donaldson et al., 1995; Azouzi and D'Amours, 2011).

Uncertainty is an inherent phenomenon in forestry due to many social, economic, biological, and technological factors. New technologies and big data show promise in reducing these uncertainties but need to be economically sound. Depending on planning level, different approaches are more appropriate to deal with uncertainty (e.g., pooling, hedging, stochastic programming, robust optimization). In some cases deterministic methods where uncertainty is considered through, for example, safety stock levels are most appropriate due to the model size and solution times. In others where it is possible to generate a number of scenarios and where the best expected result is wanted, stochastic programming is an interesting path. For others where feasibility is critical, it is better to use robust optimization approaches. For each of these alternatives it is important to evaluate them through agent-oriented simulation approaches (Palma and Nelson, 2009; Ouhimmou et al., 2010; Feng et al., 2012; Shabani et al., 2014; Abasian et al., 2015).

Collaboration across value chains has been proven to reduce overall cost considerably. However, there are many questions regarding how confidential data is used, and how cost allocation schemes are agreed on and put into contracts (Marques et al., 2016). There are also open questions about how the coalitions should be formed and managed (Audy et al., 2012c; Guajardo and Rönnqvist, 2015). The collaboration has traditionally looked at vertical integration and lately at horizontal collaboration. What is next is to study cross-chain integrations.

Most DSS have been developed by researchers through case studies and gradually introduced to the end user. The researcher's background has a big impact on the DSS structure where forestry, management science, industrial engineering, and operations research are the most dominant disciplines. Recently, more researchers from computer science, graphics, software, and social sciences have been involved in developing such DSS. Because of the complexity and multidisciplinarity of forest-integrated planning, new DSS must be designed by multidisciplinary research teams in a collaborative approach to be more successful in the future.

1.6 Conclusion

This chapter provides a broad overview of a number of planning methods and DSS for tactical decisions in the FVCN. A generic mathematical model is introduced to illustrate the typical tactical decisions to be made in a value chain. About 60 methods/DSS were discussed regarding what decisions (planning problems) were made, their applications (e.g., results reported, level of implementation), and the solution approach used. We note that they almost always rely on OR-based solution approaches and they focus on one of the value chains within the FVCN. However, in recent years, a growing number of methods/DSS have been integrating two or more value chains. Also, despite the promising results reported (e.g., case studies), it appears that a relatively low number of planning methods/DSS has been adopted/ used in practice by the DMs. This raises the need to better understand the adoption impediments and success factors in such a way to enhance in that regard the development-to-implementation innovation process followed by the researchers and practitioners. Other trends and future research directions are also presented. Social and environmental impacts have recently been added in DSS and will be fully integrated in the next generation of DSS. Integration with GIS and development of graphical user interfaces have always been a big challenge to DSS but many recent experiments have been attempted to overcome such difficulties. Big data and IoT, where all devices will be connected to the Web, is a challenge and tremendous opportunity for the next generation of DSS to have access to more accurate data in real time and to be used by more stakeholders in collaborative and group decision approaches for a truly sustainable forest value chain. A new era for research will involve developing and implementing new innovative, fast methods and algorithms to deal with a huge amount of uncertain data for multiobjective and multiple stakeholders' decision-making in forest planning.

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CHAPTER 2

DEVELOPMENT OF AN ECONOMICALLY SUSTAINABLE AND BALANCED TACTICAL FOREST MANAGEMENT PLAN: A CASE STUDY IN QUÉBEC

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Abstract

In Canada, most of the forests are publicly owned and forest products companies depend on timber licenses issued by the provincial governments for their wood supplies. According to the Sustainable Forest Development Act effective in the province of Québec since April 2013, the government is responsible for harvest area selection and timber allocation to companies. This is a complex tactical planning decision, with important impacts on downstream economic activities. Moreover, in order to avoid high-grading of forest resources and to determine a sustainable tactical plan which ensures a stable level of availability, quality and cost of supply over several years, it is necessary to simultaneously take these criteria into consideration during the planning process. We propose a mixed-integer nonlinear goal-programming formulation while employing Nadir theory as a reliable scaling technique to model this multi-objective planning problem. The model is solved by a linearization approach for a real case in the province of Québec. The proposed solution method enables us to obtain good-quality solutions for relatively large cases. Results show the proposed model outperforms conventional cost-minimization planning strategy by ensuring a more balanced use of wood supply and costs for all stakeholders over a longer period.

Keywords: Tactical forest management planning, Mutli-objective optimization, Goal programming, Nadir theory, Sustainability

2.1 Introduction and literature review

In Canada, as a major forested country, forest resources provide significant environmental, social and economic value, and in order to exploit this value the forest products industry is organized in a complex industrial system known as a value chain, starting from the forest up to markets (Audy et al., 2016). The five main value chains of a forest-based value creation network are Forest, Lumber, Panel, and Engineered Wood Products, Pulp and Paper, Biorefinery and Bioenergy. In this study we focus solely on the forest value chain, which mainly involves forest management, harvesting and log transportation activities, while other value chains produce different types of final products to be sold in various markets. Fleischmann et al. (2008) structured a two-dimensional matrix for categorization of supply chain planning problems from two perspectives: the main processes along the supply chain (i.e., procurement, production, distribution and sales) and the planning horizon (i.e., strategic, tactical and operational). Different stages of planning based on the time-perspective planning horizon could involve substantially different planning tasks. For instance, strategic forest planning normally covers a horizon of a few decades to hundreds of years and may involve decisions about the design and structure of forest value chain network, development of forest management strategies/policies, silviculture treatments, selection of conservation areas, etc. Tactical planning often addresses a full seasonal cycle (from 1 to 5 years) and decisions about how to treat standing timber and allocate them to specific mills to fulfill certain demands are made at this level. Finally, at the operational level, planners deal with day-to-day issues of harvesting and transportation; see e.g., the review by D’Amours et al. (2011).

Exploiting forest resources through more integrated and sustainable planning has proved invaluable especially for countries such as Canada with over 350 million hectares of forest land representing almost 9% of the world’s forests. Most of Canada’s forests are publicly owned and provincial governments are responsible for stewardship of Crown land. For example, in the province of Québec, forests account for 2% of the world’s forests and the forest products industry including over 400 wood processing plants is one of the main economic drivers of the province, generating about 80,000 jobs directly related to the forestry sector (Government of Québec, 2017). In recent years the Canadian forest products industry has encountered critical challenges like substantial decrease in newsprint paper demand and in softwood lumber exportation to the United States to name a few, which has forced policy makers to seek new forest management strategies and policies. In March 2010, Québec's National Assembly unanimously agreed on the Sustainable Forest Development Act (Chapter A-18.1). The new Act presents some changes in Québec's forest stewardship system. It gives the Ministry of Forests, Fauna and Parks (MFFP) responsibility for preparing and implementing integrated forest development plans, so MFFP will have the power to take local needs and goals into account (Légis Québec, 2016). Particularly, the Québec Government has become responsible for harvest planning and wood allocation to wood-processing mills since April 2013. So, in order to fully benefit from the new regime, the MFFP is in need of an integrated planning system for the development of a tactical forest management plan that ensures a balanced consumption of the woody resources over a five-year planning horizon in terms of, for instance, cost, stems' average size and average volume per hectare. Balancing these criteria throughout the planning horizon would allow the MFFP to ensure that public forest is capable of supplying the wood-processing mills and avoid wood shortages in specific territories over longer time.

Researchers particularly in countries with vast forestlands like Chile, Sweden and Canada have been studying the tactical forest value chain planning problem for years. Most of the relevant decision support systems (DSS) developed for these types of planning problems found in the literature aim to support forest harvesting and/or raw material transportation-related decisions, but solely from a single-objective optimization (revenue maximization and/or cost minimization) perspective. A few studies also include the production process.

In Chile for instance, Epstein et al. (1999a) developed a mixed-integer programming (MIP) DSS called OPTIMED, for tactical forest planning (harvesting and road building). OPTIMED uses binary variables to represent whether or not to build or upgrade roads. In order to solve the developed MIP formulation, the authors proposed to include valid inequalities to strengthen the formulation and a heuristic rounding approach to generate feasible solutions. Troncoso et al. (2015) proposed an MIP model for a demand-driven integration of forest value chain of a Chilean forest company. Results show that the integrated approach could lead to up to 5% more net present value than the decoupled strategy.

For years Swedish forest transportation planning was done manually and decentralized to districts. Forest planners recognized great potential for improved efficiency and cost saving in the supply chain through identifying a better match between the supply and demand points, better use of back haulage tours and better coordination among districts and/or companies. Forsberg et al. (2005) presented a decision aid tool FlowOpt that supports both tactical and strategic transportation and harvesting planning for the Swedish forest industry. It determines mills' allocation of timber, back hauling possibilities for reducing empty driving, location of train terminals and mechanisms for cooperation among companies. Later on, road opening/upgrading decisions with consideration of variations in road accessibility conditions due to the weather conditions were incorporated into another model developed by Karlsson et al. (2006) named RoadOpt which plans demand-driven annual harvesting and transportation. Carlgren et al. (2006) also developed an MIP model for harvesting and transportation planning, while alternative strategies for sorting the logs in the forest and the possibility of back-haulage tours have been analyzed. The authors solved the model using a combination of column generation and branch-and-bound techniques.

In Canada, Beaudoin et al. (2007) presented an MIP model to support the tactical wood procurement decisions in a demand-driven multi-facility environment. Harvest scheduling and wood transportation decisions were modeled with the goal of maximizing a firm's profit while satisfying demand for end products, wood chips as well as demand for logs from other companies. As opposed to cases with disintegrated forest value chains where decisions about optimized use of harvesting resources (e.g. machineries and teams) are made separately from harvest scheduling decisions, the authors also included the cost associated with movement of machinery from one harvesting area to the next in their model. In another study by Ouhimmou et al. (2008) the production process of an integrated furniture assembly mill supply chain is subsumed into the tactical forest management planning problem. The authors formulated the multi-site and multi-period planning for procurement, sawing, drying, and transportation operations in an MIP model. A heuristic algorithm based on time decomposition approach is used to solve the model for large-sized examples. Bouchard et al. (2017) modeled the integrated strategic and tactical forest products value chain. Testing the models for a large-scale instance located in Canada showed that using the integrated approach could lead to up to 13% profit gain.

Kangas et al. (2014) proposed a hierarchical optimization model combining top-down and bottom-up approaches to determine the annual stand-level harvest schedules. Duvemo et al. (2014) developed a simulation system to address the hierarchical tactical-operational level forest planning. Stand databases of Swedish companies are used to conduct cost-plus-loss analysis. Gautam et al. (2016) also proposed a simulation-optimization system to model hierarchical forest management. Testing the model for a Canadian case showed that between 2-3.7% increase in the profit could be obtained by allowing silvicultural flexibility at the operational level.

To sum up, in the literature of tactical forest management, harvest planning and wood allocation decisions have been addressed often accompanied by incorporation of one or more of the following matters, e.g. road engineering, back-haulage tours, log sorting strategies at the forest roadside, spatial considerations, etc. Diaz-Balteiro and Romero (2008) have reported timber harvest planning as the first branch of forestry where the multiple-criteria decision-making paradigm has been applied. However, almost all of the few published articles in this category have explored the harvest planning problem at the strategic level covering planning horizons of 25 to hundreds of years (e.g., Kao and Brodie, 1979; Ducheyne et al. 2004; Diaz-Balteiro and Romero, 2003). At short-term planning, Hotvedt et al. (1982) proposed a heuristic approach for weight setting for a cardinal goal programming (GP) model of an operational harvest scheduling problem. In fact, GP has become a well-accepted approach for multi-objective planning problems in various forestry topics. For instance, Diaz-Balteiro and Romero (2003) developed several lexicographic GP models in order for efficient incorporation of carbon sequestration into a harvest scheduling problem over a planning horizon of 100 years. Another example in the category of forest biodiversity conservation, Lundström et al. (2011) also used GP to perform a reserve selection analysis in boreal forest in Sweden. The cost of preserving each plot as a reserve was analyzed by considering seventeen biodiversity measures. Lundström et al. (2014) extended their earlier model by using Analytic Hierarchical Process (AHP) to systematically determine the relative importance of considered biodiversity criteria.

At the tactical level, Kazana et al. (2003) developed an interactive decision support framework for the management of multiple use forests. The combined MINMAX approach is used to generate many forest management alternatives. Different criteria including timber production, dispersed recreation, water-based recreation and deer stalking for certain habitat types were taken into account. Johansen et al. (2017) studied the problem of efficient forest resource usage. They developed a strategically-tactically oriented mathematical business economic model that combines value chain optimization modeling with the regional macro-economic theory. All the studied criteria were presented in monetary values and Pareto curves were used to demonstrate the trade-off between value chain profit (industry focus) and value creations related to political and social impacts (based on revenues).

Laukkanen et al. (2005) addressed a multi-criteria tactical timber-harvest planning focusing on the group decision making. The authors adopted a voting-based-theory method to generate alternative plans that were evaluated with respect to the following criteria: net harvesting income, effects on nature conservation values, effects on recreational values, expectation of logging damage and favoring local contractors. Ezzati et al. (2016) developed a spatial multi-criteria decision making tool to generate “sub-optimal” solutions for harvest operations decisions in mountainous areas. The authors employed analytical network structure method along with the weighted linear combination function to model and solve the defined problem. To the best of the authors’ knowledge, there are very few works addressing the tactical level multiple-criteria forest planning problem and there is great room for further research; and in that respect our contribution to the literature can be summarized as follows. We simultaneously consider three specific criteria in order to propose an efficient plan which ensures a stable level of cost, quality/size and availability of wood supply to forest products companies over five years of planning. In addition, we have made use of the idea of business and anticipation periods in the context of a rolling horizon re-planning strategy in order to accommodate in our model the means to prevent high-grading in the use of wood supply over the planning horizon as well as overcoming the challenge of lack of demand information for the last four years of the considered planning horizon. We have proposed a mathematical formulation for each of the considered criteria and developed a solution methodology based on GP approach where several mixed-integer nonlinear programming (MINLP) and MIP optimization models are solved and analyzed. Additionally, in this work we take advantage of the Nadir theory and Payoff Table method for the normalization of the formulated objective functions which are incommensurable and have values of different magnitude. Moreover, we have proposed a linearization approach enabling us to obtain good quality solutions for the proposed MINLP models (which are often very difficult to solve, even for small cases) in large instances within a reasonable time.

The structure of this paper is as follows: in Section 2.2 the research problem is described in detail. The solution approach and the proposed mathematical formulation are presented in Sections 2.3 and 2.4 respectively. Section 2.5 describes the developed Canadian case study. The discussion on the computational tests is presented in Section 2.6. This paper ends with conclusions and some future research avenues in Section 2.7.

2.2 Problem description

Consideration of multiple criteria in forest management planning has become a necessity rather than a special case (Rönnqvist et al., 2015). In that regard, the current study addresses the problem of selection of harvesting areas and wood allocation to forest products companies over a five-year planning horizon from a multiple objective optimization standpoint. In particular, the goal is to select harvest areas and define the wood allocation for year one to fulfill the demand at mills while concurrently balancing three specific criteria over the whole planning horizon. The examined criteria are average unit purchasing and transportation cost, average volume per stem and average volume per hectare.

Rönnqvist et al. (2015) describe the most recent research challenges and open questions on application of operations research techniques in forestry. The defined problem in this paper can relate to two of the open problems (OP) named in Rönnqvist et al. (2015):

OP 32: How can we incorporate the preferences of the decision maker for the different criteria into the multi-criteria model?

OP 33: How can we develop multi-criteria approaches that are rigorous in thoroughly incorporating the decision maker's preferences, yet user friendly?

With respect to OP 32, we collect information on several objectives, include them into a goal programming approach, make a correct scaling/normalization and finally we analyze the impact/cost of these objectives; and in connection with OP 33, we formulated multiple periods of the objectives by scaling mills' demand. Without this, it would be difficult to examine the multiple objectives correctly.

Every year, the MFFP replenishes a register of harvest areas as new areas are surveyed. Even though the MFFP aims to have enough harvest areas in the register to cover five years of harvesting, often the pool has fewer harvest areas than needed for five years. Additionally, each year the demand situation and road network accessibility may change. That is why decision makers (DM) adopt a rolling horizon re-planning strategy and need to run the proposed model each year, as new harvest areas are added to the pool and demand and road network accessibility information are updated. In fact with the proposed model in this paper, we suggest a plan for the upcoming year but covering a full five-year horizon in the planning process; in this way we can guarantee a balanced use of wood resources in terms of the considered criteria over a longer period.

In order to systematically develop/implement forest management policies, the land covered with forest is divided into forest management regions and then subdivided into forest management units (FMU) consisting of several harvest areas. The planning process under study is being considered at the forest management unit level, and each FMU is responsible for supplying the wood processing mills within its territory.

Moreover, in order to highlight the potential of using a multi-objective planning strategy, the proposed model is tested for an FMU in the province of Québec and is compared to a commonly considered planning strategy for tactical forest management which can be described as follows. Before the Sustainable Forest Development Act came to effect, the wood-processing plants that had supply and forest management agreements with the government were responsible for forest planning to obtain their required supply; at that time the MFFP was only responsible for overseeing the planning activities and eventually to consent to the forest management plans produced by the holders of agreement. Currently, planning by the MFFP is being done mostly manually with the help of a number of tools which is a very complex and time-consuming procedure. Due to the complexity of manual planning process, it is very difficult to compute a manual solution for the developed case; instead we formulate an optimization model as a close simulator of the manual procedure in which the objective is deemed to be satisfying mills' demand for the upcoming year with the least possible cost. The optimization model named MinCost mimics such a strategy in which the total purchasing and transportation cost during year 1 is minimized given the same constraints for the proposed multi-objective model. It also has to be noted that often a manual plan is more expensive than an optimized plan. In other words, a manual solution for the considered case in this study could be expected to be much more costly than the solution obtained from MinCost model.

2.3 Solution approach

To solve multiple objective optimization problems, there are two well-known approaches: weight method and ε-constraint method. The ε-constraint method chooses the highest priority criterion (that overrides the other criteria) as the objective function, and treats the lower priority criteria as constraints. However, often this approach either rules out many good solutions or leads to infeasibility if the bounds in the constraints are not chosen correctly. Since in this planning problem no single criterion can be presumed to fully override the other two, the ε-constraint method is not a suitable methodology to adopt.

On the other hand, GP considers multiple objectives simultaneously in the optimization process. In a general GP approach a specific numeric goal for each of the objectives will be established, then a solution that minimizes the weighted sum of deviations of the objective functions from their respective goals will be sought. In fact the three criteria under study have very different nature and numeric magnitude, hence, in order for adequate functioning of the GP, the respective objective functions need to be normalized. The use of Nadir theory and Payoff Table method would overcome this issue of incommensurability of the three considered objectives. Additionally, according to the MFFP, the three chosen criteria are considered to be of the same level of importance and since the respective objective functions would also be normalized, this choice of the MFFP regarding the relative importance of the criteria can be applied with confidence that every one of the criteria will equally impact the final solution. Also, the target value of each criterion is established by computing its average value (this will be explained more in the following sections). Thus, in this work we opted for GP accompanied by the Nadir theory as a suitable solution methodology for this problem setting.

We first establish a target value for each of the three optimization criteria considered, and then three individual models will be solved to minimize the maximum deviation of each criterion from the target value among all time periods. Finally, in another model, the weighted sum of deviation of formulated objective functions from their respective optimal values will be minimized. The solutions to these models will be presented in tables to demonstrate the performance of each criterion for each of the single objectives as well as for the multi-objective function.

We employ the knowledge of Nadir objective vector and Payoff Table method for the normalization purpose in the entire Pareto-optimal region. Consider two minimization objective functions f_1 and f_2. By definition, for minimization functions, the optimal objective vector represents the lower bound of each objective in the entire feasible search space and the Nadir objective vector, represents the upper bound of each objective in the entire Pareto-optimal set (not in the entire search space) (Deb, 2001). For instance, the Nadir value of f_1 equals to its value in the optimal solution of f_2 (i.e., $x^{*(2)}$): $f_1^{nad} = f_1\left(x^{*(2)}\right)$. Eq. (2.1) shows how objective function $f_1$is normalized in the entire Pareto-optimal region by means of its optimal and Nadir values.

$$f_1^{\ norm} = \frac{f_1 - f_1^{\ optimal}}{f_1^{\ nadir} - f_1^{\ optimal}} \tag{2.1}$$

It is not a straightforward task to calculate the exact value of the Nadir point for more than two objectives because the Nadir point requires the knowledge of extreme Pareto-optimal solutions (Deb and Miettinen, 2010). A standard approach to estimate the Nadir objective values is the Payoff Table method. First the individual optimum solutions are computed $(x^{*(1)}, \dots x^{*(p)})$, then a Payoff Table is constructed through computing the objective values at these optimal solutions, and eventually estimated Nadir point of each e.g., minimization objective will be its highest value in the table. For more details on this technique, interested readers are referred to Deb and Miettinen, (2010).

2.4 Model formulation

In this section we present the proposed deterministic MINLP, MIP and linear programming (LP) formulations which model the described tactical forest management planning problem.

In order to develop a sustainable tactical plan which consumes the available wood supply over several years robustly, the proposed multi-objective model aims to balance the average value of three specific criteria in each time period against their respective target values. The identified criteria are average unit purchasing and transportation cost, average volume per stem (i.e., representing average stem size) and average volume per hectare.

The target values are set by the MFFP by calculating the average value of each criterion (except for the transportation cost) over all given harvest areas; the logic behind it was that the harvest areas in each FMU have similar characteristics, so over the years the new harvest areas that will be added to the register will have similar attributes on average. In order to establish a target for the transportation cost, a separate classic constrained transportation model is solved to obtain the minimum average transportation cost as target $(\overline{c^{tr}})$. The transportation model is an LP developed in a single-period context; it minimizes the total transportation cost of allocating all the available wood in all harvest areas to mills, constrained to some conventional constraints about mills' minimum demand and harvest areas' capacity as well as the constraints related to mills' specific requests regarding some characteristics of their allocation. The obtained optimal flow of stems among harvest areas and mills is used to compute the target average unit transportation cost.

The length of the planning horizon is 5 years. Since foreseeing mill demand for more than one year in advance is very difficult, the first year is considered as the business period and only the decisions made in this period will be used in practice; the last four years, on the other hand, are aggregated to one anticipation period and the relevant decisions are used solely for the purpose of anticipating the impact of business decisions over a longer period of time.

Additionally, due to the arbitrary composition of available volume of wood at harvest areas and the minimum and maximum mills' annual demand, not all the available wood in any group of selected harvesting areas during period 1 can be allocated to mills as this would exceed the mills' maximum demand limits. Hence, in order to control the volume of uncut trees left inside the selected harvest areas during time period 1, a separate optimization model is solved to obtain the minimum volume that will inevitably be left uncut during period 1 (l^{min}). Then a planner-defined multiplication of that volume will set an upper bound for volume left uncut inside selected harvest areas during period 1 (Eq. 2.15). In addition, it is assumed that the uncut trees inside selected harvest areas during period 1 must be harvested and allocated to mills in the subsequent time period.

Despite some aspects of the defined problem being tailored to the Québec situation and the implementation of the new Act, we believe the proposed model and solution approach could easily be adapted to address similar problems in any other case. The complete list of indices, sets, parameters and decision variables is given in Table 2.1.

Table 2.1 List of indices, sets, parameters and decision variables of the model

Sets & indices	**Definition**
$a \in A$	Set of harvest areas
$s \in S$	Set of wood-processing facilities (i.e. sawmill, pulp & paper mill, veneer mill)
$p \in P$	Set of products (our definition of products includes only logs)
$t \in T = \{1, 2\}$	Set of time periods (i.e. business and anticipation periods)
$j \in J_{sp}$	Subset of harvest areas that have accessibility to mill s for transporting product p through a well-functioning road network, $(J_{sp} \subset A)$
$k \in K_p$	Subset of mills that have a positive demand for product p, $(K_p \subset S)$
$o \in O_p$	Set of species included in product type p
$i \in I = \{1,2,3\}$	Set of objective functions representing the three optimization criteria considered
Parameters	**Definition**
v_{ap}	Volume of product p available at harvest area a (m^3)
st_{ap}	Average volume per stem of product p at harvest area a $(m^3/stem)$
ρ_{apo}	Percentage of total volume of product p existing in harvest area a that is of species $o \in O_p$
vph_a	Average volume per hectare in harvest area a (m^3/ha)
ar_a	Area of harvest area a (ha)
c_a^{pur}	Purchasing cost of a unit of any type of product at harvest area a $(\$/m^3)$; this cost component includes all forest operations cost in area a, excluding transportation cost
c_{jsp}^{tr}	Transportation cost of a unit of product p from harvest area $j \in J_{sp}$ to mill s $(\$/m^3)$
di_{jsp}	Transportation distance for product p from harvest area $j \in J_{sp}$ to mill s (km)
b_a	Subsidy granted by MFFP to ensure harvest area a will be cut based on specific guidelines
b	Annual subsidy budget (it is assumed this budget is fixed during the planning horizon)
α	A planner-defined real number $(\alpha > 1)$
w_i	Relative importance of objective function i
n	Number of harvest areas
Parameters related to mills' requirements	
$de_{kp}^{min}, de_{kp}^{max}$	Minimum/maximum mill k's annual demand (m^3) of product p
$c_{kp}^{min}, c_{kp}^{max}$	Minimum/maximum unit purchasing & transportation cost of product p for mill k

Table 2.1 List of indices, sets, parameters and decision variables of the model (Continued)

Parameters	**Definition**
$di_{kp}^{min}, di_{kp}^{max}$	Minimum/maximum average transportation distance of product p between mill k and its assigned harvest areas
$st_{kp}^{min}, st_{kp}^{max}$	Minimum/maximum avg. volume per stem of product p for mill k
$\rho_{spo}^{min}, \rho_{spo}^{max}$	Minimum/maximum percentage of product p's allocation to mill s to be of specie $o \in O_p$
Other input parameters	
$\overline{c^{pur}} = \frac{\sum_a \sum_p v_{ap} c_a^{pur}}{\sum_a \sum_p v_{ap}}$	Weighted-average of purchasing cost considering all harvest areas (target value)
$\overline{st} = \frac{\sum_a \sum_p v_{ap} st_a}{\sum_a \sum_p v_{ap}}$	Weighted-average of average volume per stem considering all harvest areas (target value)
$\overline{vph} = \frac{\sum_a ar_a vph_a}{\sum_a ar_a}$	Weighted-average of average volume per hectare considering all harvest areas (target value)
$\overline{c^{tr}}$	Minimum average unit transportation cost (target value)
l^{min}	Optimum/minimum value of f^{uncut}
β	Maximum multiplication of the min & max mills demand during the business period that could be satisfied with the given harvest areas during the anticipation period
Parameters used in the linearization	
γ_t	Total allocated volume in period t (Step 1 of Linearization)
ρ_t	Total area of selected harvest areas in period t (Step 1 of Linearization)
k_t^1, k_t^2	Maximum allowed percentage of deviation from γ_t and ρ_t respectively
Decision variable	**Definition**
X_{aspt}	Flow of product p from harvest area a to mill s during time period t (m^3)
X_{aspt}^2	Flow of product p remaining inside harvest area a (i.e., left uncut at forest during time period $t-1$) to mill s during time period $t = 2$ (m^3); when $t = 1$ this variable is set to zero.
$L_{ap(t-1)}$	Volume of product p that is left uncut at harvest area a during time period $(t-1)$ that must be cut and allocated during period t (m^3)
Y_{at}	Binary decision variable equals 1, if harvest area a is selected to be harvested during time period t, 0 otherwise.
Decision variables used in the linearization	
S_t^{1+}, S_t^{1-}	Slack variables (up & down) to measure the deviation from γ_t
S_t^{2+}, S_t^{2-}	Slack variables (up & down) to measure the deviation from ρ_t

Procedure to implement GP for the defined problem in Québec context

Here we provide the step-by-step procedure required to implement GP approach for the defined problem in the Québec context.

Step 1: Since no demand information for the anticipation period is available, an optimization model needs to be solved to determine the maximum multiplication of the min & max mill demand during the business period that could be satisfied with the given harvest areas during the anticipation period.

Step 2: Solve the model that minimizes the wood left uncut inside selected areas during year 1. The purpose is to limit the volume that will inevitably be left uncut inside selected harvest areas during each time period 1.

Step 3: Solve a constrained transportation model to obtain the minimum average unit transportation cost that sets the respective target value in the following models.

Step 4: Solve the model associated to each of the three criteria individually.

Step 5: Solve the multi-objective model.

Constraints

There are different motivations for the constraints; here we present the ones which are relevant to the current planning process at the MFFP. Eq. (2.2) makes sure during time period 1 the allocated volume of each stem type to each mill is between its minimum and maximum annual demand. Since no demand information for year 2-5 was available, we have modeled the mill demand during the anticipation period as follows. We introduced a parameter β: it is assumed that the minimum and maximum demand of each mill during the anticipation period is β times its min and max demand during period 1. In other words each mill demand range in the anticipation period is modeled equally proportionate to the range of its demand during business period (Eq. 2.3). However, it is important to have the same value of β for all of our models; otherwise, different demand structure for period 2 in different models would hinder the comparability of the respective solutions. In order to determine an appropriate value for β, we solved a separate model to determine what the maximum possible value of β is, given all relevant constraints.

$$de_{kp}^{min} \leq \sum_{a \in A} X_{akpt} \leq de_{kp}^{max} \quad \forall\, k \in K_p, p \in P, t = 1 \tag{2.2}$$

$$\beta de_{kp}^{min} \leq \sum_{a \in A} \left(X_{akpt} + X_{akpt}^2\right) \leq \beta de_{kp}^{max}\ \forall\, k \in K_p, p \in P, t = 2 \tag{2.3}$$

Eqs. (2.4-2.5) respectively assure that the average transportation distance and average unit purchasing and transportation cost are kept less than a maximum limit specified by the mills. Also, some mills have been installed very close to the forest while others are located much further; so, in order to have some level of fairness among all the mills, the MFFP enforces a minimum transportation distance (di_{kp}^{min}) as well as a minimum average unit cost (c_{kp}^{min}) on the mills known to be located relatively very close to the forest vicinity, while for the rest these lower bounds are set to zero. Eq. (2.6) ensures the average size of allocated stems is in alignment with what mills need.

$$\begin{aligned} di_{kp}^{min} \sum_{j \in J_{kp}} \left(X_{jkpt} + X_{jkpt}^2\right) &\leq \sum_{j \in J_{kp}} di_{jkp}\left(X_{jkpt} + X_{jkpt}^2\right) \\ &\leq di_{kp}^{max} \sum_{j \in J_{kp}} \left(X_{jkpt} + X_{jkpt}^2\right) \qquad \forall\, k \in K_p, p \in P, t \in T \end{aligned} \tag{2.4}$$

$$\begin{aligned} c_{kp}^{min} \sum_{j \in J_{kp}} \left(X_{jkpt} + X_{jkpt}^2\right) &\leq \sum_{j \in J_{kp}} \left(c_j^{pur} + c_{jkp}^{tr}\right)\left(X_{jkpt} + X_{jkpt}^2\right) \\ &\leq c_{kp}^{max} \sum_{j \in J_{kp}} \left(X_{jkpt} + X_{jkpt}^2\right)\ \forall k \in K_p, p \in P, t \in T \end{aligned} \tag{2.5}$$

$$\begin{aligned} st_{kp}^{min} \sum_{j \in J_{kp}} \left(X_{jkpt} + X_{jkpt}^2\right) &\leq \sum_{j \in J_{kp}} st_{ap}\left(X_{jkpt} + X_{jkpt}^2\right) \\ &\leq st_{kp}^{max} \sum_{j \in J_{kp}} \left(X_{jkpt} + X_{jkpt}^2\right) \ \ \forall k \in K_p, p \in P, t \in T \end{aligned} \tag{2.6}$$

Each stem type includes a number of species; however, mills may accept to receive only a particular percentage range ($\rho_{spo}^{min}, \rho_{spo}^{max}$) of their annual allocation of a specific stem type to be of a specific species and this matter has been modeled in Eq. (2.7).

$$\begin{aligned} \rho_{kpo}^{min} \sum_{j \in J_{kp}} \left(X_{jkpt} + X_{jkpt}^{2}\right) \leq \sum_{j \in J_{kp}} \rho_{jpo}\left(X_{jkpt} + X_{jkpt}^{2}\right) \\ \leq \rho_{kpo}^{max} \sum_{j \in J_{kp}} \left(X_{jkpt} + X_{jkpt}^{2}\right) \quad \forall k \in K_p, p \in P, t \in T, o \in O_p \end{aligned} \tag{2.7}$$

Eqs. (2.8-2.10) ensure that the total allocated volume of a stem type from a specific harvesting area in each time period does not exceed its available volume at that area. During period 1 Eq. (2.8) allows some volume of wood (L_{apt}) to be left inside the selected harvest areas, and Eq. (2.9) assures this amount will be harvested and allocated during the following time period. In the anticipation period, Eq. (2.10) ensures no more than the available volume inside selected areas can be allocated from those areas. Eq. (2.11) simply states the assumption that the initial wood (remaining from before the current planning horizon) that must be allocated during time period 1 is zero.

$$\sum_{s \in S} X_{aspt} + L_{apt} = v_{ap} Y_{at} \qquad \forall a \in A, p \in P, t = 1 \tag{2.8}$$

$$\sum_{s \in S} X_{aspt}^{2} = L_{ap(t-1)} \qquad \forall a \in A, p \in P, t \in T \tag{2.9}$$

$$\sum_{s \in S} X_{aspt} \leq v_{ap} Y_{at} \qquad \forall a \in A, p \in P, t = 2 \tag{2.10}$$

$$L_{ap(t-1)} = 0 \qquad \forall a \in A, p \in P, t = 1 \tag{2.11}$$

The MFFP annually grants a limited budget for silvicultural treatment to support and encourage companies following specific prescriptions inside selected harvest areas. Eqs. (2.12-2.13) restrict this subsidy to the annual limit during business period and to β times the annual limit during the anticipation. Eq. (2.14) ensures each harvesting area will be selected at most once during the whole planning horizon.

$$\sum_{a\in A} b_a Y_{at} \leq b \quad \forall t = 1 \tag{2.12}$$

$$\sum_{a\in A} b_a Y_{at} \leq \beta b \quad \forall t = 2 \tag{2.13}$$

$$\sum_{t\in T} Y_{at} \leq 1 \quad \forall a \in A \tag{2.14}$$

Eq. (2.15) restricts the volume of uncut trees left at the selected harvest areas during period 1 to a planner-defined multiplication (α) of the minimum amount that will inevitably be left (l^{min}). In the anticipation period we limit the uncut trees to the 20% of total maximum mill demand in period 2 minus the leftover coming from the business period (Eq. (2.16)).

$$\sum_{a\in A}\sum_{p\in P} v_{ap} Y_{at} - \sum_{a\in A}\sum_{s\in S}\sum_{p\in P} X_{aspt} \leq \alpha l^{min} \qquad \forall t = 1 \tag{2.15}$$

$$\begin{aligned} &\sum_{a\in A}\sum_{p\in P} v_{ap} Y_{at} - \sum_{j\in J_{kp}}\sum_{k\in K_p}\sum_{p\in P}\left(X_{jkpt} + X_{jkpt}^2\right) \\ &\leq 0.20\left(\beta \sum_{k\in K_p}\sum_{p\in P} de_{kp}^{max} \right. \\ &\left. - \left(\sum_{a\in A}\sum_{p\in P} v_{ap} Y_{a(t=1)} - \sum_{a\in A}\sum_{s\in S}\sum_{p\in P} X_{asp(t=1)}\right)\right) \quad \forall t = 2 \end{aligned} \tag{2.16}$$

Finally, Eqs. (2.17-2.18) enforce the non-negativity and binary restriction on the decision variables.

$$X_{aspt} \geq 0, X_{aspt}^2 \geq 0, L_{ap(t-1)} \geq 0 \qquad \forall a \in A, s \in S, p \in P, t \in T \tag{2.17}$$

$$Y_{at} \in \{0,1\}\ \forall a \in A, t \in T \tag{2.18}$$

Objective functions

The objective function f^{uncut} is to find the minimum volume of trees that will inevitably be left uncut inside the selected harvest areas during period 1. The respective model is an MIP.

$$Min\ f^{uncut} \tag{2.19}$$

$$f^{uncut} = \sum_{a\in A}\sum_{p\in P} v_{ap}Y_{at} - \sum_{a\in A}\sum_{s\in S}\sum_{p\in P} X_{aspt}\ \ \forall t = 1 \tag{2.20}$$

In order to ensure that the criteria are as close as possible to the defined targets in both periods we designed the objective functions to minimize the maximum deviation of each criterion from target between the two time periods. In the objective function f^1 we have two cost components. The first component is purchasing cost which comprises costs related to all forest operations. The second one is the cost of transporting stems to the mills. The f^1 is to minimize the maximum deviation of unit purchasing plus transportation cost during each time period from their respective target value.

$$Min\, f^1 \tag{2.21}$$

$Subject\ to$:

$$f^1 \geq f_t^{1+} + f_t^{1-} \tag{2.22}$$

$$f_t^{1+} - f_t^{1-} = \left(\sum_{j\in J_{kp}}\sum_{k\in K_p}\sum_{p\in P} \left(c_{jkp}^{tr} + c_j^{pur}\right)\left(X_{jkpt} + X_{jkpt}^2\right) \Big/ \sum_{j\in J_{kp}}\sum_{k\in K_p}\sum_{p\in P}\left(X_{jkpt} + X_{jkpt}^2\right) \right) - \left(\overline{c^{tr}} + \overline{c^{pur}}\right) \tag{2.23}$$

Objective function f^2 is to minimize the maximum deviation of average volume per stem for the allocated volume during each time period from its target value. The objective function f^3 minimizes the maximum deviation of average volume per hectare of selected harvest areas during each time period from its target value. In all the cases the absolute value of deviation is considered, e.g., $f_t^{1+} + f_t^{1-}$ represents the absolute value of right-hand side of Eq. (2.23).

$$Min\, f^2 \tag{2.24}$$

$Subject\ to$:

$$f^2 \geq f_t^{2+} + f_t^{2-} \tag{2.25}$$

$$f_t^{2+} - f_t^{2-} = \sum_{j \in J_{kp}} \sum_{k \in K_p} \sum_{p \in P} (st_{ap})(X_{jkpt} + X_{jkpt}^2) \Big/ \sum_{j \in J_{kp}} \sum_{k \in K_p} \sum_{p \in P} (X_{jkpt} + X_{jkpt}^2) - \overline{st} \tag{2.26}$$

$$Min\, f^3 \tag{2.27}$$

$Subject\ to$:

$$f^3 \geq f_t^{3+} + f_t^{3-} \tag{2.28}$$

$$f_t^{3+} - f_t^{3-} = \sum_{a \in A} vph_a ar_a Y_{at} \Big/ \sum_{a \in A} ar_a Y_{at} - \overline{vph} \tag{2.29}$$

The multi-objective function f^{MO} (Eq. 2.31) minimizes the weighted-sum of the normalized deviation of f^i from its optimal value f^{i*} for each $i \in I$. The f_i^{Nadir} represents the Nadir value of objective function i, obtained by the Payoff Table method. The four single-objective and multi-objective functions are non-linear functions leading to MINLP models.

$$Min\, f^{MO} \tag{2.30}$$

$$Subject\ to: \quad f^{MO} = \sum_{i \in I} w_i \left(\frac{f^i - f^{i*}}{f_i^{Nadir} - f^{i*}}\right) \tag{2.31}$$

Also, all the constraints explained earlier are common for the models related to objective functions: $f^i\ \forall i \in I, f^{MO}$ and f^{uncut}; except for f^{uncut} model the equation (2.15) must be excluded as l^{min} is the optimum objective value of f^{uncut} model.

Linearization methodology to solve the MINLP models

Generally the MINLP problems are known to be difficult to solve with commercial solvers even for small instances. Hence, we propose a linearization approach to obtain good-quality solutions for MINLP models in large instances within a reasonable time.

This approach is based on fixing the denominator of the nonlinear objective functions (converting them to linear ones) and then trying to find the best solution around the fixed factors. The denominators of f^1 and f^2 are the allocated volume in each time period; and for the f^3 the denominator is the sum of areas of selected harvest areas in each time period. The proposed linearization procedure is explained as follows.

Step 1: Solve an MIP model that minimizes the total cost over the entire planning horizon to obtain a proper base value for the denominators of the nonlinear functions.

Step 2: The denominators of Eqs. 23 & 26 are fixed to $\gamma_t$and the denominator of Eq. 29 is fixed to ρ_t. New constraints are added (Eqs. (2.33-2.37)). Solve the transformed MIP models and follow the GP implementation procedure explained earlier.

In order to control the flexibility in the values of total allocation per period and total areas of selected harvest areas per period (i.e., denominators of the nonlinear functions) the constraints Eqs. (2.33-2.37) are introduced. These constraints allow a maximum of k_t^1% and k_t^2% deviation in total allocation and total areas of selected harvest areas per period from the fixed values γ_t and ρ_t respectively.

$$\sum_{j \in J_{kp}} \sum_{k \in K_p} \sum_{p \in P} \left(X_{jkpt} + X_{jkpt}^2 \right) + (S_t^{1+} - S_t^{1-}) = \gamma_t \quad t \in T \tag{2.33}$$

$$S_t^{1+} + S_t^{1-} \leq k_t^1 \, \gamma_t t \in T \tag{2.34}$$

$$\sum_{a \in A} ar_a Y_{at} \ + (S_t^{2+} - S_t^{2-}) = \ \rho_t \ \ t \in T \tag{2.35}$$

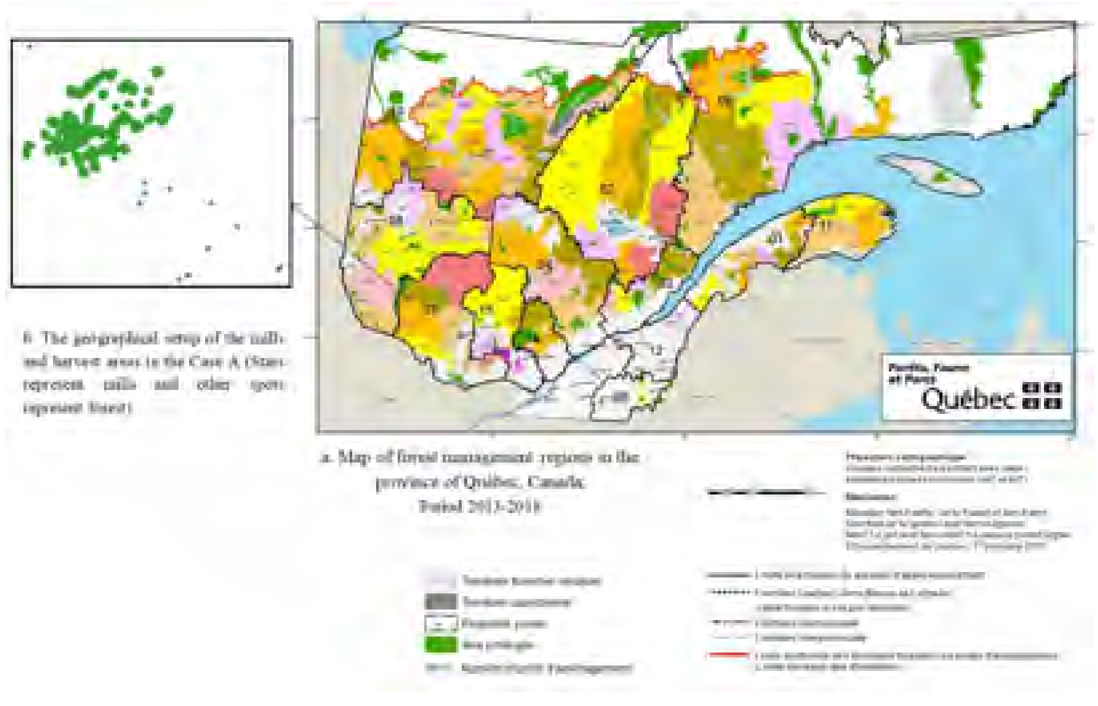
$$S_t^{2+} + S_t^{2-} \leq k_t^2 \, \rho_t \ \ t \in T \tag{2.36}$$

$$S_t^{1+}, S_t^{1-}, S_t^{2+}, S_t^{2-} \geq 0 \quad t \in T \tag{2.37}$$

2.5 Description of Canadian case study

The study is comprised of a real case (named Case A), of the FMU 07451 inside region 7, Outaouais in western Québec, Canada. The geographical location of the case and the geographical setup of the mills and harvest areas are shown in Figure 2.1 (a & b). For this case, 107 harvest areas are available in a register that could be used for the planning of supply for 13 wood-processing mills operating in the territory of this FMU. We have 10 sawmills, 2 pulp and paper mills and 1 veneer mill. Seventeen stem assortments have been defined; each encompasses a small number of species and has one specific application. Among them, two stem types (of about 71,391 m^3) do not have any buyer. In the proposed model we chose to keep them uncut; yet, this fact underlines the need to and the potential in expansion of the existing customer base.

Also, in order to assess the performance of the linearization approach, a smaller case (named Case B) of 23 harvest areas (out of the pool of 107 harvest areas in Case A) is developed. Some key information on the cases A and B are shown in Table 2.2.



b. The geographical setup of the mills and harvest areas in the Case A (Stars represent mills and other spots represent forest)

a. Map of forest management regions in the province of Québec, Canada, Period 2013-2018

Figure 2.1 Geographical location of the case under study

Table 2.2 Information on the cases A and B regarding the dimension of the planning problem and some other relevant data

Aspect	**Case A**	**Case B**
Number of harvest areas	107	23
Number of wood-processing mills	13	13
Aggregated demand range of all mills (m^3)	[435,180 – 495, 265]	[435,180 – 495, 265]
Available supply (m^3)	3,707,179	695,347
Unwanted stem types (m^3)	71,391	18,745
Number of stem types	17	17
Number of species	15	15
Average tree size $(m^3/stem)$	0.22	0.2455
Total area of all harvest areas (ha)	41,696	7,629
Number of years in the business period	1	1
Number of years in the anticipation period	4	4
The length of planning horizon (years)	5	5

All the required data for the case has been provided by the MFFP and some have particularly been extracted from the simulation software FPInterface developed by FPInnovations, the research and development center of the Canadian forest industry. Table 2.3 presents a summary of the properties of the harvest areas in the Case A.

Table 2.3 Summary of harvest areas' properties for Case A

	Volume (m^3)	**Area (ha)**	**Avg. stem size (m^3)**	**S.T.[*] budget ($)**
Average	30,233	332	0.2455	114,295
Min	2,466	25	0.02	16,328
Max	79,479	722	5.82	300,985
SD[†]	22,918	224	0.72	101,272
*Silvicultural Treatment, †Standard Deviation				

2.6 Results and discussion

The developed MINLP, MIP and LP models are implemented in the modeling language AMPL version 2015.12.2.2. The problem for Case A is solved by means of the proposed linearization technique because the MINLP solver BARON proved ineffective. All models are solved by means of either the MINLP solver BARON 16.12.7 or MIP/LP solver CPLEX 12.6.3.0 on a desktop (Windows Server 2012 R2) with 64.0 GB of RAM and 3.5 GHz processor.

The solution for Case A obtained by the proposed linearization approach is presented in Tables 2.4 & 2.5. Table 2.4 shows comparison among single-objective models, multi-objective optimization (MOO) and MinCost strategies in terms of two measures chosen as key performance indicators (KPI): (1) the maximum deviation of average value of each criterion from target between the two time periods in percentage (MDT), (2) the mean deviation of average value of each criterion from target in the two time periods in percentage (MeD). In terms of the size of models, 214 binary variables, 106,000 continuous variables and 55,900 constraints have been used in the proposed formulations.

From the results shown in Table 2.4 we observe that the proposed linearization solution procedure has been able to obtain a more balanced plan for Case A relative to MinCost strategy in about five hours while the solver BARON has not been able to solve this case. Often, and in this case also, much more supply is available than the actual demand of business period, enabling the MinCost planning strategy to do high-grading, i.e., to choose the best-located harvest areas, the ones which are more dense in terms of available volume in them per hectare and the ones with more suitable stem size for the upcoming year and to leave the worst; through such a strategy this situation deteriorates every time the problem is resolved. On the other hand by running MOO model every year on a 5-year rolling horizon basis with a replenished register of newly-surveyed harvest areas, an updated road network database and updated demand information, the MFFP would be able to ensure a balanced use of wood supply in terms of the considered criteria over a longer period.

Table 2.4 Comparison among single-objective models, MOO and MinCost strategies for Case A

		Case A		
		C1*	**C2†**	**C3‡**
	Target	48.66	0.2201	88.91
f^1 (linearization)	t_1	49.20	0.1979	93.41
	t_2	48.54	0.2239	88.96
	MDT§	1.11%	10.07%	5.06%
	MeD‖	0.67%	5.91%	2.56%
f^2 (linearization)	t_1	49.08	0.2200	90.38
	t_2	49.81	0.2136	88.28
	MDT	2.36%	2.91%	1.65%
	MeD	1.61%	1.48%	1.18%
f^3 (linearization)	t_1	49.40	0.2357	90.86
	t_2	49.95	0.1984	90.01
	MDT	2.64%	9.84%	2.19%
	MeD	2.09%	8.48%	1.71%
MOO (linearization)	t_1	49.71	0.2249	90.86
	t_2	48.64	0.2198	90.61
	MDT	2.15%	2.20%	2.19%
	MeD	1.10%	1.15%	2.05%
MinCost	t_1	47.69	0.2147	94.27
	t_2	50.34	0.2088	88.31
	MDT	3.45%	5.12%	6.02%
	MeD	2.72%	3.79%	3.35%

Note: $k_t^1 = k_t^2 = 20\%\ \forall\, t \in T, \gamma_{t=1} = 449{,}777.42\ (m^3), \gamma_{t=2} = 522{,}012.04\ (m^3),\ \rho_{t=1} = 5{,}341.91(ha), \rho_{t=2} = 6{,}898.88(ha), \alpha = 6.5, \beta = 1.2.$

*Average purchasing & transportation cost ($\$/m^3$), †Average stem size ($m^3/stem$), ‡Average volume per ha (m^3/ha), §Maximum deviation from target between the two time periods (%), ||Mean deviation from target between the two time periods (%).

Table 2.5 Solution comparison between MOO (linearization method) and MinCost for Case A

		Case A	
		MOO	**MinCost**
Harvested and transported volume (m^3)	t_1	440,317	434,701
	t_2	522,279	546,808
Volume left uncut inside selected harvest areas (m^3)	t_1	28,056	66,496
	t_2	113,937	106,065
Average unit purchasing cost ($\$/m^3$)	t_1	32.68	31.25
	t_2	31.79	32.84
Average unit transportation cost ($\$/m^3$)	t_1	17.03	16.45
	t_2	16.84	17.50
Avg. cost over the entire planning horizon	T	49.13	49.17
Purchasing cost	t_1	14.39	13.58
	t_2	16.60	17.96
Transportation cost	t_1	7.50	7.15
	t_2	8.79	9.57
Total cost	t_1	21.89	20.73
	t_2	25.39	27.53
Average transportation distance (km/m^3)	t_1	203.76	199.27
	t_2	200.78	206.05
Total area of selected harvest areas (ha)	t_1	5308.53	5467.66
	t_2	6879.62	6805.86
Number of selected harvest areas	t_1	18	19
	t_2	18	15
Note: All costs are given in CAD millions. Used parameters: $\alpha = 6.5,\ \beta = 1.2,\ w_1 = w_2 = w_3 = 1/3,\ l^{min} = 11{,}088.56\ (m^3)$			

Assessment of the linearization technique

In this section the solution for Case B applying the linearization approach is compared to the solution obtained by means of the commercial solver BARON. In terms of the size of models for Case B, 46 binary variables, 23,080 continuous variables and 12,440 constraints have been constructed in the proposed formulations.

The indicator MeD computed for each of the three criteria for MOO strategy solved by BARON vs. the linearization and MinCost alternative are compared in Table 2.6. As one might expect the MOO model solved by the linearization approach does not perform as well as the BARON solution, but still its proposed plan results in less deviation of the criteria from their respective target than MinCost's plan. It is noteworthy that solution time of the linearization approach is substantially smaller i.e., less than one minute vs. 22.5 hours needed for BARON.

A standard approach to solve the MINLP problems is to choose a scaling factor as a fixed value for the denominator of the nonlinear component. Our linearization approach aims to find a proper scaling factor. Based on a number of tests 5-10% changes in the chosen value of the denominator of nonlinear functions may cause 0.6-9% deviation in the value of those functions. This clearly shows the need to find the proper denominator.

Table 2.6 Comparing MOO and MinCost strategies for Case B solved by BARON & linearization approach

		Case B		
		C1*	**C2†**	**C3‡**
MOO (BARON)	MeD§	0.49%	4.38%	1.1%
MOO (linearization)	MeD	2.08%	4.56%	6.49%
MinCost	MeD	4.06%	7.55%	6.57%

Note: used parameters are $\alpha = 1.5, \beta = 0.44, k_t^1 = k_t^2 = 30\% \ \forall\, t \in T, \gamma_{t=1} = 436{,}839.94\ (m^3), \gamma_{t=2} = 191{,}268.45\ (m^3), \rho_{t=1} = 5{,}294.7\ (ha), \rho_{t=2} = 2{,}190.16(ha)$.
*Average purchasing & transportation cost ($\$/m^3$), †Average stem size ($m^3/stem$), ‡Average volume per ha (m^3/ha), §Mean deviation from target between the two time periods (%).

Analyzing the impact of logistics constraints

In order to explore the potential savings in the logistics costs of the whole system, another test has been conducted in which all logistics constraints imposed by the stakeholders were removed from the base multi-objective model. We call this solution, system optimality. For Case B the system's average unit transportation cost over the entire planning horizon decreased by about 4% compared to the base MOO model. It seems preferable to implement the system optimality plan in practice, however, often such harvest area allocation to mills is not perceived as a fair allocation by all companies. Specifically because of deactivating all the logistics constraints in the system optimal model, the mills located very close to the forest will often take advantage of this inherent benefit of theirs by being allocated to harvest areas very close to them (leading to a relatively very small transportation distance), while other mills located further from the forest have to transport much longer distances to access their supply. Ideally the allocation of system optimal solution should be implemented, but at the same time, in order for the MFFP to overcome the abovementioned issue, it is required to redistribute either the total cost or the extra savings compared to the base model's cost among the mills. This could get done efficiently through game theory models based on e.g. the level of contribution of each mill to finding the better solution for the whole system. Nonetheless, proposition of such game theory models for cost-redistribution is out of the scope of this paper; we refer readers interested in that field of research to the works done by Audy et al. (2012b,c).

2.7 Conclusions and future works

In this paper, we studied the tactical forest management planning problem over a five-year planning horizon in a multi-period, multi-product and multi-company setting. According to the province of Québec's new Sustainable Forest Development Act, currently the MFFP is the sole party responsible for developing such forest management plans and from its planners' perspective it is of great importance to ensure that all resources are being used in a balanced manner in terms of different criteria over longer period of time (i.e. with the least deviation of criteria from their respective target).

In this research the considered resources were the harvest areas with their specific attributes in terms of size, volume, species composition, and average tree size that should be used robustly. The importance of this matter could be justified by the fact that if the MFFP does not deliberately enforce a balanced tactical plan, due to availability of supply more than the annual demand any other plan would usually do high-grading of the resources. This is precisely what the proposed MOO model aimed to prevent. Three most important criteria to the MFFP were identified and the main goal was to stabilize them at the same time over the whole planning horizon while satisfying specific constraints. For that purpose, we employed the idea of business and anticipation periods and developed a MOO model based on the GP technique. By comparing the MOO model with the conventional cost-minimization alternative, we observed that the MOO leads to much less deviation of the criteria from their respective target, which is a more stable plan in terms of those criteria over longer period.

Multiple avenues for future development of the presented work are identified. First, the model could be modified to add a fourth optimization criterion in order to control the spatial dispersion of selected harvest areas during each period. Secondly, future research could include aggregation of the FMUs into groups so that the optimization could be performed at the regional level to explore transportation synergies and wood swap (or wood bartering) possibilities. This may give rise to some coordination conflicts among mills and coordination mechanisms must be developed and compared to the current practices with no coordination. Thirdly, since not all harvest areas are accessible through Québec's current road network, the decisions about building new roads or upgrading existing ones have to be made based on when harvesting is expected to occur in the stands served by that road segment and its required accessibility conditions. Moreover, game theoretic models could be applied to present a framework to share associated costs among involved mills in a fair manner.

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CHAPTER 3

MINIMIZING SPATIAL DISPERSION OF FOREST HARVEST AREAS USING SPECTRAL CLUSTERING AND SET COVERING MODELLING

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Abstract

In recent years, spatial forest management has attracted great attention by both researchers and practitioners. In the province of Quebec, Canada, forest product companies sub-contract harvesting operations to contractors. One of the challenges faced by the harvesting teams relates to moving the harvesting machineries between harvest areas, which is usually very costly and time consuming. So in order to facilitate these operations, we propose a planning support tool to group the harvest areas in a way that the spatial dispersion of the clusters is reduced, meaning the logistics of moving the machinery between areas in each cluster becomes more efficient. Such a tool can be used by the Ministry of Forests, Fauna and Parks to do the planning. We applied the spectral clustering algorithm to partition a set of harvest areas based on their transportation distance from one another and their available timber volume. We used a set covering model to choose the clusters corresponding to the least spatial dispersion and approximately equal volume of timber. The approach is tested in a real case in Quebec and the proposed bi-objective set covering model outperformed the single-objective formulation as it presents a better balance between the two considered objectives.

Key words: Forest management, Spatial dispersion, Minimum spanning tree, Spectral clustering, Set covering

3.1 Introduction

In the province of Quebec, Canada, forestry companies sub-contract timber harvesting operations to third-party contractors. In order for these contractors to continue earning profits, they need to find a reasonable balance between satisfying the expectation of companies for lower costs and the implementation of costly harvesting methods respecting the provincial forestry regulations (Bonhomme and LeBel, 2003). A typical harvest team has five machines: one feller-buncher, two forwarders, and two delimbers. In order to move such heavy harvesting equipment between harvest areas, they are put on trailers and then transported to the next harvest area. This process is potentially very time-consuming and costly especially when two harvest areas are located far from one another. In this regard, the problem that the Quebec Ministry of Forests, Fauna and Parks (MFFP) needs to tackle is how to group harvest areas in a forest management unit (FMU) in a way that each harvesting team working in that region is able to harvest a group of areas that are located close to one another. In this paper we study this problem and present a decision support tool for the MFFP by which the harvest areas that have been surveyed at the time of planning will be divided among the harvesting teams in a way that the areas given to each team are spatially dense and the total timber volume in each of these clusters of harvest areas is about the same (i.e., approximately similar workload for every team). Such clusterization will promote a more efficient logistics for the movement of machineries between harvest areas by each team when the short-term harvest scheduling is being planned, leading to reductions in both the cost and the time consumed for such transportation of equipment and machineries. Often, at the time of planning the pool of harvest areas has enough volume of timber to satisfy about 1 to 1.5 years of demand of wood-processing mills operating in an FMU, so the developed tool can be rerun by the MFFP at the end of that time horizon as new harvest areas are being surveyed and added to the pool.

Harvesting of forest (as a renewable resource) can be seen as both beneficial and damaging for the environment. On the one hand, harvest activities can cause soil erosion, decrease water quality, disturb some species and deteriorate the beauty of natural scenery; on the other hand, harvesting can provide the required space for the growth of specific species, reduce the risk of forest fires and the spread of infestation. For this reason, the decisions on sequencing of harvest areas need to be made carefully, taking into account explicit spatial and environmental concerns in addition to fulfilling timber demand in a profitable manner (Ronnqvist et al., 2015). In the forestry literature, one of the common approaches to address the spatial concern related to forest harvesting operations is to include adjacency type and green-up constraints in the classic harvest planning models, mostly at the tactical level (Thompson et al., 1973 and Murray, 1999). For instance, Lockwood and Moore (1993) employed the simulated annealing approach to solve large-scale harvest scheduling problem as a combinatorial optimization problem considering block size constraints aiming to reach target harvest volume while the selected area is minimized. Clark et al. (2000) modelled the harvest scheduling problem considering spatial and temporal aspects incorporating road network development. The authors solved the defined problem by means of a three-stage heuristic procedure. Könnyu and Toth (2013) proposed a cutting plane algorithm to solve a spatially-explicit harvest scheduling problem formulated as an integer program that includes adjacency and green-up constraints. Kašpar et al. (2016) proposed a spatial harvest scheduling model with the goal of maximizing the net present value and having compact harvesting locations in each time period over a 5-year planning horizon. Bhérer *et al.* (2016) studied the tactical forest management planning problem with the aim of reducing the spatial dispersion of harvest areas selected to be harvested. The authors employed the King algorithm to group the harvest areas. In a recent work by Mobtaker *et al.* (2018) the problem of harvest area selection and stem allocation to wood-processing mills over a 5-year planning horizon was studied considering multiple objectives. The proposed model was demonstrated for a case in Quebec. An interesting recommendation for a future research topic by the authors raises the question of how could the MFFP reduce the spatial dispersion of harvest areas that a typical harvesting team would cut for mills over a specific planning horizon. As described earlier, in this paper we aim to study this research question.

Our contribution to the literature could be summarized as follows: we applied a modern clustering technique in order to group harvest areas together based on their distance from one another and the available volume of timber; this step produces a large pool of possible clusters. Next, to pick the most desirable clusters among the many alternatives, one for each harvesting team, the mixed integer programming (MIP) set covering modelling is utilized. Two main objectives were pursued: (1) minimizing the spatial dispersion of the grouping of harvest areas and (2) balancing out the volume of available timber among the chosen clusters. For that, a bi-objective set covering model is formed, for which the goal programming (GP) technique coupled with the Nadir theory for the normalization of the two objective values are employed. Also, a single-objective MIP model is developed and compared to the results of bi-objective model. The proposed models are tested for a real case study in the province of Quebec. This novel use of clustering techniques in forest management helps the MFFP planners to reduce the spatial dispersion of the harvest areas that each harvesting team should eventually cut over a number of years in a specific FMU; in other words, it reduces the machineries' movement distance between harvest areas which, when such solutions are being used as the input for short-term operational harvest scheduling could guarantee a more efficient logistics for the movement of the machineries rather than when a team needs to move among harvest areas that are spatially disperse.

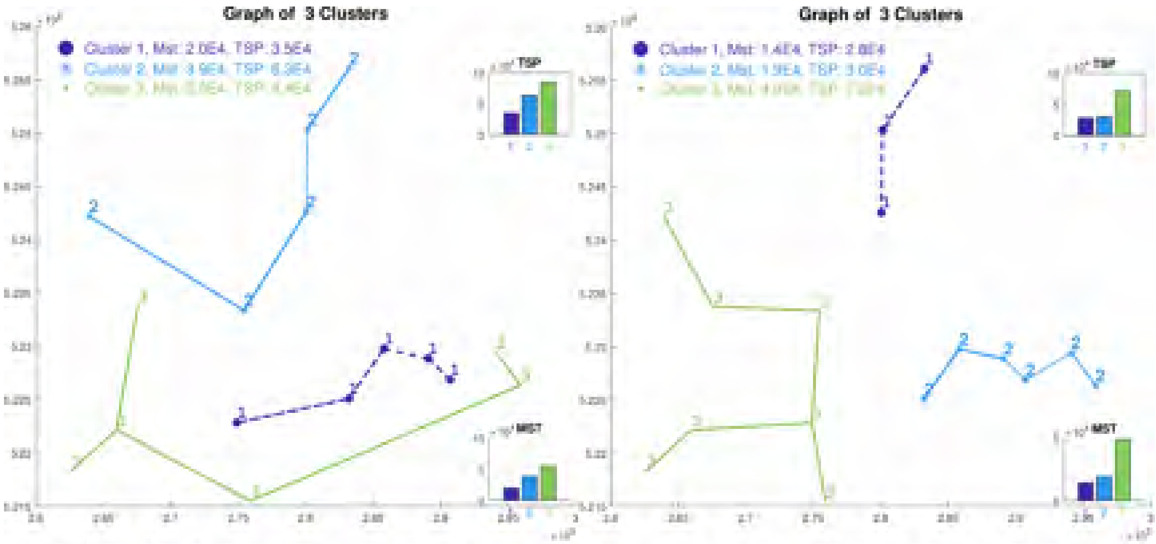
The structure of this paper is as follows. In Section 3.2, the research problem is described in detail. The proposed two-phase approach consisting of the application of clustering technique and the mathematical formulation are presented in Sections 3.3. Section 3.4 presents the developed Canadian case study. The discussion on the computational tests is presented in Section 3.5. This paper ends with conclusions and describes the path to take by future research in Section 3.6.

3.2 Problem statement

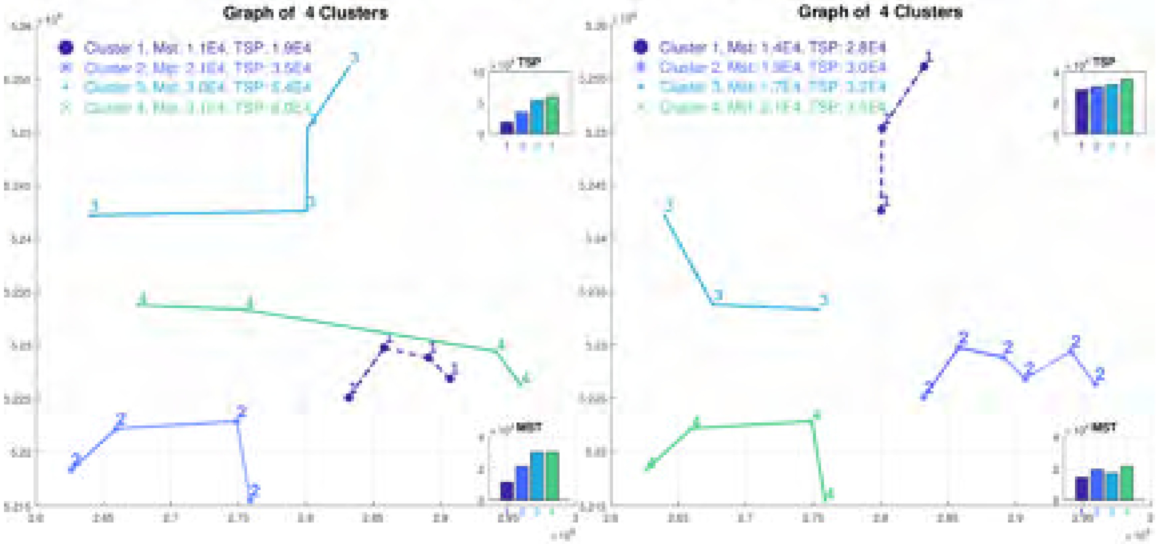
A known number of harvesting teams often operates at each FMU. One of the challenges that they face is to move the machinery between harvest areas that are situated very far apart. It would be of great value if the MFFP could systematically group harvest areas that are relatively closer to each other for every team. At the same time, the volume of timber that will be dedicated to each team needs to be almost equal. For this purpose, we propose a decision-support tool that groups the harvest areas, minimizes the overall spatial dispersion of the clustered harvest areas and ensures a balanced distribution of volume of timber among the teams working in a specific FMU. By using this tool the MFFP could contribute to reducing the cost and time required for the movement of machinery between harvest areas.

In particular, we studied the problem of dividing the harvest areas given in a specific FMU among the harvesting teams with the goal of minimizing the spatial dispersion corresponding to the overall clusterization and balancing out the available volume of timber among the teams. First, a clustering algorithm is applied to generate a large pool of clusters and in order to be able to compare the formed clusters and choose the most suitable ones that satisfy our objectives. We defined two key performance indicators (KPI) for each cluster: (1) the length of its minimum spanning tree (MST) as a measure of the spatial dispersion of the harvest areas in each cluster and (2) the sum of deviation of volume of timber of each selected cluster from a defined target volume (so that the overall workload of the teams is as similar as possible). Accordingly, two respective objectives are pursued to select the same number of clusters as the number of harvesting teams which have the least total MST value and to minimize the total deviation of the timber volume of each cluster from a pre-defined target volume. Since it is important to distribute the harvest areas among the teams equally in terms of volume of timber, the above-mentioned target for the latter objective is computed by dividing the total volume of available timber inside all given harvest areas by the number of harvesting teams working in the considered region. Then using a set covering bi-objective optimization model the most suitable clusters are chosen.

Figure 3.1 shows a small hypothetical example of 16 harvesting sites. Two clustering approaches are used to make 3 and 4 clusters: an efficient one (spectral clustering) and a very simplistic technique (N-nodes diameter clustering). The clusters are sorted based on the Travelling Salesman Problem (TSP) cost (which is almost identical to the MST sort).



(a) N-nodes Diameter clustering, 3 clusters (b) Spectral Clustering, 3 clusters



(c) N-nodes Diameter clustering, 4 clusters (d) Spectral Clustering, 4 clusters

Figure 3.1 An example of the defined problem: Spectral Clustering ((b) and (d)) and the N-Node Diameter Clustering ((a) and (c)), considering 3 (upper) and 4 clusters (lower) for 16 sites

In order to clarify the logic behind choosing MST as a measure of spatial dispersion of the clustered harvest areas, let us look at the problem at hand from the graph theory perspective: each harvest area is considered as a node and the edge connecting two nodes is represented by the road connection between the two areas with the length of road being the edge's weight. In order to accurately measure the efficiency of a cluster of harvest areas the following question needs to be answered: what is the problem that one needs to solve in order to minimize the moving cost in a cluster? Solving a TSP for a cluster provides a valid solution for this question. However, to solve a TSP for a very large number of clusters is computationally very expensive. Therefore, we needed to find a good representation of the TSP in the context of the defined problem. In fact for the same sites, the MST cost is equal or inferior to the TSP cost which is natural because subtracting one edge of the TSP solution is a spanning tree. There is also the realistic assumption that the TSP and the MST have many edges in common and the TSP cost could not be greater than or equal to the double of the MST cost. The best-known approximation ratio for the TSP is given by the Christofides algorithm that assures a 3/2 ratio of the exact solution cost, based on the MST (Christofides, 1971). In the example illustrated in Figure 3.1, the TSP and the MST have an average ratio in the interval [1.47, 1.97], which is natural for small graphs. As mentioned earlier, it is very reasonable to use the MST as it can be calculated much faster than the TSP and the results are very much correlated. Figure 3.1 also shows that the TSP and the MST costs are lower for spectral clustering; the clusters get a better separation and the results are stable (i.e. when changing the desired number of clusters from 3 to 4, the inefficient clustering method has completely reshaped but the spectral clustering changes by only one edge).

3.3 Modelling and solution methodology

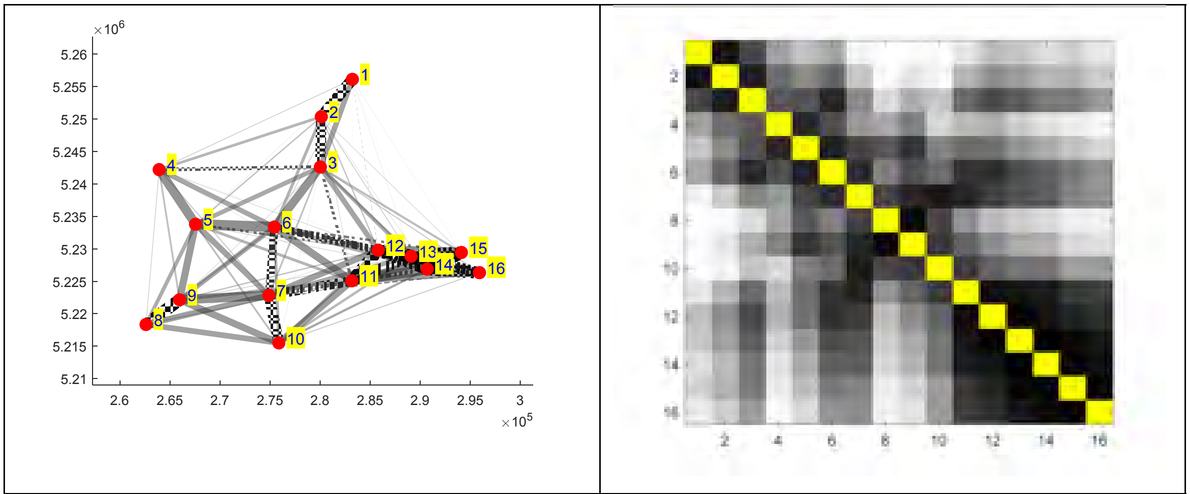
To model and solve the defined problem we propose a two-phase approach. The first phase involves generating a large pool of systematically formed clusters of harvest areas and consequently in the second phase a set covering model is used to pick the clusters that correspond to an optimal solution for the two considered objectives.

Phase 1: Spectral clustering

Producing the complete enumeration of all possible clusters of the given harvest areas would lead to a very large number of alternatives. Instead, in order to generate a tractable number of clusters, we decided to adopt one of the most popular modern clustering algorithms known as the spectral clustering algorithm (von Luxburg, 2007). This algorithm is capable of defining clusters with substantial distinctions and is widely used for clustering and visualization (Seary & Richards, 2003; Seary & Richards, 1995). A recent successful application of this algorithm for the case of a water distribution network partitioning is conducted by Di Nardo et al. (2018). The spectral clustering algorithm has reportedly outperformed the traditional clustering algorithms such as the k-means algorithm. The spectral clustering algorithm is a graph-based partitioning method which aims to minimize the normalized cut of the graph representation of the respective clustering problem (e.g., in this study the problem of clustering of harvest areas into compact groups). In what follows we explain the framework of this method; however, interested readers are referred to von Luxburg (2007) for a detailed tutorial of the algorithm.

Given a set of harvest areas (sites), we can imagine that all of them are connected in a dense mesh in a plane (a complete undirected graph). Then distinct clusters can be realized by deleting edges that represent weaker relation between the harvesting sites. A common relationship indicator is the transportation or movement distance for the machinery mainly because of its economic importance. The degree of “dissimilarity” between two sub-graphs (two distinct clusters of sites) is the sum of the length of the edges that were removed to produce the separation. One way to create a good clustering solution could be to maximize such dissimilarity measure, or in order to represent the problem as minimization, a “similarity” measure can be considered as a reciprocal value proportional to the distance. This problem is known as the min-cut problem, because we would like to make cuts that separate clusters corresponding to the smallest summation value of the deleted edges. A drawback of min-cut solution in the clustering context is that it allows the creation of isolated small clusters in the extreme nodes (sites). To compensate for this behaviour, a normalization of the cluster cost is considered for the cut minimization. Since such normalized cut minimization problem is very difficult to solve, researchers have designed heuristic methods to find efficient solutions, for instance Hansen et al. (2010) proposed a Variable Neighborhood Search Heuristic for normalized cut segmentation.

In order to construct a similarity matrix, usually a similarity function is used to model the neighbourhood relationships, for instance, the Gaussian similarity function: $s(x_i, x_j) = e^{\frac{\|x_i - x_j\|^2}{2\sigma^2}}$. Figure 3.2 shows the same hypothetical example of 16 sites presented earlier, for which the similarity matrix is produced based on the Gaussian distance between each pair of sites. In this figure, the darker bold lines correspond to the smaller distances in the graph. Figure 3.2.a shows a complete graph of sites where the links represent an affinity measure of the similarity (a value based on the distance). The corresponding similarity (affinity) symmetric matrix is shown in Figure 3.2.b. The colour follows the same gray scale in both plots. The possible cluster candidates appear in this matrix as dark diagonal blocks. Around the diagonal (in yellow), it is possible to distinguish the clusters formed by $\{1, \ldots, 3\}$ and by $\{11, \ldots, 16\}$. It is also possible to distinguish with more difficulty, the relation between the sites $\{4, \ldots, 10\}$. A mild relationship of sites $\{2, \ldots, 6\}$ is almost perceptible.



(a) Network of harvest sites (the link follows a distance similarity value in gray scale)	(b) The similarity matrix representation of the network with sites ordered according to the darkest linked sites

Figure 3.2 Network plot and similarity matrix visualization

For the use of the spectral clustering algorithm, the graph of the underlying problem needs to be defined in the form of an affinity matrix, for which the corresponding Laplacian matrix could be calculated by means of standard linear algebra methods. If the goal is to generate k

(i.e., a pre-specified input parameter for this algorithm, as the desirable number of clusters to be generated) clusters, then the k smallest eigenvalues and their corresponding eigenvectors will be used to distinguish the k clusters representing the minimum normalized-cut of the considered affinity matrix (von Luxburg 2007). This algorithm converges most of the time to a unique clustering solution and hence it is known to be deterministic. However, in the problem under study, we have two different dimensions that we would like to consider to generate clusters based on them, so a second parameter α (in addition to k) will be introduced later enabling us to incorporate both dimensions in forming a single affinity matrix.

Constructing the affinity matrix T is an important step ahead of clustering. The relations among the elements of a cluster of harvest areas must reflect 2 different dimensions: one dimension for distance proximity and a second dimension that approximates identical timber volume of clusters. In order to construct the final matrix T incorporating these two dimensions, first each of the two needs to be defined in the form of a matrix: one that accounts for the site-to-site proximity (matrix D) and another one which approximates the site-to-site affinity by volume (matrix W). Then the convex combination of matrices D and W will be considered as the main affinity matrix T. Matrix D accounts for the bilateral relationships among sites and it is defined using the transportation distance matrix. Defining the affinities in terms of timber volume (matrix W) in terms of bilateral relations is not straightforward, nor is it well defined in terms of "n-sites" relations as it must consider for the addition of site volumes. Let N be the number of sites. Then we define $S = \{2, \dots, k\}$, with $k \in Z$ as $2 <= k < N/2$, assuming clusters of two sites to be the smallest clusters allowed. Following the hierarchical clustering principle, we begin with the largest cluster of all sites and then we split this cluster in $s \in S$ clusters. With the help of a "partition problem" heuristics we partition the sites into clusters of almost equal timber volume. At every step, we keep a record of the members of every cluster to later construct the matrix W. Matrix W is defined as the normalized matrix that accounts for the number of times that a site i is assigned to the same cluster as site j, with $i \neq j$, where $i, j \in \{1, \dots, N\}$. This partition problem based on the timber volume of clusters is NP-complete, but the matrix W is

easily found in "$O(N^2)$" for $2 < k$ if the Children-sorting heuristic is used. If the solution quality is important, there are other non-greedy heuristics available or an exact but time-constrained MIP can be applied to improve the solution. Matrix W considers the sites which often end up in a common cluster among the $|S|$ recorded partitioning solutions and it is agnostic in terms of the number of site members of any cluster. In Matrix T, in order to account for sites that have never been put in the same cluster, a small number (1/N) can be assigned as the minimal acceptable site-to-site affinity. It is also possible to define a different beginning cluster for the splitting procedure by taking big subsets of the N-sites and repeating the procedure several times hoping that we can cover for all the possible couples.
As mentioned before, convex combination of the matrices W and D gives us matrix T. Matrix T can be parameterized by α $(0 \leq \alpha \leq 1)$, as $T(\alpha) = \alpha * D + (1-\alpha) * W$. Taking $\alpha = 1$, generates a clustering based solely on movement distance.

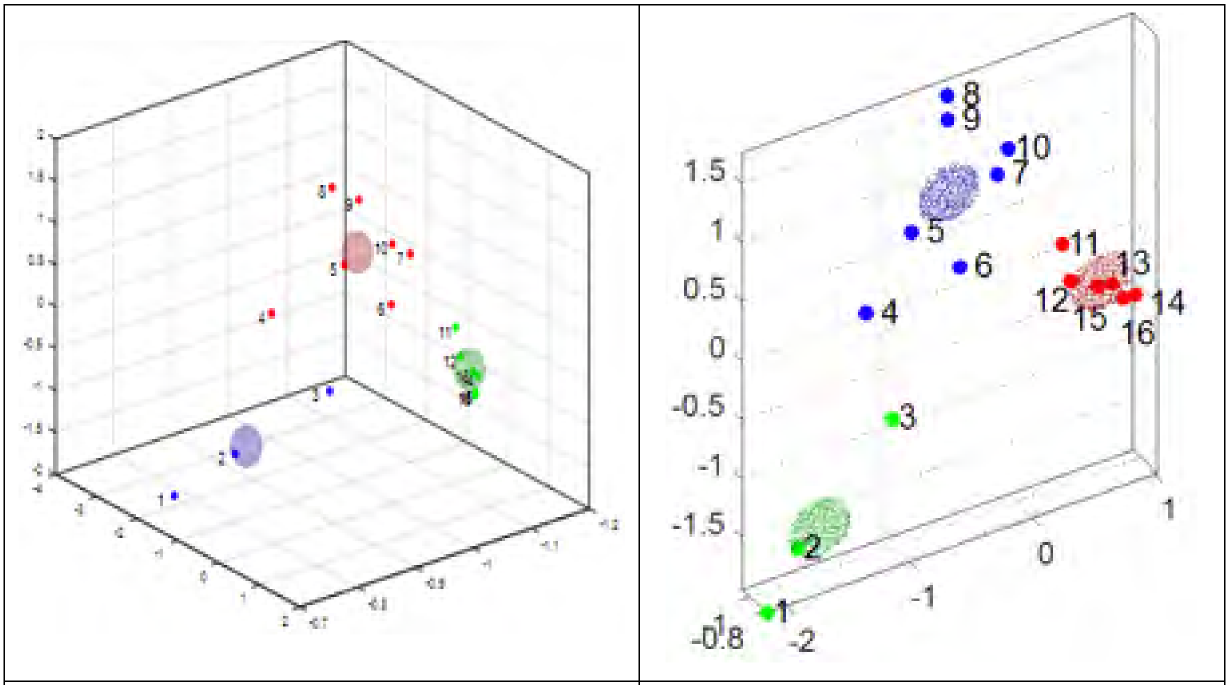
The Normalized cut k-Clustering algorithm named Spectral algorithm that was used in this study is adopted from Shi and Malik (2000) and can be summarized as follows:

1. Define k, as the number of clusters wanted.
2. Consider the network of sites V, and the edges E, forming the graph G= (V, E, w). The edges of the graphs have been assigned weight w, corresponding to a similarity function applied to the distance between every pair of sites.
3. Set the similarity matrix with the weights' edges of the network as W. Let D be the diagonal of W.
4. Find k eigenvectors corresponding to the smallest eigenvalues of the generic Eigen problem: $(D - W)x = \lambda Dx$. The eigenvalues and eigenvectors are those of the normalized Laplacian.
5. Use the eigenvectors to partition the graph:
    a) Set a new matrix U, which is formed by the k eigenvectors taken as columns.

b) Using an auxiliary algorithm to discretize the eigenvectors. This is equivalent to assigning the rows of U to k groups.

6. The groups formed in step 5 are the k clusters. Every row of U corresponds to a site (node) of the network in a cluster.
7. Stop.

Figure 3.3 illustrates a scatter plot of eigenvectors for the same example. The coloured shadows indicate mass centroids. The auxiliary algorithm, k-means or Yu's Optimal Discretization (Yu, 2003), operates in the k-dimensional eigenvector space instead of the 2-dimensional original problem. In the example, the third dimension allows an important separation (Figure 3.3.a), without it, the problems are as difficult as the original.



(a) expanded 3rd dimension | (b) shuttered 3rd dimension

Figure 3.3 Eigenvectors scatter plot

It is possible to use nested loops for varying both k and α to produce several different sets of clusters. Once the $T(\alpha)$ matrix is defined in the outer loop, the inner loop generates k clusters. Most of the final clusters are unique and can be characterized in terms of the total available timber volume inside each and their respective minimal spanning tree distance. These two elements defining each of the generated clusters will be used in the second phase to choose the most suitable clusters.

Phase 2: Set covering model

In order to choose the desirable clusters among the pool of alternatives created in the previous phase, MIP set partitioning modelling is employed. Two versions of such a model are proposed: Bi-O is a bi-objective MIP set covering model and the Min-MST_2 is a single-objective MIP set covering model. The notation for the proposed models is provided in Table 3.1.

Table 3.1 List of indices, sets, parameters and decision variables of the model

Sets and indices	**Definition**
$a \in A$ $c \in C$	Set of harvest areas Set of clusters obtained by the spectral clustering method
Parameters	**Definition**
v_c v_T h w_i $n = \|A\|$ l_c m_{ac} p $\bar{v} = \frac{v_T}{h}$	Volume of timber available in cluster c (m^3) Total volume in all given areas (m^3) Number of harvesting teams working in the territory of the FMU Relative importance of objective function i Number of harvest areas Minimum spanning tree length of cluster c Binary parameter: equals 1 when harvest area a is included in cluster c; 0 otherwise Percentage of flexibility allowed for deviation from target volume Target volume of timber for each selected cluster
Decision variables	**Definition**
Y_c S_c^{up}, S_c^{down}	Binary decision variable equals 1 if cluster c is selected; 0 otherwise Slack variables (up & down) to measure the deviation of cluster c's volume from the target $\bar{v}$

To solve Bi-O we used the GP technique for simultaneous optimization of the two objectives $f^1$and f^2 in the form of objective f^{Bi-O}. This required running two auxiliary models named Min-MST and Min-Slacks, each of which separately optimizes one of the two considered objectives, $f^1$and f^2, respectively. In addition, with the help of Nadir theory it was ensured that the two incommensurable functions having values of different magnitude are normalized. A recent application of GP and Nadir theory approach in the context of multi-objective tactical forest management has been done by Mobtaker *et al.* (2018). The model Min-MST_2 minimizes the single objective function, f^1 as defined by eq. 1. Another difference between Bi-O and Min_MST_2 is that, for Min-MST_2 the set of input clusters has been filtered prior to the optimization: the clusters whose timber volume deviates more than a pre-defined percentage (p) from the target are excluded from the set of input clusters. It should be noted that the set of constraints is common between the two models. In what follows, first the formulation of the objective functions and afterwards the considered constraints are elaborated.

Objective functions

The first objective function f^1 aims to minimize the sum of MST lengths of all selected clusters.

$$\min f^1 = \sum_{c \in C} l_c Y_c \tag{3.1}$$

The second objective function f^2 minimizes the total deviation of the volume of available timber inside each of selected clusters from the target $\bar{v}$.

$$\min f^2 = \sum_{c \in C} \left(S_c^{up} + S_c^{down} \right) \tag{3.2}$$

The bi-objective f^{Bi-O} minimizes the weighted normalized deviation of each objective from its optimum value (f_i^{Opt}) when it has been solved individually.

$$\min f^{Bi-O} = w_1\left(\frac{f^1 - f_1^{Opt}}{f_1^{Nadir} - f_1^{Opt}}\right) + w_2\left(\frac{f^2 - f_2^{Opt}}{f_2^{Nadir} - f_2^{Opt}}\right) \tag{3.3}$$

Constraints

Equation (3.4) ensures that every site is included without overlapping among clusters, meaning that among the selected clusters each of the n harvest areas is included exactly once.

$$\sum_{c \in C} m_{ac} Y_c = 1 \quad \forall a \in A \tag{3.4}$$

Since we would like to choose one cluster for each of the h harvesting teams working in the considered FMU, equation (3.5) enforces the selection of exactly h clusters from the pool.

$$\sum_{c \in C} Y_c = h \tag{3.5}$$

Equation (3.6) is formed to be able to compute the absolute value of the deviation of the volume inside each selected cluster from the chosen target value.

$$(v_c - \bar{v})Y_c + S_c^{up} - S_c^{down} = 0 \quad \forall c \in C \tag{3.6}$$

Finally, eqs. 3.7 and 3.8 enforce the binary and non-negativity restriction on the decision variables:

$$Y_c \in \{0,1\} \quad \forall c \in C \tag{3.7}$$

$$S_c^{up}, S_c^{down} \geq 0 \quad \forall c \in C \tag{3.8}$$

3.4 Case study description

The applicability of the model is shown through a case study in the FMU 07451 inside region 7 (Figure 3.4), Outaouais in western Quebec provided by the MFFP. This case comprises 107 harvest areas with a total timber volume of $3.71*10^6$ (m^3); their geographical setup along with their available timber volume are shown in Figure 3.5. The timber volume of each site is shown by the bars presented at the bottom of Figure 3.5. Table A in the appendix presents each harvest area's identity in terms of its associated number and name, timber volume (m^3) and surface area (ha). These harvest areas may not be considered typical sites as they are larger than the norm like the instance of site#107 “SEIGNEURS” with 1935 ha of area, 1.76*10^5 of timber volume (m^3); so they could be considered an aggregation of a number of cut-blocks, which are usually defined with a much smaller size. The transportation matrix consisting of the distance between any pair of harvest areas is generated by the FPInterface software developed by FPInnovations, the research and development centre of the Canadian forest industry and is based on the existing road network in the Outaouais. This case is same as the one studied by Mobtaker et al., (2018); for more information on it, we refer the reader to that article. Moreover, according to the historical data, six harvesting teams work in the territory of this FMU ($h = 6$). Given the volume of timber available and enough for about 1-1.5 years of mill demand having supply agreement with the government in that FMU, the number of harvesting teams could be varied between 5-7; for which we ran our model and analyzed the results.

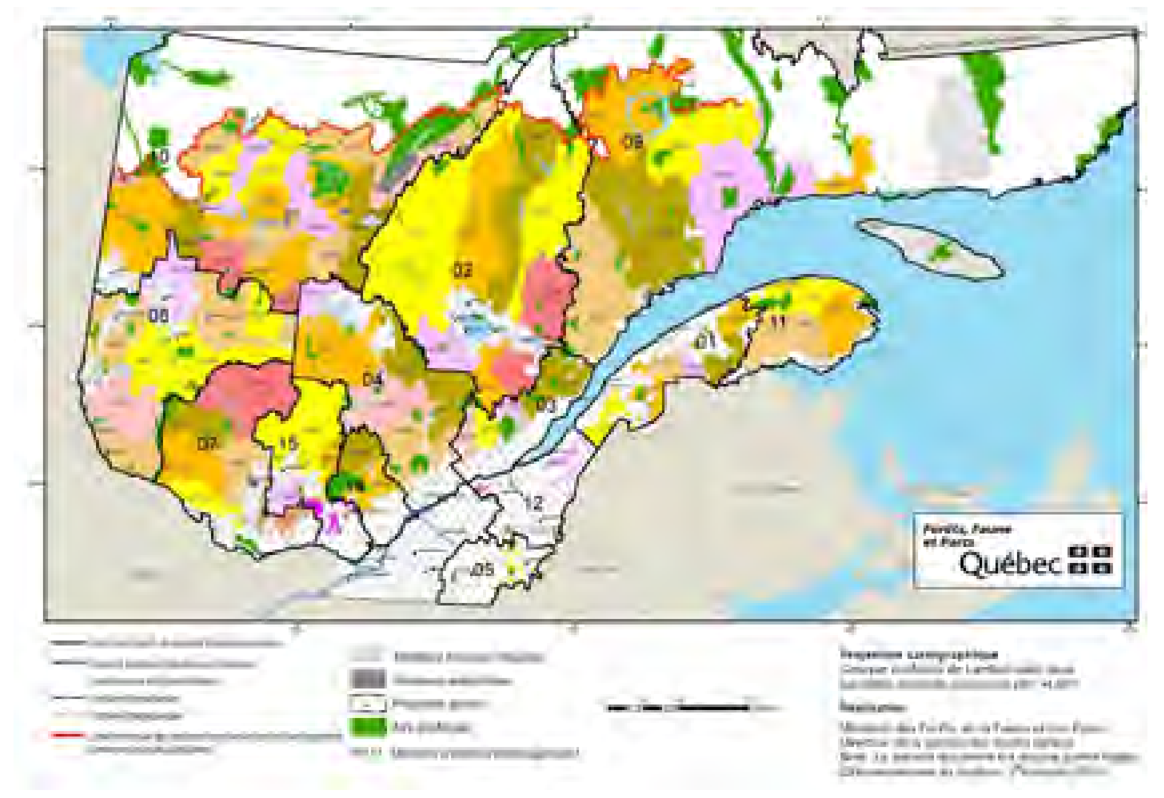


Figure 3.4 Map of forest management regions in the province of Québec, Canada; period 2013-2018 (MFFP-maps, 2018)

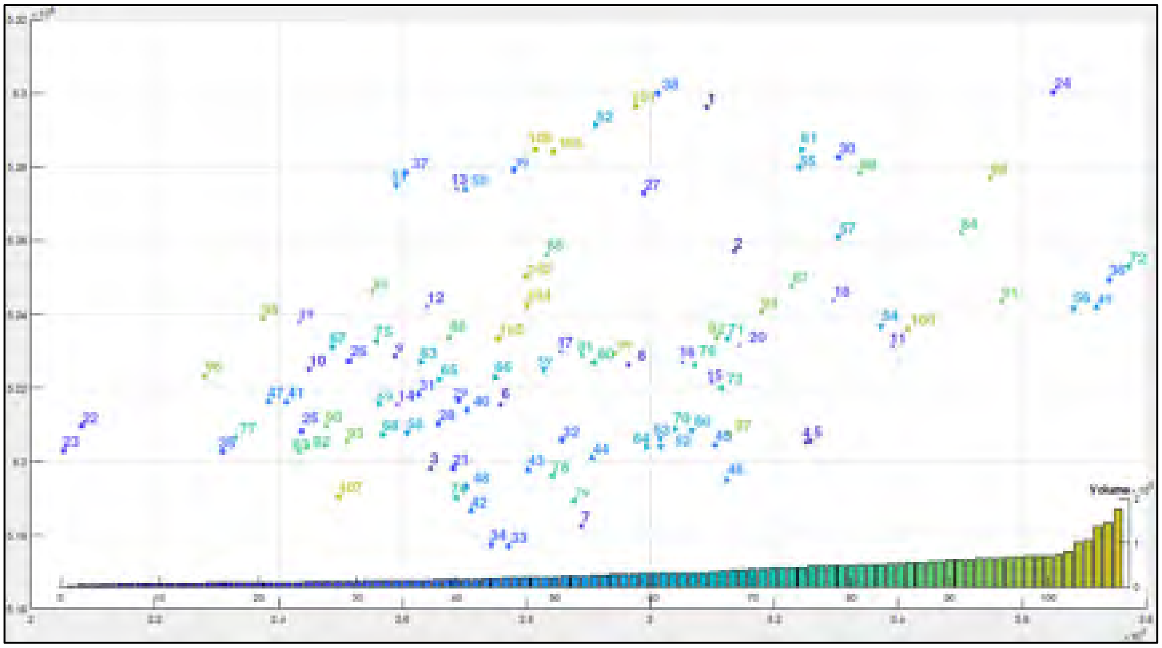


Figure 3.5 Geographical setup of the 107 harvest areas and their timber volume considered in the case under study in the bar plot below (in $10^5\ m^3$)

3.5 Results and discussion

We implemented the spectral clustering algorithm in MATLAB and ran it for our case of 107 harvest areas; given changing α and k parameters of the spectral algorithm, 239,652 unique clusters were created. Also, the developed MIP models are implemented in the modelling language AMPL version 2017.11.1.1. They are solved by means of the MIP solver CPLEX 12.6.3.0 on a desktop (Windows Server 2012 R2) with 64.0 GB of RAM and 3.5 GHz processor. In terms of the size of model, for the case under study, 239,652 binary variables, 958,611 continuous variables, and 479,415 constraints were used.

Creating the affinity matrix for this case study has taken around 5 hours and generation of clusters has also taken about 5 hours in total. Four MIP models were solved: Min-MST, Min-Slacks, Bi-O, and Min-MST_2. All the tests for models Min-MST and Min-MST_2 were solved in less than a minute. The Min-Slacks required between 3 minutes to 7 hours for different tests. The Bi-O model was solved in less than 30 minutes in all tests. The results of these experiments are presented in Table 3.2. In this table for the solution of each model, the name of the 6 selected clusters (Name), the number of areas existing in those clusters (Num), their MST value in km, the available timber volume (m^3), the average and standard deviation (STD) of MST values, and the STD of volume inside clusters are reported. In this case the target (average) volume equals $\bar{v} = \frac{3.71*10^6}{6} = 6.18 * 10^5\ (m^3)$.

Comparing the average of MST of the 4 models, we can see that Min-MST model has the least average MST (taken over the 6 selected clusters). This value increases with the following order for the other 3 models: Min-MST_2, Bi-O, and Min-Slacks. This trend is in alignment with the established objectives of the models.

Table 3.2 Results of the 4 models for $h = 6$

Min-MST

Name	**Num**	**MST (km)**	**Volume (m^3)**
C25412	10	103.87	4.02
C33906	7	32.74	1.78
C63764	19	319.96	8.41
C92479	3	69.62	1.15
C152488	49	565.02	13.9
C175576	19	232.30	7.78
MST: Avg. =220.58, STD =182.73 Volume: STD =4.42			

Min-Slacks

Name	**Num**	**MST (km)**	**Volume (m^3)**
C7652	20	734.83	6.08
C14931	16	561.27	5.16
C49652	14	615.42	6.47
C64907	18	579.61	6.42
C150014	20	665.90	6.35
C224211	19	556.82	6.58
MST: Avg. =618.97, STD =63.74 Volume: STD =0.48			

Bi-O

Name	**Num**	**MST (km)**	**Volume (m^3)**
C61911	9	204.73	4.69
C109101	16	304.31	5.70
C151960	27	287.22	6.51
C175540	14	160.84	5.74
C225147	19	251.27	6.46
C232661	22	290.82	7.97
MST: Avg. =249.86, STD =51.64 Volume: STD =1.00			

Min-MST_2

Name	**Num**	**MST (km)**	**Volume (m^3)**
C25413	12	145.16	4.99
C61911	9	204.73	4.69
C109101	16	304.31	5.70
C151928	33	384.33	7.82
C175559	22	250.77	7.97
C232651	15	180.99	5.89
MST: Avg. =245.05, STD =80.25 Volume: STD =1.28			

Note: Volume values are in 10^5, $w_1 = w_2 = 0.5, (p = 30\%)$

An interesting observation can be made regarding the STD of MST: Bi-O is the model leading to a solution with the lowest STD of MST. This measure increases in the following order for the rest: Min-Slacks, Min-MST_2, and Min-MST. It seems that because both Min-MST and Min-MST_2 models are solely minimizing the sum of MST value of selected clusters they end up with highest variation in MST among the selected clusters. Between these two models Min-MST_2 has a lower STD of MST, the reason is that for this model the input clusters has been already filtered and the clusters whose volume deviates more than 30% are excluded from the pool. So it can be observed that the three models Bi-O, Min-Slacks and Min-MST_2 that each to some level try to have equal volume in the chosen clusters are able to pick clusters whose MST length is also closer to one another. Regarding the STD of timber volume, the solution to Min-Slacks has the lowest variation among the volume of selected clusters, which is precisely what the purpose of this model was. The STD of volume increases for the solutions to Bi-O, Min-MST_2 and Min-MST models in the respective order. This pattern in the behavior of these models is meaningful; in a sense that when to different levels we aim to choose the clusters whose volume is similar the STD of volume among the selected clusters will be less depending on how much emphasis we have put on this objective.

In order to gain some insights on how the value of the two functions f^1 and f^2 may change with respect to the number of teams, two other scenarios ($h = \{5,7\}$) were also tested. In Table 3.3, the results of Min-MST show that increasing the number of harvesting teams (h) leads to smaller values for the total MST (f^1), because the model has more options to search for clusters with lower MST. However, when we run the Min-Slacks model the value of f^1 worsens. Also, considering the model Min-Slacks, it can be observed that increasing k results in higher values of f^2 which shows that it gets more difficult to balance out the available volume among more teams.

Table 3.3 Comparing the scenarios: $h = 5, 6, 7$

		$\boldsymbol{h = 5}$	$\boldsymbol{h = 6}$	$\boldsymbol{h = 7}$
$\boldsymbol{f^1}$ $(\boldsymbol{km})$	Min-MST	1.36	1.32	1.29
	Min-Slacks	3.62	3.71	4.07
	Bi-O	1.59	1.50	1.54
	Min-MST_2	1.49	1.47	1.44
$\boldsymbol{f^2}$ $(\boldsymbol{m^3})$	Min-MST	$1.81*10^3$	$2.32*10^3$	$2.22*10^3$
	Min-Slacks	$1.38*10^2$	$2.23*10^2$	$2.33*10^2$
	Bi-O	$5.65*10^2$	$4.80*10^2$	$3.66*10^2$
	Min-MST_2	$7.88*10^2$	$6.87*10^2$	$6.35*10^2$
Note: All values are in 10^3				

The behaviour of model Min-MST_2 in terms of the changes in f^1 is similar to Min-MST, which makes sense as both minimize the same objective f^1. Regarding the changes in f^2, we need to keep in mind that the value of parameter p considered for each scenario was different

($p = 35\%, 30\%, 25\%$ for $h = 5,6,7$ respectively); hence, no specific trend can be expected. This is due to the fact that in each scenario, the smallest value for p that would allow the Min-MST_2 model to find a feasible solution was set.

Comparing solutions of the two main models Bi-O and Min-MST_2 for any h in Table 3.3, it can be noted that solutions of Min-MST_2 in all scenarios have lower total MST, yet the value of f^2 is much higher than its counterpart in the solutions of Bi-O. In Table 3.4 we considered another KPI to compare these two models: the normalized deviation of each function from its optimal value $\left(\frac{f^i - f_i^{Opt}}{f_i^{Nadir} - f_i^{Opt}}\right)$. It can be noted that in all three examined scenarios, Min-MST_2 performs slightly better (4%, 1%, and 3%) in minimizing the total MST, which makes sense as this model exclusively aims to minimize the total MST. However, in terms of evening out the available timber volume among the h harvesting teams, the Bi-O model performs better than Min-MST_2 by 13%, 10%, and 13% respectively for each of the three scenarios. This behaviour reveals that Bi-O outperforms Min-MST_2 by coming up with better compromises between the two objectives.

Figures 3.6-3.9 illustrate the spatial representation of the clusters chosen by the four models for $h = 6$. Please note that the straight line connecting any two harvesting areas is only a figurative (not the actual) representation of the road connecting the two areas. The distance info used for the MST calculation and the clustering algorithm is in fact the actual transportation distance (i.e. the considered distance for moving harvesting machineries between harvest areas) through the existing road network in the region under study.

Table 3.4 Another comparison of the scenarios: $h = 5, 6, 7$

		$h = 5$	$h = 6$	$h = 7$
$\frac{f^1 - f_1^{Opt}}{f_1^{Nadir} - f_1^{Opt}} * 100$	Bi-O	10.24%	7.35%	8.87%
	Min-MST_2	6.02%	6.14%	5.44%
$\frac{f^2 - f_2^{Opt}}{f_2^{Nadir} - f_2^{Opt}} * 100$	Bi-O	25.57%	12.30%	6.65%
	Min-MST_2	38.97%	22.16%	20.15%

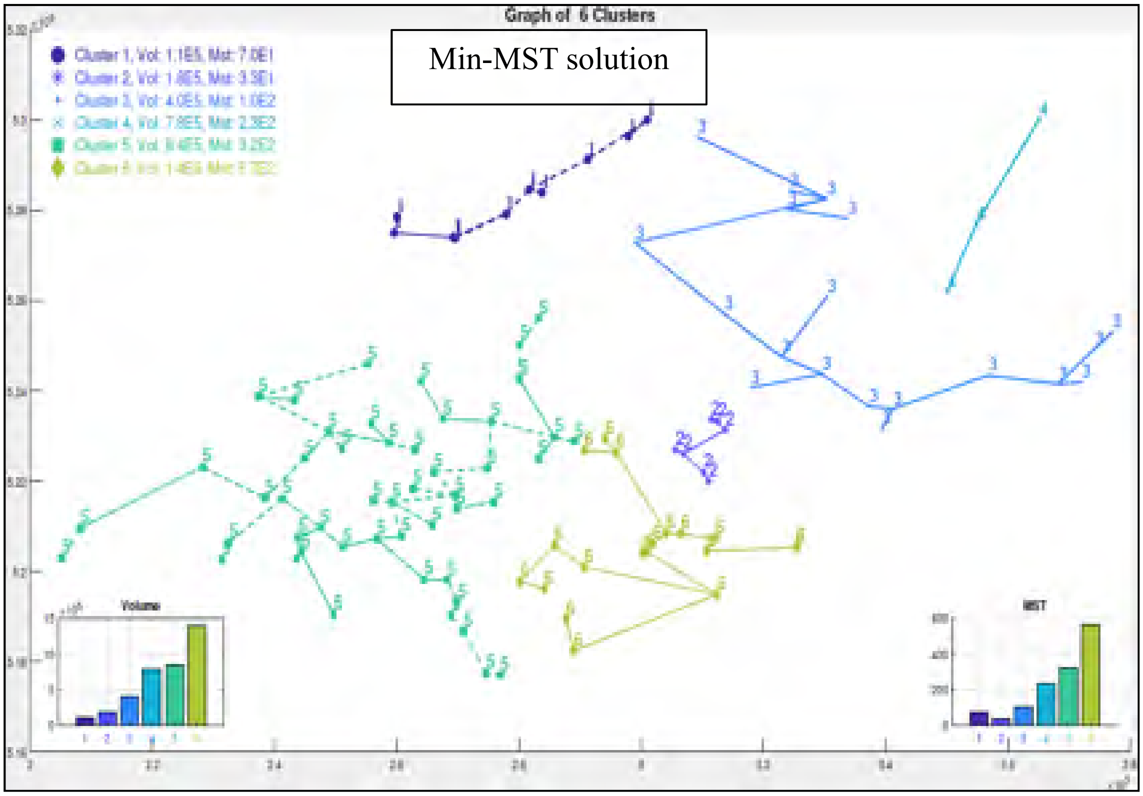


Figure 3.6 Spatial representation of the clusters chosen by Min-MST for $h = 6$

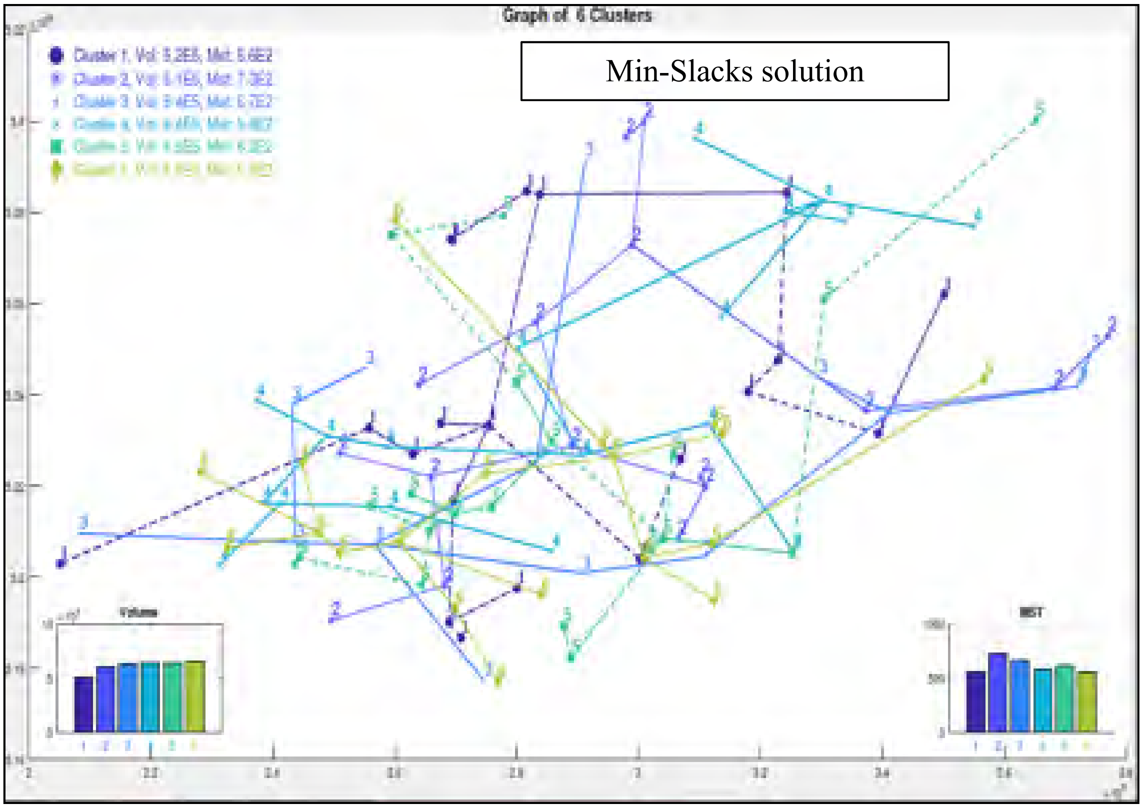


Figure 3.7 Spatial representation of the clusters chosen by Min-Slacks for $h = 6$

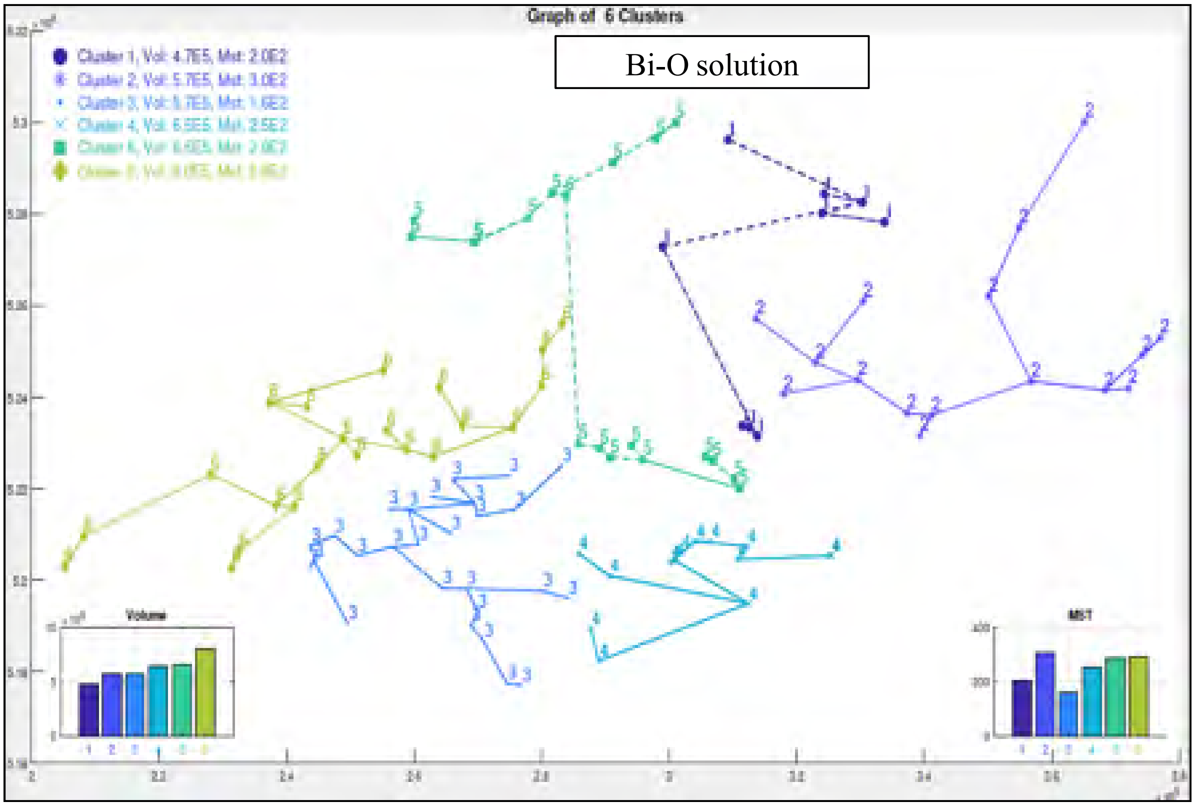


Figure 3.8 Spatial representation of the clusters chosen by Bi-O for $h = 6$

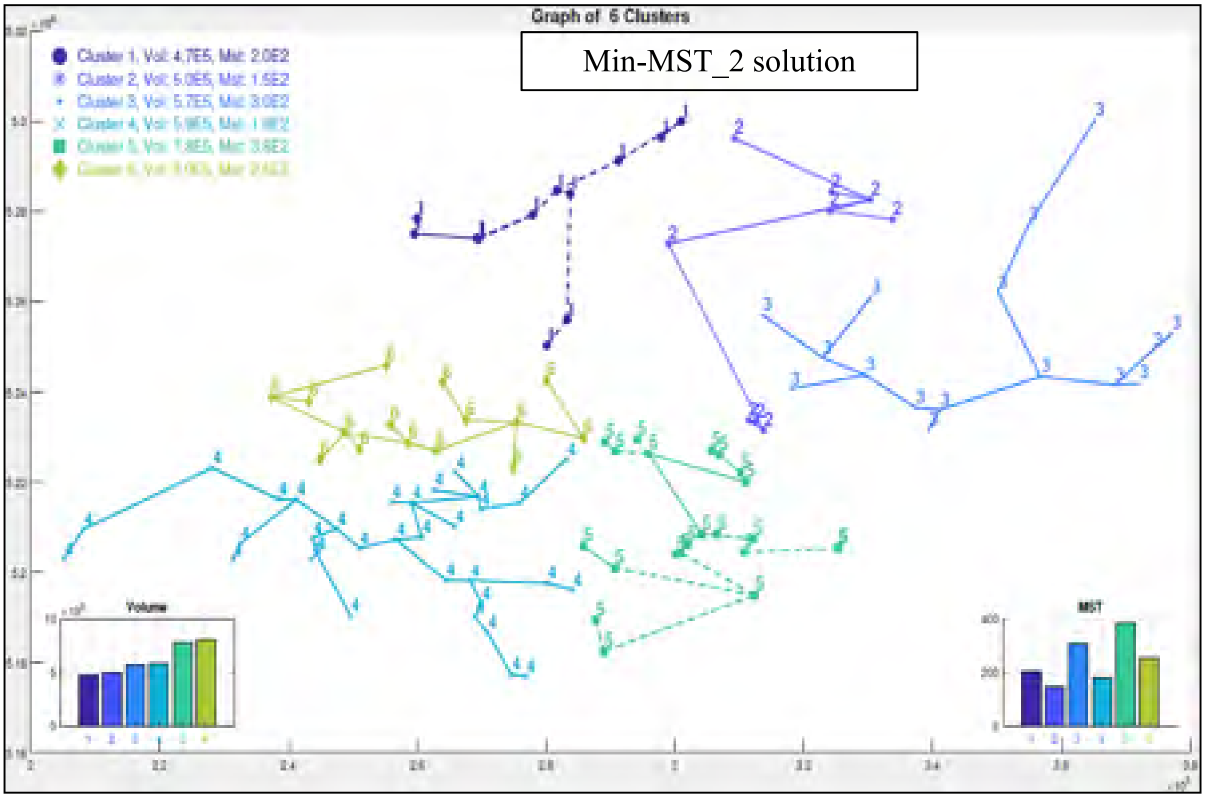


Figure 3.9 Spatial representation of the clusters chosen by Min-MST_2 for $h = 6$

Figures (3.6-3.9) show that both Bi-O and Min-MST_2 very well group the areas together so that the total MST is minimized and hence the spatial dispersion of areas to be harvested by a harvesting team is reduced and controlled. From the computational difficulty perspective, we observed that as the number of harvesting teams increases the Min-Slacks model gets more difficult to be solved to optimality; hence, our recommendation is for large instances of k, the Min-MST_2 be used as it is capable of providing good-quality solutions in a reasonable time.

3.6 Conclusions and future works

In this article, we studied the problem of dividing a given pool of harvest areas in a specific FMU into groups, each group expected to be harvested by a harvesting team working in that territory over a couple of years. Our goal was to do the clustering in such a manner that would promote efficient logistics for the movement of the heavy harvesting machinery between harvest areas for a harvesting team later when the team generates its operational plan. Additionally, the available timber inside the given areas needed to be balanced out among the teams, so that they have an approximately similar overall work load. For this purpose, we adopted the spectral clustering technique to smartly group the harvest areas. This resulted in a large pool of well-grouped alternatives. Then, in order to pick the clusters that would satisfy our goals and restrictions, two MIP set covering models (Bi-O and Min-MST_2) were formulated and compared. The applicability of the spectral clustering approach and the proposed optimization models was demonstrated in a real case study in the province of Quebec. Both models were able to present good-quality solutions for the case. As was reported in Table 3.3 the value of the first objective (f^1, the total MST of all the chosen clusters in km) is very close when comparing the solutions of the two models for each of the three examined scenarios ($h \in \{5,6,7\}$); when comparing the values of the second objective (f^2, the sum of deviation of each chosen cluster's timber volume from the established target) shows that the Bi-O solution provides between 28% to 42% less deviation (better) than the results of the Min-MST_2. In other words, the Bi-O model outperforms Min-MST_2 with respect to equal-distribution of the volume among the teams. That being said, it was noticed that given the fixed number of harvest areas (n) as we increased the number of teams from 5 to 7, solving the Bi-O model (more specifically the Min-Slacks models) became more difficult and took significantly more time; on the other hand the Min-MST_2 model converged to optimality in less than a minute for all tested scenarios. Therefore, based on our observations we could conclude that the Bi-O model and more specifically the Min-Slacks model may act as a liability (i.e. be more difficult to solve to optimality or even not tractable at all) for some combinations of n and h, in such cases we would recommend using Min_MST_2 model as it is able to find practically reasonable solutions in a tractable time.

Moreover, developing an integrated multi-period model to simultaneously control multiple objectives such as the spatial dispersion of harvest areas, procurement cost, average stem size, and average volume per hectare for the problem of selection of harvest areas and allocation of stems to wood-processing mills introduces an interesting path for future work.

Additionally, instead of decomposing the problem into two problems, solution methodologies for solving large size linear problems such as column generation can be adopted to explore all possible clustering enumerations and the result can be compared with the proposed two-phase methodology.

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CONCLUSION

We studied the forest management planning at the tactical level over five-year planning horizon in a multi-period, multi-product and multi-company setting and we developed a decision support tool to cluster the harvest areas in a FMU based on their distance from one another and their available timber volume. According to the new Sustainable Forest Development Act in effect since April 2013 in the province of Quebec the MFFP is responsible for selection of harvest areas and allocation of stems to wood-processing mills operating in the territory of a FMU. It is of great importance to ensure that all resources are being used in a balanced manner in terms of different criteria over longer period of time (i.e. with the least deviation of criteria from their respective target); more specifically the harvest areas with their specific attributes in terms of size, volume, species composition, and average tree size that should be used robustly. Additionally, the harvest teams that work in the region of a FMU usually face the challenging task of moving their harvesting machineries between harvest areas that they are responsible of cutting; these areas could potentially be located very far one another which would lead to high cost and time spent for these movement activities. Through collaboration with both the MFFP and FPInnovations we were able to develop a case study of the FMU Outaouais in western Québec and demonstrated the applicability and benefits of our proposed optimization models.

The thesis has started with the first research question on: What are the planning methods and DSS for tactical decisions in the forest based value creation network since the 1990s that have been published in the literature? What are the most successful DSSs with significant applications? To answer these questions we conducted a review of literature on published articles in the defined scope and presented about 60 methods/DSS regarding what decisions (planning problems) were made, their applications, and the employed solution approach. In addition the trends and gaps in planning methods/DSS, as well as future research directions were provided. Moreover, a generic mathematical model was introduced to illustrate the typical tactical decisions to be made in a value chain.

Afterwards, we have concentrated on second research question about: How can we consider multiple objectives simultaneously while planning for tactical forest management? How could we avoid high grading and ensure a more balanced and economically sustainable use of forest timber? We developed a multi-objective mixed integer nonlinear optimization model to take into account three defined objectives at once. In addition, normalization techniques were adopted to ensure that the three objectives are being treated equally and to avoid cases where one objective dominates the solution, e.g., because of its much larger values. A solution approach to solve the non-linear model was proposed. Testing the model for the developed case study showed that the multi-objective programming outperforms the single-objective cost minimization strategy in using the forest resources in a more balanced manner in terms of the considered objectives ensuring an economically sustainable use of resources.

In the third part of the thesis, we have developed a two-phase approach to answer the following questions: how can a clustering technique be used to effectively reduce the spatial dispersion of harvest areas assigned to a typical harvesting team in a forest management unit? How the spatial dispersion of harvest areas can be modeled? How to choose the most suitable clusters among a large pool of alternatives? First, we generated many alternative clusters of a given set of harvest areas based on their proximity to one another and their available timber volume, and then in order to choose the clusters that would satisfy our goals and restrictions, two set covering models were formulated and compared. The applicability of the spectral clustering approach and the proposed set covering models was demonstrated for the case study in Outaouais.

FUTURE RESEARCH

There are various stakeholders affected and involved in the development and management of the forest-based value creation network: industry, governments, landowners, communities, etc. Each has different and sometimes conflicting goals, for instance, economic performance is no longer the ultimate goal and environmental and social considerations need to be taken into account in the planning process. So in order to have a truly sustainable forest value chain, new DSSs must address the planning problems as multiobjective optimization problems and include interactive planning approaches such as decision theaters to support the coordination and interactions among stakeholders. Also, the Internet and the use of advanced technologies provides the planners with vast amount of data including large spatial data sets, GIS information, ERP systems, ecological information, social and environment-related data sets, government regulations, GPS-based solutions and sensors to track products/machines in real time, and so on. This highlights the value in developing new DSS able to handle and process such information and produce valuable analytical decisions.

Due to many social, economic, biological, and technological factors, consideration of uncertainty in the forest value chain planning is inevitable. Hence, more advanced optimization techniques need to be used in the development of new DSS such as stochastic programming and robust optimization. Additionally, collaboration among the stakeholders has proved to reduce the overall cost, but still there are many issues (e.g., how confidential information should be shared, and what cost allocation schemes should be produced and put into contracts) that must be addressed in order to form successful coalitions and maintain collaboration among the stakeholders.

In short, among the main drivers that will form advances in the new generation of DSS in tactical planning in forest industry are big data and Internet, sustainability, group decision-making by stakeholders, uncertainty, interfirm collaboration, integrated planning, and multidisciplinary research approaches.

In particular, our developed multi-objective tactical forest management model can be expanded by incorporation of additional objectives in the optimization process, for instance the consideration of the spatial dispersion of harvest areas that are being selected to be harvested each year. In addition, the FMUs could be aggregated and the planning get done at the regional level to capture transportation synergies and wood swap opportunities. This may lead to some coordination conflicts among mills and coordination mechanisms must be developed. Moreover, not all the harvest areas are accessible through the existing road network, so roads building and/or upgrading decisions needs to be made according to when a specific harvest area will be harvested and what are the required accessibility conditions. In such context, game theory models could be employed to share the respective cost among the stakeholders.

Additionally, the proposed two-phase approach to cluster harvest areas in a given FMU can be integrated into a multi-period tactical harvest planning model. In the future work also solution methodologies for solving large size linear problems such as column generation could be explored to solved the clustering problem and the results could be compared with the two-step approach that was developed in this project.

APPENDIX

Table A. Data of the harvest areas in the case under study

#	Name	Volume (m^3)	Area (ha)
1	LAC_ROLLAND	$2.47 * 10^3$	25
2	OLLIERES	$3.85 * 10^3$	64
3	GARDNER	$3.92 * 10^3$	47
4	RIDEAU	$4.66 * 10^3$	51
5	GALE_1	$4.86 * 10^3$	119
6	JACINTHE	$6.91 * 10^3$	84
7	LYON	$6.96 * 10^3$	111
8	BAKER	$7.07 * 10^3$	112
9	GABION	$7.11 * 10^3$	72
10	KENNEDY	$7.51 * 10^3$	80
11	LARIVE	$7.66 * 10^3$	79
12	YANKEE_1	$7.69 * 10^3$	94
13	DANEAU	$7.74 * 10^3$	70
14	ATTANA	$8.32 * 10^3$	133
15	PISKARET	$8.55 * 10^3$	93
16	DOROTHE	$9.19 * 10^3$	107
17	FACADE	$9.22 * 10^3$	124
18	CAUTLEY	$9.40 * 10^3$	96
19	DRYSON	$9.52 * 10^3$	91
20	LABAYE	$1.00 * 10^4$	101
21	BARK_1	$1.01 * 10^4$	306
22	ROWE	$1.04 * 10^4$	136
23	VALIN	$1.04 * 10^4$	251
24	STONY	$1.07 * 10^4$	110
25	MCLATCHIE	$1.13 * 10^4$	188
26	LEBEAU	$1.18 * 10^4$	122
27	ROBERT_NORD	$1.19 * 10^4$	212
28	MARGINAL	$1.22 * 10^4$	354
29	CAWATOSE	$1.26 * 10^4$	191
30	DESFOSSILES	$1.27 * 10^4$	140
31	RIDEAU-MALONE	$1.33 * 10^4$	134
32	FABLIER	$1.35 * 10^4$	265
33	RETTY_1	$1.35 * 10^4$	162
34	DRAGEON	$1.36 * 10^4$	154
35	FITZGERALD_2	$1.36 * 10^4$	183

Table A. Data of the harvest areas in the case under study (Continued)

#	Name	Volume (m^3)	Area (ha)
36	PAROI	$1.39 * 10^4$	131
37	CANTUEL	$1.49 * 10^4$	144
38	NOLLET	$1.66 * 10^4$	152
39	NIZARD	$1.68 * 10^4$	217
40	GULL_NORD	$1.73 * 10^4$	145
41	KONDIARONK	$1.77 * 10^4$	322
42	STAMOUR_2	$1.78 * 10^4$	213
43	PINE	$1.97 * 10^4$	201
44	SHOLIAO	$1.98 * 10^4$	323
45	BARK_2	$2.08 * 10^4$	221
46	DEVAY	$2.10 * 10^4$	279
47	SCOLYTES	$2.11 * 10^4$	491
48	RETTY_2	$2.21 * 10^4$	249
49	CANIMINA	$2.24 * 10^4$	270
50	VANSITTARD	$2.27 * 10^4$	210
51	WANEL	$2.28 * 10^4$	274
52	VINCENT	$2.37 * 10^4$	271
53	EDOUARD	$2.51 * 10^4$	273
54	MYON	$2.62 * 10^4$	259
55	GUDANNE	$2.73 * 10^4$	345
56	LEGENDE_2	$2.96 * 10^4$	246
57	TIMBER	$2.98 * 10^4$	554
58	DUMOINE_SUD	$3.00 * 10^4$	265
59	BONDEVAL_1	$3.15 * 10^4$	349
60	POMEROL	$3.15 * 10^4$	380
61	LUSSIER_1	$3.17 * 10^4$	658
62	NEVIN_1	$3.17 * 10^4$	271
63	TOUCHETTE	$3.17 * 10^4$	266
64	BRIQUET_1	$3.18 * 10^4$	340
65	RODIN	$3.18 * 10^4$	349
66	KINGS	$3.30 * 10^4$	525
67	REDAN	$3.67 * 10^4$	433
68	WARREN_2014	$3.79 * 10^4$	334
69	DUMOINE	$3.86 * 10^4$	332
70	CHAUMONT	$4.17 * 10^4$	496
71	LUXEUIL	$4.17 * 10^4$	371

Table A. Data of the harvest areas in the case under study (Continued)

#	Name	Volume (m^3)	Area (ha)
72	TURNER	$4.27 * 10^4$	469
73	MOUSKA	$4.28 * 10^4$	417
74	WARREN	$4.29 * 10^4$	407
75	NICHCOTEA_2	$4.35 * 10^4$	533
76	GEOFFRION	$4.70 * 10^4$	428
77	GALE_2	$4.71 * 10^4$	722
78	PINUS	$4.88 * 10^4$	510
79	ST_AMOUR	$4.88 * 10^4$	417
80	SEAMAN	$4.89 * 10^4$	682
81	CABONGA	$4.98 * 10^4$	598
82	HARCY	$5.02 * 10^4$	569
83	DRIOT	$5.12 * 10^4$	503
84	LUCIE	$5.22 * 10^4$	441
85	GULL_SUD	$5.32 * 10^4$	436
86	ERVIN	$5.57 * 10^4$	833
87	EPINOCHE	$5.62 * 10^4$	568
88	PATRICIA_LIZZIE	$5.68 * 10^4$	552
89	SLOE	$5.71 * 10^4$	582
90	MOUFLON	$5.92 * 10^4$	445
91	OVICELLE	$5.97 * 10^4$	700
92	CENDRILLON	$6.09 * 10^4$	489
93	RAQUETTE	$6.44 * 10^4$	819
94	PICKEREL	$6.57 * 10^4$	639
95	VERNA	$6.57 * 10^4$	1041
96	LEGENDE	$6.76 * 10^4$	617
97	MITELLA	$6.80 * 10^4$	680
98	MITCHELL	$6.95 * 10^4$	894
99	PAGEOT	$6.96 * 10^4$	767
100	LUCIE_NORD	$7.07 * 10^4$	604
101	ECHOUANI	$7.12 * 10^4$	604
102	AKOS	$7.95 * 10^4$	721
103	FESTUBERT	$1.01 * 10^5$	803
104	THALLE	$1.07 * 10^5$	1324
105	LECOINTRE	$1.36 * 10^5$	1534
106	TOOKE	$1.45 * 10^5$	1593
107	SEIGNEURS	$1.76 * 10^5$	1935

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