Exploring wood procurement system agility to improve the forest products industry's competitiveness

Thèse

Shuva Hari Gautam

Doctorat en sciences forestières
Philosophiae Doctor (Ph.D.)

Québec, Canada

Exploring wood procurement system agility to improve the forest products industry’s competitiveness

Thèse

Shuva Hari Gautam

Sous la direction de :

Dr. Luc LeBel, directeur de recherche

Dr. Daniel Beaudoin, codirecteur de recherche

RÉSUMÉ

Les difficultés vécus par l'industrie canadienne des produits forestiers dans la dernière décennie l'ont amené vers une transformation importante. L'innovation dans les produits et les processus est encore nécessaire afin de maximiser la valeur économique des ressources forestières. Cette thèse se concentre sur le les systèmes d'approvisionnement en bois de l'industrie forestière qui est responsable de la récolte et de la livraison des matières premières de la forêt vers les usines. Les entreprises les plus compétitives sont celles qui peuvent fournir les bons produits aux bons clients au bon moment. L'agilité du système d'approvisionnement en bois devient ainsi une des caractéristiques nécessaires à la compétitivité. Les objectifs de la thèse sont d'identifier les possibilités d'améliorer l'agilité du système d'approvisionnement en bois, de quantifier les gains potentiels et de proposer un mécanisme dans le but d'anticiper son impact à long terme. L'agilité est la capacité des systèmes d'approvisionnement en bois à répondre rapidement et efficacement à des fluctuations inattendues de la demande. Premièrement, nous identifions les capacités requises par le système d'approvisionnement en bois qui permettent l'agilité; ensuite, nous examinons la littérature portant sur les systèmes d'approvisionnement en bois pour trouver des signes de ces capacités. Suite à cette étape, une opportunité d'améliorer l'agilité des systèmes d'approvisionnement a été identifiée. Celle-ci implique une plus grande flexibilité dans le choix des traitements sylvicoles au niveau opérationnel afin de mieux aligner l'offre avec la demande. Une expérimentation a été menée en utilisant des données industrielles pour quantifier les avantages potentiels associés à l'approche. Dans les scénarios avec flexibilité permise, des profits significativement plus élevés et des taux plus élevés de satisfaction de la demande ont été observés. Ensuite, un système de simulation-optimisation de la planification hiérarchique a été développé pour étudier l'influence de la flexibilité au niveau opérationnel sur l'approvisionnement en bois à long terme. Le système a été mis en œuvre en utilisant les données hypothétiques d'une forêt du domaine public québécois pour un horizon de 100 ans. Le système développé a permis de mesurer les impacts à courts et à long terme des décisions d'approvisionnement. Il devrait permettre de mieux intégrer les pratiques d'aménagements forestiers avec les besoins de la chaîne d'approvisionnement.

ABSTRACT

The significant downfall experienced by the Canadian forest products industry in the past decade has catalyzed the industry into a process of transformation. A concerted effort to maximize economic value from forest resources through innovation in both products and processes is currently underway. This thesis focuses on process innovation of wood procurement systems (WPS). WPS includes upstream processes and actors in the forest products supply chain, responsible for procuring and delivering raw materials from forests to manufacturing mills. The competitiveness of the industry depends on the agility of WPS to deliver the right product to the right customer at the right time. The specific aims of the thesis are to identify opportunities to improve wood procurement system agility, quantify the potential improvement in performance and propose a mechanism to anticipate its long-term impact. Agility is the ability to respond promptly and effectively to unexpected short-term fluctuation in demand. We first identify the capabilities a WPS needs to possess in order to enable agility; we then review the literature in the WPS domain to search for evidence of these capabilities. An opportunity to improve agility of WPS was then identified. It entailed providing managers with flexibility in the choice of silvicultural treatments at the operational level to permit better alignment of supply with the prevailing demand. An experiment was conducted using industry data to quantify the potential benefits associated with the approach. In scenarios where flexibility was permitted, significantly higher profits and demand fulfillment rates were observed. Next, a simulation-optimization system for hierarchical forest management planning was developed to examine the influence of operational level silvicultural flexibility on long-term wood supply. The system was implemented to a forest management unit in Québec in a rolling planning horizon basis for a 100 year horizon. The system demonstrated a capability to measure short and long-term impacts of supply decisions. It will prove to be a useful tool to better integrate forest management practices and supply chain needs.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

To my parents and my grandmother

ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr. Luc LeBel for his consistent support during the course of my study. His encouragement and high expectations has required me to develop skillsets that will serve me well throughout my career. Through working with him, I have learned the importance of professionalism and rigour in order to make meaningful contributions in the field. I would also like to thank my co-supervisor Dr. Daniel Beaudoin who provided considerable guidance over the years. I am grateful to Dr. Frédéric Raulier, Dr. Jean-Martin Lussier and Dr. Michel Soucy for serving on my thesis committee and providing me with thorough reviews to improve the quality of the thesis. Although not directly involved in my project, Mr. Pierre-Serge Tremblay has been instrumental; access to his vast wealth of knowledge has been invaluable.

I would like to extend my gratitude to staff at FORAC, ForValueNet and CIRRELT. I would like to thank Ms. Catherine Lévesque in particular for her consistent support. I would not have been able to carry out my research without the technical support from Mr. Martin Simard and Sébastien Lemieux. During the course of my study I have been fortunate to have friends, colleagues and mentors with whom I could discuss my ideas. These discussions have allowed me to gain a deeper understanding on various topics pertinent to my research. To this end, I wish to thank Mr. Eric Ntabe, Dr. Elaine Mosconi, Dr. Gregory Paradis, Mr. Ricardo Cantu, Dr. Jean-François Audy, Mr. Matheius Pinnotti, Ms. Shaïma Tilouche, Mr. Baburam Rijal, Dr. Sishir Gautam, Dr. Krish Homagain, Dr. Bharat Shrestha, Dr. Narayan Dhital, Mr. François Morin, Mr. Guillaume Cyr and Dr. David Pelster.

On a more personal note, I wish to thank my friends Kevin Pruys, Todd Yakielashek, Owen Bott, Pete Gammond and Rajieve Sharma for their consistent encouragement and support. I have been blessed to have friends such as Michèle and Jean, and Anna and Jean-Louis, who have made our stay in Québec such a wonderful experience. I wish to thank my roommates Shyam Suwal and Sagar Bhatta. Shyam has been my partner in crime who has inspired me and pushed me to keep moving forward. I wish to thank my entire family for their unconditional love and support. The new arrivals, my nephews and nieces have provided me with a better context, and inspire me to work harder. Finally I wish to thank my wife Dikshya for her patience, love and unwavering support.

PREFACE

The work presented henceforth was conducted under the supervision of Dr. Luc LeBel and it was co-supervised by Dr. Daniel Beaudoin. The financial support for the research was provided by ForValuNet Project (Development of Integrated Forest Management and Wood Manufacturing Decision-Support Systems for a Value-Added Forest Industry), FORAC Research Consortium at Université Laval and Dr. LeBel's NSERC Discovery Grant (# 203193). The main contributions of the thesis are the following three articles of which I am the principal author:

1. Gautam, S., LeBel, L and Beaudoin D. 2013. Agility capabilities in the wood procurement systems: a literature synthesis. International Journal of Forest Engineering, 24(3):216-232. (Thesis Chapter 2)
2. Gautam, S., LeBel, L and Beaudoin D. 2014. Value-adding through silvicultural flexibility: an operational level simulation study. Forestry: An International Journal of Forest Research, 88(2):213-223. (Thesis Chapter 3)
3. Gautam, S., LeBel, L, Beaudoin D. 2014. A simulation-optimization system to anticipate the long-term impact of operational level silvicultural flexibility. To be submitted. (Thesis Chapter 4)

The long-term planning component in the experiment for the third article was carried out in the SilviLab application with support from Mr. Martin Simard, Research Professional at FORAC.

CHAPTER 1: THESIS INTRODUCTION

Forest industry has played an important role in Canada's economic development (Lindsay 2014). Lumber, Pulp and paper have traditionally been the staples of the industry (Wallace 2002). Canada's success over the past several decades can be attributed to the competitive advantages held at the time, mainly due to abundance of superior quality wood, proximity to market, and lesser environmental regulations in today's comparison (Nakamura et al. 2003). Also the fact that the industry was operating in big tracts of lands with large manufacturing mills led to excellence in production efficiency (Hailu and Veeman 2003).

However, the situation has changed markedly over the past decade. Worldwide demand for newsprint has been on the decline since the 1990s (Hurmekoski & Hetemäki 2013). Most experts do not foresee a rebound in this sub-sector. With regards to lumber, the US housing crisis plunged demand below the normal cyclical lows (Bumgardner et al. 2013). Naturally, Canadian export also declined (Figure 1.1) leaving the industry in a turmoil. A large number of mills across the country were forced to shut down leading to significant job losses (Faiola 2008). A closer examination of the situation has identified some key weaknesses in the industry (Mockler and Fairbairn 2009). The main flaws are summarized by the following three points: i) excessive reliance on the US market, ii) focused primarily on producing commodity with lack of diversity in the secondary manufacturing sector, and iii) outdated manufacturing facilities requiring reinvestment.

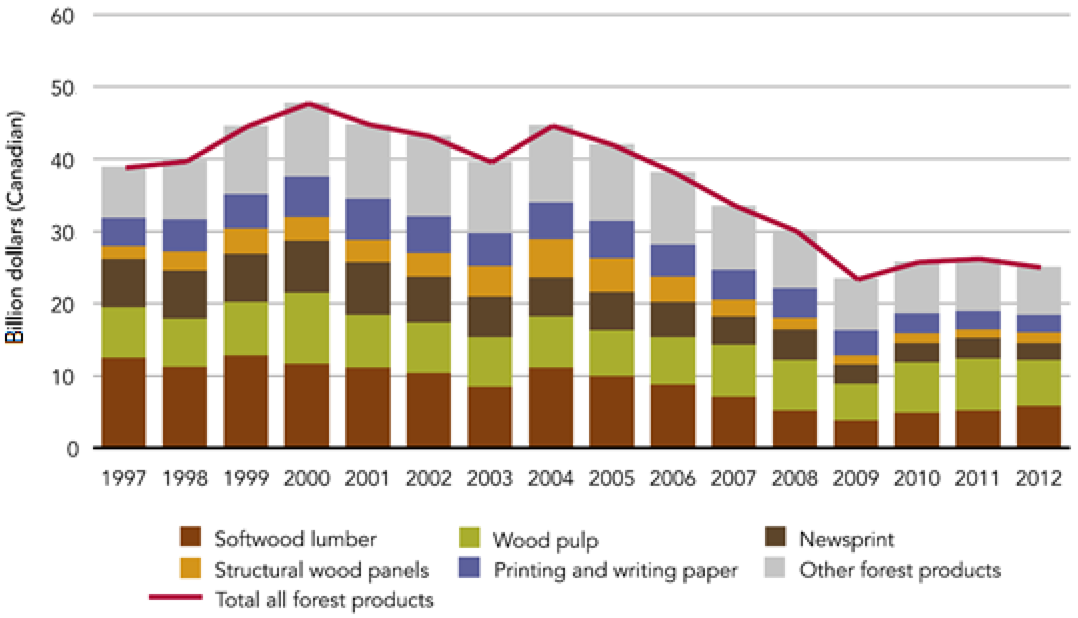

Figure 1.1. Total forest products export from Canada between 1997 and 2012. Source: NRC (2013)

Thus, the Canadian forest industry is currently in the process of transformation (FPAC 2010; Hanna 2010). There is now a concerted effort to enter new markets through innovation (Lindsay 2014). However, product development is only a part of the equation, the industry needs to possess agility to manufacture and deliver these products to customers in a timely fashion (Christopher 2000); a number of studies have demonstrated a strong link between supply chain agility and competitiveness (Vokurka et al. 2002; Li et al. 2008).The proportion of forest products export to the US has diminished (UN 2013). As seen in Figure 1.2, Canada has increased its share to Asia. However, the distance to market increases significantly. Furthermore, new competition is emerging from countries with efficient supply chains supported by short rotation plantations (West 2014). Additionally, the size of the wood basket in Canada is continuing to shrink in response to environmental concerns (Andrew et al. 2014).

Forest management and supply chain activities have to be aligned as much as possible to ensure industry competitiveness in the global market.

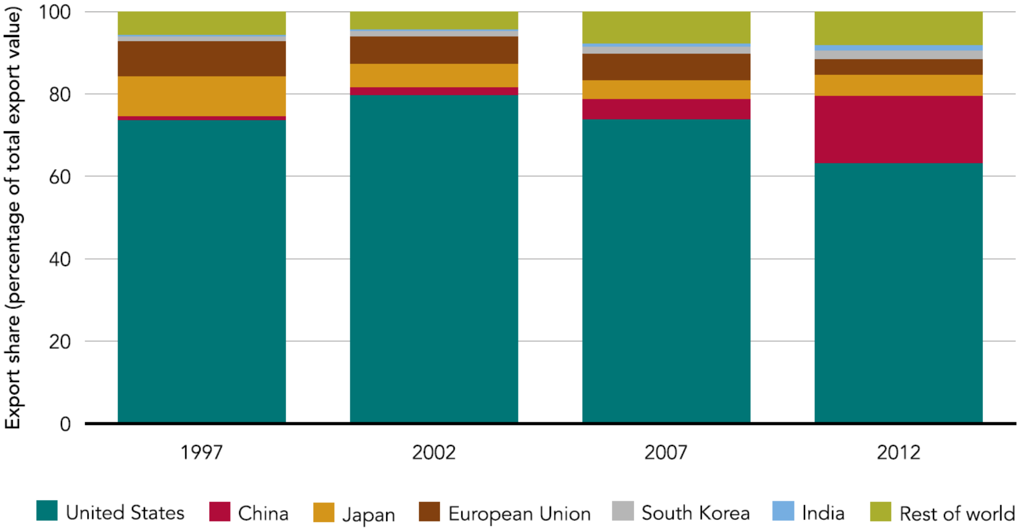

Figure 1.2. Export destination of Canadian wood products between 1997 and 2012.

Source: NRC (2013)

The forest products supply chain encompasses a number of entities that are involved in transforming wood into a product of value to the final customers (D'Amours et al. 2008). The activities involve generic many-to-many processes with multiple firms contributing in the transformation and distribution (Haartveit et al. 2004; D'Amours et al. 2008). The forest products supply chain network, through which the raw material and information flows, is illustrated in Figure 1.3. The focus of the thesis is the area enclosed within the dotted line in the figure; it encompasses an essential component of the of supply chain that is responsible for supplying raw material to support all downstream manufacturing activities. We refer to this region as the wood procurement system (WPS).

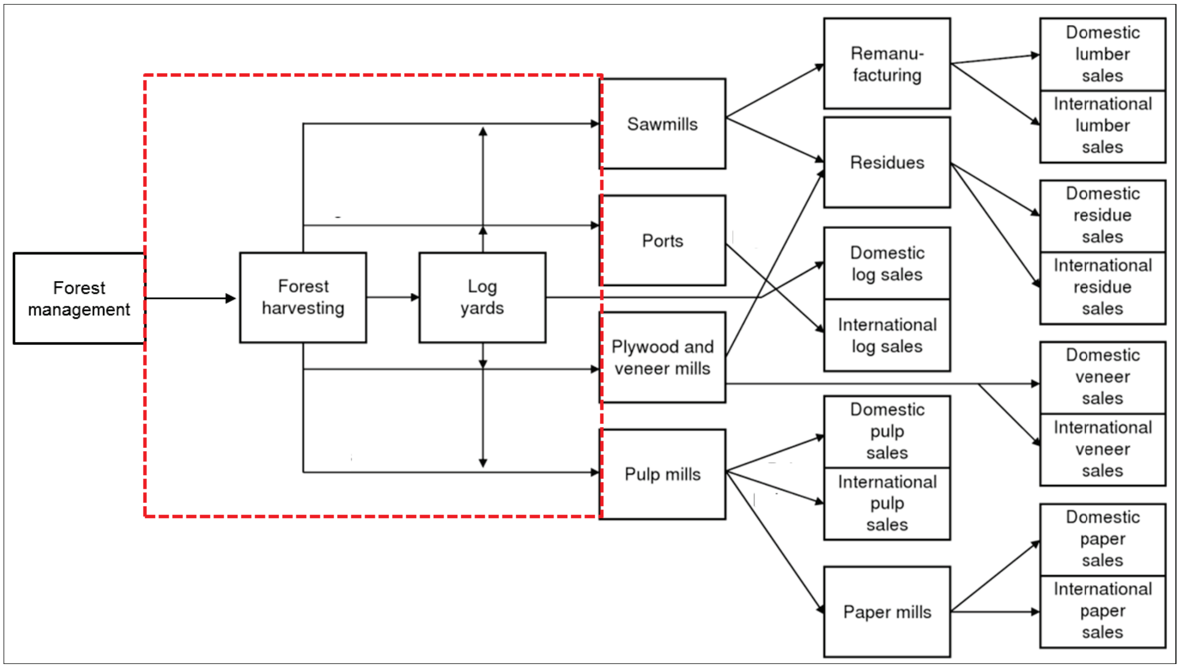

Figure 1.3. An example of forest industry supply chain adopted from Bettinger et al. (2009)

WPS activities are very much influenced by forest management decisions (Bettinger et al. 2009). In fact, it is the outcome of the forest management planning process that determines the quantity and types of raw materials available for the forest products industry. Plans for forest management are generated through a top-down hierarchical approach to better manage the complexity of the problem. The approach entails aggregation and disaggregation of information through the various hierarchies allowing separation of the grand problem into sub problems (Beaudoin et al. 2008). These planning levels can be broadly divided into three stages, strategic, tactical and operational (Weintraub and Cholaky 1991; Bettinger et al. 2009). Strategic plans cover a long time horizon and are generally broad in scope whereas operational plans have shorter time horizon but are much more specific in scope (Church 2007). As such, strategic plan informs the development of tactical forest plan, and tactical plan informs the operational plans.

More specifically, a strategic plan determines the annual allowable cut (AAC) taking into consideration long-term forest productivity, and ecological and social concerns. The volume targets are spatially disaggregated at the tactical level, while incorporating additional economical, ecological and social constraints. The outcome of the process is a tactical plan that is explicit in terms of cutblocks to be treated and silvicultural treatments to be prescribed. The plan is developed ensuring that the total volume harvested in the forest will be within a target range, set at the strategic level. Further down the hierarchy, the WPS receives a list of cutblocks available for harvest. Operational plans are then developed outlining schedules and specific plans of action to meet industrial demand for timber (D'Amours et al. 2008). Subsequently, planning and preparatory work needs to be carried out prior to harvest (Pulkki 2003). The task includes marking cutblock boundaries, building or upgrading access roads, scheduling harvest, and equipment allocation. Upon completion of harvest, transportation of wood has to be planned to fill demand from mills (Epstein et al. 2007). Although this may seem like a straight forward logistics problem, there are a number of factors that significantly increase the complexity. There are inaccuracies associated with inventory in the forest (Thompson et al. 2007). Also, productivity can be unpredictable due to forest ground conditions, and weather factors that dictate operability (Blair 2001; Jeglum 2003; Whitson et al. 2005). This multitude of factors can bring uncertainty regarding raw material, in terms of cost, quantity and assortment types. Thus, WPS are faced with uncertainties in both supply and demand side.

Strict implementation of the top-down hierarchical management approach can be debilitating for the industry in its quest to develop value creation networks which requires prompt response to customer demand. Hierarchical planning can lead to sub-optimality, depending upon the quality of the coordination scheme used to link together the decision levels (Beaudoin et al. 2008; Weintraub and Cholaky 1991). The option of altering plan at the operational level is generally not considered because of its potential impact on the AAC (Gunn 2009). As a result, the responsiveness can be thwarted in the face of volatile market conditions. A certain amount of latitude should be allowed at the operational level to permit the WPS to overcome the uncertainty and satisfy emerging demand in an agile manner. It will then be necessary to develop mechanisms to anticipate the impact of amendments made at the operational level on the long-term AAC. A number of methods are proposed in the literature to bridge the gap between different hierarchical levels (Weintraub and Cholaky 1991; Nelson et al. 1991; Beaudoin et al. 2008; Marinescu and Manness 2010). Anticipating the impact of operational level activities on long-term AAC requires modelling of activities in each of the hierarchies.

1.1. OBJECTIVES & RESEARCH QUESTIONS

The aim of this thesis is to identify opportunities to improve wood procurement system agility, quantify the potential improvements in supply chain performance attributable to exploring the opportunities, and anticipate its long-term impact. The following research questions were constructed to realise the aims:

i. What is the definition of agility in the wood procurement planning context?
ii. What are potential avenues to improve agility in the forest management and the wood procurement system interface?
iii. What are potential improvements in supply chain profits and demand satisfaction rates associated with improved wood procurement system agility?
iv. How should the long-term impact of short-term agile wood procurement strategy be measured?

1.2. CONTRIBUTIONS & THESIS STRUCTURE

In the second chapter of the thesis, we address research questions (i) and (ii). Given that agility is a fairly broad concept, it is important to first define it in the context of WPS. Thus, the first part of the chapter defines the concept in our area of research delineated in Figure 1.3. We then conduct a literature review in the wood procurement system domain to identify opportunities to improve agility. In chapter 3, we address research question (iii) focusing specifically on operational level silvicultural flexibility to improve WPS agility to overcome uncertainty associated with market demand. In fact, the thesis deals only with uncertainty relating to market demand in this chapter and onwards. We conduct an experiment to quantify the benefits associated with operational level silvicultural flexibility. The experiment entailed carrying out operational level planning on a receding planning horizon basis under different scenarios. The approach was tested in a hypothetical case study based on industrial data from Québec. Significant improvement in supply chain performance was observed. Additionally, a range of conditions under which gains could remain feasible were outlined. Chapter 4 addresses research question (iv) by developing a simulation-optimization system to anticipate the impact of exercising operational level silvicultural flexibility on long-term wood supply. The mechanism consisted of a simulation-optimization framework to model the hierarchical planning process. The system was then implemented to a hypothetical case study based on a dataset obtained from the Quebec Ministry of Forests, Wildlife and Parks. Chapters 2, 3 and 4 are self-contained with each comprising of introduction, objectives, materials and methods, results, discussion and conclusion sections. A general conclusion of the thesis and future directions are provided in chapter 5. The main contributions of the thesis are summarized in Figure 1.4.

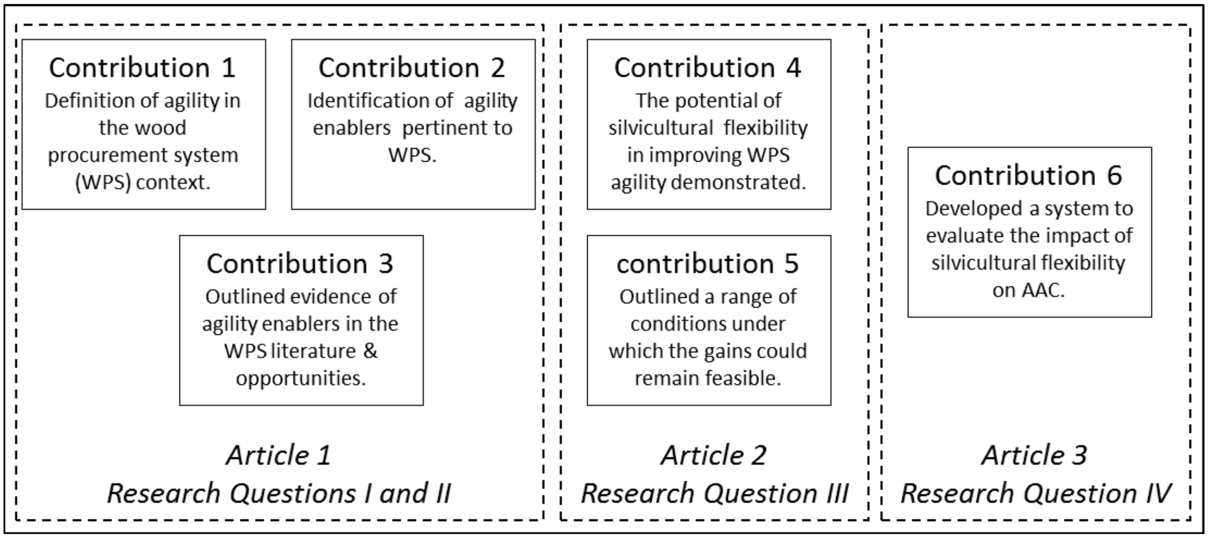

Figure 1.4. Summary of thesis contributions

1.3. LITERATURE CITED

Andrew, M. E., Wulder, M. A., & Cardille, J. A. (2014). Protected areas in boreal Canada: a baseline and considerations for the continued development of a representative and effective reserve network 1. *Environmental Reviews*, *22*(2), 135-160.

Beaudoin, D., Frayret, J. M. and LeBel, L. 2008. Hierarchical Forest Management with Anticipation: an application to tactical-operational planning integration. Canadian Journal of Forest Research 38:2198-2211.

Bettinger, P., Siry, J., Boston, K., & Grebner, Donald L. 2008 *Forest Management and Planning*. Academic Press, 331pp.

Blair, C. (2001). Extending hauling operations on thawing roads by using road-friendly technologies. The International Mountain Logging and 11th Pacific Northwest Skyline Symposium, 152-161.

Bumgardner, M., Johnson, S., Luppold, W., Maplesden, F., & Pepke, E. (2013). Markets and market forces for lumber. In Hansen, E., Panwar, R., & Vlosky, R. (Eds). *The Global Forest Sector: Changes, Practices, and Prospects*. CRC Press.

Christopher, M. (2000). The agile supply chain: competing in volatile markets. *Industrial marketing management*, *29*(1), 37-44.

Church, R. 2007. Tactical-Level Forest Management Models: Bridging between strategic and operational problems. Pages 343-363 *in* A. Weintraub, C. Romero, T. Bjorndal, R. Epstein, eds. Handbook of operations research in in natural resources. Springer.

CWFC. 2010. The Principal Attributes of Canadian Wood Fibre. Canadian Wood Fibre Centre, Natural Resources Canada. Report 22 pp.

D'Amours, S., Rönnqvist, M. and Weintraub, A. 2008. Using Operational Research for Supply Chain Planning in the Forest Products Industry. Canadian Operations Research Society 46(4):265-282.

Epstein, R., Rönnqvist, M., & Weintraub, A. (2007). Forest transportation. In A. Weintraub, C. Romero, T. Bjorndal, R. Epstein, eds. *Handbook Of Operations Research In Natural Resources* (pp. 391-403). Springer US.

Faiola, A. 2008. Canadian Mill Towns Pay For US Housing Collapse. *Washington Post*, February 1 2008. NEWSPAPER ARTICLE

FPAC. 2010. Transforming Canada's Forest Products Industry, Summary of findings from the Future Bio-Pathways Project. Report, Forest Products Association of Canada. 12pp.

Gunn, E. 2009. Some Perspectives on Strategic Forest Management Models and the Forest Products Supply Chain. *INFOR: Information Systems and Operational Research* 47(3): p.261–272.

Gingras J.-F. 1989. Feller-buncher performance in adverse stand and terrain conditions. Technical Report. TR-89 Forest Engineering Research Institute of Canada. 10pp.

Haartveit, E. Y., Kozak, R. A., & Maness, T. C. (2004). Supply chain management mapping for the forest products industry: Three cases from western Canada. *Journal of Forest Products Business Research*, *1*(5), 31.

Hailu, A., & Veeman, T. S. (2003). Comparative analysis of efficiency and productivity growth in Canadian regional boreal logging industries. *Canadian journal of forest research*, *33*(9), 1653-1660.

Hanna, K. 2010. Transition and the need for innovation in Canada's forest sector. Chapter 10. In Mitchell B. Resource and Environmental Management in Canada, Addressing Conflict and Uncertainty. Oxford University Press, Fourth Edition.

Hurmekoski, E., & Hetemäki, L. (2013). Studying the future of the forest sector: Review and implications for long-term outlook studies. *Forest Policy and Economics*, *34*, 17-29.

Jeglum, J.K., Kershaw, H.M., Morris, D.M. and Cameron, D.A. 2003. Best Forestry Practices: A Guide for the Boreal Forest in Ontario. Natural Resources Canada, 117pp

Lindsay, D. 2014. Forest products – Canada's groundbreaking industry. The Forestry Chronicle, 90(3): 269-271.

Marinescu, M. V., & Maness, T. C. (2010). A Hierarchical Timber Allocation Model to Analyze Sustainable Forest Management Decisions. *Mathematical and Computational Forestry & Natural-Resource Sciences (MCFNS)*, 2(2), Pages-117.

Mockler, P. and Fairbairn, J. 2009. The Canadian Forest Sector: Past, present and Future. Interim report of the standing senate committee on agriculture and forestry. www.parl.gc.ca.

Nakamura, M., Nelson, H., & Vertinsky, I. (2003). Cooperative R&D and the Canadian forest products industry. *Managerial and Decision Economics*, *24*(2-3), 147-169.

Nelson, J., Brodie, J. D., & Sessions, J. (1991). Integrating short-term, area-based logging plans with long-term harvest schedules. *Forest Science*, 37(1), 101-122.

NRC. 2013. The State of Canada's Forests, Annual Report 2013. Canadian Forest Service, Natural Resources Canada. 62 pp

Pulkki, R. 2003. Minimizing negative environmental impacts of forest harvesting operations. In P. J. Burton, C. Messier, D. W. Smith, & W. L. Adamowicz (eds) *Towards Sustainable Management of the Boreal Forest*, 581–628. National Research Council of Canada.

Thompson, I. D., Maher, S. C., Rouillard, D. P., Fryxell, J. M., & Baker, J. A. (2007). Accuracy of forest inventory mapping: some implications for boreal forest management. *Forest Ecology and Management*, *252*(1), 208-221.

UN. 2013. Forest Products Annual Market Review 2012-2013. United Nations. 134 pp.

Vokurka, R. J., Zank, G. M., & Lund III, C. M. (2002). Improving competitiveness through supply chain management: a cumulative improvement approach. *Competitiveness Review: An International Business Journal*, *12*(1), 14-25.

Wallace, I. (2002). *A geography of the Canadian economy*. Oxford University Press. 266 pp

Weintraub, A., & Cholaky, A. (1991). A hierarchical approach to forest planning. *Forest Science*, *37*(2), 439-460.

West, P. 2014. Growing Plantation Forests. Berlin: Springer-Verlag. 2nd edition.

Whitson, I. R., Chanasyk, D. S., & Prepas, E. E. (2005). Effect of forest harvest on soil temperature and water storage and movement patterns on Boreal Plain hillslopes. *Journal of Environmental Engineering and Science*, *4*(6), 429-439.

CHAPTER 2. AGILITY CAPABILITIES IN THE WOOD PROCUREMENT SYSTEMS: A LITERATURE SYNTHESIS

Abstract

The capability of a firm to detect changing demands and efficiently respond to them can be described as agility. The past decade has seen a significant rise in the literature on the concept of agility. It has been identified as a requirement to growth and competitiveness. However, a review of the related literature reveals that the concept was scarcely studied in the forest industry context. This study contributes to filling this gap. More specifically, we contextualize agility in wood procurement systems (WPS). WPS includes upstream processes and actors in the forest products supply chain, responsible for procuring and delivering raw materials from the forest to the mill. We first identify the capabilities a WPS needs to possess in order to enable agility. Next, we review the literature in the WPS domain to search for evidence of these capabilities. It was found that aspects of the practices embodied in agility capabilities are already proposed in the WPS literature without explicit reference to agility. However, opportunities to further improve agility of WPS were also identified. It is suggested that future research focus on determining optimal levels of investments towards agility in order to maximize supply chain profits.

Keywords: wood procurement, forest operations, forest products supply chain, agility enablers.

2.1. INTRODUCTION

The key to success in the global market lies in a firm's ability to sustain its competitive advantage and maintain its competitiveness (Porter 1998). Turbulence and volatility has become the norm in today's global marketplace, thus, firms must be able to respond appropriately to the changing market requirements to remain competitive (Crespell et al. 2006; Tokarczyk et al. 2006). Firms need to be agile, not just at the firm level but also at the supply chain level (Christopher 2000). This requires firms to collaborate with and extract from the strengths of their supplier's supplier and customer's customer and streamline operations (Lin et al. 2006). Competing as a supply chain allows a firm to realise a level of agility that is not achievable by individual firms (Christopher et al. 2001). This is especially true for the forest products supply chains that are characterized by their variability and complexity. They include government agencies, non-governmental organisations, environmental groups, and community stakeholders that all have an influence on the global production system (Vahid et al. 2010).

In the early stages of the forest supply chain a management plan is prepared that details the location of eligible harvest areas (Tittler et al. 2011). Subsequently, procurement plans are prepared to provide the wood procurement system (WPS) with raw materials (Bettinger et al. 2008). The WPS links forest with markets; the activities of the system include identifying harvest blocks, scheduling harvesting activities, harvesting, bucking the logs into different specifications, sorting the logs, managing inventory and finally transporting products to different industrial systems (Grebner et al. 2005; Uusitalo 2005; Audy et al. 2012). Decision-making at each stage entails selecting from a range of options. For example, harvesting can be conducted using different systems; transportation can be carried out using various truck-trailer configurations and transportation modes. Bucking, the process of cutting tree stems into merchantable logs, can be done in infinite number of ways. Industrial systems include mills that produce sawn lumber, pulp and paper, engineered wood products and other small-scale value added manufacturers (Grebner et al. 2005; D'Amours et al. 2008). Decisions at different stages of the WPS have a significant impact on the downstream supply chain processes. It is likely that certain options enhance agility in the wood procurement system while others enhance efficiency; efficiency implies a focus on cost reduction and productivity as done in mass production, such a strategy is effective in situations with stable market conditions with low product variety (van Hoek et al. 2001). Agility on the other hand also implies cost reduction but it is not the main focus, customer satisfaction is the primary goal (Christopher et al. 2001).

In spite of the importance of agility in the WPS, a literature search for the term in the domain in scientific journals indexed by the Web of Science research platform yielded no results. A sole report exists prepared by Audy et al. (2012) that evaluates the agility capabilities of various wood supply chains. This study aims to contextualize the concept of agility to WPS and analyse the literature with an objective to identify opportunities to improve agility of WPS.

The rest of the paper is structured as follows: the methods are outlined in section 2 followed by results in section 3. Finally, a summary of key findings and a general conclusion is presented in Section 4.

2.2. METHODS

The research approach depicted in Figure 2.1 was employed to realise the aims of the study. In stage 1, the concept of agility was defined in the WPS context through a review of scientific literature. Stage 2 entailed identifying WPS agility enablers; these are practices, methods and tools that improve agility of the supply chain. In stage 3, literature in the WPS domain was searched for evidence of agility enablers. Finally, in stage 4, the key findings were summarized and potential avenues to improving agility of the WPS were outlined.

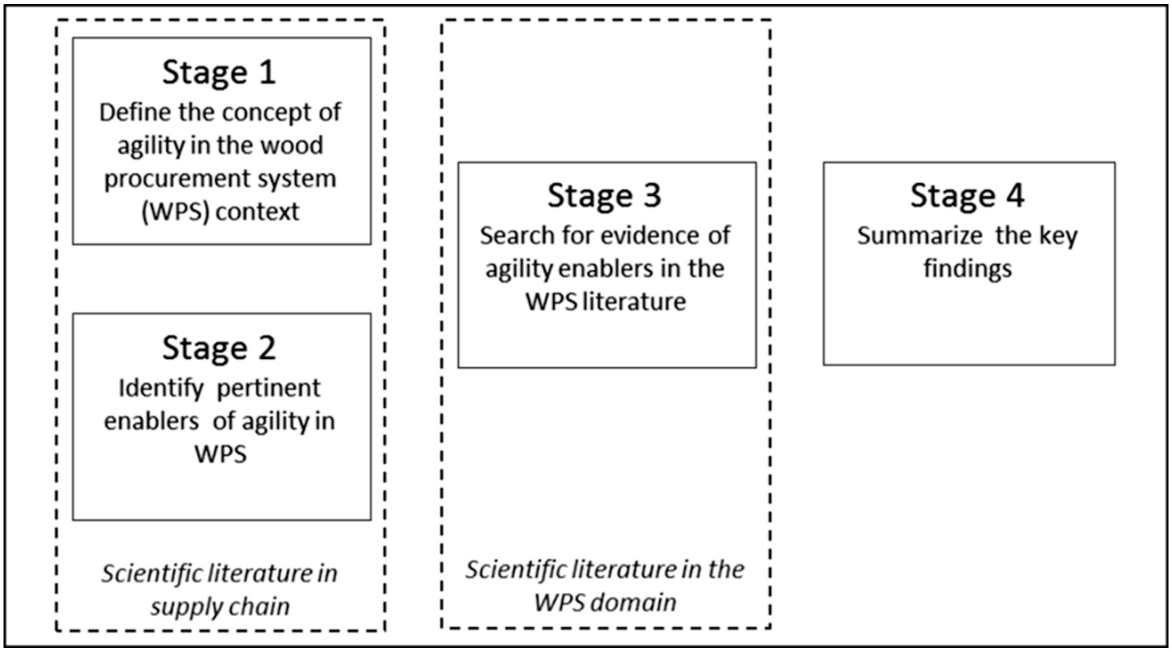

Figure 2.1. An overview of the research approach.

Candidates for literature reviews at stages 1 and 2 were identified using Web of Science database and Google Scholar. The following keywords were used without restriction on the time period: Agility, agile supply chain, supply chain agility. Pertinence of each article was determined by first scanning the title, then reading the abstracts, and finally through a cursory glance of the article. Documents that have cited the qualified articles and their references were also searched to locate additional resources. Two criteria were used to select the pertinent articles for inclusion in this review: 1) the concept of agility was discussed in a supply chain context, and 2) the paper proposed a definition for agility. A total of 11 articles were located through this process to develop a definition of agility and additional 32 articles were reviewed for supplemental information on supply chain agility. At the completion of stage 2, five enablers for WPS agility were established.

The subsequent review at stage 3 entailed searching for evidence of the five enablers identified in stage 2, in the WPS literature. The review was conducted using the same method outlined for the stages 1 and 2, however, using keywords “forest supply chain” and “wood supply system” along with the title of each enabler. The first criteria for selecting the literature was that only peer reviewed articles published in scientific journals would be considered for the core analysis to ensure quality and acceptance from the academic community. In certain cases, however, book chapters were used as supporting evidence to core findings. For the category logistics management, three additional key words, harvesting system, transportation system and inventory, were used for the search.

2.3. RESULTS

2.3.1. Defining agility

Agility as a business concept was popularised with the publication of "21st Century Manufacturing Enterprise Strategy" by a group of scholars at Iaccoca Institute of Lehigh University, USA in 1991 (Yusuf et al. 1999; Gunasekaran 2001; Li et al. 2008). The concept was targeted for application to the manufacturing sector, subsequently numerous publications on agile manufacturing started emerging (Kidd 1995; Goldman et al. 1995; DeVor et al. 1997; Yusuf et al. 1999; Sharifi et al. 1999). The concept was eventually applied to the supply chain context (Christopher 2000; van Hoek et al. 2001; Christopher et al. 2001) and successful application in various industries have been reported since (Christopher et al. 2002; Stratton et al. 2003; Collin et al. 2006).

Agility has been defined as, "a business-wide capability that embraces organizational structures, information systems, logistics processes, and, in particular mindsets"(Christopher 2000). Some characteristics a supply chain must possess in order to become agile based on a model originally developed by Harrison et al. (1999) are: 1) market sensitiveness, which refers to capability of the supply chain in reading and responding to real demand, 2) virtual, referring to the extent of use of information technology to connect with suppliers and customers, 3) process integration between suppliers and customers to manufacture or develop products and 4) network based, implying the entire supply chain operating as a unit to achieve market responsiveness. Sharifi & Zhang (1999) provide a conceptual model for achieving agility; the model contains three parts: agility drivers, agility capabilities and agility enablers (Figure 2.2). Agility drivers are the factors in business environment that drive companies to change their strategies and reconstruct it to become agile. Identification of the drivers helps determine the required level of agility and also establish capabilities necessary to become agile in the changing business environment. Capabilities are the essential headlines of abilities required by a supply chain to respond to the changes. These capabilities are achieved through agility enablers which are practices, methods and tools applied at various supply chain processes.

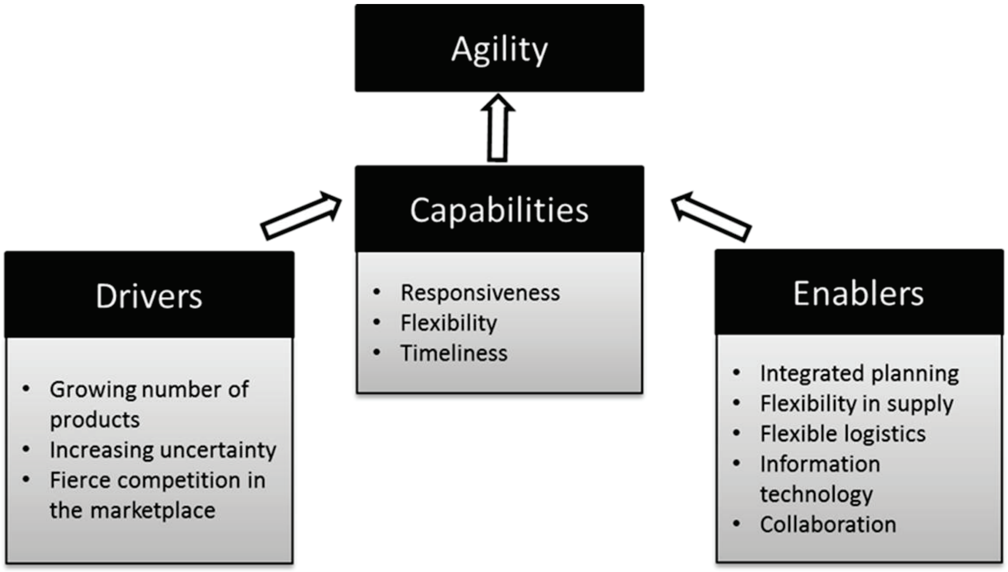

Figure 2.2. A conceptual model of agility adopted from Sharifi & Zhang (1999).

The diversity in the proposed definitions demonstrates that a consensus has not yet been established (Table 2.1). There are some commonalities and differences; response capability is generally deemed essential however, the alertness dimension is absent in some of the definitions. The variation in the definitions is not surprising given that a supply chain includes a wide range of entities (Shapiro 2001) and agility can be leveraged from different sources

(Sambamurthy et al. 2003). In the next paragraph, existing definitions are explored and the pertinent capabilities are extracted to formulate a definition as it applies to the scope of this study.

According to Swafford et al. (2006) supply chain agility is a function of flexibility; more specifically, flexibility is an antecedent of agility. Flexibility is a function of range and adaptability, where range is the number of different states or different processes that can be exercised in the supply chain given existing resources while adaptability is the ability to change from one state to another state in a timely and cost effective manner.

While Swafford et al. (2006) have incorporated speed of response into the flexibility capability, Prater et al. (2001), Li et al. (2008), Lin et al. (2006) and Sharifi & Zhang, (1999) have viewed speed as a separate capability. They have been referred to synonymously using the following terms: quickness and timeliness. Sharifi and Zhang (1999) and Lin et al. (2006) define it as the ability to complete a task as quickly as possible. However Li et al. (2008) argue that the emphasis should be on ability to deliver value at an appropriate time rather than as quick as possible, thus shifting the focus away from quickness to the right time as in just-in-time. The goal is to reduce the lead-time to a level that does not negate customer satisfaction.

Table 2.1. Supply chain agility definitions and capabilities from various sources.

Source	Definition	Capabilities	Explanation
Sharifi and Zhang (1999)	The ability to cope with unexpected changes, to survive unprecedented threats of business environment, and to take advantage of changes as opportunities.	Responsiveness	Ability to identify changes and respond fast to them, reactively or proactively, and recover from them. It is a factor of sensing/anticipating, reaction to and recovering from change.
		Competency	The extensive set of abilities that provide productivity, efficiency and effectiveness of activities towards the aims and goals of the company.
		Flexibility	Ability to process different product and achieve different objectives with the same facilities. It is a function of flexibility in volume, model/configuration, organisation and people.
		Quickness	Ability to carry out tasks and operations in the shortest possible time. It includes products and services delivery time, operations time and now products time to market.
Prater et al. (2001)	The degree to which a firm's supply chain is agile is determined by how its physical components (i.e sourcing, manufacturing and delivery) are configured to incorporate speed and flexibility.	Speed	Measure of time it takes to ship or receive a good.
		Flexibility	The promptness with and the degree to which a firm can adjust its supply chain speed, destinations, and volumes
Swafford et al. (2006)	The supply chain's capability to adapt or respond in a speedy manner to a changing marketplace environment.	Flexibility	Flexibility is a function of range and adaptability. Range is the number of different states (levels, positions, or options) that can be achieved with existing resources. Adaptability is the ability to change from one state to another state in a timely and cost effective manner.
Lin et al. (2006)	Ability of a supply chain to rapidly respond to changes in market and customer demands (adopted from Sharp et al. 1999)	Responsiveness	The ability to identify changes and respond to them quickly, reactively or proactively, and also to recover from them.
		Competency	The ability to efficiently and effectively realize enterprise objectives.
		Flexibility/ Adaptability	The ability to implement different processes and apply different facilities to achieve the same goals.
		Quickness/ Speed	The ability to complete and activity as quickly as possible
Li et al. (2008)	Agility is the result of integrating an alertness to changes (opportunities/challenges)- both internal and environmental- with a capability to use resources in responding (proactively/reactively) to such changes, all in a timely, and flexible manner.	Alertness	Defined using two dimensions: strategic foresight and systematic insight (adopted from Sambamurthy et al. 2003).
		Responsiveness	Defined using four dimensions: value evaluation, coordination, learning and reconfiguration.
		Flexibility	The range of ways to achieve success. An active capacity and willingness to recognize new options, to overcome inertia, and to accommodate unanticipated change.
		Timeliness	Delivery of value at an appropriate time.
Charles et al. (2010)	The ability to respond quickly and adequately to short-term changes in demand, supply or the environment.	Flexibility	Ability to change or react with little time, effort cost or performance. It is a function of flexibility in volume, delivery, mix and product.
		Responsiveness	Ability to respond to change within an appropriate time frame. It is a function of reactivity, velocity and visibility.
		Effectiveness	Doing all the right things. It is a function of reliability (doing all the right things) and completeness (doing all).

In addition to flexibility and speed capabilities, responsiveness (Charles et al., 2010; Li et al., 2008; Lin et al., 2006; Sharifi & Zhang, 1999), competency (Sharifi et al. 1999; Lin et al. 2006) and effectiveness (Charles et al. 2010) have been identified as other capabilities of an agile supply chain. First off, competence is the ability to sustain the coordinated deployment of assets in ways that help a firm achieve its goals (Sanchez et al. 1996) and effectiveness is defined as being able to do all the right things to realize all goals (Charles et al. 2010); despite being termed differently, their essence is the same. Secondly, we argue that rather than competence or effectiveness being an independent capability of agility, it is an underlying theme of responsiveness. Responsiveness is the ability to coordinate and reconfigure in order to respond effectively to information derived from market sensing (Sharifi et al. 1999). Competence is required to evaluate and coordinate different technologies and production skills in order to allow business to respond to changing opportunities in a timely fashion.

Continuing on with the response capability, while most authors (Sharifi et al. 1999; Lin et al. 2006; Charles et al. 2010) have recognized alertness as being part of the response capability, Li et al. (2008) recognize alertness as a separate capability. Alertness is an important capability because agility requires outside focus to identify changes in the external environment (Christopher 2000). However, since our study has a supply side focus, strict market forecasting is outside its scope. Thus we are focused more on the internal capabilities to respond to the changes occurring in the outside environment. Nevertheless, it is essential to possess a capability to incorporate information derived from market sensing at a different point in the supply chain and respond to it. The responsiveness capability as defined by Sharifi and Zhang (1999), Lin et al. (2006) and Charles et al. (2010) ensure the information derived from alertness capabilities is incorporated in the response.

In addition to the capabilities, there are other features to the existing definitions that need to be acknowledged in formulating a definition for agility. Charles et al. (2010) define supply chain agility as, “the ability to respond quickly and adequately to short-term changes in demand, supply or the environment”. The interesting aspect of this definition is that they put an emphasis on “short-term” and is similar to the definition proposed by Lee (2004) which is, “respond to short-term changes in demand or supply quickly”. Longer term structural changes in the market should be overcome with adaptation strategies or transformation of supply chain (McCullen et al. 2006). In addition, Prater et al. (2001) and Swafford et al. (2006) state that the capabilities identified earlier need to be inherent in each of the supply chain processes, i.e, sourcing, manufacturing and delivery. Li et al. (2008) argue that the capabilities need to be inherent not only to the supply chain processes but also at the different management hierarchies which they term as the level of work-design. It is implied that supply chain agility is the result of interplay of decisions made at various planning hierarchies, i.e. strategic, tactical and operational.

Thus in the context of our study, we define supply chain agility as the ability of wood procurement systems to respond promptly and effectively to unexpected short-term fluctuation in the demand. It is a function of the following capabilities: flexibility, responsiveness and timeliness. These capabilities are leveraged from practices, methods and tools implemented at various wood procurement phases.

It is important to distinguish the term agility from other similar terms such as adaptability and resilience. Adaptability differs from agility on a time scale; agility is the capability to respond to short-term fluctuations in demand, but if there are structural, permanent changes in the market, the supply chain needs to realign their internal functions to adapt to the new conditions (McCullen et al. 2006). Resilience is a term reserved for calamities, it is a supply chain's ability to rebound to its original state after a disturbance, as opposed to agility's opportunistic nature (Christopher et al. 2004).

2.3.2. Identifying WPS agility enablers

A list of enablers proposed in the literature, including those in Gunasekaran (1998), Agarwal et al. (2007) and Faisal et al. (2007) were compiled to extrapolate enablers pertinent to the scope of this study. It was observed that there is ambiguity and in some cases overlap in the enablers. Consequently, the next step entailed grouping the enablers into categories to remove redundancy and defining the scope for each to eliminate ambiguity. They were assessed one at a time, enablers with no pertinence to the WPS were removed, and closely related enablers were grouped into a category. In this manner, the following categories of enablers were generated: flexible supply, flexible logistics, integrated planning, collaboration, and information technology. The enablers are illustrated in Figure 2.3 with their associated supply chain processes; each of the enablers can be applied to the linked processes to improve agility. We adopt processes outlined in the Supply Chain Operations Reference (SCOR®) model: plan, source, make, deliver and return (SCC 2010). The return process was however eliminated because it is not a common practice to return raw materials from mills back to the forest in the WPS. The enabler integrated planning relates specifically to the planning process, flexible supply concerns specifically with sourcing, and flexible logistics relates to the make and deliver processes. The remaining two enablers on the left hand side of the figure, collaboration and information technology can be applied to all processes of the WPS.

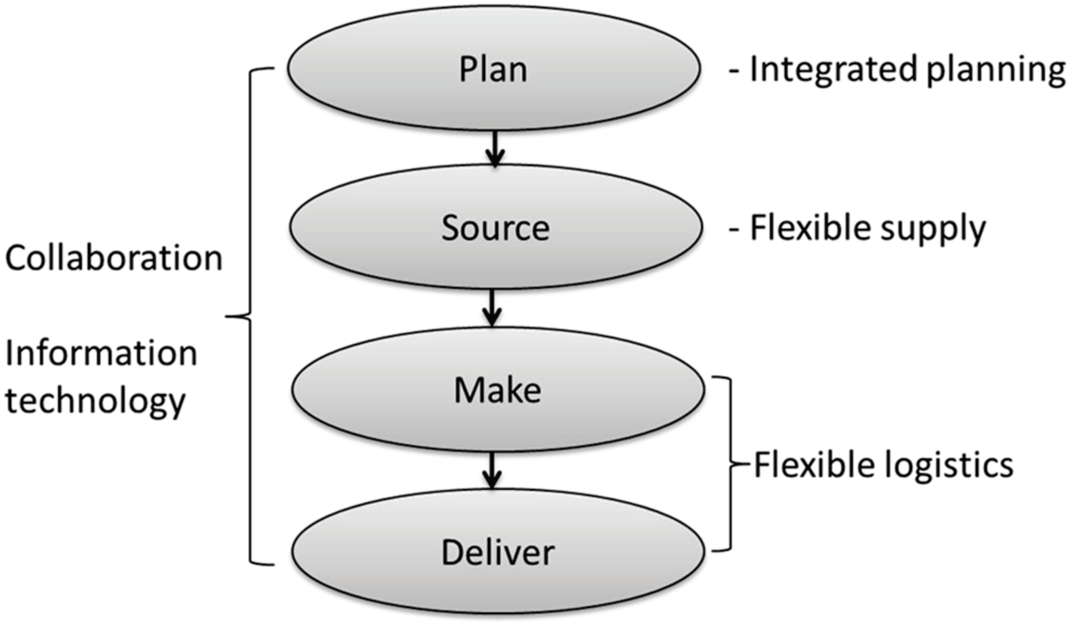

Figure 2.3. Agility enablers of a wood procurement system and associated supply chain processes.

First, we discuss the enabler flexible supply; there is a strong relationship between the capabilities of supplier base and supply chain agility. This phase of the supply chain is responsible for fulfilling material requirements of the downstream processes (Swafford et al. 2006). Flexibility in supply influences the capability of a supply chain to meet changing market demand (Hahn et al. 1990; Narasimhan et al. 1999). According to Masson et al. (2007) an effective method to increase agility is through maintaining access to large network of suppliers. Studies also report that improved supplier and manufacturer partnership increase flexibility (Clark et al. 1989; Dyer 1996). The next enabler, flexible logistics deals with issues concerning procurement activities, material handling, inventory and transportation management for order fulfillment (Mentzer et al. 2000). A dependable logistics system is an important requirement of an agile supply chain (Lee 2004). Significant reduction in lead-times can be obtained through improved logistics systems. Agarwal et al. (2007) proposes reducing lead-times using supply chain mapping and focusing on material flow bottle necks. Lee (2004) recommends building inventory buffers of key but inexpensive components in strategic locations to increase agility.

The enabler integrated planning relates to planning of activities to respond effectively and efficiently to market demand. Planning is critical to achieving the goal of increasing the level of supply chain agility (Power et al. 2001); an integrated approach can reduce lead-times and improve efficiency and responsiveness (Agarwal et al. 2007). Integrated planning may lead to an increase in the global benefit for the supply chain but benefits to individual partners can only be realised through collaboration between supply chain partners (Frisk et al. 2010; Masson et al. 2007). Thus, the next enabler focuses on developing collaborative relationships with supply chain partners. Collaboration amongst supply chain partners has been identified as a key strategy to enabling agility (Christopher 2000; Power et al. 2001; Lee 2004; Agarwal et al. 2007). Collaboration presents supply chain partners opportunity for process integration which is a key characteristic of an agile supply chain (Christopher 2000).

The final enabler concerns with utilizing information technology as a means to gather and share information amongst supply chain partners. The effectiveness of integrated planning and collaboration depends on the quality of information in hand (Yusuf et al. 1999). Transparent information flow between supply chain partners improves agility performance (Katayama et al. 1999; Mondragon et al. 2004; Lee 2004; McCullen et al. 2006). Investment in information technology enables supply chain partners to efficiently coordinate supply chain activities (Sambamurthy et al. 2003).

2.3.3. Evidence of agility enablers in the WPS literature

Findings from the literature review conducted to identify evidence of agility enablers in the WPS literature are discussed below (also see Table 2.2); this is not an exhaustive list of evidences.

2.3.3.1. Flexibility in Supply

Raw material supply in the forest industry can be procured from either private or public forests. To achieve flexibility in supply while working with private landowners, a good working relationship with suppliers of different mix of products have to be developed (Helstad 2006), ownership objectives have to understood (Kuuluvainen et al. 1996), and appropriate type of contracts have to be in place (Björheden et al. 2005).

Table 2.2. Wood procurement system literature with pertinence to agility.

Enabler	Study	Description	Source Country
Flexibility in Supply	Andreassen and Øyen (2002)	Assess financial feasibility of alternative silvicultural treatments	Norway
	Gunn (2009)	To include market information in strategic planning	Canada
	Hanewinkel and Pretzsch (2000)	Explore methods to implement flexible silviculture systems	Germany
	Liu et al. (2007)	Assess financial feasibility of alternative silvicultural treatments	Canada
	Lussier (2009)	To implement a market focused procurement plan	Canada
	Moore et al. (2012)	Assess financial feasibility of alternative silvicultural treatments	Canada
	Pukkala et al. (2010)	Assess financial feasibility of alternative silvicultural treatments	Finland
Logistics	Adebayo et al. (2007)	To determine factors affecting cost and productivity of different harvest systems	Canada
	Andersson and Eliasson (2004)	Comparison of harvesting systems to determine suitability under different scenarios	Sweden
	Bradley (2006)	Leveraging agility through transportation systems	Canada
	Broad (1989)	Procedure to identify the efficient placement of a sort yard	New Zealand
	Brown and Sessions (1999)	Application of variable tire pressure system to improve accessibility for transportation	North America
	Cass et al. (2009)	Method to determine the marginal cost and productivity impact of product sorting.	USA
	Erdle et al. (1981)	To determine the optimal level of inventory at different locations	Canada
	Galbraith and Meng (1981)	Determine the optimum level of inventory through simulation	Canada
	Greene et al. (1997)	Implications of varying harvest block sizes and harvesting systems on profitability	USA
	Han et al. (2011)	Financial feasibility analysis of a log sort yard	USA
	Kärhä (2006)	Comparison of harvesting systems to determine suitability under different scenarios	Finland
	LeBel and Carruth (1997)	Determine the optimum level of inventory through simulation between harvest and transportation phase	USA
	Sessions and Parades (1987)	Procedure to identify the efficient placement of a sort yard	USA
	Sibal et al. (1984)	Evaluated the economic impact of different sorting systems	USA
	Simmons (1947)	Review of equipment utilized in forest operations	USA
Integrated Planning	Beaudoin et al. (2008)	Ensuring feasibility of plans at the operational phase through anticipation mechanism	Canada
	Bredström et al. (2010)	Decision on harvesting and scheduling integrated	Sweden
	Carlgreen et al. (2006)	Integrating sorting and transportation decisions	Sweden
	Chauhan et al. (2011)	Anticipation function to synchronize procurement planning and bucking	Canada
	Epstein et al. (1999)	Integrated plan for harvesting and bucking	Chile
	Karlsson et al. (2004)	Integrated planning of harvesting and crew assignment	Sweden
Collaboration	Audy et al. (2012a)	Explore business models to build and manage collaboration between firms for wood transportation.	Sweden
	Beaudoin et al. (2010)	Propose negotiation approaches to develop wood procurement plans in multi-firm setting	Canada
	Hof and Field (1987)	Discusses various methods to benefit sharing during collaboration	USA
	Frisk et al. (2010)	Collaboration in tactical transportation planning between forest companies	Sweden
	Palander and Väätäinen (2005)	Collaboration between industries to minimize empty travel during transportation	Finland
Information Technology	Bergstörm et al. (2000)	Use of GIS to support decision on new roads to be built	Sweden
	Devlin et al. (2008)	Use of GPS to improve transportation logistics	Ireland
	Dykstra et al. (2003)	Summary of log tracking technologies	North America
	Goychuck et al. (2011)	Technology to monitor and predict machine productivity	USA
	McDonald and Fulton (2005)	Automating productivity studies using GPS	USA
	Maltamo et al. (2005)	Potential of LIDAR for collecting accurate forest inventory data	Finland
	Murphy and Franich (2004)	Technology for log tracking is explored	USA
	Uusitalo et al. (2004)	Use of automatic bucking technology in harvesters	Finland

Working in public forests poses a different set of challenges to achieve flexibility in supply. Supply for a WPS is established in a forest management plan which is generally prepared using a top-down hierarchical approach (Bettinger et al. 2008); top-down hierarchical approach implies disaggregating long-term and short term plans with the short term plans being constrained by long-term plan. The objective of the forest management plan is to safeguard the integrity of forest thus ensuring ecological sustainability in the long term. Proceeding through the hierarchies, an annual plan describing harvest activities for the upcoming year is prepared (Tittler et al. 2011). Supply chain activities are subsequently planned around the harvest blocks allocated and silvicultural treatments prescribed in the forest management plan. During the preparation of the plan, the focus is on volume, with a hap-hazard effort to match raw material with demand (Gunn 2009). Regardless, the flexibility of supply is generally limited to the number of harvest blocks allocated for the particular year. Gunn (2009) argues that a different set of harvest blocks that better match the market demands will also be feasible at the strategic planning level whilst meeting sustainability objectives. Alternatively, Lussier (2011) demonstrates that silvicultural treatment in a harvest block can be used as a tool to improve profitability while meeting ecological objectives. Thus it can be hypothesized that flexibility in silvicultural treatments and postponement of allocation decisions until accurate demand information is available can improve response capability of a WPS.

Silvicultural treatments determine the quantity, species and in some instances the quality of wood that can be harvested from the forest stands to supply the WPS (Macdonald 1995). Smith et al. (1997) provide a good description on the subject. Profitability of a silvicultural treatment in a harvest block depends on the prevalent market conditions (Davis et al. 2001; Moore et al. 2012). Harvest blocks consist of a wide array of wood assortments suitable for different final products, and harvesting without knowledge of the market would generate large volumes of inventory that has to be managed until demand arises in the market. This high level of inventory in the supply chain can lead to significant rise in the inventory cost, furthermore, wood being a biological matter, it can decay while in inventory leading to a net loss. Flexibility in silvicultural treatments and postponement of allocation decisions would enable practitioners to better match demand with the right raw materials whilst reducing inventory. A number of silvicultural treatments can be financially feasible for a single harvest block (Howard et al. 1997; Liu et al. 2007; Moore et al. 2012; Wikström 2000; Andreassen et al. 2002; Pukkala et al. 2010; Laiho et al. 2011).

2.3.3.2. Logistics

In WPS, logistics includes management of harvesting systems, transportation systems and inventory strategies. Harvesting system refers to the combination of equipment used to fell, delimb and skid trees to roadside (Pulkki 2003). The most prevalent mechanized harvest systems in use are full-tree-system and cut-to-length (CTL) system. Visser and Stampfer (2003), Jirousek et al. (2007), Kellogg and Bettinger (1994) and Pulkki (2003) provide descriptions of equipment employed under each system. The full tree system is suited for harvesting large patches of land where its production is high (Adebayo et al. 2007) leading to higher cost efficiency (Hartsough et al. 1997; Yaoxiang et al. 2006). In situations with smaller, fragmented harvest blocks that is characteristic of partial cutting scenarios, CTL system may be more suitable because of lower relocation time, setup time and relocation costs due to fewer equipment (Cubbage 1983; Greene et al. 1997). A system that offers even lower moving and setup time and relocation costs is the harwarder system (Talbot et al. 2003; Andersson et al. 2004). In comparing the harwarder system to the CTL system, Kärhä (2006) found that the harwarders were more competitive in smaller patches of land with shorter forwarding distances. These multipurpose machines are better suited to fill surge demands due to their lower relocation costs but in general they are less cost efficient and also less productive (Asikainen 2004; Greene et al. 1997). It is imperative that a WPS have access to these wide of array systems so that appropriate machine can be employed under each scenario.

Forest harvested using any of the different systems discussed above can yield various assortments of raw material. Log sorting can improve agility of a WPS, it permits the supply chain to improve its response capability (Sessions et al. 2005). It can be done during harvest, at the roadside, or at a centralized log sort yard (Blinn and Sinclair 1986). The ideal location will depend on a number of factors such as the number of sorts required, landing related costs, log size, number of log destinations, etc. Sessions and Paredes (1987) and Broad (1989) present mathematical models to identify the best location, and Sessions et al. (2005) expand the problem to incorporate uncertainty in the decision. Blinn and Sinclair (1986) through simulation find that the profitability of product sorting depends on the stand parameters as well as the harvesting system used. CTL systems are capable of sorting logs in the forest as they are being harvested whereas creating sorts using tree-length system has negative impact on productivity and requires additional machines (Cass et al. 2009; Hamsley et al. 2009). If sorting is necessary while using full-tree or whole tree system, a centralized log sort yard is most suitable (Sibal et al. 1984). The downside to a centralized system is that significant cost is incurred and it has to be ensured that the value generated outweighs the incremental investment (Sunderman et al. 2003; Han et al. 2011).

Similar to a sort yard, inventory can also be strategically stored at various points in the forest supply chain to improve the responsiveness of the WPS; in the forest, roadside, satellite log yards and mill yards (Erdle et al. 1981; Stier et al. 1986). Keeping an adequate level of inventory is particularly important in the WPS to overcome weather related restrictions (LeBel and Carruth 1997; Todd et al. 2005). However, it is essential to determine the optimal size and distribution of inventory so that neither the wood costs nor mill production is negatively impacted due to excess or dearth of supply. Galbraith and Meng (1981) developed a stochastic simulation model to determine the optimum level of inventory in a mill log yard using probability distribution of supply and demand, and cost data. Once the model determines the optimum level of inventory for each time period, they recommend establishing a safe range at an additional cost to improve the robustness of the output. Erdle et al. (1982) expand the model to determine optimal levels of inventory at various points along the supply chain.

LeBel and Carruth (1997) developed a stochastic spreadsheet model to optimize wood inventory level and logging capacity setting simultaneously to supply wood to a pulp mill. The model takes into consideration production and capacity utilization for harvesting and transportation, mill demands, inventory levels and weather impacts. A run of the model under a hypothetical scenario showed that keeping a buffer between harvesting and transportation made the mill less vulnerable to wood supply uncertainties. The buffer should be placed at a decoupling point whether it is at a roadside or a satellite yard to take advantage of the leagile approach; placing the inventory in a satellite yard close to the forest instead of roadside allows wood to be sorted and stored at a lower inventory costs until demand arises (Stier et al. 1986). However the lower inventory cost that is achieved through delaying transportation costs may be offset by added handling costs incurred at the satellite yard (Erdle et al. 1981).

These intermediary yards can also potentially be used as intermodal nodes to reap benefits offered by multi-modal transportation systems. Use of multimodal transportation systems has been identified as a method to improve agility by allowing raw materials to reach their final destination in the most efficient manner (Kasarda et al. 1998). Rauch and Gronalt (2011) present a mixed integer programming model to optimize delivery of forest products through intermodal transportation system. There are numerous options to transport the raw material from the forest to the mills (Asikainen 1998; Nurminen et al. 2007; Hajek et al. 2008); some are suitable for efficient oriented operations while others for operations focused on agility. An interesting design of a log truck mentioned in the literature with implications to agility, is a self-loading truck (Simmons 1947). Generally, a truck is loaded by a loader at the roadside then unloaded at the destination by another loader (Adebayo et al. 2007). Such a system is more cost efficient than utilizing a self-loading truck given there are large volumes of wood to be transported from the harvest block. Trucks without self-loading capability have higher payload carrying capacity thus are more efficient (Kanzian et al. 2009). However, in settings where harvest blocks are small and widespread, continual relocation of loader adds significant cost (Cubbage 1983; Stokes 1992). The option of a self-loading truck, despite its lowered payload carrying capacity, becomes more appealing. It gives practitioners the flexibility to transport wood from any area in the forest without having to transport a loader to the site regardless of the volume to be transported (Stokes 1992). Another significant development in transportation system with pertinence to agility is central tire inflation (CTI) system. As stated earlier, wet weather conditions can severely limit the transportation of raw material from the forest to mills during certain periods of the year. Either weight restrictions are put in place or trucking is outright halted during these periods impacting the response capability of a WPS (Todd et al. 2005; Bradley 2006). A common approach to overcome this issue is to build a stock of inventory (Bradley 2006); another approach to minimise the impact is through the utilisation of the CTI system (Brown et al. 1999; Bradley 2006; Kestler et al. 2011). In trucks equipped with CTI, drivers can conveniently adjust air pressure in tires to match the road conditions. This consequently improves accessibility of trucks to weather worsened roads and improve agility of the system.

2.3.3.3. Integrated Planning

There are several approaches proposed in the WPS literature to integrate planning of interrelated activities. Epstein et al. (1999) present a linear programming model which supports decision on which stands to harvest, what volumes of timber to obtain, what bucking pattern to apply, and which harvesting machinery to use to satisfy demand for products defined by length and diameter. Karlsson et al. (2004) propose a model that integrates harvesting and transportation planning. A mixed integer programming (MIP) model is developed to make decision on harvest areas, harvest teams to assign, and roads to utilize to meet monthly demand from wood-processing facilities. In Karlsson et al. (2003), a MIP model is presented to support shorter term decisions regarding scheduling of each harvest teams to meet industrial demand while minimizing storage and transportation cost. Carlgren et al. (2006) present a MIP model that integrates decision on log sorting and transportation. Bredström et al. (2010) propose an integrated planning approach that supports decision-making regarding assignment of machines to harvest areas and harvest scheduling. A two-phase solution method is proposed to improve solution time; machines are allocated to harvest areas in the first phase and the detailed scheduling is done in the second phase.

Planning approaches with greater level of integration are presented by Gunnarsson et al. (2007) and Troncoso et al. (2011). Troncoso et al. (2011)

propose an approach to planning where decisions on stand allocation, prescribed bucking patterns, transportation volumes and destinations, and the mill processes to run are integrated taking into consideration the market information. The proposed MIP model applied to a case study in the Chilean forest industry demonstrated that the approach improved the net present value of the entire supply chain by 5%. Gunnarsson et al. (2007) presents a MIP model that integrates planning of activities further downstream the supply chain. The model integrates decision on the type of raw material to procure from a given area, destination mill, production at pulp mills, and distribution to satisfy demand from the final customers. The obstacle to integrating the various aspects of a supply chain is that it requires large and complex models that are difficult to solve; Rönnqvist (2003) suggests column generation and heuristics development to ensure reasonable solution time.

Chauhan et al. (2011) and Beaudoin et al. (2008) use the hierarchical modelling framework proposed by Schneeweiss and Zimmer (2004) to integrate plans. In the proposed methodology, separate models are formulated but solved iteratively until an ideal solution is found. In the study by Chauhan et al. (2011) the goal is to formulate an optimal procurement plan to satisfy demands of several mills. Two models - a procurement planning model and a bucking optimization model are formulated. The bucking optimization model is simply used to anticipate the cost effectiveness of the various procurement plans in satisfying the demand from the mills. Similarly, Beaudoin et al. (2008) use the mechanism to ensure feasibility of wood allocation plans at the harvest scheduling phase.

2.3.3.4. Collaboration

There are several studies that propose collaboration in the industry, mainly in the transportation phase. Palander and Väätäinen (2005) conducted a study to explore the benefits of collaboration between forest companies to implement backhauling during wood transportation. Backhauling means that a truck carries a load when returning from a destination to the areas where the first load originated (Palander et al. 2004); the opportunity to backhaul depends on the geographical location of mills and harvest blocks. Four scenarios, with and without collaboration, and with and without backhauling, were evaluated. The problem was formulated as a linear programming model with heuristics to select backhauling. It was found that collaboration and incorporating backhauling reduced roadside inventory, the average transportation distance and the overall cost. Also, Weintraub et al. (1996) and Murphy (2003) report collaboration during transportation results in reduced truck fleet size. Carlsson and Rönnqvist (2007), who also developed a LP backhauling model with solution based on column generation, state that prior to application of such a model it is imperative that the issue of benefit sharing amongst participants be addressed.

Hof and Field (1987) address the issue of benefit sharing in collaborative ventures. They introduce a number of cost allocation methods to determine timber costs when timber is produced concurrently with recreational and wildlife values. Frisk et al. (2010) proposed a new approach, i.e. equal profit method

(EPM), for cost sharing. The study reports on collaboration between several companies to coordinate the monthly transportation of logs from the forest to mills. A case study with eight forest companies from Sweden is presented. The transportation problem is solved using a decision support system (FlowOpt). Various scenarios are created with different levels of coordination between firms. Once again, the results showed that the global cost decreased with an increasing level of coordination between companies. The authors state that the EPM approach to cost sharing is easier to understand compared to other approaches discussed in Hof and Field (1987) and also produced allocation that were acceptable to forest companies.

Beaudoin et al. (2010) present a study comparing different approaches to collaboration and cost sharing. The study compares distributed, collaborative and centralized planning to develop procurement plans under different economic conditions. The study demonstrates that collaborative planning that is based on direct negotiation between companies to coordinate individual procurement plan yields better results for all parties involved. Certain areas that are economically restrictive for individual companies can become viable through collaboration. Audy et al. (2012a) probe further into collaboration strategies; they evaluate different business models and negotiation strategies with a network model for collaboration between forest companies to transport wood from forest to mills. This approach based on cooperative and non-cooperative game theory allows the integration of practical considerations in defining the allocation rule and the coalition formation process. However there were limitations due to the network model; negotiation could take place only one player at a time and negotiation could take place only once.

All studies found on collaboration have focused on transportation with the exception of Beaudoin et al. (2010). Opportunities for collaboration between companies during execution of activities such as harvest planning and inventory management also exist and should be explored to improve agility of WPS.

2.3.3.5. Information technology

Information technology is increasingly being utilized in the WPS. Major technologies in application include Geographical Information System (GIS) and Global Positioning System (GPS) for harvest and road planning, onboard computers to monitor forestry equipment and optimal bucking software to aid in decision making.

Managing spatial data is inevitable in WPS planning therefore GIS is widely used in the industry (Brinker et al. 1991; Shao et al. 2006). GIS technology, due to its capability to incorporate spatial data, aids practitioners in developing clear and cohesive plan (Gerasimov et al. 2008). Bergström and Walter (2000) propose application of GIS to support decision-making on road building for optimal transportation of wood from harvest areas. Devlin et al. (2008) show that truck haulage routes can be modelled within a GIS to either lower costs or decrease lead-times. From the early 1960s to the 1990s, maps in GIS were developed using photogrammetric techniques which can be laborious and time consuming (Sessions et al. 2006). In the 1990s remote sensing method, LIDAR (Light Detection and Ranging), in combination with the GPS technology for airborne surveying started emerging (Kruczynski et al. 1993). LIDAR technology is capable of collecting vegetation and topography data with high level of accuracy (Maltamo et al. 2005). The high resolution mapping of the forest topography allows planners to distinguish between harvestable and non-harvestable areas thus improving the accuracy of volume estimates. Furthermore research has demonstrated that the technology can be used to accurately estimate tree heights which are an important variable in equations to estimate wood supply (Weller et al. 2003). Accurate and detailed knowledge of forest resource inventory is a key enabler of the response capability.

Numerous technologies have been developed to help forest managers collect information on the productivity of equipment during harvesting. Goychuk et al. (2011) conduct a study using Yellow Activity Monitoring System (YAMS), an electronic vibration recorder to measure productivity. Davis and Kellogg (2005) present a similar technology, MultiDAT, a data logger developed by FPInnovations. McDonald and Fulton (2005) present a method to conduct productivity studies using the GPS technology on tree-length harvesting equipment. Logging system productivity can be affected by a number of factors including, stand density, ground conditions, slope, tree size, branchiness, weather conditions (Kluender et al. 1994; Eliasson et al. 1999; Visser et al. 2004). Automated monitoring systems can be valuable tools that provide forest managers data to assess their system productivity and identify factors that affect productivity. Furthermore, it can provide data to generate production models that incorporate stand conditions leading to accurate production estimates (Davis et al. 2005). Accurate estimation of system production allows forest managers to develop harvest plans and truck scheduling that is capable of satisfying demand in a timely fashion. Also, GPS has been used to improve truck scheduling and routing (Devlin et al. 2009). Unanticipated delays can disrupt schedules leading to resource underutilization; in such cases, Hubbard (2000) states that dispatchers can use real-time information to generate new schedules to better coordinate trucks to hauls.

Advances in technology have also led to bucking decisions being automated. Modern harvesters are equipped with computers that can optimize bucking pattern for each tree being handled (Murphy et al. 2004; Uusitalo et al. 2004). There are two approaches to optimize the bucking process: buck-to-value and buck-to-demand (Malinen et al. 2004; Murphy et al. 2004). In buck-to-value approach, the optimization is based on a price matrix thus maximizing the value of the stem. In buck-to-demand, a demand matrix is used in addition to the price matrix (Malinen et al. 2004). The optimization process then generates bucking decisions attempting to fulfill the demand. The technology allows operators to make bucking decisions that are customer-oriented (Kivinen et al. 2002; Uusitalo et al. 2004). Nevertheless, the technology has its limitations; automatic bucking cannot be applied to all species due to difficulty in predicting the stem taper (Uusitalo et al. 2004). Marshall et al. (2006) state that complete scan using advanced sensing technologies can alleviate the problem at an additional cost.

Technologies have also emerged in the log tracking front. Log tracking has multiple benefits to a WPS striving to fulfill demand in a timely fashion

(Bettinger et al. 2008). Among other benefits, it can improve logistics, inventory management, and help identify the right raw material to fulfill product demand (Murphy & Franich 2004). Various methods for tracking logs along the supply chain are outlined in Dykstra et al. (2003). According to Sessions et al. (2006), the most practical method of tagging logs is attaching bar-codes to the logs but there are problems associated with it during bucking. Murphy and Franich (2004) describe the potential of aroma tagging and electronic nose technology.

2.4. CONCLUSION

Agility has been identified as an essential element to improving competitiveness of forest products supply chains in today’s environment characterized by change and uncertainty. This research was undertaken to contextualize the concept to wood procurement system in order to identify opportunities to improve agility. First, a definition of agility was formulated in the wood procurement context; three capabilities were identified as being essential to improving agility: flexibility, responsiveness and timeliness. Subsequently, five enablers that allow these capabilities to be realised were established: flexible supply, flexible logistics, integrated planning, collaboration and information technology. Finally, a literature search was conducted in the wood procurement domain to identify the presence of these enablers, in effect, identifying opportunities to improve agility. The search yielded ample evidence of each of the enablers. An elaborate list of methods to improve WPS agility is presented. It is recommended that future research emphasis be placed on the enabler “flexibility in supply” to improve

WPS agility. In contrast with the other enablers, “flexibility in supply” is unique to the forest industry. Raw material for the supply chain originates from forests which are not managed solely to maximize economic value; ecological and social objectives generally take precedence. Forest management plans are developed to allocate raw material for the supply chain. The fact that social, ecological as well as economic aspects have to be taken into consideration renders forest management planning a complex process. A systems analysis approach is required to analyse the current process to identify opportunities to improve agility for the WPS. Studies have demonstrated that a number of alternative solutions will be equally successful in achieving forest management objectives. From a wood procurement systems perspective, an alternative solution may provide a better opportunity to align supply with demand. Nevertheless, there are costs to improving agility. Thus, prior to investment towards improving agility, empirical testing to assess its potential benefits needs to be carried out.

2.5. LITERATURE CITED

Adebayo, A.B., Han, H.-S., & Johnson, L. 2007. Productivity and cost of cut-to-length and whole-tree harvesting in a mixed-conifer stand. *Forest products journal* 57(6): p.59–69.

Agarwal, A., Shankar, R., & Tiwari, M. 2007. Modeling agility of supply chain. *Industrial Marketing Management* 36(4): p.443–457.

Andersson, J., & Eliasson, L. 2004. Effects of three harvesting work methods on Harwarder productivity in final felling. *Silva Fennica* 32(2): p.195–202.

Andreassen, K., & Øyen, B.H. 2002. Economic consequences of three silvicultural methods in uneven-aged mature coastal spruce forests of central Norway. *Forestry* 75(4): p.483–488.

Asikainen, A. 1998. Chipping terminal logistics. *Scandinavian Journal of Forest Research* 13(1-4): p.386–392.

Asikainen, A. 2004. Integration of Work Tasks and Supply Chains in Wood Harvesting - Cost Savings or Complex Solutions? *International Journal of Forest Engineering* 15(2): p.11–17.

Audy, J.-F., Moreira, M., et al. 2012. Alternative logisitics concepts fitting different wood supply situtations and markets. *CIRRELT* 2012-24.

Audy, J.-F., D'Amours, S., & Rönnqvist, Mikael. 2012a. An empirical study on coalition formation and cost/savings allocation. *International Journal of Production Economics* 136(1): p.13–27.

Beaudoin, D., Frayret, J.-M., & LeBel, L. 2008. Hierarchical forest management with anticipation: an application to tactical–operational planning integration. *Canadian Journal of Forest Research* 38(8): p.2198–2211.

Beaudoin, D., Frayret, J.-M., & LeBel, L. 2010. Negotiation-based distributed wood procurement planning within a multi-firm environment. *Forest Policy and Economics* 12(2): p.79–93.

Bergström, J., & Walter, F. 2000. GIS-based benefits analysis of new forest truck roads. *Resultat-SkogForsk* 23: p.4.

Bettinger, P., Siry, J., Boston, K., & Grebner, Donald L. 2008. *Forest Management and Planning*. Academic Press.

Björheden, R., & Helstad, K. 2005. Raw material procurement in sawmills' business level strategy - a contingency perspective. *International Journal of Forest Engineering* 16(2): p.47–56.

Blinn, C.R., & Sinclair, S.A. 1986. Profitability of Various Timber Harvesting Systems as Affected by Product Sorting and Timber Stand Parameters. *Northern Journal of Applied Forestry* 3(4): p.167–172.

Bradley, A. 2006. Hauling with Full Axle Weights and Reduced Tire Pressures on Weight-Restricted Roads in British Columbia. *Transportation Research Record: Journal of the Transportation Research Board* 1967: p.20–26.

Bredström, D., Jönsson, P., & Rönnqvist, Mikael. 2010. Annual planning of harvesting resources in the forest industry. *International Transactions in Operational Research* 17(2): p.155–177.

Brinker, R.W., & Jackson, B.D. 1991. Using a geographic information system to study a regional wood procurement problem. *Forest science* 37(6): p.1614–1631.

Broad, L.R. 1989. Note on log sort yard location problems. *Forest science* 35(2): p.640–645.

Brown, C., & Sessions, J. 1999. Variable tire pressures for tropical forest? a synthesis of concepts and applications. *Journal of Tropical Forest Science* 11(2): p.380–400.

Carlgren, C.-G., Carlsson, D., & Rönnqvist, Mikael. 2006. Log sorting in forest harvest areas integrated with transportation planning using backhauling. *Scandinavian Journal of Forest Research* 21(3): p.260–271.

Carlsson, D., & Rönnqvist, Mikael. 2007. Backhauling in forest transportation : models, methods, and practical usage. *Canadian journal of forest research* 37(12): p.2612–2623.

Cass, R.D., Baker, S.A., & Greene, W. D. 2009. Cost and productivity impacts of product sorting on conventional ground-based timber harvesting operations. *Forest Products Journal* 59(11/12): p.108–114.

Charles, A., Lauras, M., & Wassenhove, L.V. 2010. A model to define and assess the agility of supply chains: building on humanitarian experience. *International Journal of Physical Distribution & Logistics Management* 40(8/9): p.722–741.

Chauhan, S., Frayret, J.-M., & LeBel, Luc. 2011. Supply network planning in the forest supply chain with bucking decisions anticipation. *Annals of operations research* 190(1): p.93–115.

Christopher, Martin. 2000. The Agile Supply Chain. *Industrial Marketing Management* 29(1): p.37–44.

Christopher, Martin, & Peck, H. 2004. Building the Resilient Supply Chain. *The International Journal of Logistics Management* 15(2): p.1–14. Available at: http://www.emeraldinsight.com/journals.htm?issn=0957-4093&volume=15&issue=2&articleid=1527548&show=html [Accessed January 31, 2013].

Christopher, Martin, & Towill, D. 2001. An integrated model for the design of agile supply chains. *International Journal of Physical Distribution & Logistics Management* 31(4): p.235–246.

Christopher, Martin, & Towill, D. 2002. Developing Market Specific Supply Chain Strategies. *The International Journal of Logistics Management* 13(1): p.1–14.

Clark, K.B., & Fujimoto, T. 1989. Lead time in automobile product development explaining the Japanese advantage. *Journal of Engineering and Technology Management* 6(1): p.25–58.

Collin, J., & Lorenzin, D. 2006. Plan for supply chain agility at Nokia: Lessons from the mobile infrastructure industry. *International Journal of Physical Distribution & Logistics Management* 36(6): p.418–430.

Crespell, P., Knowles, C., & Hansen, E. 2006. Innovativeness in the North American Softwood Sawmilling Industry. *Forest Science* 52(5): p.568–578.

Cubbage, F.W. 1983. Tract Size and Harvesting Costs in Southern Pine. *Journal of Forestry* 81(7): p.430–478.

Davis, C., & Kellogg, L. 2005. Measuring machine productivity with the MultiDat datalogger: a demonstration on three forest machines. *USDA Forest Service* Gen. Tech.(PSW-GTR-194.2005): p.10.

Davis, L.S., Johnson, K.N., Bettinger, P., & Howard, T.E. 2001. *Forest Management: to Sustain Ecological, Economic, and Social Values* 4th ed. McGraw-Hill Companies Inc.

DeVor, R., Graves, R., & Mills, J.J. 1997. Agile manufacturing research: accomplishments and opportunities. *IIE Transactions* 29(10): p.813–823.

Devlin, G.J., & McDonnell, K. 2009. Assessing Real Time GPS Asset Tracking for Timber Haulage. *Open Transportation Journal* 3: p.78–86.

Devlin, G.J., McDonnell, K., & Ward, S. 2008. Timber haulage routing in Ireland: an analysis using GIS and GPS. *Journal of Transport Geography* 16(1): p.63–72.

Dyer, J.H. 1996. How Chrysler created an American keiretsu. *Harvard Business Review* 74(4): p.42–56.

Dykstra, D.P. Kuru, G. Nussbaum, R. 2003. Technologies for log tracking. *International Forestry Review* 5(3): p.262–267.

D'Amours, S., Rönnqvist, Mikael, & Weintraub, Andres. 2008. Using Operational Research for Supply Chain Planning in the Forest Products Industry. *INFOR: Information Systems and Operational Research* 46(4): p.265–281.

Eliasson, L., Bengtsson, J., Cedergren, J., & Lageson, H. 1999. Comparison of Single-Grip Harvester Productivity in Clear- and Shelterwood Cutting. *International Journal of Forest Engineering* 10(1): p.43–48.

Epstein, R., Nieto, E., Weintraub, A., Chevalier, P., & Gabarró, J. 1999. A system for the design of short term harvesting strategy. *European Journal of Operational Research* 119(2): p.427–439.

Erdle, T.A., Arp, P.A., & Meng, C.H. 1981. Optimizing pulpwood inventories at roadsides, millyards and concentration yards: a case study [Models]. *The Forestry Chronicle* 57(5): p.218–225.

Faisal, M.N. Banwet, D.K. Shankar, R. 2007. Supply chain agility: analysing the enablers. *International Journal of Agile Systems and Management* 2(1): p.76–91.

Frisk, M., Göthe-Lundgren, M., Jörnsten, K., & Rönnqvist, M. 2010. Cost allocation in collaborative forest transportation. *European journal of operational research* 205(2): p.448–458.

Galbraith, J.E., & Meng, C.H. 1981. Simulating Optimum Inventory of Harvested Wood. *Journal of Forestry* 79(5): p.292–295.

Gerasimov, Y., & Sokolov, A. 2008. GIS-Based Decision-Support Program for Planning and Analyzing Short-Wood Transport in Russia. *Croatian Journal of Forest Engineering* 29(2): p.163–175.

Goldman, S.L., Nagel, R.N., & Preiss, K. 1995. *Agile Competitors and Virtual Organizations*. N.Y. :Van Nostrand Reinhold.

Goychuk, D., Kilgore, M.A., Blinn, C.R., Coggins, J., & Kolka, R.K. 2011. The Effect of Timber Harvesting Guidelines on Felling and Skidding Productivity in Northern Minnesota. *Forest Science* 57(5): p.393–407.

Grebner, D L, Grace, L.A., Stuart, W., & Gilliland, D.P. 2005. A Practical Framework for Evaluating Hauling Costs. *International Journal of Forest Engineering* 16(2): p.115–128.

Greene, W. Dale, Harris, T.G., DeForest, C.E., & Wang, J. 1997. Harvesting Cost Implications of Changes in the Size of Timber Sales in Georgia. *Southern Journal of Applied Forestry* 21(4): p.193–198.

Gunasekaran, A. 1998. Agile manufacturing: Enablers and an implementation framework. *International Journal of Production Research* 36(5): p.1223–1247. Available at: http://dx.doi.org/10.1080/002075498193291 [Accessed February 5, 2013].

Gunasekaran, A. 2001. *Agile Manufacturing: The 21st Century Competitive Strategy*. Elsevier.

Gunn, E. 2009. Some Perspectives on Strategic Forest Management Models and the Forest Products Supply Chain. *INFOR: Information Systems and Operational Research* 47(3): p.261–272.

Gunnarsson, H., Rönnqvist, Mikael, & Carlsson, D. 2007. Integrated Production and Distribution Planning for Södra Cell AB. *Journal of Mathematical Modelling and Algorithms* 6(1): p.25–45.

Hahn, C.K., Watts, C.A., & Kim, K.Y. 1990. The supplier development program: A conceptual model. *Journal of Purchasing and Materials Management* 26(2): p.2–7.

Hajek, J., Billing, J., & Swan, D. 2008. Transportation of raw forest products in northern ontario by trucks. In B. Jacob, P. Nordengen, A. O'Connor, & M. Bouteldja (eds) *International Conference on Heavy Vehicles*, 377–386.

Hamsley, A.K., Greene, W. D., & Baker, S.A. 2009. Comparison of value harvested by modified and conventional tree-length systems in the southeastern United States. *Forest products journal* 59(4): p.1–6.

Han, H.-S., Ted Bilek, E.M., Dramm, J. (Rusty), Loeffler, D., & Calkin, D. 2011. Financial Feasibility of a Log Sort Yard Handling Small-Diameter Logs: A Preliminary Study. *Western Journal of Applied Forestry* 26(4): p.174–182.

Harrison, A, Christopher, M, & van Hoek, R.I. 1999. Creating the agile supply chain. *School og Management Cranfield University, Cranfield*: p.1–60.

Hartsough, B.R., McNeel, J.F., Durston, T.A., & Stokes, B.J. 1997. Comparison of mechanized systems for thinning ponderosa pine and mixed conifer stands. *Forest products journal* 47(11/12): p.59–68.

Helstad, K. 2006. *Managing timber procurement in Nordic purchasing sawmills*. Växjö University.

van Hoek, Remko I., Harrison, Alan, & Christopher, Martin. 2001. Measuring agile capabilities in the supply chain. *International Journal of Operations & Production Management* 21(1/2): p.126–148.

Hof, J.G., & Field, R.C. 1987. On the possibility of using joint cost allocation in forest management decision making. *Forest science* 33(4): p.1035–1046.

Howard, A.F., & Temesgen, H. 1997. Potential financial returns from alternative silvicultural prescriptions in second-growth stands of coastal British Columbia. *Canadian journal of forest research* 27(9): p.1483–1495.

Hubbard, T.N. 2000. The Demand for Monitoring Technologies: The Case of Trucking*. *The Quarterly journal of economics* 115(2): p.533–560.

Jirousek, R., Klvac, R., & Skoupy, A. 2007. Productivity and costs of the mechanised cut-to-length wood harvesting system in clear-felling operations. *Journal of Forest Science - UZPI* 53(10): p.476–482.

Kanzian, C., Holzleitner, F., Stampfer, Karl, & Ashton, S. 2009. Regional energy wood logistics : optimizing local fuel supply. *Silva Fennica* 43(1): p.113–128.

Karlsson, J., Ronnqvist, M., & Bergstrom, J. 2003. Short-term harvest planning including scheduling of harvest crews. *International Transactions in Operational Research* 10(5): p.413–431.

Karlsson, Jenny, Rönnqvist, Mikael, & Bergström, Johan. 2004. An optimization model for annual harvest planning. *Canadian Journal of Forest Research* 34(8): p.1747–1754.

Kasarda, J.D., & Rondinelli, D.A. 1998. Innovative infrastructure for agile manufacturers. *Sloan management review* 39(2): p.73–82.

Katayama, H., & Bennett, D. 1999. Agility, adaptability and leanness: A comparison of concepts and a study of practice. *International Journal of Production Economics* 60-61: p.43–51.

Kellogg, L.D., & Bettinger, P. 1994. Thinning Productivity and Cost for a Mechanized Cut-to-Length System in the Northwest Pacific Coast Region of the USA. *International Journal of Forest Engineering* 5(2): p.43–52.

Kestler, M. a. et al. 2011. Keeping Springtime Low-Volume Road Damage to a Minimum. *Transportation Research Record: Journal of the Transportation Research Board* 2205(-1): p.155–164.

Kidd, P.T. 1995. *Agile manufacturing: forging new frontiers*. Boston, MA: Addison-Wesley Longman Publishing.

Kivinen, V-P, & Uusitalo, J. 2002. Applying Fuzzy Logic to Tree Bucking Control. *Forest Science* 48(4): p.673–684.

Kluender, R.A., & Stokes, Bryce J. 1994. Productivity and Costs of Three Harvesting Methods. *Southern Journal of Applied Forestry* 18(4): p.168–174.

Kruczynski, L.R., & Jasumback, A. 1993. Forestry management applications: Forest Service experiences with GPS. *Journal of forestry* 91(8): p.20–24.

Kuuluvainen, J., Karppinen, H., & Ovaskainen, V. 1996. Landowner objectives and nonindustrial private timber supply. *Forest science* 42(3): p.300–309.

Kärhä, K. 2006. Whole-tree harvesting in young stands in Finland. *Forestry Studies / Metsanduslikud Uurimused* 45: p.118–134.

Laiho, O., Lähde, E., & Pukkala, T. 2011. Uneven- vs even-aged management in Finnish boreal forests. *Forestry* 84(5): p.547–556.

LeBel, L., & Carruth, J.S. 1997. Simulation of woodyard inventory variations using a stochastic model. *Forest products journal* 47(3): p.52–57.

Lee, H.L. 2004. The triple-A supply chain. *Harvard Business Review* 82(10): p.102–112.

Li, X., Chung, C., Goldsby, T.J., & Holsapple, C.W. 2008. A unified model of supply chain agility: the work-design perspective. *The International Journal of Logistics Management* 19(3): p.408–435.

Lin, C.-T., Chiu, H., & Chu, P.-Y. 2006. Agility index in the supply chain. *International Journal of Production Economics* 100(2): p.285–299.

Liu, C., Ruel, Jean-Claude, & Zhang, S.Y. 2007. Immediate impacts of partial cutting strategies on stand characteristics and value. *Forest Ecology and Management* 250(3): p.148–155.

Lussier, Jean-Martin. 2009. Changing our mental model from growing volume to producing value: The case of uneven-aged hardwood management. *The Forestry Chronicle* 85(3): p.382–386.

Macdonald, G. 1995. The Case for Boreal Mixedwood Management: An Ontario Perspective. *The Forestry Chronicle* 71(6): p.725–734.

Malinen, Jukka, & Palander, Teijo. 2004. Metrics for Distribution Similarity Applied to the Bucking to Demand Procedure. *International Journal of Forest Engineering* 15(1): p.33–40.

Maltamo, M. et al. 2005. Identifying and quantifying structural characteristics of heterogeneous boreal forests using laser scanner data. *Forest Ecology and Management* 216(1-3): p.41–50.

Marshall, H.D., Murphy, G.E., & Boston, K. 2006. Evaluation of the economic impacts of length and diameter measurement error on mechanical harvesters and processors operating in pine stands. *Canadian journal of forest research* 36(7): p.1661–1673.

Masson, R., Iosif, L., MacKerron, G., & Fernie, J. 2007. Managing complexity in agile global fashion industry supply chains. *The International Journal of Logistics Management* 18(2): p.238–254.

McCullen, P., Saw, R., Christopher, Martin, & Towill, D. 2006. The F1 Supply Chain: Adapting the Car to the Circuit - the Supply Chain to the Market. *Supply Chain Forum: An International Journal* 7(1): p.14–23.

McDonald, T.P., & Fulton, J.P. 2005. Automated time study of skidders using global positioning system data. *Computers and Electronics in Agriculture* 48(1): p.19–37.

Mentzer, J.T., Foggin, J.H., & Golicic, S.G. 2000. Supply chain collaboration: enablers, impediments, and benefits. *Supply Chain Management Review* 4(4): p.52–58.

Mondragon, A.E.C., Lyons, A.C., & Kehoe, D.F. 2004. Assessing the value of information systems in supporting agility in high-tech manufacturing enterprises. *International Journal of Operations & Production Management* 24(12): p.1219–1246.

Moore, T.Y., Ruel, J.-C., Lapointe, M. -a., & Lussier, J.-M. 2012. Evaluating the profitability of selection cuts in irregular boreal forests: an approach based on Monte Carlo simulations. *Forestry* 85(1): p.63–77.

Murphy, G. 2003. Reducing Trucks on the Road through Optimal Route Scheduling and Shared Log Transport Services. *Southern Journal of Applied Forestry* 27(3): p.198–205.

Murphy, Glen, & Franich, R. 2004. Early experience with aroma tagging and electronic nose technology for log tracking. *Forest products Journal* 54(2): p.28–35.

Murphy, Glen, Marshall, H., & Bolding, M.C. 2004. Adaptive control of bucking on harvesters to meet order book constraints. *Forest products Journal* 54(12): p.114–121.

Narasimhan, R., & Das, A. 1999. An Empirical Investigation of the Contribution of Strategic Sourcing to Manufacturing Flexibilities and Performance. *Decision Sciences* 30(3): p.683–718.

Nurminen, T., & Heinonen, J. 2007. Characteristics and time consumption of timber trucking in Finland. *Silva Fennica* 41(3): p.471–487.

Palander, T, Väätäinen, J, Laukkanen, S., & Malinen, J. 2004. Modeling backhauling on Finnish energy-wood network using minimizing of empty routes. *International Journal of Forest Engineering* 15(2): p.79–85.

Palander, Teijo, & Väätäinen, Janne. 2005. Impacts of interenterprise collaboration and backhauling on wood procurement in Finland. *Scandinavian Journal of Forest Research* 20(2): p.177–183.

Porter, M.E. 1998. *Competitive Strategy: Techniques for Analyzing Industries and Competitors : with a New Introduction*. Simon and Schuster.

Power, D.J., Sohal, A.S., & Rahman, S.-U. 2001. Critical success factors in agile supply chain management - An empirical study. *International Journal of Physical Distribution & Logistics Management* 31(4): p.247–265.

Prater, E., Biehl, M., & Smith, M.A. 2001. International supply chain agility - Tradeoffs between flexibility and uncertainty. *International Journal of Operations & Production Management* 21(5/6): p.823–839.

Pukkala, T., Lähde, E., & Laiho, O. 2010. Optimizing the structure and management of uneven-sized stands of Finland. *Forestry* 83(2): p.129–142.

Pulkki, R. 2003. Minimizing negative environmental impacts of forest harvesting operations. In P. J. Burton, C. Messier, D. W. Smith, & W. L. Adamowicz (eds) *Towards Sustainable Management of the Boreal Forest*, 581–628. National Research Council of Canada

Rauch, P., & Gronalt, M. 2011. The effects of rising energy costs and transportation mode mix on forest fuel procurement costs. *Biomass and Bioenergy* 35(1): p.690–699. Available at:

http://dx.doi.org/10.1016/j.biombioe.2010.10.015 [Accessed February 3, 2013].

Rönnqvist, Mikael. 2003. Optimization in forestry. *Mathematical programming* 97(1-2): p.267–284.

SCC. 2010. Supply chain operations reference (SCOR) model overview, version 10.0. : p.23.

Sambamurthy, V., Bharadwaj, A., & Grover, V. 2003. Shaping agility through digital options: Reconceptualizing the role of IT in contemporary firms. *MIS Quarterly* 27(2): p.237–264.

Sanchez, R., Heene, A., & Thomas, H. 1996. *Dynamics of competence-based competition : theory and practice in the new strategic management*. Pergamon.

Schneeweiss, C., & Zimmer, K. 2004. Hierarchical coordination mechanisms within the supply chain. *European Journal of Operational Research* 153(3): p.687–703.

Sessions, J, Akay, A., Murphy, G, Chung, W., & Aruga, K. 2006. Road and harvesting planning and operations. In G. Shao & K. Reynolds (eds) *Computer Applications in Sustainable Forest Management: Including Perspectives on Collaboration and Integration*, 83–89. Springer

Sessions, John, Boston, K., Hill, R., & Stewart, R. 2005. Log sorting location decisions under uncertainty. *Forest products journal* 55(12): p.53–57.

Sessions, John, & Paredes, G. 1987. A Solution Procedure for the Sort Yard Location Problem in Forest Operations. *Forest Science* 33(3): p.750–762.

Shao, G., & Reynolds, K. 2006. digitial forestry. In G. Shao & K. Reynolds (eds) *Computer Applications in Sustainable Forest Management: Including Perspectives on Collaboration and Integration*, 3–16. Springer

Shapiro, J.F. 2001. *Modeling the Supply Chain*. Cengage Learning.

Sharifi, H., & Zhang, Z. 1999. A methodology for achieving agility in manufacturing organisations: An introduction. *International Journal of Production Economics* 62(1-2): p.7–22.

Sibal, P.V., Bowyer, J.L., & Bradley, D.P. 1984. Log Merchandising in Aspen. *Journal of Forestry* 82(7): p.420–425.

Simmons, F.C. 1947. Mechanizing Forest Operations. *Journal of Forestry* 45(5): p.345–349.

Smith, D.M., Larson, B.C., Kelty, M.J., & Ashton, P.M.S. 1997. *The practice of silviculture: applied forest ecology.* John Wiley and Sons, Inc.

Stier, J.C., Steele, T.W., & Engelhard, R.J. 1986. Pulpwood Procurement Practices in the Wisconsin-Upper Michigan Pulp and Paper Industry. *Northern Journal of Applied Forestry* 3(1): p.10–14.

Stokes, Bryce J. 1992. Harvesting small trees and forest residues. *Biomass and Bioenergy* 2(1-6): p.131–147.

Stratton, R., & Warburton, R.D.. 2003. The strategic integration of agile and lean supply. *International Journal of Production Economics* 85(2): p.183–198.

Sunderman, R., & Warburton, R. 2003. Establishment of the Creston log sort yard: Case study. *BC Journal of Ecosystems and Management* 31(1): p.1–6.

Swafford, P.M., Ghosh, S., & Murthy, N. 2006. The antecedents of supply chain agility of a firm: Scale development and model testing. *Journal of Operations Management* 24(2): p.170–188.

Talbot, B., Nordfjell, T., & Suadicani, K. 2003. Assessing the Utility of Two Integrated Harvester-Forwarder Machine Concepts Through Stand-Level Simulation. *International Journal of Forest Engineering* 14(2): p.31–43.

Tittler, R., Messier, Christian, & Burton, Philip J. 2011. Hierarchical forest management planning and sustainable forest management in the boreal forest. *The Forestry Chronicle* 77(6): p.998–1005.

Todd, K.M., & Rice, R.W. 2005. Factors affecting pulpwood inventory levels in the northeastern United States. *Forest products journal* 55(7-8): p.17–21.

Tokarczyk, J., & Hansen, E. 2006. Creating intangible competitive advantages in the forest products industry. *Forest Products Journal* 56(7/8): p.4–13.

Troncoso, J., D’Amours, S., Flisberg, P., Rönnqvist, Mikael, & Weintraub, Andrés. 2011. A mixed integer programming model to evaluate integrating strategies in the forest value chain - A case study in the Chilean forest industry. : p.29. Available at: https://www.cirrelt.ca/DocumentsTravail/CIRRELT-2011-28.pdf.

Uusitalo, Jori. 2005. A Framework for CTL Method-Based Wood Procurement Logistics. *International Journal of Forest Engineering* 16(2): p.37–46.

Uusitalo, Jori, Kokko, S., & Kivinen, Veli-Pekka. 2004. The effect of two bucking methods on Scots pine lumber quality. *Silva Fennica* 38(3): p.291–303.

Vahid, S., & Maness, T. 2010. Modelling customer demand in forest products industry supply chains: a review of the literature. *International Journal of Simulation and Process Modelling* 6(2): p.103–114.

Visser, R.J.M., McDonagh, K.D., Meller, R.D., & McDonald, Timothy P. 2004. Harvesting System Simulation Using a Systems Dynamic Model. *Southern Journal of Applied Forestry* 28(2): p.91–99.

Visser, R.J.M., & Stampfer, K. 2003. Tree-Length System Evaluation of Second Thinning in a Loblolly Pine Plantation. *Southern Journal of Applied Forestry* 27(2): p.77–82.

Weintraub, A., Epstein, R., Morales, R., Seron, J., & Traverso, P. 1996. A Truck Scheduling System Improves Efficiency in the Forest Industries. *Interfaces* 26(4): p.1–12.

Weller, D., Denham, R., Witte, C., Mackie, C., & Smith, D. 2003. Assessment and monitoring of foliage projected cover and canopy height across native vegetation in Queensland, Australia, using laser profiler data. *Canadian journal of remote sensing* 29(5): p.578–591.

Wikström P. 2000. A Solution Method for Uneven-Aged Management Applied to Norway Spruce. *Forest Science* 46(3): p.452–463.

Yaoxiang, L., Jingxin, W., Miller, G., & McNeel, J. 2006. Production economics of harvesting small-diameter hardwood stands in central Appalachia. *Forest products journal* 56(3): p.81–86.

Yusuf, Y.., Sarhadi, M., & Gunasekaran, A. 1999. Agile manufacturing: *International Journal of Production Economics* 62(1-2): p.33–43.

CHAPTER 3. VALUE-ADDING THROUGH SILVICULTURAL FLEXIBILITY: AN OPERATIONAL LEVEL SIMULATION STUDY

Abstract

Forest products industry's competitiveness is influenced by the agility of wood procurement systems in delivering raw material to support downstream manufacturing activities. However, in a hierarchical forest management planning context, silvicultural treatments are prescribed and set as constraints for supply chain managers, restricting supply flexibility and consequently value-adding potential. This study was conducted with an objective of quantifying the benefits of improving wood procurement systems agility through flexibility in the choice of silvicultural treatments at the operational level. The aim was also to determine the range of conditions under which benefits from flexibility can be realized while accounting for the impact on long-term supply. We present a novel approach that integrates silvicultural options into operational level decision-making to solve the multi-product, multi-industry problem with divergent flow. The approach entails solving a mixed integer programming model in a rolling planning horizon framework. Subsequently, we demonstrate benefits associated with integrating supply chain and silvicultural decisions through a case study. Future impact of exercising flexibility on long-term supply was accounted through incorporating costs associated with applying different silvicultural regimes. The presented approach will prove to be useful in implementing an adaptive forest management system that integrates the complexity of social, economic and ecological dimensions.

Keywords: agility, wood procurement, silviculture, mixed-integer programming, forest products industry, supply flexibility.

3.1. INTRODUCTION

Creation of value-added products and diversification from traditional commodity focus has been sought in the forest products industry as a strategy to adapt to the emerging economic challenges (FPAC 2011). These challenges result from changes that have taken place in the global forest sector following the U.S. housing crisis, Russian log export tax, emergence of China, changes in energy policies, etc. Significant progress has already been made in the development of bio-energy, bio-chemicals and bio-materials. However, in a highly competitive globalized market characterized by turbulence and volatility, product development is only a part of the equation; success also depends on the capability of a supply chain to deliver these products to markets in a timely manner (Christopher 2010). Supply chains need to be agile to capture opportunities in these uncertain market conditions.

Agility of forest product supply chains depends largely on the agility of wood procurement systems (WPS). WPSs are responsible for procuring wood from forests to supply raw material for all downstream manufacturing activities (D’Amours et al. 2008). The task entails delineating cutblocks, constructing roads, and conducting harvesting and transportation operations. A cutblock is a group of adjacent forest stands that are treated as a basic unit in management plans for which harvesting and regeneration schedule is prescribed. Under the changing context, characterized by greater market volatility, WPSs are faced with an emerging challenge of fulfilling volatile demand from a diverse set of manufacturers (Hansen et al. 2013). WPSs need to be able to adjust their production accordingly whilst taking into consideration the full range of social, economic and environmental factors involved in forest management (Pulkki 2003). In the past, WPSs based their production on market forecasts and placed inventory at strategic points to withstand market fluctuations (Stier 1986; LeBel and Carruth 1997). However, WPSs need to better align their production with demand in a volatile and competitive context. This requires identifying forest stands with the appropriate raw material, harvesting, and delivering it to the customers in a timely manner. Audy et al. (2012), in a study conducted in six different countries (in Europe and America), show that WPSs are limited in their capability to change existing harvest plans to align raw materials with prevailing demand. This can be attributed to the disconnection between forest products supply chain and forest management planning as discussed in Church (2007) and Gunn (2009).

Forest management planning is conducted using a top-down hierarchical approach aggregating and disaggregating information at the various levels to reduce complexity (Bettinger et al. 2008). Savard (2011) provides a comprehensive schematic of decisions made at each hierarchy based on a case study in Quebec, Canada. First, a long-term strategic plan is devised outlining management strategy to achieve spatial and temporal objectives of species composition and age structure in the forest land base (Grenon et al. 2011). The outcome of the plan is the determination of annual allowable cut by species group and silvicultural treatments to be applied. Silvicultural treatments are actions prescribed to forest stands to meet the objectives set at the strategic level (Davis et al 2001). Subsequently, the volumes set at the strategic level are spatially allocated at the tactical level. Forest stands are aggregated to form cutblocks and silvicultural treatments are prescribed to individual cutblocks. Next, an annual plan is formulated from this pool of cutblocks, attempting to match supply with the forecast of demand. Once the annual plan has been established, a schedule is developed for the supply chain to fulfill prevailing demand from within this annual pool of cutblocks using the silvicultural treatments already prescribed. Even if the prevailing demand differs significantly from forecast, altering silvicultural treatments to better align supply with demand is not contemplated (Gunn 2009; Savard 2011). Strictly constraining the short-term planning process in a hierarchical planning framework impedes full value-creation potential (Paradis et al. 2013). Moreover, due in part to the natural variability of forest ecosystems, a multitude of operational level plans may allow achieving objectives set at an upper hierarchy (Gunn 2009). Thus, there are a number of different silvicultural treatments that can be prescribed without impacting long-term sustainability.

Fixing silvicultural treatments based on a year-old market forecast can negatively impact supply chain performance. Besides market volatility, there is also the issue of uncertainty concerning forest resource inventory. Forest inventory data used at upper hierarchical planning levels are approximations derived through sample-based procedures; there are inaccuracies associated with estimations. The inaccuracies are exacerbated by unpredictable events such as fire, insect outbreak and even climate change (Yousefpour et al. 2012).

Flexibility in the choice of silvicultural treatments would enable practitioners to better match supply with demand (Gautam et al. 2013). Such flexibility could be exercised without undermining ecological and social objectives. Lussier (2009) conducted a study in eastern Canada to evaluate the impact of changing prescriptions to fulfil supply chain requirements in lieu of implementing pre-determined treatments. Improvement in supply chain profits was demonstrated, whilst respecting ecological constraints. However, flexibility in silvicultural treatment was not exercised in the study, but simply flexibility in tree choice within the partial harvest treatment. Nevertheless, it provides motivation to explore the advantage of flexibility in the choice of silvicultural treatment itself at the operational level to better align supply with demand.

Prior to exercising flexibility in the choice of silvicultural treatment, the financial feasibility of the alternative treatments have to be ensured. Several studies have been conducted on the subject in recent times. Howard and Temesgen (1997) conducted a study to assess the potential financial returns from forest stands under different silvicultural prescriptions over a 30-year planning horizon in western Canada. The financial analysis included harvesting, hauling and regeneration costs. Market prices were used to calculate the revenue. The resulting net present values (NPV) indicated that a range of silvicultural treatments could be economically viable depending on stand specific parameters. Andreassen and Øyen (2002) conducted a study to estimate and compare the net present value of three silvicultural systems in central Norway: single tree selection, group selection and clearcutting. The NPV calculations were based on an assumption of perpetual application of the chosen treatment. Clearcutting consistently yielded the greatest NPV, however, two other silvicultural treatments were also found to be reasonable options. Liu et al. (2007) calculated the benefit cost ratio of several different silvicultural treatments applied to forest stands in Québec. The treatments included clearcut, shelterwood and two variations of partial cuts. The result showed that clearcut generated the highest average net income; however, the benefit cost ratio was highest under partial harvest. Moore et al. (2012) conducted a similar study but with a time horizon of 200 years. Their calculation of NPV acknowledged the inherent uncertainty associated with parameters in the long-term. The median NPV values were positive for all treatments, with clearcut yielding the highest value. However, based on the simulation, there was also the possibility that clearcut could be less profitable than other treatments.

The studies discussed above demonstrate financial feasibility potential of various silvicultural treatments. However, their feasibility in the operational level wood procurement context remains to be demonstrated. The following limitations were observed in regards to these studies: (i) they all assumed that infinite demand existed for all assortments produced, and could be sold at market prices to generate revenue. The assumption is unrealistic considering that mills are geographically dispersed and it is not economically viable to transport all assortments from the forest to their highest value yielding mills due to long distances; this will vary on a case-by-case basis; (ii) except in the study by Moore et al. (2012), the prices of different assortments were kept constant throughout the study horizon although our investigation of recent data reveals a high volatility in market prices (Sun and Ning 2014; UN 2013). The prices have a significant impact on the revenue generated and consequently the NPV; (iii) the studies were conducted at the stand level; an analysis under a broader context is bound to vary the outcome. As an example, if a group of cutblocks were clustered in an area, economies of scale could be applied to reduce overall cost; (iv) transportation costs were excluded in their analyses except in Howard and Temesgen (1997). The exclusion of transportation cost is justifiable given uncertainty with regards to destination mills in such studies. Nevertheless, transportation cost represents a significant proportion of the overall cost, subsequently dictating feasibility of silvicultural treatments.

Thus, financial feasibility of silvicultural treatments needs to be further assessed at the operational level where uncertainties associated with demand and price forecasts are greatly reduced. Also, at the operational level, the knowledge of the spatial setting of mills and other allocation decisions allow better estimation of harvesting and transportation costs. Numerous models have been proposed to support decision-making at the operational level. Walker and Preiss (1988) developed a mixed integer programming model to support decision-making on areas to harvest and allocation of log assortments from harvest areas to surrounding mills. Burger and Jamnick (1995) constructed a linear programming model to include decisions on the harvest method to be employed. Epstein et al. (1999) and Chauhan et al. (2009) incorporated bucking decisions. Bucking is the process of cutting a tree into lengths according to the specifications provided by customer mills. Karlsson et al. (2004) formulated a Mixed Integer Programming (MIP) model to incorporate harvest crew assignment in the decision-making. A MIP model that generates procurement plans taking into consideration fiber freshness is presented in Beaudoin et al. (2007). However, to the best of our knowledge, silvicultural treatment has not been explicitly included as a decision variable in any operational level wood procurement model described in the scientific literature.

In lieu of flexibility in silvicultural treatments, flexible harvest policies as described in Brazee and Mendelsohn (1988) and Knoke and Wurm (2006) could be employed. At the operational level, however, it would entail identifying a new set of harvest blocks to generate a plan, consultation with stakeholders, road construction for access, and performing other preparatory tasks. From an agility viewpoint, flexibility in silvicultural treatment offers the potential to add even more benefits. Thus, the objective of the study is to examine the potential improvement in supply chain performance through flexibility in silvicultural treatment decisions at the operational level. The specific goals are: (i) to provide an operational level wood procurement planning model which uses silvicultural treatment as a decision variable; (ii) to employ a mechanism to account for the impact of operational level silvicultural flexibility on long-term supply and to incorporate it in decision-making; (iii) to quantify the improvement in supply chain profits and demand fulfillment rates under a range of conditions to account for the impact on long-term supply.

3.2. METHOD

The problem was set up from the perspective of a wood procurement company responsible for harvesting cutblocks and delivering raw materials to meet demands from various manufacturing mills. This can be characterized as a multi-product, multi-industry problem with divergent flow. It was assumed that a strategic plan, a 5-year spatial plan, and an annual plan had already been prepared based on long-term economic analysis such as NPV. On the market side, the prevailing demand was a random parameter that differed from the forecast. Thus the short-term operational plan was to be redeveloped in light of the prevailing demand for profit maximization.

3.2.1. Simulation experiment

An experiment was designed to measure the potential financial gains and demand fulfillment rates from allowing redevelopment of the operational level plan with alternate silvicultural treatment prescriptions. In this study, silvicultural treatment refers only to activities that yield merchantable volume. Various scenarios were constructed and simulated to quantify the benefits. The simulation process is illustrated in Figure 3.1; plans are developed and executed under demand uncertainty on a rolling planning horizon basis. First, a random number generator was used to simulate demands from a set of mills. On the supply side, there were volumes of assortments available in cutblocks that are a function of the silvicultural treatment applied. Using this information, a scenario was generated and used as input to the operational level wood procurement planning model. The first period statistics were collected from the plan generated by the model since it is the only period executed. The statistics collected included profit generated and demand fulfillment rates. Demand fulfillment rate is the percentage of the volume supplied relative to the demand. Unfulfilled demand is not transferred to the subsequent period. The volumes prescribed in the first period were deducted from the initial inventory and the next iteration was run with the updated demand information (randomly generated).

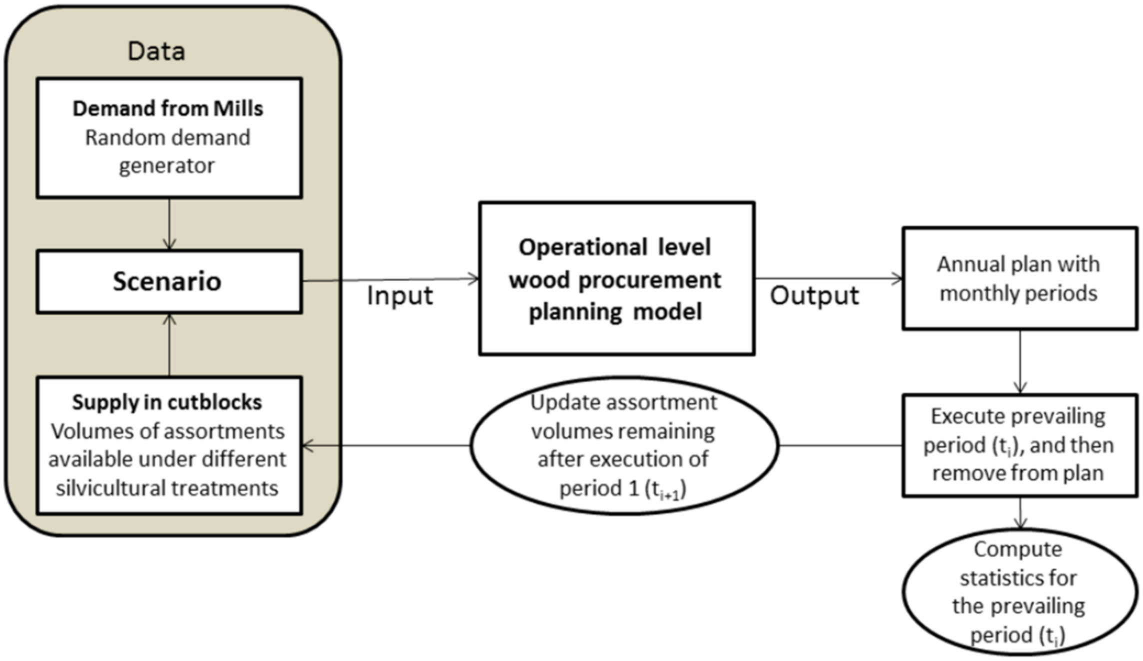

Figure 3.1. An illustration of the planning process simulation.

The simulated scenarios are outlined in Table 3.1. Scenarios 1 and 2 represent the status quo approach; there was no flexibility in the choice of silvicultural treatment. As indicated in the third column of Table 1, scenario 1 represents a setting with low demand volatility and scenario 2 represents a setting with high demand volatility. It was assumed that demand is a random parameter with a normal probability distribution. The low and high volatility represent a standard deviation that is 15% and 40% of the base demand, respectively. These values are based on studies by Childerhouse and Towill (2000), Zhang and Zhang (2007), UN (2013). In scenarios 3 to 10, silvicultural treatment could be changed to improve supply-demand alignment. In scenarios 3 and 4, no additional cost was incurred to exercise this flexibility. Thus, we did not account for future impact of changing silvicultural treatment from what was initially prescribed to a cutblock. However, in scenarios 5 to 10, future impact of changing silvicultural treatment was accounted through applying different intensities of flexibility cost. The different intensities were established to conduct sensitivity analysis; further discussion on this cost is provided in the next section.

Table 3.1. The list of scenarios used for the experiment.

Scenario	Flexibility in silvicultural treatment	Demand volatility	Cost imposed based on the following silvicultural intensity		
			Extensive	Basic	Intensive
1	No	Low	Not applicable		
2		High			
3	Yes	Low	Cost not imposed		
4		High			
5	Yes	Low	√		
6		Low		√	
7		Low			√
8		High	√		
9		High		√	
10		High			√

The planning horizon for each scenario was one year divided into 12 monthly periods. The plan was executed in a rolling planning horizon approach; this framework minimizes the incorporation of uncertain data in decision-making. The approach is depicted in Figure 3.2; in each prevailing period, a plan was developed for the entire horizon with knowledge of demand for the prevailing period and forecasts for the remaining periods. However, the plan was implemented only in the prevailing period. At the start of the next period, a new plan was developed using updated demand and forecast information. Both actual and forecast demands were generated randomly assuming a normal distribution. The process continued until the end of the planning horizon. For each scenario, 50 repetitions were carried out under simulated stochastic demand.

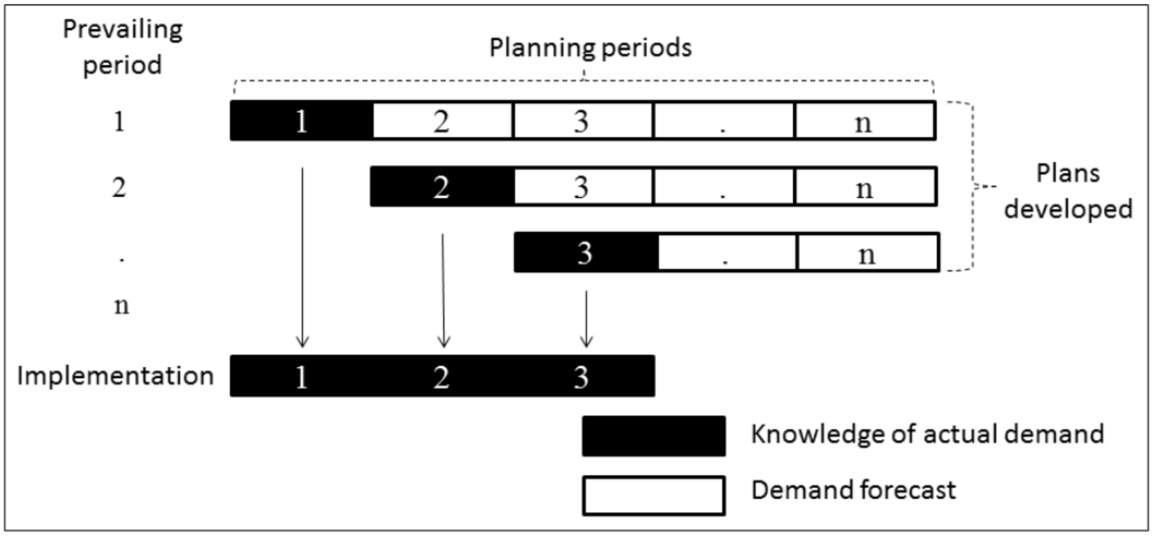

Figure 3.2. An illustration of the rolling planning horizon approach.

3.2.2. Flexibility cost

The complexity in forest dynamics and forest management renders the task of anticipating the precise long-term effect of altering silvicultural treatment at the operational level quite challenging. Nevertheless, to avoid undesirable impact of operational level amendments on long-term sustainability, we imposed a cost in conjunction with a change in the silvicultural treatment. This is referred to as flexibility cost. The cost was estimated based on an assumption that forest succession can be influenced through applying a silvicultural regime (Fujimori 2001; Homagain et al. 2011). A silvicultural regime is a series of interventions imposed on the cutblock over time that includes regeneration, tending and harvesting activities. If the treatment was altered, we assumed that silvicultural regime could be prescribed to ensure that the cutblock still reaches an initially desired state. Theoretically, reaching this state will ensure that the long-term sustained yield of the forest is not significantly impacted. A sensitivity analysis was then conducted on cost associated with silvicultural regimes. The range of values used for the sensitivity analysis was based on different silvicultural regimes (Table 3.2). These regimes were inspired by those proposed in Bell et al. (2008) in a similar context. The costs of the three regimes were subsequently used to conduct the sensitivity analysis.

Table 3.2. The silvicultural regimes used to estimate flexibility cost for sensitivity analysis

Activity	Silvicultural regime		
	Extensive	Basic	Intensive
Site preparation	√	√	√
Plant		√	√
Pre-commercial thinning		√	√
Fill Plant			√
Tending			√

3.2.3. Mathematical formulation

The overall plan components are illustrated in Figure 3.3. The objective was to maximize profit; revenue was generated through delivery of product assortments from cutblocks to customer mills. The costs stemmed from harvesting and transportation activities as well as flexibility cost. The yield of product assortments from cutblocks depended on the silvicultural treatment applied. There was also a decision to be made on harvesting systems to be employed. The cost of harvesting a cutblock depended on the productivity of the chosen system. Stand specific parameters were assumed to be uniform with regards to their influence on the productivity of harvest systems. It was assumed that the land base already had an existing road network. Only the costs associated with the portions of roads that needed to be built or upgraded to join the cutblocks to the existing network was taken into consideration and included in the harvesting cost. We assume that inventory could be stored on roadsides until demand arose in the future.

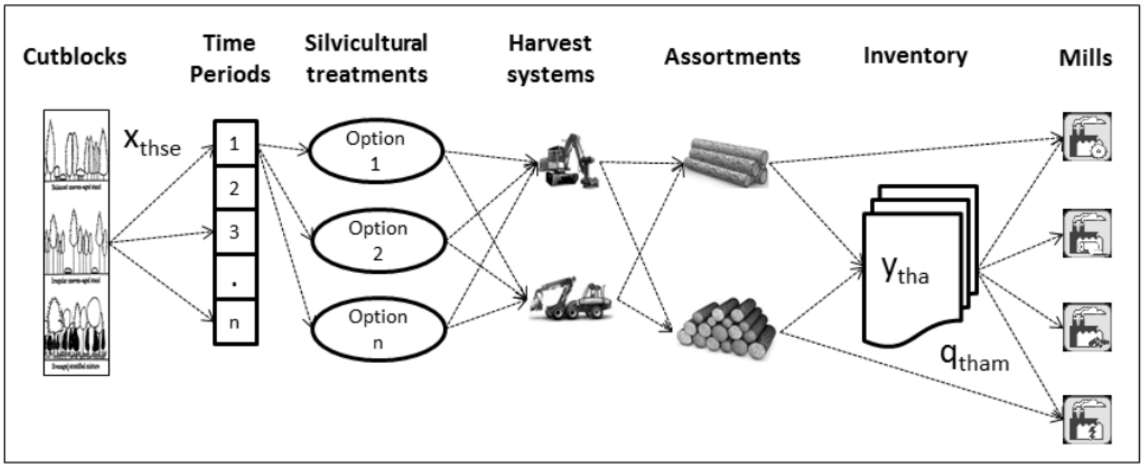

Figure 3.3. A depiction of the overall plan components with the decision variables.

Table 3.3. Description of the sets used in the mathematical model.

Notation	Description
T	Set of time periods *t*
H	Set of cutblocks *h*
S	Set of silvicultural treatments *s*
E	Set of harvest systems *e*
A	Set of assortments *a*
M	Set of mills *m*

Table 3.4. Description of the input data for the mathematical model.

Notation	Description
V_{hsa}	Maximum volume of assortment *a* available in cutblock *h* when subjected to silvicultural treatment *s* (m^3)
N_a	The selling price per cubic meter of assortment *a* ($\$\cdot m^{-3}$)
C_e	Harvest cost under harvest system *e* ($\$\cdot day^{-1}$)
B_{hm}	Round trip distance from cutblock *h* to mill *m* (km)
G_{hm}	Unit transportation cost between cutblock *h* and mill *m* ($\$\cdot m^{-3}\cdot km^{-1}$)
R_t	Maximum transportation capacity during period *t* (m^3)
J_{hs}	The cost incurred to alter the prescribed treatment in cutblock *h* to silvicultural treatment *s* ($)
Y^I_{ha}	Initial roadside inventory of assortment *a* in cutblock *h* (m^3)
Y^C_{th}	Unit stocking cost in cutblock *h* during period *t* ($\$\cdot m^{-3}$)
P_{se}	The productivity of harvest system *e* under silvicultural treatment *s* ($m^3\cdot day^{-1}$)
O_{te}	Number of work days available for harvest system *e* during period *t*
D_{tam}	Volume of assortment *a* demanded by mill *m* during period *t* (m^3)
V	A very small number

Table 3.5. Decision variables of the mathematical model.

Notation	Description
b_{hse}	1, if block *h* is planned for harvesting in any period using silvicultural treatment *s* and harvest system *e,* 0, otherwise
x_{thse}	The proportion of cutblock *h* cut in period *t* under silvicultural treatment *s* using system *e*
q_{tham}	The volume of assortment *a* transported from cutblock *h* to mill *m* in period *t* (m^3)
y_{tha}	The volume of assortment *a* stored in cutblock *h* at the end of period *t* (m^3)
r_h	Integer variable used to limit the number of periods during which cutblock h is cut

[1]
$$
\begin{aligned}
&\text{Maximize Profit}\\
&= \sum_{t\in T}\sum_{h\in H}\sum_{a\in A}\sum_{m\in M} q_{tham}(N_a \; - G_{hm}B_{hm})\\
&- \sum_{t\in T}\sum_{h\in H}\sum_{s\in S}\sum_{e\in E}\sum_{a\in A} x_{thse}V_{hsa}C_eP_{se}^{-1}\\
&- \sum_{t\in T}\sum_{h\in H}\sum_{a\in A} y_{tha}Y_{th}^{C} - \sum_{h\in H}\sum_{s\in S}\sum_{e\in E} b_{hse}J_{hs}
\end{aligned}
$$

Subject to,

[2] $$y_{tha} = Y_{ha}^{I} + \sum_{s\in S}\sum_{e\in E} x_{thse}V_{hsa} - \sum_{m\in M} q_{tham} \quad \forall\, h, a, t = 1$$

[3] $$y_{tha} = \sum_{s\in S}\sum_{e\in E} x_{thse}V_{hsa} + y_{t-1,h,a} - \sum_{m\in M} q_{tham} \quad \forall\, h, a, t > 1$$

[4] $$\sum_{h\in H} q_{tham} \leq D_{tam} \qquad \forall\; t, a, m$$

[5] $$\sum_{h\in H}\sum_{s\in S}\sum_{a\in A} V_{hsa}x_{thse} \leq \sum_{s\in S} P_{se}O_{te} \qquad \forall\, t, e$$

[6] $$\sum_{t\in T}\sum_{e\in E} x_{thse} \leq 1 \qquad \forall\, h, s$$

[7] $$\sum_{s\in S}\sum_{e\in E} b_{hse} \leq 1 \qquad \forall\; h$$

[8] $$b_{hse}V \leq \sum_{t\in T} x_{thse} \qquad \forall\, h, s, e$$

[9] $$b_{hse} \geq \sum_{t\in T} x_{thse} \qquad \forall\, h, s, e$$

[10] $$\sum_{t\in T}\sum_{s\in S}\sum_{e\in E} x_{thse} = \sum_{s\in S}\sum_{e\in E} b_{hse} \qquad \forall\, h$$

[11] $$\sum_{h\in H}\sum_{a\in A}\sum_{m\in M} q_{tham} \leq R_t \qquad \forall\, t$$

[12] $$\sum_{s\in S}\sum_{e\in E} x_{thse} + \sum_{s\in S}\sum_{e\in E} x_{t+1,h,s,e} = r_h \quad \forall\, h, t = 1..t-1$$

[13] $$r_h \leq 1 \qquad \forall\; h$$

[14] $$b_{hse}, r_h \in \{0,1\}$$

[15] $$x_{thse}, q_{tham}, y_{tha} \geq 0 \qquad \forall\, t, h, s, e, a, m$$

The sets, input data and decision variables of the mathematical model are presented in Tables 3.3, 3.4 and 3.5, respectively. The objective function (eqn. 1) was formulated as profit maximization. The first element represents the revenue generated through delivery of wood assortments to mills minus transportation cost. The second and third elements represent the variable costs associated with harvesting and inventory, respectively. The last element represents flexibility cost imposed for altering silvicultural treatment from what was initially prescribed to a cutblock.

Equations 2 and 3 are flow conservation constraints that ensure storage balance of assortments in cutblocks. Equation 2, handles the first period of the planning horizon and equation 3 handles the remaining periods. Equation 4 ensures that the volume of wood assortments transported to a mill during a particular period is less than or equal to the demanded volume. Equation 5 is a harvest capacity constraint; it ensures that the volume harvested per period is less than or equal to the maximum production capacity. Equation 6 ensures the total volume harvested in a cutblock in all periods is less than or equal to the maximum available under a silvicultural treatment. Equation 7 forces application of the same silvicultural treatment to a cutblock even if harvesting is partitioned to different periods and different harvest systems. Equations 8-9 establish a relationship between the variables b_{hse} and x_{thse} by triggering variable b_{hse} to 1 if a cutblock is planned to be harvested over the planning horizon. V ensures Equation 8 is satisfied when $x>0$. Equation 10 ensures that if a cutblock is selected for harvest, the entire available volume is harvested over the planning horizon. Equation 11 ensures that the total volume delivered to all mills in each period is lower than the transportation capacity. Equation 12 and 13 limit harvesting of a cutblock to be partitioned to a maximum of two subsequent periods. Finally, equations 14 and 15 assign binary restrictions and non-negativity restrictions to respective variables.

3.2.4. Statistical Analysis

Statistical analyses were performed using SigmaPlot®, version 12.0 for Windows. Friedman repeated measures analysis of variance on ranks were conducted to compare the effects of flexibility in the choice of silvicultural treatment, the different intensities of flexibility costs imposed, and demand volatility levels, on profit and demand fulfillment rates. Tukey's post hoc tests (Tukey 1949) were carried out to further analyze the statistical significance effect of levels of the independent variables on the dependent variable in each model. Also, analysis of variance (Fisher 1959) tests were carried out to examine effects of intensities of flexibility costs imposed on proportion of silvicultural treatments prescribed. The residuals were tested for normality and homogeneity of variance prior to conducting the tests.

3.3. CASE STUDY

3.3.1. Description

A hypothetical case study was developed based on data received from a forest products company operating in Quebec, Canada. The wood procurement company operates in the boreal mixedwood forest region. The region is characterized by forests with several of the following species: black spruce (*Picea mariana* (Mill.) BSP), white spruce (*Picea glauca* (Moench) Voss), jack pine (*Pinus banksiana* Lamb.), white pine (Pinus strobus L.), red pine (Pinus resinosa Sol.), balsam fir (*Abies balsamea* (L.) Mill.), larch (*Larix larcina* (Du Roi) K. Koch), eastern red cedar(*Juniperus virginiana* L.), trembling aspen (*Populus tremuloides* Michx.), yellow birch (Betula alleghaniensis Britt.), paper birch (*Betula papyrifera* Marsh.), balsam poplar (*Populus balsamifera* L.), sugar maple (*Acer saccharum* Marshall). With regards to the size of the cutblocks, 83% were below 50 ha, and the remaining 17% were between 50 and 100 ha. The company manages demand from 10 mills in the region. The acquired data contained information on volumes demanded during a one year horizon which was used as the base demand for the experiment (Table 3.6 in Appendix). The transportation capacity was set to be unlimited.

3.3.2. Supply

There were 50 cutblocks allocated for harvest in a one-year period with information on volumes by assortment. It was assumed that clearcut was the default treatment prescribed to all cutblocks. With clearcut as the default treatment, the total volume available of each assortment was at least 1.5 times greater than the base demand. The volumes available under alternative treatments were therefore estimated assuming that they would be a subset of the clearcut treatment. Four additional treatments were developed based on proportions of volumes in the cutblocks. While these treatments might be considered coarse representation of natural dynamics for a given forest, their use permits a practical approach to carry out the experiment. In practice, more refined prescriptions should be developed for each cutblock based on stand specific parameters. Option 1 and 2 are construction treatments inspired by Raymond et al. (2009) where 50% of the default volume is removed from the block. They represent two variants of the extended irregular shelterwood system. Under option 1, 75% of the extracted volume is softwood while only 25% of hardwood is removed. In contrast, under option 2, 75% of the extracted volume is hardwood and 25% of it is softwood. In cutblocks with insufficient softwood or hardwood volumes, the restriction on proportion of species to be extracted was relaxed. Option 3 and 4 were treatments inspired by Ruel et al. (2007), they represent different intensities of partial harvesting of the cutblocks with 40% and 30% of the volumes being removed, respectively. The volumes under these treatments were estimated by multiplying the default values by 0.4 (option 3), and 0.3 (option 4). Data were generated for all cutblocks to specify volumes available under each option. Table 3.7 displays the assortments and the prices used in the experiment; grade 1 and 2 represent higher and lower value logs, respectively. Log prices used in the experiment were obtained from the Wood producers association of Québec (SPFRQ 2013).

Table 3.7. Example of assortment volumes by silvicultural treatment for a cutblock.

Assortment	Volumes available under silvicultural treatment ($m^3 \cdot ha^{-1}$)					Price
	Default	Option 1	Option 2	Option 3	Option 4	($\$ \cdot m^{-3}$)
Yellow birch Grade 1	0.07	0.07	0.07	0.03	0.02	407
Yellow birch Grade 2	0.39	0.39	0.39	0.15	0.12	169
Paper birch Grade 1	0.59	0.59	0.59	0.24	0.18	390
Paper birch Grade 2	5.97	5.97	5.97	2.39	1.79	105
Sugar maple Grade 1	0.00	0.00	0.00	0.00	0.00	407
Sugar maple Grade 2	0.00	0.00	0.00	0.00	0.00	169
Deciduous pulp	30.60	17.98	30.60	12.24	9.18	60
Trembling aspen	53.39	0.00	37.38	21.36	16.02	85
White pine	0.28	0.28	0.28	0.11	0.08	105
Red pine	0.00	0.00	0.00	0.00	0.00	105
Fir/spruce/pine/tamarack	108.71	74.72	24.72	43.49	32.61	93

3.3.3. Costs

Two options on harvesting systems were utilized to implement the treatments: cut-to-length (CTL) and full-tree systems (FT). The productivity of the systems varies depending on the treatment being implemented. The productivity values used in the case study were estimates based on values published in Meek (2006) and Gingras (1994). The cost of transportation was estimated at $\$0.032 \cdot m^{-3} \cdot km^{-1}$ based on a payment rate of $\$80 \cdot hr^{-1}$ and volume capacity of $50m^3$. Information on distances between mills and cutblocks were part of the acquired data (Table 3.9 Appendix). The hourly costs for cut-to-length and full-tree systems were estimated at Canadian $260 and $322 per scheduled machine hour, respectively, based on Gautam et al. (2010) and Puttock et al. (2005). Costs were actualised to the year 2013 using the bank of Canada inflation calculator (BOC 2013). The total harvesting cost depended on the productivity of the chosen system in a particular cutblock. Inventory cost structure is particularly difficult to estimate, as it includes carrying cost, ordering costs, backlog costs, deterioration cost, opportunity cost, etc. The cost was set to a high value in this experiment to restrict the model from excessively stocking in the forest. The model's decision to store inventory will be based on forecast data. However, due to the execution of the model on a rolling period basis, the demand will eventually change when it materializes. Thus inserting a high cost for inventory forces the model to match current demand with supply rather than stocking. However, the costs were not made to be exceedingly high because exact match between supply and demand cannot be made, and it would be necessary to store some inventory. With regards to flexibility cost, the costs associated with each regime were estimated using a government report (MRN 2009) and converted to 2013 Canadian dollar (BOC 2013); the costs were $\$2\cdot m^{-3}$, $\$12\cdot m^{-3}$ and $\$21\cdot m^{-3}$ for extensive, basic and intensive, respectively.

3.4. RESULTS

The mathematical model was coded using the AMPL modeling language (Fourer et al. 2003) and solved using CPLEX 12.5 in a 3.07 GHz PC with 12 GB RAM. An iteration of the case study with 12 time periods contained 35,232 linear variables, 1,500 binary variables and 8,342 constraints. The optimality gap was set to within 1% and a time limit for computation was fixed at 1000 seconds. The solutions obtained in the experiment were between 0.068% and 1.78% of the relaxed problem. 50 repetitions of each of the 10 scenarios were run on a rolling planning horizon basis for 12 monthly periods. In general, it was found that both the profit values as well as demand fulfillment rates were higher under scenarios with flexibility in the choice of silvicultural treatment at the operational level (Figures 3.4-3.7). The values represent a total generated by the entire realized plan.

The distributions of the profit values under the low and high volatility scenarios are shown in Figures 3.4 and 3.5, respectively. Trends under both volatility levels were similar; when given flexibility in the choice of silvicultural treatment, the profits increased and subsequently showed a decreasing trend with an increasing flexibility cost. A one-way repeated measures analysis of variance by ranks showed that there was a statistically significant difference in the profit values ($p < 0.001$). Results of the multiple comparison procedures (Tukey test) are included in the figures. Scenarios without flexibility in the choice of silvicultural treatment (1 and 2) generated profits significantly lower than the remaining scenarios. Even with the most intensive flexibility cost imposed, the profits were still significantly higher than the scenario without flexibility in the choice of silvicultural treatment. Flexibility in the choice of silvicultural treatment permitted the model to develop a plan that procured a mix of products more aligned with the emerging demand.

Under low volatility in demand (scenario 3), an average increase in profit of $862,931 was observed when allowing flexibility in the choice of silvicultural treatment without imposing flexibility cost. The difference was reduced to $674,242, $639367 and $322,600 when extensive (scenario 5), basic (scenario

6) and intensive (scenario 7) flexibility costs were applied, respectively. Similarly, an increase of $950,124 was observed under high demand volatility (scenario 4) when flexibility in the choice of silvicultural treatment was permitted. The subsequent differences as the flexibility cost increased were $923,286 (scenario 8), $663,855 (scenario 9) and $384,078 (scenario 10). Increases in profits were greater under high demand volatility scenarios. The percentage increases were on average 5.5% (scenario 4), 5.4% (scenario 8), 4.1% (scenario 9) and 2.6% (scenario 10) under high demand volatility. The percentage increases in scenarios with low demand volatility were 2.8% (scenario 3), 2.0% (scenario 5), 1.8% (scenario 6) and 0.2% (scenario 7).

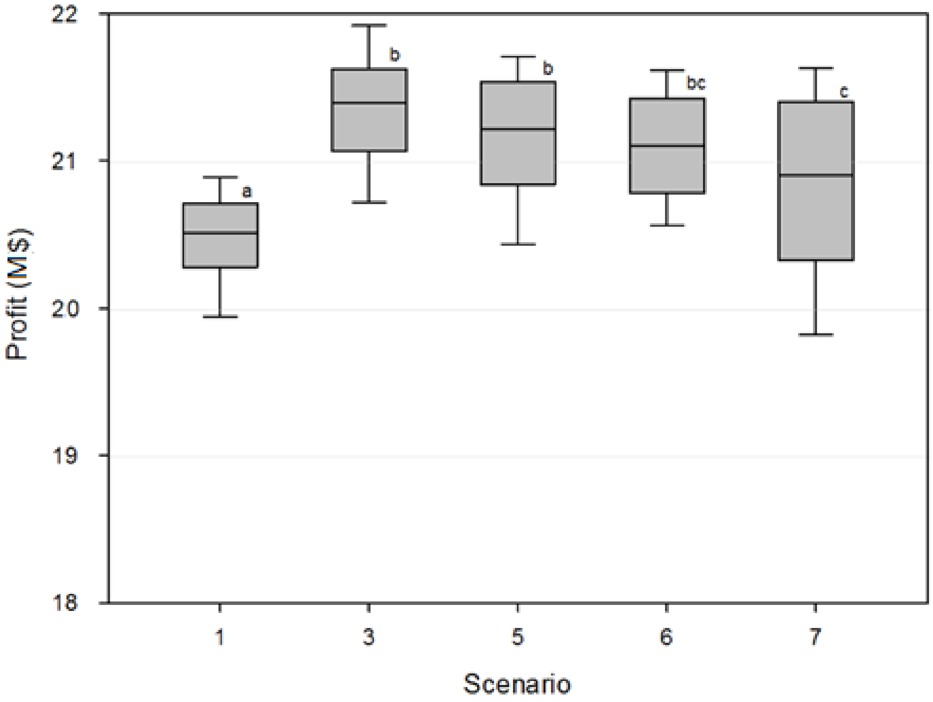

Figure 3.4. A box and whisker graph showing distribution of profit values for the low volatility scenarios (scenario 1, 3, 5, 6 and 7). Boxes labeled with the same alphabet are not significantly different from each other.

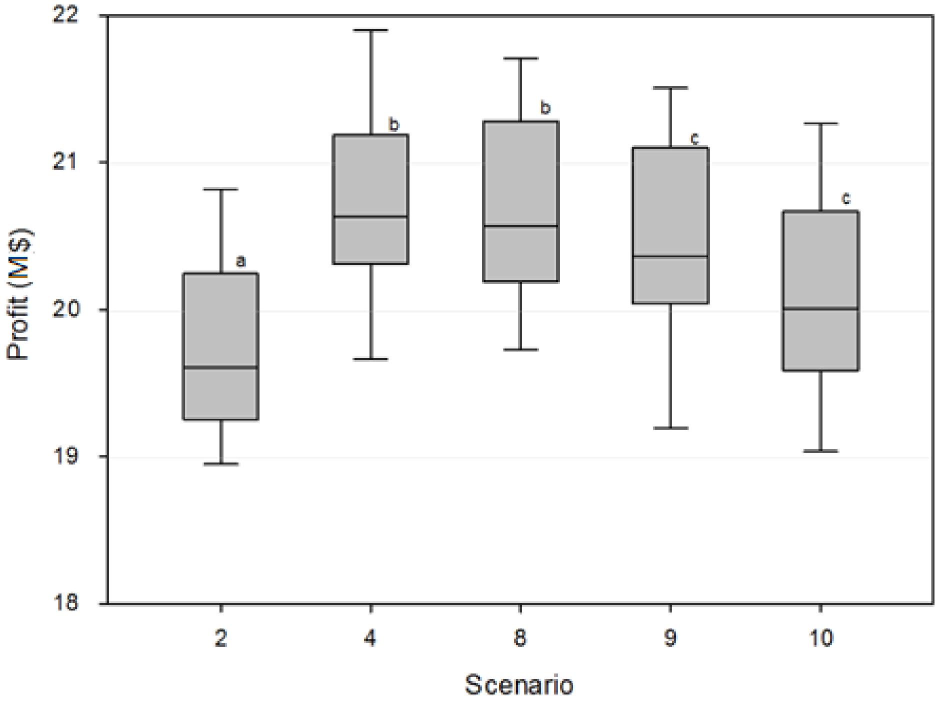

Figure 3.5. A box and whisker graph showing distribution of profit values for the high volatility scenarios (2, 4, 8, 9 and 10). Boxes labeled with the same alphabet are not significantly different from each other.

The distribution of demand fulfillment rates from 50 experimental runs are shown in Figures 3.6 and 3.7 for the lower and higher volatility levels, respectively. Repeated measures analyses of variance by ranks showed statistically significant difference in the demand fulfillment rates ($p < 0.001$). Results of the multiple comparison procedures (Tukey test) are included in the figures; boxes labeled with the same letter are not significantly different from each other. Flexibility in the choice of silvicultural treatment significantly increased the demand fulfillment rates. In lower volatility scenarios, the rates increased from 83.6% to 87.3% when flexibility in the choice of silvicultural treatment was permitted without imposing a cost. The rates were 86.7%, 86.8% and 85.8% when imposed flexibility costs based on extensive, basic and intensive silviculture intensity, respectively. In higher volatility scenarios, the increase in the demand fulfillments rates through permitting flexibility ranged from an average of 81.6% to 85.2%. Subsequently, imposing flexibility costs based on extensive, basic and intensive silviculture intensity led to demand fulfillments rates of 85.8%, 84.6% and 83.5%, respectively.

Unlike profit values, the difference in demand fulfillment rates due to providing flexibility in the choice of silvicultural treatment was not definitively greater under high volatility scenarios. Under high volatility scenarios, the increases were 3.6%, 4.2%, 3.0% and 1.9% for no flexibility cost, extensive, basic and intensive silviculture intensity, respectively. The corresponding values for low volatility scenarios were, 3.7%, 3.1%, 3.2% and 2.2%, respectively. The greater increase in profit under higher volatility scenarios without the same increases in demand fulfillment rates can be explained through the differences in the assortment prices. The model would have focused on fulfilling demand of assortments that generated higher revenue rather than overall demand fulfillment since the objective function sought to maximize profit.

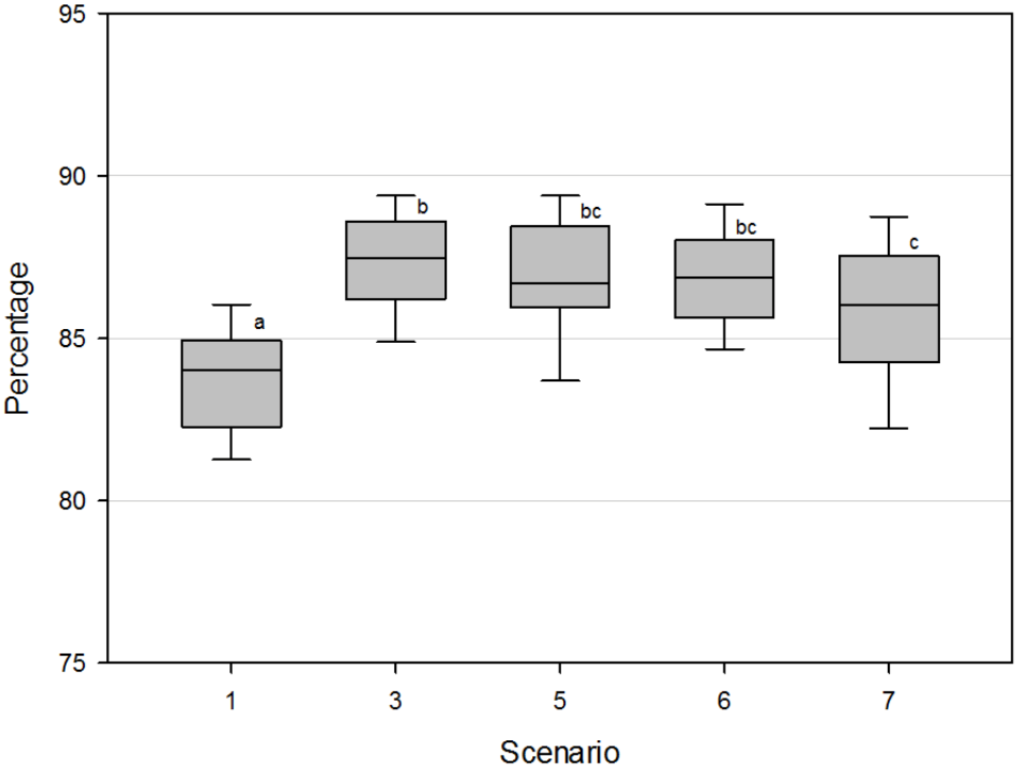

Figure 3.6. A box and whisker graph showing distribution of demand fulfillment rates for low volatility scenarios.

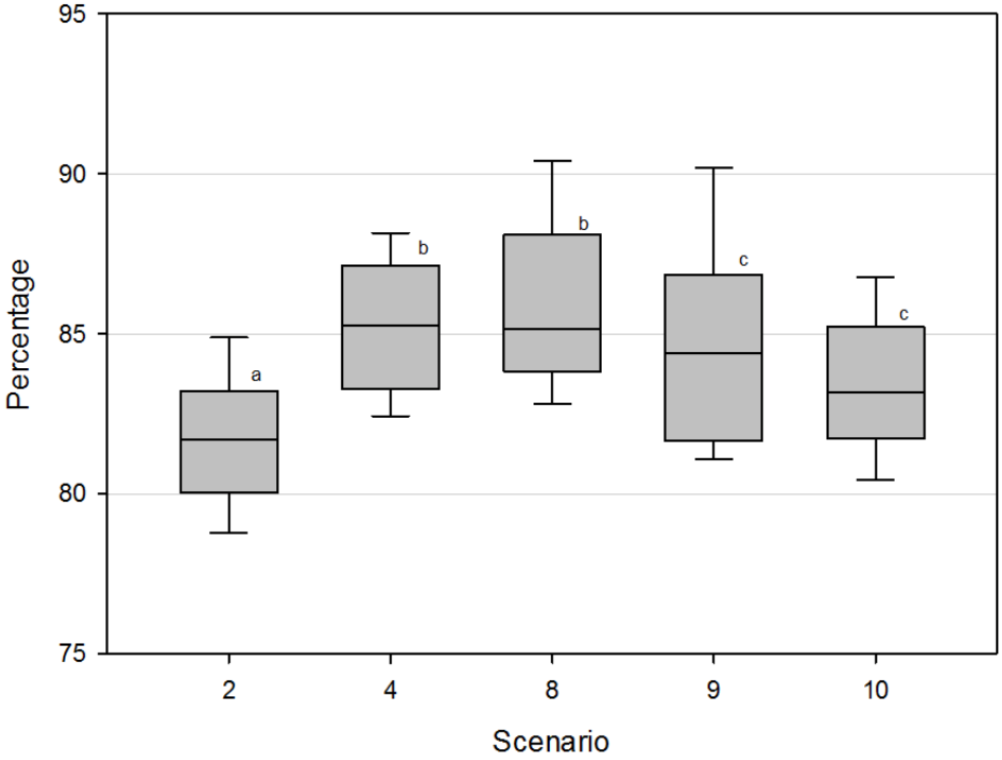

Figure 3.7. A box and whisker graph showing distribution of demand fulfillment rates under high volatility scenarios.

A summary of the proportions of silvicultural treatments implemented under different scenarios is shown in Table 3.7. The proportions reflect average values from 50 runs of the model and are based on volume. ANOVAs were carried out for each silvicultural treatment proportions prescribed under different scenarios. The results of the analyses have been included in Table 3.8; numbers labeled with the same letter are not significantly different from each other. The proportions of silvicultural treatments prescribed did not vary significantly with demand volatility levels. The proportions did, however, vary significantly depending on the intensity of flexibility costs imposed. Multiple comparison tests (Holm-Šídák) showed that the difference between "no cost" and "extensive" was not statistically significant but the remaining regimes all produced proportions significantly different from each other. The trend of increased application of the default treatment was observed as the flexibility cost was augmented.

Table 3.8. Descriptive statistics of proportions of silvicultural treatments prescribed under different scenarios based on volume (m³).

Basis for Penalty	Prescribed treatment	Low volatility			High volatility		
		Average	Min	Max	Average	Min	Max
No cost	Default	58.3 (5.3)[a]	46.0	70.5	58.6 (6.3)[a]	43.7	74.1
	Option 1	16.8 (4.5)[d]	7.0	27.8	15.0 (5.2)[d]	3.8	27.6
	Option 2	13.0 (5.2)[g]	2.9	25.7	12.7 (4.5)[g]	4.4	22.4
	Option 3	7.0 (2.8)[j]	0.0	12.7	8.2 (3.6)[j]	1.0	16.8
	Option 4	4.8 (2.2)[m]	0.6	10.9	5.5 (2.3)[m]	1.8	12.4
Extensive	Default	57.3 (5.5)[a]	44.5	67.8	58.2 (6.9)[a]	42.6	75.5
	Option 1	16.2 (4.5)[d]	7.8	28.3	15.0 (5.6)[d]	2.5	30.4
	Option 2	14.3 (4.2)[g]	5.3	23.5	12.3 (5.3)[g]	2.4	28.7
	Option 3	7.3 (3.4)[j]	0.5	14.9	8.9 (3.7)[j]	1.8	18.6
	Option 4	4.9 (2.6)[m]	0.2	13.2	5.5 (2.6)[m]	0.4	11.2
Basic	Default	71.6 (6.5)[b]	57.7	87.6	74.5 (5.1)[b]	63.7	85.3
	Option 1	9.9 (4.7)[e]	0.9	19.0	9.7 (4.3)[e]	0.0	18.5
	Option 2	10.0 (5.0)[h]	1.1	20.7	8.1 (3.5)[h]	1.0	17.3
	Option 3	4.8 (2.9)[k]	0.0	11.2	4.8 (2.7)[k]	0.0	10.7
	Option 4	3.6 (2.7)[n]	0.0	12.3	3.0 (2.2)[n]	0.0	9.0
Intensive	Default	81.2 (5.4)[c]	66.5	92.1	84.4 (6.6)[c]	71.4	97.4
	Option 1	6.7 (3.5)[f]	0.0	15.5	5.8 (4.7)[f]	0.0	18.6
	Option 2	6.8 (4.4)[i]	0.0	19.7	5.5 (4.0)[i]	0.0	18.2
	Option 3	2.4 (1.6)[l]	0.0	5.9	2.5 (2.2)[l]	0.0	10.4
	Option 4	2.9 (2.3)[o]	0.0	10.7	1.9 (1.9)[o]	0.0	7.0

* Values in parentheses represent the standard deviation

3.5. DISCUSSION AND CONCLUSION

The study was conducted to quantify the benefits of improving agility on supply chain profits and demand fulfillment rates. It also allowed the determination of a range of conditions under which benefits can be realized. The proposed approach of improving agility entailed allowing flexibility in the choice of silvicultural treatments at the operational level. A simulation experiment based on a rolling planning horizon framework with uncertain demand was implemented to a case study in Quebec, Canada. The process should be considered as a further development of the analyses presented by Howard and Temesgen (1997) and Moore et al. (2012). Treatments with an acceptable benefit-cost ratio should be considered as an option; the prevailing demand should then partly influence the decision on the actual treatment to be applied as the eventual profitability depends on it.

The importance of the approach is demonstrated by Figures 3.6 and 3.7. Under status quo (scenarios 1 & 2), demand fulfillment rates were lower despite the availability of assortments in the cutblocks; confirmed by the fact that rates were higher under scenarios with flexibility (Scenarios 3-10). Furthermore, an increase in profit through the approach was greater under high demand volatility (Figure 3.5) than in low volatility (Figure 3.4). This result has important implications for wood procurement systems operating in mixedwood stands that are responsible for supplying to value-added manufacturers. On the market side, these manufacturers are exposed to high demand volatility (Grace 2013); this will be reflected in the demand put forward to the wood procurement systems. On the supply side, mixedwood stands are characterized by variability in the composition of species among other features. The treatment applied will dictate the volume and ratio of assortments procured from a cutblock. The procurable mixture may contain both assortments with and without demand in the market. The decision to harvest is then based on whether the profit generated from the demanded assortments can offset the harvesting and storage of non-demanded assortments. There is an element of risk associated with future demand and also likelihood of quality deterioration during storage leading to a net loss. Thus, the cutblock may be bypassed altogether accepting a reduction in demand satisfaction as in scenarios 1 & 2. Flexibility in silvicultural treatment permits selection of a treatment that produces assortments reflective of the demand (Scenarios 3-10). As pointed out by Puettmann et al. (2009), there are generally a range of treatments applicable to any given forest stands. In this study, treatments were developed based on volume proportions. In practice, silviculturists should develop a range of close-to-nature silvicultural treatment options for each cutblock. Forest managers can then produce and execute harvest plans that are both ecologically and economically viable. Such multiple scale integration through incorporating input from silviculturists in supply chain management allows for adaptive management system with greater value-creation opportunity (Messier et al. 2013). Our results also suggest that significant improvement can be realised even if flexibility is permitted in only a certain proportion of the cutblocks. Table 3.8 demonstrates that even without any penalty imposed for exercising flexibility; almost 60% of the volume was procured through initially prescribed treatments. On the other hand, even under the condition where maximum penalty was imposed for exercising flexibility, the model procured almost 20% of the volumes through alternative treatments due to the associated benefits. These results reinforce the importance of silvicultural flexibility for wood procurement systems in delivering raw material to the forest products supply chain.

Despite the potential advantages, there are some challenges for implementation. This study was conducted under the assumption that the assortments in cutblocks can be accurately estimated, and that harvesting systems can procure just the targeted assortments under a prescribed treatment. The assumptions are supported by the advent in technology. For example, terrestrial LiDAR technology now permits accurate estimation of volumes by assortments in cutblocks (Dassot et al. 2011). On the harvesting front, machines can be equipped with GPS technology and computer algorithms to accurately identify and execute bucking patterns (Marshall 2007). However, costs can be a barrier to acquiring these technologies. The decision to adopt these tools and technologies depends on the return on investment. Future studies should conduct analysis such as cost plus loss based on profit gains displayed in Figures 3.4 & 3.5 to support decision-making.

Lastly, this study was based on an assumption that forest succession (productivity and species composition) can be controlled through applying silvicultural regimes; investments can be made to redirect the trajectory of stands within a desired range to overcome the impact of altering silvicultural treatment at the operational level. The assumption was necessary to maintain the focus of this study towards quantifying the benefits associated with flexibility in silvicultural treatments at the operational level. Alternatively, the experiment would have to be significantly expanded; the task would entail formulating a long-term plan, creating harvesting blocks over the land base in each period, simulating implementation of annual harvests on a rolling basis and observing the impact.

As such, it is a daunting task well beyond the scope of this paper. Nevertheless, such a study should be carried out in the future to anticipate the precise impact on the long-term wood supply.

3.6 ACKNOWLEDGEMENTS

The authors wish to acknowledge the technical support from FORAC research consortium. The authors would also like to express their gratitude to the review team consisting of Dr. Gary Kerr, Dr. Thomas Knoke and two anonymous reviewers for their valuable comments.

3.7. LITERATURE CITED

Andreassen, K. and Øyen, B.H. 2002 Economic consequences of three silvicultural methods in uneven-aged mature coastal spruce forests of central Norway. *Forestry* 75, 483-488.

Audy, J.-F., Moreira, M. P., Westlund, K., D'Amours, S., LeBel, L., & Rönnqvist, M. 2012 Alternative Logistics Concepts Fitting Different Wood Supply Situations and Markets. *CIRRELT* vol. 2024.

Beaudoin, D., LeBel, L., & Frayret, J. M. 2007 Tactical supply chain planning in the forest products industry through optimization and scenario-based analysis. *Canadian Journal of Forest Research* 37, 128-140.

Bell, F. Wayne, John Parton, Neil Stocker, Dennis Joyce, Doug Reid, Monique Wester, Al Stinson, Gordon Kayahara, and Bill Towill. 2008 Developing a silvicultural framework and definitions for use in forest management planning and practice. *The Forestry Chronicle* 84, 678-693.

Bettinger, P., Siry, J., Boston, K., & Grebner, Donald L. 2008 *Forest Management and Planning*. Academic Press, 331pp.

BOC. 2013 *the bank of Canada inflation Cacluator*. http://www.bankofcanada.ca/rates/related/inflation-calculator (accessed on 12 November, 2013)

Brazee, R., & Mendelsohn, R. 1988 Timber harvesting with fluctuating prices. *Forest Science* 34, 359-372.

Burger, D. H., & Jamnick, M. S. 1995 Using linear programming to make wood procurement and distribution decisions. *The Forestry Chronicle* 71, 89-96.

Chauhan, S., Frayret, J.M., Lebel, L. 2009 Multi-product supply planning in forest supply chain. European Journal of Operational Research. 196(2):688-696.

Christopher, Martin. 2010 *Logistics and supply chain management*. 4th edition. Financial Times/Prentice Hall, 288 pp.

Church, R. L. 2007 Tactical-level forest management models. In *Handbook of operations research in natural resources* . A. Weintraub, J.P. Miranda, C. Romero, T. Bjørndal, & R. Epstein. Springer US, pp. 343-363.

Childerhouse, P., & Towill, D. 2000 Engineering supply chains to match customer requirements. *Logistics Information Management*, 13(6), 337-346.

Dassot, M., Constant, T., & Fournier, M. 2011 The use of terrestrial LiDAR technology in forest science: application fields, benefits and challenges. *Annals of forest science* 68(5), 959-974.

D'Amours, S., Rönnqvist, M., & Weintraub, A. 2008 Using operational research for supply chain planning in the forest products industry. *INFOR: Information Systems and Operational Research* 46, 265-281.

Epstein, R., Nieto, E., Weintraub, A., Chevalier, P., & Gabarró, J. 1999 A system for the design of short term harvesting strategy. *European journal of operational research* 119, 427-439.

Fisher, R.A. 1959 *Statistical methods and scientific inference* (2nd edition). Hafner Publishing Co., New York, 1959.

Fourer, R. Gay D., and Kernighan B. 2003 *AMPL: A Modeling Language For Mathematical Programming*. Thomson/Brooks/Cole, 517pp.

FPAC. 2011 The New Face of The Canadian Forest Industry: The Emerging Bio-revolution, the Bio-pathways Project. *Forest Products Association of Canada & FPInnovations* 9pp.

Fujimori, T. 2001 *Ecological and silvicultural strategies for sustainable forest management*. Elsevier, 398 pp.

Gautam, S., LeBel, L., & Beaudoin, D. 2013 Agility capabilities in wood procurement systems: a literature synthesis. *International Journal of Forest Engineering* 24, 216-232.

Gautam, S., Pulkki, R., Shahi, C., & Leitch, M. 2010 Economic and energy efficiency of salvaging biomass from wildfire burnt areas for bioenergy production in northwestern Ontario: A case study. *Biomass and Bioenergy* 34, 1562-1572.

Gardiner, B., Byrne, K., Hale, S., Kamimura, K., Mitchell, S. J., Peltola, H., & Ruel, J. C. 2008 A review of mechanistic modelling of wind damage risk to forests. *Forestry* 81(3), 447-463.

Grace, P. G. 2013 Assessing the keys and barriers to success in the value-added wood product manufacturing sector: a multiple-case study analysis of small and medium-sized enterprises' Msc Thesis, The University of British Columbia.

Grenon, F., J.-P. Jetté and M. LeBlanc. 2011. Reference Manual for cosystem-Based Forest Management in Québec. Module 1 – Foundations and Implementation Approach. Québec, Centre d'enseignement et de recherche en foresterie de Sainte-Foy inc. and Ministère des Ressources naturelles et de la Faune, Direction de l’aménagement et de l’environnement forestiers. 51 p.

Gunn, E. 2009 Some Perspectives on Strategic Forest Management Models and the Forest Products Supply Chain. *INFOR: Information Systems and Operational Research* 47, 261–272.

Gingras J.-F. 1994 A comparison of full-tree versus cut-to-length systems in the Manitoba model forest. *Forest Engineering Research Institute of Canada* SR-92.

Hansen, E., Panwar, R., & Vlosky, R. 2013 *The Global Forest Sector: Changes, Practices, and Prospects*. Taylor and Francis Group, 462pp.

Homagain, K., Shahi, C., Luckai, N., Leitch, M., & Bell, F. W. 2011 Benefit–cost analysis of vegetation management alternatives: An Ontario case study. *The Forestry Chronicle* 87, 260-273.

Howard, A.F., & Temesgen, H. 1997 Potential financial returns from alternative silvicultural prescriptions in second-growth stands of coastal British Columbia. *Canadian journal of forest research* 27, 1483–1495.

Karlsson, J., Rönnqvist, M., & Bergström, J. 2004 An optimization model for annual harvest planning. *Canadian Journal of Forest Research* 34, 1747–1754.

Knoke, T., & Wurm, J. 2006 Mixed forests and a flexible harvest policy: a problem for conventional risk analysis?. *European Journal of Forest Research 125*(3), 303-315.

Lebel, L., & Carruth, J. S. 1997 Simulation of woodyard inventory variations using a stochastic model. *Forest products journal* 47, 52-57.

Liu, C., Ruel, Jean-Claude, & Zhang, S.Y. 2007 Immediate impacts of partial cutting strategies on stand characteristics and value. *Forest Ecology and Management* 250, 148-155.

Lussier, Jean-Martin. 2009 Changing our mental model from growing volume to producing value: The case of uneven-aged hardwood management. *The Forestry Chronicle* 85, 382–386.

Malcolm, J.R., & Harvey, B.D. 2013 The need for multi-cohort management in boreal forests. *The Forestry Chronicle* 89, 3, 271-274.

Marshall, H. 2007 Log merchandizing model used in mechanical harvesting. In *Handbook Of Operations Research In Natural Resources*. Springer US pp. 379-389.

Meek, P. 2006 Trials of four trial layouts adapted to shelterwood cuts. *Advantage* 7, 1-8

Messier, C., Puettmann, K. J., & Coates, K. D. 2013 *Managing forests as complex adaptive systems: building resilience to the challenge of global change*. Routledge.

Moore, T.Y., Ruel, J.-C., Lapointe, M. -A., & Lussier, J.-M. 2012 Evaluating the profitability of selection cuts in irregular boreal forests: an approach based on Monte Carlo simulations. *Forestry* 85, 63–77.

MRN. 2009 Enquête Sur Les Coûts De La Sylviculture Des Forêts Du Domaine De L’état : 2007-2008. *Ressources Naturelles et Faune, Québec* 109pp.

Paradis, G., LeBel, L., D'Amours, S., & Bouchard, M. 2013 On the risk of systematic drift under incoherent hierarchical forest management planning. *Canadian Journal of Forest Research* 43, 480-492.

Pulkki, R. 2003 Minimizing negative environmental impacts of forest harvesting operations. In *Towards Sustainable Management of the Boreal Forest*. P. J. Burton, C. Messier, D. W. Smith and W. L. Adamowicz (eds). National Research Council of Canada, pp. 581-628.

Puttock, D., Spinelli, R., & Hartsough, B. R. 2005 Operational trials of cut-to-length harvesting of poplar in a mixed wood stand. *International Journal of Forest Engineering* 16, 39-49.

Puettmann, K. J., Coates, K. D., & Messier, C. C. 2008 *A critique of silviculture: managing for complexity*. Island Press.

Raymond, P., Bedard, S., Roy, V., Larouche, C., & Tremblay, S. 2009 The irregular shelterwood system: review, classification, and potential application to forests affected by partial disturbances. *Journal of Forestry* 107, 405-413.

Ruel, J. C., Roy, V., Lussier, J. M., Pothier, D., Meek, P., & Fortin, D. 2007 Mise au point d'une sylviculture adaptée à la forêt boréale irrégulière. *The Forestry Chronicle* 83, 367-374.

Savard, M. 2011 *Planification Strategique D'un Réseau Logistique: Cas d'une entreprise forestière au Québec et de ses activités d'approvisionnement*. Université Laval, 158pp.

SPFRQ. 2013 *Syndicat des Propriétaires Forestiers de la Région de Québec*. http://www.spfrq.qc.ca. (accessed 20 October, 2013).

Stier, J. C., Steele, T. W., & Engelhard, R. J. 1986 Pulpwood procurement practices in the Wisconsin-upper Michigan pulp and paper industry. *Northern Journal of Applied Forestry* 3, 10-14.

Sun, C., & Ning, Z. 2014. Timber Restrictions, Financial Crisis, and Price Transmission in North American Softwood Lumber Markets. *Land Economics*, *90*(2), 306-323.

Tukey, J.W. 1949 Comparing individual means in the analysis of variance. *Biometrics* 5, 99-114.

UN. 2013 Forest products Annual Market Review 2012-2013. United Nations. 133pp

Walker, H. D., & Preiss, S. W. 1988 Operational planning using mixed integer programming. *The Forestry Chronicle* 64, 485-488.

Yousefpour, R., Jacobsen, J. B., Thorsen, B. J., Meilby, H., Hanewinkel, M., & Oehler, K. 2012 A review of decision-making approaches to handle uncertainty and risk in adaptive forest management under climate change. *Annals of forest science 69*(1), 1-15.

Zhang, C., & Zhang, C. 2007 Design and simulation of demand information sharing in a supply chain. *Simulation Modelling Practice and Theory* 15(1): 32-46.

3.8. APPENDIX

Table 3.6. Total base demand of all mills by assortment for the simulation horizon

Assortment	Volumes demanded (m^3) in month											
	1	2	3	4	5	6	7	8	9	10	11	12
Yellow birch Grade 1	298	291	374	301	312	263	314	338	361	338	299	300
Yellow birch Grade 2	291	239	314	275	365	244	265	312	316	279	290	313
Paper birch Grade 1	596	637	636	518	497	601	607	418	679	489	598	522
Paper birch Grade 2	1941	1560	2166	1827	1702	1936	2159	1541	1500	1595	1738	1930
Sugar maple Grade 1	28	26	35	40	29	33	29	32	36	37	32	36
Sugar maple Grade 2	34	47	46	46	40	27	31	40	38	39	30	32
Deciduous pulp	8476	6494	6690	8180	8212	5596	8720	10635	7687	8755	8544	6351
Trembling aspen	10603	10938	14326	13849	10104	9904	10008	10163	12309	10159	9760	10861
White pine	75	62	77	74	52	58	80	59	96	61	80	66
Red pine	0	0	0	0	0	0	0	0	0	0	0	0
Fir/spruce/pine/tamarack	38362	35235	34822	38843	41803	30508	40087	40169	37165	37413	37411	38100

Table 3.9. Round-trip distances between cutblocks and customer mills.

Harvest block	Mill									
	240	244	245	256	263	265	266	329	347	349
A1	95.27	95.27	95.27	95.27	95.27	95.27	91.10	88.87	95.27	88.87
A10	83.34	83.34	83.34	83.34	83.34	83.34	83.34	92.46	83.34	92.46
A11	61.77	61.77	61.77	61.77	61.77	61.77	57.61	55.38	61.77	55.38
A12	60.01	60.01	60.01	60.01	60.01	60.01	55.84	53.62	60.01	53.62
A13	62.55	62.55	62.55	62.55	62.55	62.55	58.39	56.16	62.55	56.16
A14	63.43	63.43	63.43	63.43	63.43	63.43	59.27	57.04	63.43	57.04
A15	61.83	61.83	61.83	61.83	61.83	61.83	57.67	55.44	61.83	55.44
A16	58.07	58.07	58.07	58.07	58.07	58.07	53.91	51.68	58.07	51.68
A17	60.87	60.87	60.87	60.87	60.87	60.87	56.70	54.48	60.87	54.48
A18	71.68	71.68	71.68	71.68	71.68	71.68	71.68	80.80	71.68	80.80
A19	71.84	71.84	71.84	71.84	71.84	71.84	71.84	80.96	71.84	80.96
A2	94.40	94.40	94.40	94.40	94.40	94.40	90.24	88.01	94.40	88.01
A20	71.89	71.89	71.89	71.89	71.89	71.89	71.89	81.01	71.89	81.01
A21	95.27	95.27	95.27	95.27	95.27	95.27	91.10	88.87	95.27	88.87
A22	94.40	94.40	94.40	94.40	94.40	94.40	90.24	88.01	94.40	88.01
A23	80.26	80.26	80.26	80.26	80.26	80.26	103.20	100.97	80.26	100.97
A24	76.32	76.32	76.32	76.32	76.32	76.32	99.26	97.03	76.32	97.03
A25	74.63	74.63	74.63	74.63	74.63	74.63	70.47	68.24	74.63	68.24
A26	83.52	83.52	83.52	83.52	83.52	83.52	79.35	77.13	83.52	77.13
A27	80.33	80.33	80.33	80.33	80.33	80.33	76.17	73.94	80.33	73.94
A28	80.17	80.17	80.17	80.17	80.17	80.17	80.17	89.29	80.17	89.29
A29	81.85	81.85	81.85	81.85	81.85	81.85	81.85	90.97	81.85	90.97
A3	80.26	80.26	80.26	80.26	80.26	80.26	103.20	100.97	80.26	100.97
A30	83.34	83.34	83.34	83.34	83.34	83.34	83.34	92.46	83.34	92.46
A31	61.77	61.77	61.77	61.77	61.77	61.77	57.61	55.38	61.77	55.38
A32	60.01	60.01	60.01	60.01	60.01	60.01	55.84	53.62	60.01	53.62
A33	62.55	62.55	62.55	62.55	62.55	62.55	58.39	56.16	62.55	56.16
A34	63.43	63.43	63.43	63.43	63.43	63.43	59.27	57.04	63.43	57.04
A35	61.83	61.83	61.83	61.83	61.83	61.83	57.67	55.44	61.83	55.44
A36	58.07	58.07	58.07	58.07	58.07	58.07	53.91	51.68	58.07	51.68
A37	60.87	60.87	60.87	60.87	60.87	60.87	56.70	54.48	60.87	54.48
A38	71.68	71.68	71.68	71.68	71.68	71.68	71.68	80.80	71.68	80.80
A39	71.84	71.84	71.84	71.84	71.84	71.84	71.84	80.96	71.84	80.96
A4	76.32	76.32	76.32	76.32	76.32	76.32	99.26	97.03	76.32	97.03
A40	71.89	71.89	71.89	71.89	71.89	71.89	71.89	81.01	71.89	81.01
A41	95.27	95.27	95.27	95.27	95.27	95.27	91.10	88.87	95.27	88.87
A42	94.40	94.40	94.40	94.40	94.40	94.40	90.24	88.01	94.40	88.01
A43	80.26	80.26	80.26	80.26	80.26	80.26	103.20	100.97	80.26	100.97
A44	76.32	76.32	76.32	76.32	76.32	76.32	99.26	97.03	76.32	97.03
A45	74.63	74.63	74.63	74.63	74.63	74.63	70.47	68.24	74.63	68.24
A46	83.52	83.52	83.52	83.52	83.52	83.52	79.35	77.13	83.52	77.13
A47	80.33	80.33	80.33	80.33	80.33	80.33	76.17	73.94	80.33	73.94
A48	80.17	80.17	80.17	80.17	80.17	80.17	80.17	89.29	80.17	89.29
A49	81.85	81.85	81.85	81.85	81.85	81.85	81.85	90.97	81.85	90.97
A5	74.63	74.63	74.63	74.63	74.63	74.63	70.47	68.24	74.63	68.24
A50	83.34	83.34	83.34	83.34	83.34	83.34	83.34	92.46	83.34	92.46
A6	83.52	83.52	83.52	83.52	83.52	83.52	79.35	77.13	83.52	77.13
A7	80.33	80.33	80.33	80.33	80.33	80.33	76.17	73.94	80.33	73.94
A8	80.17	80.17	80.17	80.17	80.17	80.17	80.17	89.29	80.17	89.29
A9	81.85	81.85	81.85	81.85	81.85	81.85	81.85	90.97	81.85	90.97

CHAPTER 4. A SIMULATION-OPTIMIZATION SYSTEM TO ANTICIPATE THE LONG-TERM IMPACT OF OPERATIONAL LEVEL SILVICULTURAL FLEXIBILITY

Abstract

Flexibility in the choice of silvicultural treatment at the operational level has been identified as a possible way to mitigate the impact of uncertain demand on supply chain performance. However, its influence on long-term wood supply has not yet been investigated. This study proposes a simulation-optimization system to examine the impact of such flexibility on the long-term wood supply. The system includes mathematical models to optimize plans of different forest management hierarchies, i.e. strategic, tactical and operational. In the system, the strategic model is first solved to determine the annual allowable cut (AAC). Next, the tactical model allocates cutblocks to annual plans, also prescribing silvicultural treatments. The subsequent operational level model generates monthly plans in a rolling planning horizon basis to satisfy prevailing market demand. Upon execution of all operational level plans for the five years, the land base inventory is updated and the change in AAC is evaluated. The system was implemented to a case study using a forest management unit in Quebec, Canada for a period of 100 years. Permitting silvicultural flexibility at the operational level led to profit improvements between 2-3.7%. Significant impact on long-term wood supply was not observed in this specific case. The system contributes towards better integration of forest management practices and supply chain needs.

Keyword: Agility, flexibility, wood procurement, silviculture, SilviLab, hierarchical planning, simulation-optimization, Monte-Carlo integer programming.

4.1. INTRODUCTION

Forest management planning is an important task that governs the value adding capacity of different stakeholders, each with unique ways in which forests are valued. Developing a plan deemed optimal presents a complex challenge due to the stochastic and dynamic nature of the forest systems, social constructs and economic parameters. The planning problem is exacerbated by imprecise knowledge of inventory (Thompson et al. 2007). In this context, it is important to devise a credible plan and permit flexibility to readjust plans as new information becomes available. Permitting flexibility generates value adding opportunity also for wood procurement systems (WPS) through an improved agility to satisfy supply chain's timber demand. Agility in the WPS context implies the ability to respond promptly and effectively to unexpected short-term fluctuations in demand (Gautam et al. 2013). One possible way to improve WPS agility is through flexibility on the choice of silvicultural treatments at the operational level instead of fixing the decision at an upper hierarchy (Gautam et al. 2014). More precisely, flexibility in the choice of harvest treatments that yield merchantable volume for the supply chain. Such a practice allows better alignment of supply with emerging demand considering that silvicultural treatments dictate the array of assortments and their quantities produced from cutblocks (Lussier 2009; Gautam et al. 2014). Practitioners could be provided with an array of ecologically feasible silvicultural treatments for a cutblock from which a selection can be made to satisfy market demand.

Exercising silvicultural flexibility requires postponement of the final decision-making rights to the operational level. Postponement has been identified as an effective strategy to improve supply chain agility (Christopher 2000). However, considering that forest management planning is carried out using a top-down hierarchical approach, it leads to a situation of distributed decision making as described by Schneeweiss (2003). Hierarchical approach is used in forest management planning due to the complexity associated with capturing all elements of forest systems in a single model (Church 2007). First, a strategic plan is devised taking into consideration long-term forest productivity, and ecological and social concerns. The outcome of the plan is the determination of annual allowable cut (AAC) by species group and silvicultural treatments to be applied. Subsequently, a tactical plan spatially disaggregates the volume targets incorporating additional economical, ecological and social constraints. The process results in the identification of cutblocks, affixed with a silvicultural treatment prescription. The silvicultural treatments are prescribed ensuring that the total volume harvested in the forest will be within a target range, set at the strategic level. Further down the hierarchy, operational plans outline schedules and specific plans of action to meet industrial demand for timber (D'Amours et al. 2008). Therefore, it is reasonable to hypothesize that AAC could be impacted when silvicultural treatments are altered at the operational level, despite the biological suitability of the applied treatment. The extent of the impact will, however, vary based on the total harvest at the forest level. A number of studies have demonstrated the link between harvest levels and the AAC (Armstrong

2004; Paradis et al. 2013). Altering silvicultural treatment in a specific cutblock also changes the harvest level. However, we can hypothesize that if the total volume harvested in a forest is well below the AAC, the incremental impact induced by altering silvicultural treatment may be negligible. Conversely, if the harvest level is close to the AAC, there will be a greater chance of a significant impact on AAC. A mechanism capable of simulating the hierarchical framework of forest management is needed to carry out the analysis.

A number of studies have proposed procedures to simulate the hierarchical framework of forest management. Weintraub and Cholaky (1991) presented a manual approach specifically to improving consistency between strategic and tactical planning levels. At the strategic level, the forest is divided into smaller zones and aggregated information is used to reduce the size of the problem. Decision variables of the strategic model include determination of harvest levels at each zone and road building schedule. The outcome of the strategic model provides directives for the tactical model in terms of timber production goals as well as road building budget. The tactical level model then aims to maximize profit using disaggregated information under constraints imposed by the strategic level plan. If there are inconsistencies between the two levels, adjustments are made at both levels and a second iteration of the process is conducted. In Nelson et al. (1991), a long-term, strata based, model is first used to determine volume targets for 15 decades. Subsequently, Monte Carlo integer programming technique is used to solve spatial harvest scheduling problem with adjacency constraints for the first three decades. In the bottom-up phase, the long-term plan is solved again with the solution of the short-term plan imposed into the first three decades. Davis and Martell (1993) presented a system that allows tactical level decision to be made based on knowledge of its long-term implications. Cea and Jofré (2000) proposed a method to simultaneously consider strategic and tactical planning. First, aggregation of forest stands is done through a cluster analysis technique to form macro stands. A strategic plan for a 45-year horizon is then developed to set volume targets and decide on plant locations. The plan is disaggregated at the tactical phase where decisions are made on roads to be built, cutblocks to be harvested, and volumes to be transported from cutblocks to mills. The extent of discrepancy in harvest and road costs between the two levels is then measured. If deemed unacceptable, further iterations are run re-aggregating the first period solution to a lesser extent until an acceptable strategic-tactical solution is attained. Beaudoin et al. (2008) used an anticipative approach to ensure feasibility of the tactical plan at the operational level. At the tactical level, a number of candidate plans are generated with decisions on harvesting, transportation and inventory. The operational level logistical costs associated with the developed plans are then anticipated for each of the candidate plans. The final decision-making at the tactical level (selection of a plan from amongst the candidate plans) is influenced by the anticipated information, eliminating plans that would be infeasible at the operational level. A similar concept was applied by Marinescu and Maness (2010) who proposed an algorithm that links models to support decision making at different hierarchies, between a multi-criteria timber allocation model and a sawmill optimization model. This algorithm allows iterative negotiation between the models to maximize value at both levels.

To our knowledge, the impact of allowing flexibility in the choice of silvicultural treatment at the operational level on long-term wood supply has not been studied. This study proposes a planning system to simulate the development and execution of three-level hierarchical forest management plans with an objective to anticipate the impact of operational level silvicultural flexibility on long-term wood supply. The system is subsequently implemented to a typical forest management unit in Eastern Canada to test the following hypotheses:

(i). Operational level silvicultural flexibility has a positive relationship with wood procurement system profitability and demand fulfillment rates.

(ii). Operational level silvicultural flexibility has a significant impact on long-term annual allowable cut.

4.2. AN OVERVIEW OF THE PLANNING SYSTEM

The proposed system simulates iterative development and execution of hierarchical plans in a forest land base on a rolling planning horizon basis (Figure 4.1). First, a strategic model is used to maximize AAC for a time horizon of 150 years. Next, a tactical model spatially identifies cutblocks to be harvested while respecting the AAC. As such, the strategic and tactical plans are developed from a government or land owner's perspective, with a goal of sustaining long-term wood supply. The output of the tactical phase consists of five annual plans with a list of cutblocks allocated for each year and a silvicultural treatment prescribed to each cutblock. At the operational level, the annual plans are optimized to develop monthly schedules to meet the prevailing demand in a rolling planning horizon basis. The operational level plans are developed from the perspective of a wood supplier attempting to maximize economic value. This process of development and implementation of plans at each hierarchy is depicted in Figure 4.2.

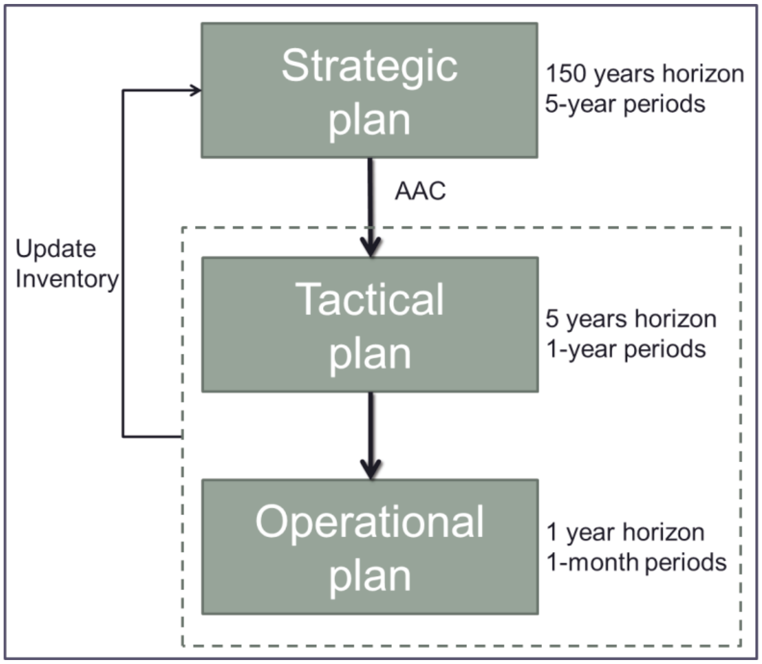

Figure 4.1. An overview of the hierarchical planning process simulation.

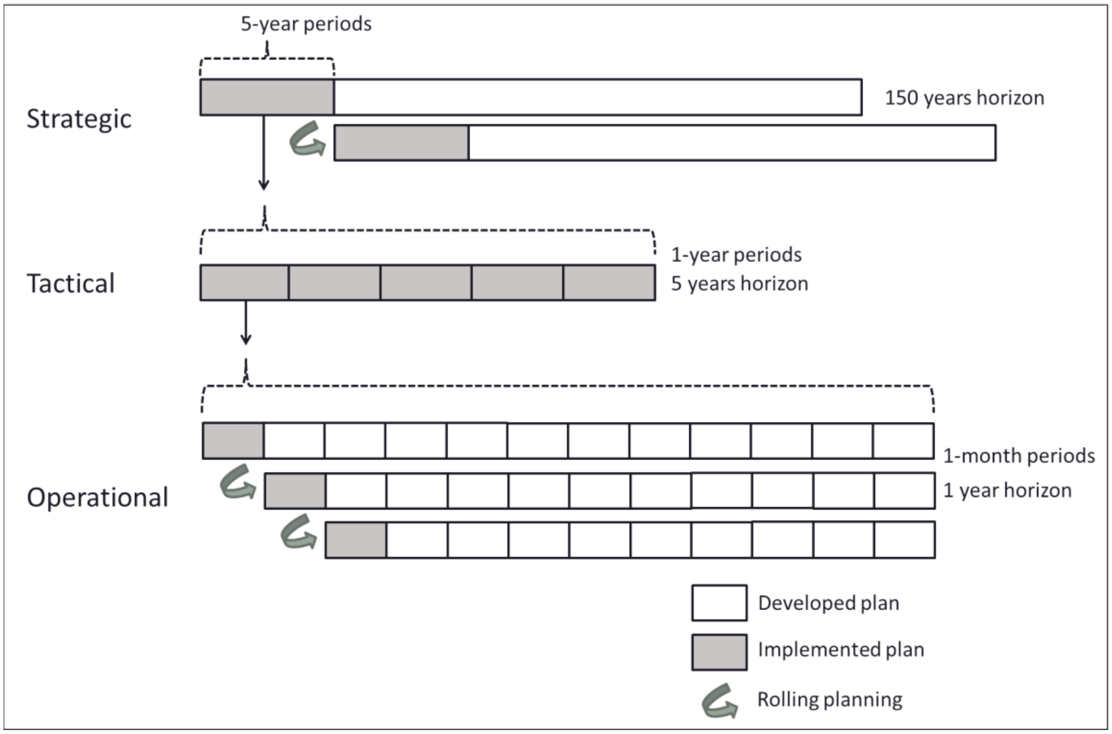

Figure 4.2. The overall plan development and implementation strategy in the system.

Once all operational level plans are implemented, the land base inventory is updated followed by subsequent iterations of the process as displayed in Figure 4.1. At each iteration of this simulation-optimization process, fluctuation in annual allowable cut and WPS' profits are recorded. The next sub-section provides a description of the models used in each of the planning hierarchy.

4.2.1. Hierarchical planning models

The strategic model is formulated as a model II linear program (Johnson and Scheurman 1977) in SilviLab, a modelling platform developed by FORAC research consortium for forest growth simulation and optimization (Simard et al. 2012). The objective (equation 4.1) of the model is to maximize volume harvest over thirty 5-year periods. h_t represents the total volume harvested (m^3) in period t. N is the number of periods in the planning horizon.

$$[4.1] \qquad \text{Maximize Volume harvest} = \sum_{t=1}^{N} h_t$$

The constraints include: (i) area accounting constraints (ii) even flow constraint to limit periodic harvested volume fluctuation to within 5%, and, (iii) non-negativity constraints.

The tactical model minimizes volume allocation to each of the time periods while meeting volume targets set at the strategic level. It is assumed that the cutblocks eligible for harvest in the 5-year period have been delineated and the data is available for the tactical model.

Sets
T: is the set of time periods t
H: is the set of cutblocks h
S: is the set of silvicultural treatments s
A: is the set of species a

Input Data

V_{hsa}	Volume of species *a* available in cutblock *h* when subjected to silvicultural treatment *s* (m^3).
N_h	Set of adjacent cutblocks.
$\nexists_{sat}$	Volume target of species *a* in period *t* under silvicultural treatment *s*.

Decision Variables
O_{hst} 1, if cutblock *h* is allocated for harvest under silvicultural treatment *s* in period t, 0, otherwise

Objective Function

$$[4.2] \qquad \text{Minimize volume allocation} = \sum_{h}\sum_{a}\sum_{s}\sum_{t} V_{hsa}\, O_{hst}$$

Subject to,

[4.3] $$\sum_{h} V_{hsa}\, O_{hst} \geq \nexists_{sat} \;\forall\, s, a, t$$

[4.4] $$\sum_{s}\sum_{t} O_{hst} \leq 1 \;\forall\; h$$

[4.5] $$\sum_{h \in N_h}\sum_{s} O_{hst} \leq 1 \;\forall\; t, N_h$$

The objective of the model is to minimize the total volume harvested (equation 4.2) of assortment *a* from cutblock *h* using silvicultural treatment *s* in period *t*. Equation 4.3 forces the model to meet volumes targets set by the strategic model. Equation 4.4 ensures that only one silvicultural treatment is applied to each of the selected cutblock. Finally, equation 4.5 prohibits the harvesting of adjacent cutblocks until free-to-grow stage is attained.

A heuristic technique, Monte Carlo integer programming, is used to attain a solution in a practical time frame. Monte Carlo integer programming is an algorithm to generate a plan through randomly selecting and adding cutblocks that respect the adjacency constraint until the volume targets are met (Boston and Bettinger 1999). Although the algorithm cannot guarantee the optimal solution, the time frame in which solutions are generated makes it a practical choice for carrying out the experiment. The flowchart in Figure 4.3 illustrates the technique. The method was executed in Microsoft Excel 2010 using Visual Basic for Applications (VBA).

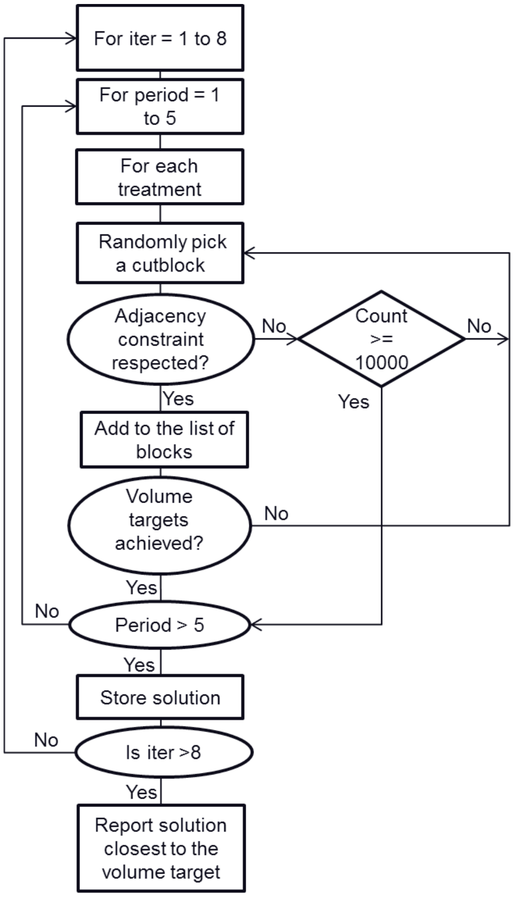

Figure 4.3. Flowchart of the Monte Carlo integer programming procedure.

The output of the tactical plan is a list of cutblocks to be cut with a silvicultural treatment prescribed to each cutblock. The objective at the operational level is to optimally allocate these cutblocks taking into consideration market information on a monthly basis. The operational model is adopted from Gautam et al. (2014) with two changes: (i) cost imposed in association with altering silvicultural treatment was removed from the objective function. The cost is no longer required since long-term impacts are simulated in the current study. (ii) Market transaction unit was changed from assortments to species groups to allow interoperability between different hierarchical models. The model is presented below.

Sets

T: is the set of time periods *t*
H: is the set of cutblocks *h*
S: is the set of silvicultural treatments *s*
E: is the set of harvest systems *e*
A: is the set of species *a*
M: is the set of mills *m*

Input Data

V_{hsa}	maximum volume of species *a* available in cutblock *h* when subjected to silvicultural treatment *s* (m^3)
N_a	is the selling price per cubic meter of species *a* ($\$\cdot m^{-3}$)
C_e	harvest cost under harvest system *e* ($\$\cdot day^{-1}$)
B_{hm}	round trip distance from cutblock *h* to mill *m* (km)
G_{hm}	unit transportation cost between cutblock *h* and mill *m* ($\$\cdot m^{-3}\cdot km^{-1}$)
R_t	maximum transportation capacity during period *t* (m^3)
Y^I_{ha}	initial roadside inventory of species *a* in cutblock *h* (m^3)
Y^C_{th}	unit stocking cost in cutblock *h* during period *t* ($\$\cdot m^{-3}$)
P_{se}	is the productivity of harvest system *e* under silvicultural treatment *s* ($m^3\cdot day^{-1}$)
O_{te}	number of work days available for harvest system *e* during period *t*
D_{tam}	is the volume of species *a* demanded by mill *m* during period *t* (m^3)
AAC_a	is the maximum harvestable volume of species *a*, set at the strategic level
V	is a very small number

Decision Variables

b_{hse}	1, if cutblock *h* is planned for harvest in any period using silvicultural treatment *s* and harvest system *e*, 0, otherwise
x_{thse}	is the proportion of cutblock *h* cut in period *t* under silvicultural treatment *s* using system *e*
q_{tham}	is the volume of species *a* transported from cutblock *h* to mill *m* in period *t* (m^3)
y_{tha}	is the volume of species *a* stored in cutblock *h* at the end of period *t* (m^3)

Objective Function

$$[4.6] \quad \text{Maximize Profit} = \sum_{t\in T}\sum_{h\in H}\sum_{a\in A}\sum_{m\in M} q_{tham}N_a - \sum_{t\in T}\sum_{h\in H}\sum_{s\in S}\sum_{e\in E}\sum_{a\in A} x_{thse}V_{hsa}C_eP_{se}^{-1} - \sum_{t\in T}\sum_{h\in H}\sum_{a\in A}\sum_{m\in M} q_{tham}G_{hm}B_{hm} - \sum_{t\in T}\sum_{h\in H}\sum_{a\in A} y_{tha}Y^C_{th}$$

Subject to,

[4.7] $$y_{t,h,a} = Y_{ha}^{I} + \sum_{s \in S} \sum_{e \in E} x_{t,h,s,e} V_{hsa} - \sum_{m \in M} q_{t,h,a,m} \qquad \forall\, h, a, t = 1$$

[4.8] $$y_{tha} = \sum_{s \in S} \sum_{e \in E} x_{thse} V_{hsa} + y_{t-1,h,a} - \sum_{m \in M} q_{tham} \qquad \forall\, h, a, t > 1$$

[4.9] $$\sum_{h \in H} q_{tham} \leq D_{tam} \qquad \forall\ t, a, m$$

[4.10] $$\sum_{h \in H} \sum_{s \in S} \sum_{a \in A} V_{hsa} x_{thse} \leq \sum_{s \in S} P_{se} O_{te} \qquad \forall\, t, e$$

[4.11] $$\sum_{t \in T} \sum_{e \in E} x_{thse} \leq 1 \qquad \forall\, h, s$$

[4.12] $$\sum_{s \in S} \sum_{e \in E} b_{hse} \leq 1 \qquad \forall\ h$$

[4.13] $$b_{hse}\, V \leq \sum_{t \in T} x_{thse} \qquad \forall\, h, s, e$$

[4.14] $$b_{hse} \geq \sum_{t \in T} x_{thse} \qquad \forall\, h, s, e$$

[4.15] $$\sum_{t \in T} \sum_{s \in S} \sum_{e \in E} x_{thse} = \sum_{s \in S} \sum_{e \in E} b_{hse} \qquad \forall\, h$$

[4.16] $$\sum_{h \in H} \sum_{a \in A} \sum_{m \in M} q_{tham} \leq R_t \qquad \forall\, t$$

[4.17] $$\sum_{h \in H} \sum_{s \in S} \sum_{a \in A} \sum_{t \in T} x_{thse} V_{hsa} \leq AAC_a \qquad \forall\, a$$

[4.18] $$x_{thse}, q_{tham}, y_{tha} \geq 0 \qquad \forall\, t, h, s, e, a, m$$

The objective function (equation 4.6) aims at maximizing profit. Revenue is generated through delivery of volumes per species from cutblocks to mills.

Costs include harvesting cost, transportation cost and inventory cost. Flow conservation constraints (equations 4.7 and 4.8) maintain balance of harvested volumes. Volumes transported to a mill in each period is constrained to be less than or equal to the demanded volume (equation 4.9). Volume harvested per period is less than or equal to the maximum logging production capacity (equation 4.10). It is assumed that the stand parameters are uniform in all cutblocks. The total volume harvested in a cutblock in all periods is less than or equal to the maximum volume available for a selected silvicultural treatment (equation 4.11), and the same treatment is applied even if harvesting is partitioned to multiple periods (equation 4.12). Equations 4.13 and 4.14 ensure that the variable b_{hse} attains a value of 1 even if a block is partially harvested. All volumes available must be procured over the planning horizon if a cutblock is selected for harvest (equation 4.15). Transportation capacity constraints are established through equation 4.16. Equation 4.17 restricts the total volume harvested of each species to the limits set at the strategic level. Finally, non-negativity restrictions are assigned to respective variables using equations 4.18. The mixed integer programming model is coded in AMPL modeling language (Fourer et al. 2003) and solved using CPLEX 12.5.

4.3. A CASE STUDY

The system was applied to a forest management unit covering an area of 897,048 ha in Quebec, Canada (Figure 4.4). The land base information was obtained from the Quebec Ministry of Forests, Wildlife and Parks. The database contained information on initial state of the forest. The initial age class distribution by area is shown in Figure 4.5, the forest is dominated by mostly mature and over-mature spruce-fir. Softwood species represented approximately 90% of the total volume in the forest, and hardwood species represented approximately 10%. The database also contained information on admissibility criteria for silvicultural treatments, growth and yield models, and transition rules defined by the Ministry as per Bureau du forestier en chef (2013) and "le Guide Sylvicole du Québec" (Larouche et al. 2013). The land base information along with the strategic planning model described earlier was input into SilviLab.

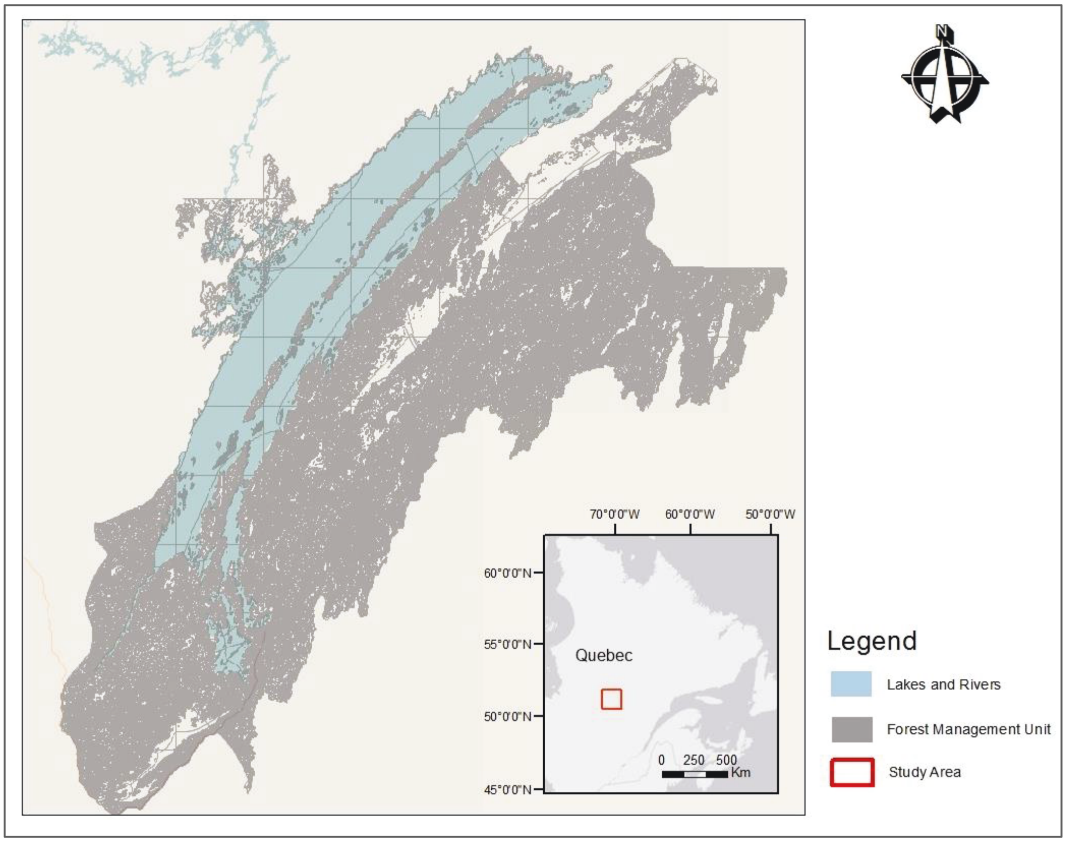

Figure 4.4. A map of the study area in Quebec, Canada.

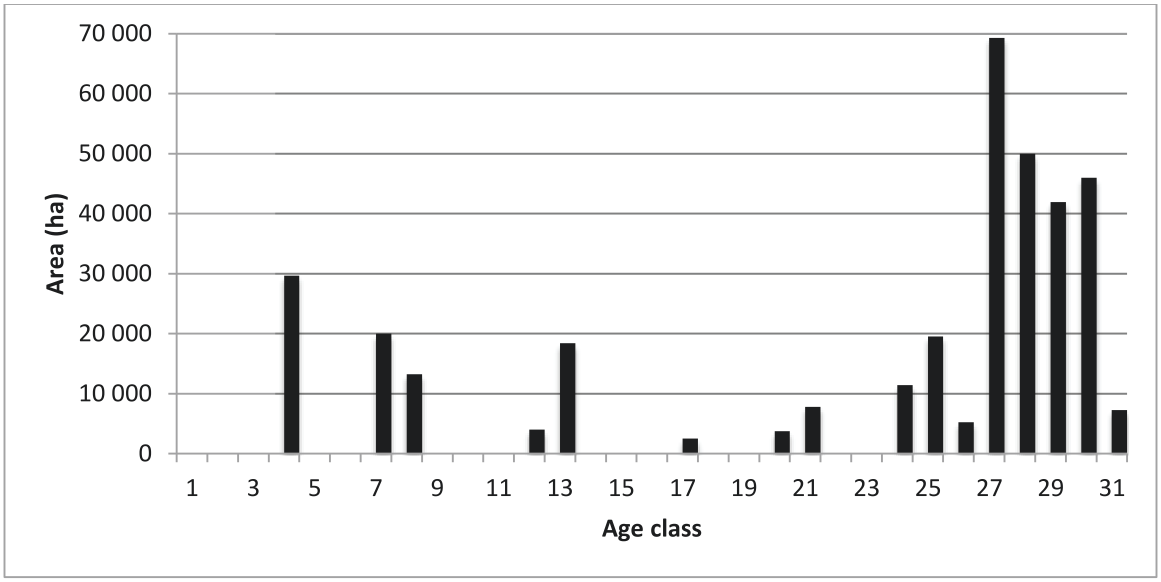

Figure 4.5. The initial age class structure of the case study forest. Each age class represents a 5-year interval.

For the purpose of tactical planning, a grid with a cell size of 800m X 800m was superimposed on the map of the land base in SilviLab. Each cell was then treated as a cutblock. Next, a query was made in SilviLab to retrieve a list of cutblocks with volumes eligible for harvest in the upcoming 5-year period. The volumes were categorised into four species groups: spruce/pine/fir, paper birch, poplar and other hardwood species. Table 4.2 (Appendix) provides an example of data retrieved from SilviLab for a cutblock; it contained information on volumes available by species under different treatments. The data also included adjacency information. The tactical planning model was subsequently used to make a spatial plan for five 1-year periods.

The output of the tactical planning process was input into the operational planning model. The output data included: (i) a list of cutblocks available for harvest in the next five 1-year periods, (ii) the silvicultural treatment prescribed to it, (iii) non-prescribed but feasible silvicultural treatments, (iv) volumes (m³) by species group, and (v) distance between cutblocks and customer mills (km). Monthly demand in terms of volume was assumed to be a random parameter with normal probability distribution with a standard deviation that is 40% of the base demand. These values are based on studies by Childerhouse and Towill (2000), Zhang and Zhang (2007) and UN (2013). Base demand was generated using historical mill consumption pattern as described in Gautam et al. (2014). An example of annual demand of each mill is shown in Table 4.3 (Appendix).

The selling price per cubic meter of each species group was obtained from Wood Producers Association of Quebec (SPFRQ 2014). Prices paid at the mill gates were set at \$200, \$105, \$85 and \$93 per cubic meter for other hardwood, paper birch, poplar and spruce/ pine/fir, respectively. Concerning harvesting systems, two options were made available: cut-to-length (CTL) and full-tree systems (FT). The productivity of CTL system ranged from 15.6 -18.9 m^3 per hour depending on the type of silvicultural treatment and corresponding values for FT system ranged between 18.9 - 22.1 m^3 per hour. With regards to the cost values, figures published in Gautam et al. (2014) were used for the experiment.

4.3.1. Scenarios development and statistical analysis

Scenarios were developed based on the following two criteria and a summary of the scenarios are displayed in Table 4.1:

1. Silvicultural flexibility: This criterion determines whether the scenario in consideration is permitted operational level silvicultural flexibility or not. In scenarios where flexibility is not permitted, the operational level model is forced to implement the prescription made at the tactical level. In

scenarios where it is permitted, the treatment decision made at the tactical level is revised. The same list of feasible treatments that was used at the tactical level is made available to the operational level model. Thus, allowing a new choice to be made to better align supply with demand.

2. Base demand: We evaluated the long-term impact under two different market conditions. The first represents a scenario with monthly demand for 100% of the first period AAC; the second represents a scenario with monthly demand for only 60% of the first period AAC. The demand levels are reflective of the consumption levels by companies in many Canadian jurisdictions between 2001 and 2011 (NRC 2013).

Table 4.1. Summary of the scenarios simulated in the experiment

Scenario	Silvicultural flexibility	Base demand (% of allocation)
1	Yes	100
2	No	100
3	Yes	60
4	No	60

Wilcoxon Signed Rank Tests were carried out in SigmaPlot 12.0 to test the null hypothesis of no significant difference in annual allowable cut and profit due to operational level silvicultural flexibility. Separate tests were carried out for each base demand levels with annual allowable cut (m^3) and profit values ($) as the dependent variable, and the silvicultural flexibility as the independent variable. Thus, tests were carried out for scenario 1 vs scenario 2 (base demand set at 100% of the initial AAC), and scenario 3 vs scenario 4 (base demand set at 60% of the initial AAC).

4.4 RESULTS AND DISCUSSION

Wood procurement system profits under the different scenarios across a 20 period horizon are displayed in Figure 4.6; each period represents five years. The average profit per period in scenario 1 was approximately 3.7% higher than in scenario 2. Similarly, average profit per period in scenario 3 was approximately 2% higher than in scenario 4. Statistical analysis showed that the differences in the profit values between scenarios 1 & 2, and scenarios 3 & 4 were significant ($p < 0.001$). The average demand fulfillment rate over the simulated period under scenario 1 was approximately 80% as opposed to 76% in scenario 2. Similarly, demand fulfillment rate under scenario 3 was 83% as compared to 77% in scenario 4.

Higher demand fulfillment would have potentially been observed if inventory was allowed to be stored liberally, or unfulfilled demand could be carried over to the subsequent period. However, the experiment was carried out depicting a demand driven supply chain with volatile market conditions. In such context, the experiment found an average increase in demand fulfillment rate of approximately 4% (scenario 1 vs. 2) and 6% (scenario 3 vs. 4) when flexibility was permitted.

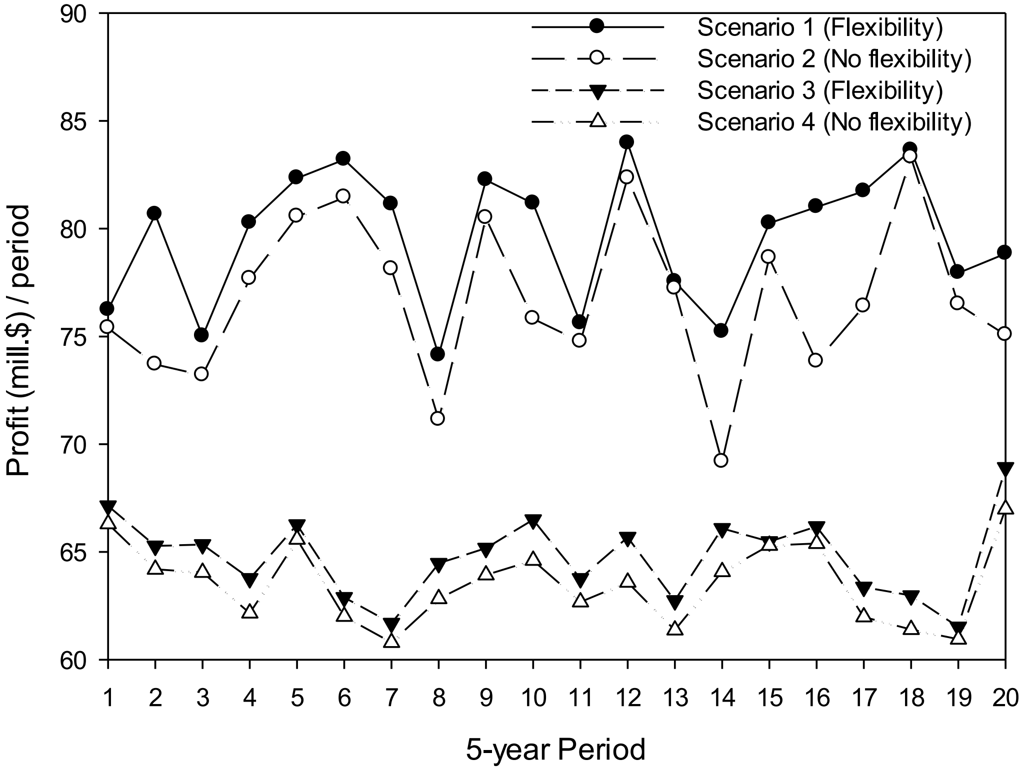

Figure 4.6. The total profit values yielded under different scenarios per period.

Figures 4.7 and 4.8 show the proportion of area harvested by silvicultural treatment under different scenarios. In all scenarios, treatments were limited to clearcut (CT) and variable retention (CRV). In scenario 2 (Figure 4.7), these two treatments were applied to an equal number of hectares (50% apiece on average over the 20 period horizon). With silvicultural flexibility permitted (scenario 1), the proportion diverged slightly, favoring CT at 53% over CRV at 47%. In scenario 4 (Figure 4.8), without silvicultural flexibility, the proportion of area treated with CT (49%) was on average lower than that of CRV (51%). In this case, permitting silvicultural flexibility (scenario 3) has led to an increase in the application of CT (52%). In terms of the total area treated, on average, scenario 2 (no flexibility permitted) harvested approximately 6% more area than scenario 1. Similarly, scenario 4 (no flexibility permitted) harvested approximately 8.5% more area than Scenario 3.

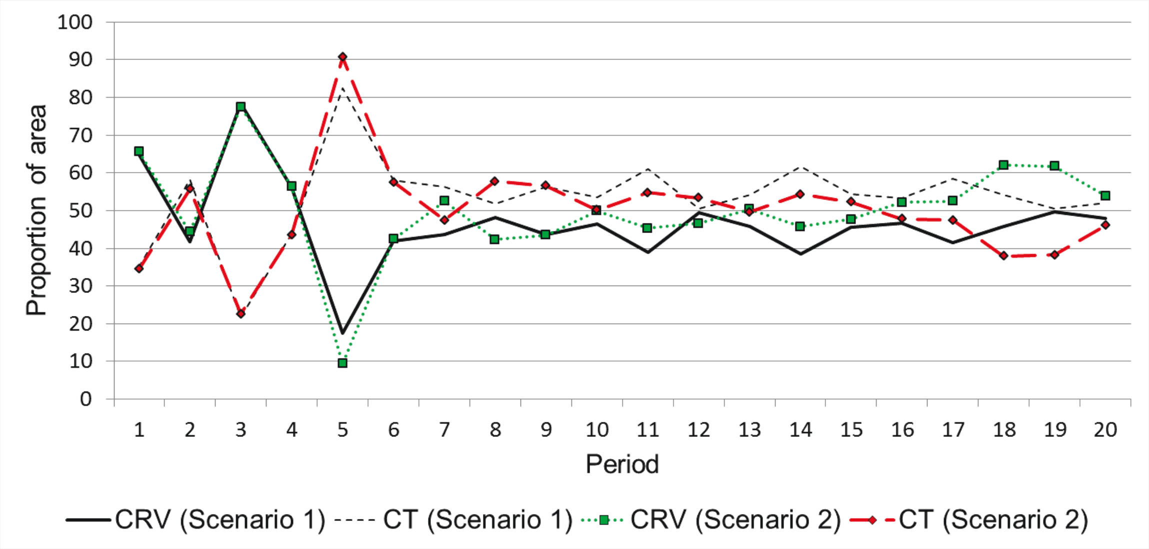

Figure 4.7. Proportions of silvicultural treatments applied under scenarios 1 & 2.

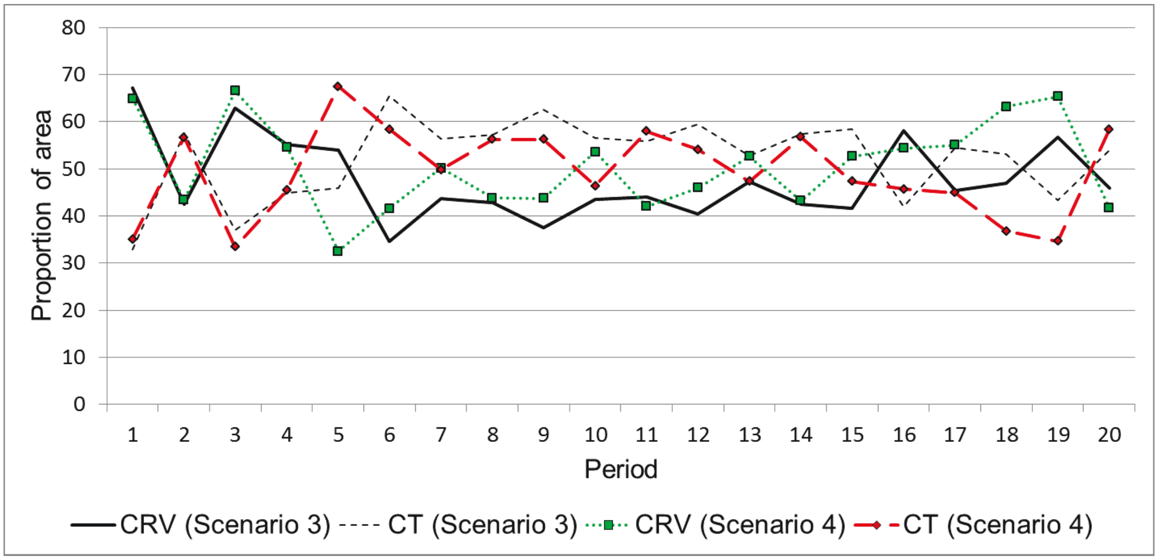

Figure 4.8. Proportions of silvicultural treatments applied under scenario 3 & 4.

Higher profits observed in scenarios with flexibility in silvicultural treatment was not unexpected considering that plans were permitted to be readjusted to the changing demand. In this particular case, permitting flexibility led to a greater use of CT. From a wood procurement standpoint, CT is a more efficient treatment. With its application, higher volumes of wood can be procured from the same unit of area. Consequently, total area harvested was also lower in scenarios with flexibility permitted. This result is opposite to the findings reported in the third chapter where permitting flexibility led to a greater use of partial harvest treatments. This can be attributed to the differences in forest composition in the two case studies. In contrast to the case presented in the third chapter, the forest was much more homogeneous, with spruce/pine/fir representing approximately 90% of the volume. Thus, there would have been rare instances of one assortment (with low demand in the market) restricting procurement of another assortment. In this case, the model would have focused on higher volume yielding treatments to improve production efficiency. In the earlier case with mixedwood forest, the model would have made greater use of partial treatments to produce the right mix of assortments demanded in the market.

The changes in AAC under different scenarios over the simulated time horizon are displayed in Figures 4.9 and 4.10. Comparable patterns can be observed in each of the scenarios. The AAC shows an increasing trend until the 8-9th periods, then a slight decline till the end of the horizon. In comparing scenario 1 and 2, the AAC is slightly higher for scenario 1 in periods 5, 6, 7, 8, 13 and 14, but lower in periods 15, 16, 17, 18 and 20. In making a similar comparison between scenarios 3 and 4, the AAC is higher in periods 4-8, but remains lower for the remainder of the periods. Statistical analyses did not demonstrate significant differences in the AAC values neither between scenarios 1 & 2, nor scenarios 3 & 4.

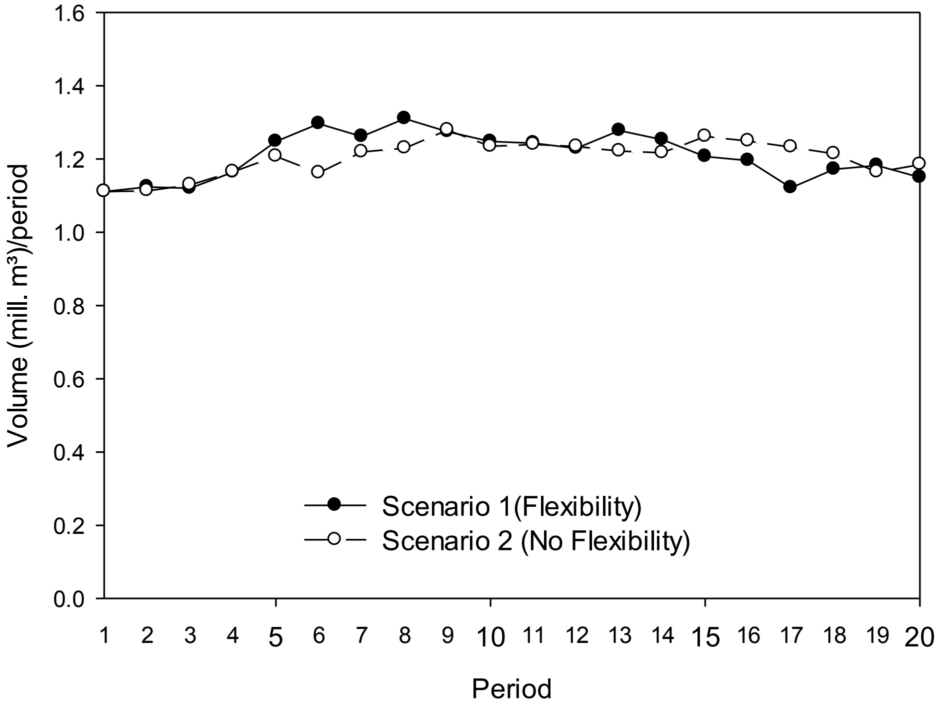

Figure 4.9. Comparison of annual allowable cut under scenarios 1 and 2.

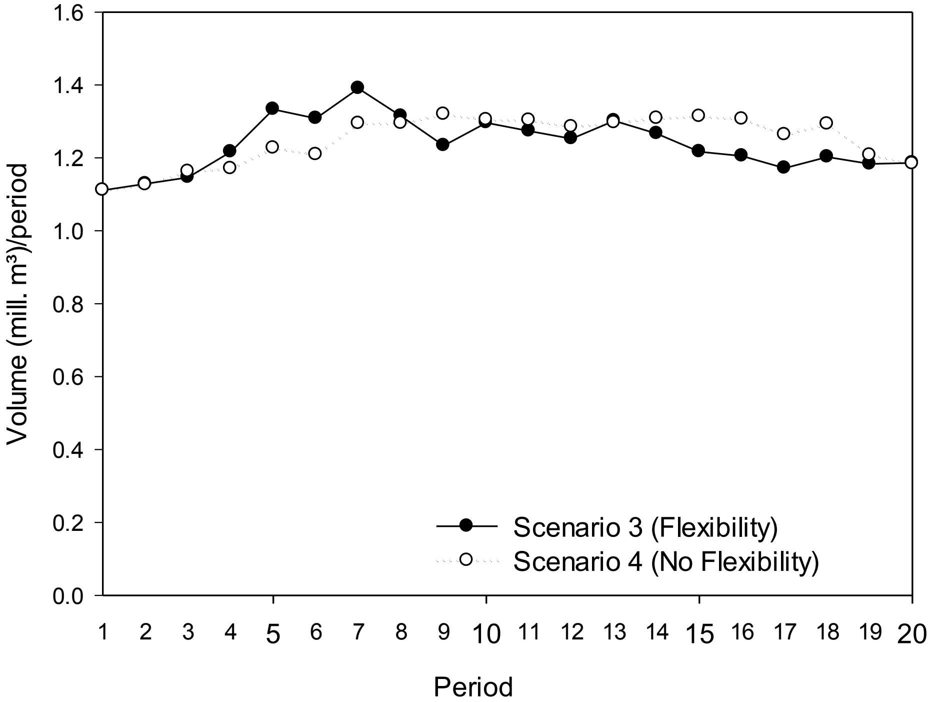

Figure 4.10. Comparison of annual allowable cut under scenarios 3 and 4.

The lack of significant difference in AAC can be attributed to the fact that silvicultural options were limited to two relatively similar treatments, CT and CRV. Switching between CT and CRV would not have had as much of an impact as compared to a change from CT to other partial cut treatments. Although we reject the null hypothesis of significant impact on AAC in this case, an experiment in a more heterogeneous forest could yield a different conclusion. In a more heterogeneous forest, as in chapter 3, the operational level model would make use of a wider array of silvicultural treatments. The accumulation of changes to considerably different treatments could ultimately lead to a significant impact on the AAC.

Another factor that would have contributed to the lack of significant impact on AAC is the harvest level. The harvest levels were below the allowable cut in all the scenarios. Thus, even though permitting flexibility led to utilisation of a more intensive treatment, the build-up of inventory may have mitigated the impact of choosing alternative silvicultural treatments. Furthermore, it was earlier speculated that, if the harvest level is well below the AAC, the incremental change induced by altering silvicultural treatment may be negligible, and if it is close to the AAC, impact will be greater. However, our experiment does not support this claim. The extent of the impact on the AAC was not noticeably different between scenarios that harvested closer to AAC (scenarios 1 & 2) and much lower than the AAC (scenarios 3 & 4).

Application of the proposed system to a case study has helped identify a number of opportunities to further refine the system, to better represent the hierarchical planning process. In practice, cutblocks are formed through combining a number of forest stands that are similar in terms of species composition and age. This is generally a manual procedure carried out using mapping software. However, since our simulation was carried out for a 100 years horizon, manually generating cutblocks was not a practical option. Thus, a grid based method was used to develop cutblocks. However, indiscriminately superimposing a grid over the land base led to formation of cutblocks that were heterogeneous, particularly in terms of age class. As a result, some cutblocks contained very little volume; these would have been economically infeasible to be harvested (Greene et al. 1997). This would have contributed to the relatively low demand fulfillment rates. It must be stated that this would have influenced both scenarios, with and without flexibility in silvicultural treatment. Thus, it was still useful for our purpose, where the focus was on the differences between the scenarios. Nevertheless, it is imperative that the system be able to generate realistic cutblocks to measure precisely the future impacts. There are a number of methods proposed to automate the development of cutblocks (Flanders et al. 2003; Mustonen et al. 2008). Approaches to incorporate these algorithms into the proposed planning system must be explored.

Continuing on with the discussion on cutblocks, in practice, they are generally clustered to minimize operations cost (Mathey et al. 2012). Cost efficiency is achieved through mainly minimizing road construction and maintenance cost. Clustering minimizes the spread of cutblocks across the forest thus common roads can be used to transport wood from several cutblocks. As a result, road construction and maintenance costs are reduced. However, we did not take into consideration road building costs. Our objective of anticipating impact of silvicultural flexibility could be achieved without considering road related costs, as long as it was kept constant in all of the scenarios. However, to be able to precisely anticipate future impacts, modifications will need to be made to the proposed planning system. The tactical model will have to be reconfigured to include annual road building costs. Acquiring data on current state of the roads in the forest will also pose a significant challenge. Developing an optimal plan that reduces road building costs associated with all combinations of cutblocks and the mills will add significant complexity to the model. Nevertheless, there are a number of approaches proposed in the literature to incorporate cutblocks' clustering (e.g. Öhman and Lämås 2003; Smaltschinski et al. 2012).

Interoperability between models was attained through using volume (m³) by species as the input and output at each hierarchy in the planning system. Although the approach is capable of representing the divergent process that is typical of the wood procurement system, it may not be adequate for all instances. In the presented case study, the demand from each mill was assumed to be a specified volume of particular species. Thus, raw materials in a cutblock could be diverted to different mills based simply on species. However, a single tree can be processed to different segments and be sent to separate mills to maximise the value yielded (Rönnqvist 2003). Simulating such divergent process requires the bucking model to be included in the proposed planning system. Such models can be used to seek optimal decisions on log bucking according to specifications provided by the customer mills (Murphy 2008).

4.5. CONCLUSION

This paper presents a planning system to simulate the development and execution of hierarchical forest management plans with an objective to anticipate the impact of operational level sivicultural flexibility on long-term wood supply. It was hypothesized that operational level sivicultural flexibility significantly improves wood procurement system profits. It was also hypothesized that exercising silvicultural flexibility at the operational level has a significant impact on the long-term AAC. The proposed system was implemented to a case study to test the hypotheses. The experiment did demonstrate small but a statistically significant improvement in profit for wood procurement systems as a result of permitting silvicultural flexibility at the operational level. In terms of the long-term impact of silvicultural flexibility on AAC, significant impact was not observed in this particular case; however, this finding certainly cannot be generalized. The finding must be viewed in light of the forest type used in the case study. The outcome will certainly vary in more heterogeneous forest type with broader choice on silvicultural treatments. The proposed system could be further refined for its implementation to other applications. Procedures could be developed to create more realistic cutblocks. Algorithms could be incorporated to cluster cutblocks to minimize the dispersion of harvesting activities across the land base. Bucking models could be incorporated into the system to represent the divergent process, a characteristic of the forest products supply chain. However, the extent of these refinements should be based on the intended use of the system as it will increase its complexity.

4.6. LITERATURE CITED

Armstrong, G. W. 2004. Sustainability of timber supply considering the risk of wildfire. *Forest Science*, *50*(5), 626-639.

Beaudoin, D., Frayret, J. M., & LeBel, L. 2008. Hierarchical forest management with anticipation: an application to tactical-operational planning integration. *Canadian journal of forest research*, 38(8), 2198-2211.

Boston, K., & Bettinger, P. 1999. An analysis of Monte Carlo integer programming, simulated annealing, and tabu search heuristics for solving spatial harvest scheduling problems. *Forest Science*, *45*(2), 292-301.

Bureau du forestier en chef. 2013. Manuel de détermination des possibilités foretières 2013-2018. Gouvernement du Québec, Roberval, Qc, 247p.

Cea, C., & Jofré, A. 2000. Linking strategic and tactical forestry planning decisions. *Annals of Operations Research*, 95(1-4), 131-158.

Childerhouse, P., & Towill, D. 2000. Engineering supply chains to match customer requirements. *Logistics Information Management*, 13(6), 337-346.

Christopher, M. 2000. The agile supply chain: competing in volatile markets. *Industrial Marketing Management*, 29(1), 37-44.

Church, R. L. 2007. Tactical-level forest management models. In Handbook of operations research in natural resources (pp. 343-363). Springer US.

Davis, R. G., & Martell, D. L. 1993. A decision support system that links short-term silvicultural operating plans with long-term forest-level strategic plans. *Canadian Journal of Forest Research*, 23(6), 1078-1095.

D'Amours, S., Rönnqvist, M., & Weintraub, A. 2008. Using operational research for supply chain planning in the forest products industry. *INFOR: Information Systems and Operational Research*, 46(4), 265-281.

Flanders, D., Hall-Beyer, M., & Pereverzoff, J. 2003. Preliminary evaluation of eCognition object-based software for cut block delineation and feature extraction. *Canadian Journal of Remote Sensing*, *29*(4), 441-452.

Fourer, R. Gay D. and Kernighan B. 2003 AMPL: A Modeling Language For Mathematical Programming. Thomson/Brooks/Cole, 517pp.

Gautam, S., LeBel, L., & Beaudoin, D. 2013. Agility capabilities in wood procurement systems: a literature synthesis. *International Journal of Forest Engineering*, 24(3), 216-232.

Gautam, S., LeBel, L., & Beaudoin, D. 2014. Value-adding through silvicultural flexibility: an operational level simulation study. *Forestry: An International Journal of Forest Research*. cpu045

Greene, W. D., Harris, T. G., DeForest, C. E., & Wang, J. 1997. Harvesting cost implications of changes in the size of timber sales in Georgia. *Southern Journal of Applied Forestry*, *21*(4), 193-198.

Gunn, E. 2009. Some perspectives on strategic forest management models and the forest products supply chain. *INFOR: Information Systems and Operational Research*, 47(3), 261-272.

Johnson, K. N., & Scheurman, H. L. 1977. Techniques for prescribing optimal timber harvest and investment under different objectives--discussion and synthesis. *Forest Science*, 23(Monograph 18), 31 pp.

Larouche, C., Guillemette F., Raymond P. & Saucier J.-P. 2013. Le Guide Sylvicole Du Québec : Les Concepts et l'Application de la Sylviculture. Gouvernement du Québec. 710pp.

Lussier, J. M. 2009. Changing our mental model from growing volume to producing value: The case of uneven-aged hardwood management. The *Forestry Chronicle*, 85(3), 382-386.

Marinescu, M. V., & Maness, T. C. 2010. A Hierarchical Timber Allocation Model to Analyze Sustainable Forest Management Decisions. *Mathematical and Computational Forestry & Natural-Resource Sciences (MCFNS)*, 2(2), Pages-117.

Mathey, A. H., Krcmar, E., Innes, J., & Vertinsky, I. 2008. Opportunities and costs of intensification and clustering of forest management activities. *Canadian journal of forest research*, *38*(4), 711-720.

Mathey, A. H., Nelson, H., & Gaston, C. 2009. The economics of timber supply: Does it pay to reduce harvest levels? *Forest Policy and Economics*, 11(7), 491-497.

Murphy, G. 2008. Determining stand value and log product yields using terrestrial lidar and optimal bucking: a case study. *Journal of Forestry*, *106*(6), 317-324.

Mustonen, J., Packalén, P., & Kangas, A. 2008. Automatic segmentation of forest stands using a canopy height model and aerial photography. *Scandinavian Journal of Forest Research*, *23*(6), 534-545.

Nelson, J., Brodie, J. D., & Sessions, J. 1991. Integrating short-term, area-based logging plans with long-term harvest schedules. *Forest Science*, 37(1), 101-122.

NRC. 2013 The State of Canada's Forests: Annual Report. Canadian Forest Service, Natural Resources Canada. 62pp

Öhman, K., & Lämås, T. 2003. Clustering of harvest activities in multi-objective long-term forest planning. *Forest ecology and management*, *176*(1), 161-171.

Paradis, G., LeBel, L., D'Amours, S., & Bouchard, M. 2013. On the risk of systematic drift under incoherent hierarchical forest management planning. *Canadian Journal of Forest Research*, 43(5), 480-492.

Rönnqvist, M. 2003. Optimization in forestry. *Mathematical programming*, *97*(1-2), 267-284.

Schneeweiss, C. 2003. Distributed decision making. Springer.

Simard, M., Lemieux, S., Bouchard, M. & D'Amours, S. 2012. Système d'aide à la décision en aménagement forestier. Note de Recherche, ForValueNet, N^{o}9.

Smaltschinski, T., Seeling, U., & Becker, G. 2012. Clustering forest harvest stands on spatial networks for optimised harvest scheduling. *Annals of forest science*, *69*(5), 651-657.

SPFRQ. 2014. Syndicat des Propriétaires Forestiers de la Région de Québec. http://www.spfrq.qc.ca. (accessed 20 June, 2014).

Thompson, I. D., Maher, S. C., Rouillard, D. P., Fryxell, J. M., & Baker, J. A. (2007). Accuracy of forest inventory mapping: some implications for boreal forest management. *Forest Ecology and Management*, *252*(1), 208-221.

UN. 2013. Forest products Annual Market Review 2012-2013. United Nations. 133pp

Weintraub, A., & Cholaky, A. 1991. A hierarchical approach to forest planning. *Forest Science*, 37(2), 439-460.

Zhang, C., & Zhang, C. 2007. Design and simulation of demand information sharing in a supply chain. *Simulation Modelling Practice and Theory* 15(1): 32-46.

4.7. APPENDIX

Table 4.2. Example of cutblock data retrieved from SilviLab with information on volumes of species available under different silvicultural treatments.

Cutblock	Species	Volumes available (m³)				
		Commercial thinning	Shelterwood	Partial cut	Variable retention	Clearcut
1	Other hardwood	0	0	0	0	0
	Paper birch	0	0	634	634	641
	Poplar	0	0	0	29	17
	Spruce/pine/fir	0	0	1,649	2,825	3,081
2	Other hardwood	0	0	0	0	0
	Paper birch	0	0	0	428	524
	Poplar	0	0	0	44	52
	Spruce/pine/fir	0	0	0	196	329
3	Other hardwood	0	0	0	0	0
	Paper birch	0	5	5	74	92
	Poplar	0	5	5	44	54
	Spruce/pine/fir	0	210	210	1748	2163
4	Other hardwood	0	0	0	0	0
	Paper birch	0	0	0	12	15
	Poplar	0	0	0	6	7
	Spruce/pine/fir	0	0	0	780	965

Table 4.3. Example of annual demand by mill in the case study.

Mill	Species	Month											
		1	2	3	4	5	6	7	8	9	10	11	12
1	Other Hardwood	0	0	0	0	0	0	0	0	0	0	0	0
	Paper birch	0	0	0	0	0	0	0	0	0	0	0	0
	Poplar	0	0	0	0	0	0	0	0	0	0	0	0
	Spruce/Pine/Fir	3329	995	1942	1407	1028	2415	3239	357	1673	3528	1016	2510
2	Other Hardwood	0	0	0	0	0	0	0	0	0	0	0	0
	Paper birch	0	0	0	0	0	0	0	0	0	0	0	0
	Poplar	0	0	0	0	0	0	0	0	0	0	0	0
	Spruce/Pine/Fir	652	516	123	344	571	375	193	1076	206	762	1141	34
3	Other Hardwood	0	0	0	0	0	0	0	0	0	0	0	0
	Paper birch	0	0	0	0	0	0	0	0	0	0	0	0
	Poplar	0	0	0	0	0	0	0	0	0	0	0	0
	Spruce/Pine/Fir	1008	726	837	592	213	645	352	493	1154	630	97	584
4	Other Hardwood	0	0	0	0	0	0	0	0	0	0	0	0
	Paper birch	0	0	0	0	0	0	0	0	0	0	0	0
	Poplar	231	246	485	407	31	630	398	289	333	420	792	209
	Spruce/Pine/Fir	0	0	0	0	0	0	0	0	0	0	0	0
5	Other Hardwood	0	0	0	0	0	0	0	0	0	0	0	0
	Paper birch	586	152	541	327	157	697	800	138	436	569	265	768
	Poplar	0	0	0	0	0	0	0	0	0	0	0	0
	Spruce/Pine/Fir	0	0	0	0	0	0	0	0	0	0	0	0
6	Other Hardwood	0	0	0	0	0	0	0	0	0	0	0	0
	Paper birch	813	965	778	1066	531	635	582	715	1080	766	446	533
	Poplar	0	0	0	0	0	0	0	0	0	0	0	0
	Spruce/Pine/Fir	0	0	0	0	0	0	0	0	0	0	0	0
7	Other Hardwood	8	19	8	23	22	3	21	20	10	22	23	22
	Paper birch	36	86	24	89	170	43	118	102	105	116	128	105
	Poplar	0	0	0	0	0	0	0	0	0	0	0	0
	Spruce/Pine/Fir	0	0	0	0	0	0	0	0	0	0	0	0
8	Other Hardwood	0	0	0	0	0	0	0	0	0	0	0	0
	Paper birch	0	0	0	0	0	0	0	0	0	0	0	0
	Poplar	0	0	0	0	0	0	0	0	0	0	0	0
	Spruce/Pine/Fir	5198	13400	17575	18448	15273	9854	15686	8183	21574	7787	11239	14935

CHAPTER 5. GENERAL CONCLUSION

This thesis identifies opportunities to improve wood procurement system agility, explores operational level silvicultural flexibility as a means to improve agility and proposes a mechanism to anticipate its impact on long-term wood supply. Chapter 2 of the thesis summarizes the numerous approaches to improve wood procurement systems agility that had already been outlined in the wood procurement literature albeit without explicit reference to agility. One yet unexploited method to improving agility, silvicultural flexibility, was further investigated in Chapter 3. More specifically, the method entailed providing decision makers with flexibility in the choice of silvicultural treatment at the operational level. An experiment conducted based on a case study demonstrated significant improvement in profit and demand fulfillment rates as a result of permitting flexibility. The case study has demonstrated the effectiveness of the approach to overcome problems associated with demand uncertainty. One issue associated with altering treatments at the operational level is that the new plan may lie outside the feasible region as outlined in the upper hierarchy plan. The credibility of the entire forest management planning process could thus be jeopardized. A mechanism was proposed in Chapter 4 to examine the impact of permitting operational level silvicultural flexibility on long-term wood supply. The mechanism was implemented to a hypothetical case study based on a dataset from a forest management unit in Quebec. The results of the case study suggested that we are able to measure potential difference in future wood supply resulting from permitting operational level silvicultural flexibility.

5.1. RESEARCH APPLICATION

The ideas and modelling approaches presented in this thesis will prove to be useful for the forest products industry as it strives to improve its performance, especially in regards to forest products supply chain management. It should help the industry mitigate the effects of demand uncertainties. Providing operational level model with as many treatment options as possible will permit better alignment of supply with demand. New forest management regimes grounded on ecosystem based management principles are being adopted across Canada (McAfee and Malouin 2008; Gauthier et al. 2009). From a forest operations perspective, it implies prescription of a range of silvicultural treatments to mimic natural disturbances (Groot et al. 2004). As such, new silvicultural treatments are also being proposed (Raymond et al. 2009). With the new regime in Quebec, the proportion of these treatments are fixed in the annual plans, flexibility on these treatments are not explicitly discussed. There are multiple ways to achieve the goals set in the management strategy; fixing these decisions in the annual plan will certainly contribute to ensuring that the targets are achieved. However, allowing flexibility could also achieve the stated goals in addition to permitting WPS to better align supply with demand.

The research findings have implications particularly for firms operating in mixedwood areas. Mixedwood areas represent a significant proportion of the total productive forest land in Canada. These areas are composed of stands with varying mixtures of softwood and hardwood species (Thomas et al. 2006). During periods when markets for certain species are less attractive, managers face a challenge in implementing the prescribed treatments as they may entail harvesting species without demand in the market. Allowing managers to choose an alternative treatment, still ecologically suitable, allows managers to procure a composition with a greater chance of yielding profit. The mechanism presented in chapter 4 should be implemented to anticipate the long-term impact prior to application.

Sweeping changes are currently occurring around the world as increased environmental awareness is giving way to the green economy (Hanna 2010). The industry is well positioned to support the green economy. Forest products that were unimaginable just even a decade ago are tested and ready for commercialization (FPAC 2011; Leavengood and Bull 2013). Manufacturing of these products have to be supported by wood procurement systems with the capability to timely provide the right type of raw material. Policies permitting approaches to access the right type of raw material with greater precision helps to attract capital investments towards establishment of manufacturing plants in the region (Haley and Nelson 2007).

5.2. STUDY LIMITATIONS AND FUTURE RESEARCH

This thesis focused primarily on one method, operational level silvicultural flexibility, to improve supply flexibility and consequently the agility of WPS. A number of other enablers have also been identified in the second chapter with potential to improve agility. Further analyses should be carried out in future studies to quantify the gains associated with improving agility through those enablers.

The operational level models in the third and the fourth chapter do not take into consideration equipment relocation cost. Incorporating the cost would require information on distances between each of the cutblocks and detailed sequencing of harvest. It certainly would increase the complexity of the model. Instead, the model was constrained to harvest cutblocks in subsequent periods, if chosen for harvest. This helps reduce the procurement cost incurred due to equipment relocation. Perhaps in certain situations, there could be cutblocks voluminous enough that equipment could be moved in and out several times and still remain profitable. In such instances, equipment relocation will need to be modeled explicitly.

Continuing on with the limitations of the modelling approach, the model depicted a supply chain with just one pipeline, i.e. a pipeline with a strategy to address volatile demand. However, a single wood procurement company can have multiple pipelines with strategy differing based on the product type. The placement of the decoupling point will vary according to the product types. Commodities with a predictable demand should have a different strategy from value-added products with a volatile demand. In this thesis, all products were assumed be equally volatile in terms of the demand in the market. Volatility should be adjusted according to the product types and their operations strategy should be modelled accordingly in the future. Additionally, in this study, only demand was assumed to be uncertain, a perfect knowledge was assumed on the supply side. In reality, there is a degree of uncertainty associated with forest inventory which could influence supply chain performance. The advantages of silvicultural flexibility in the context of supply uncertainty should also be investigated in the future.

With regards to the method proposed in the fourth chapter to anticipate the long-term impact, the accuracy of the system in representing the hierarchical planning process needs to be further refined. Given the enormity of the process, we were compelled to adopt crude methods to successfully carry out the experiment. These included the process of cutblock generation, assumptions on road network, and assumptions on product recovery. It is recommended that future studies incorporate greater detail in the hierarchical management planning modelling process.

5.3. FINAL REMARK

Canada has a vast amount of forest resources with superior quality material that lent the country a huge competitive advantage in the past. However, the current state of the industry reflects a lack of anticipation and consequently the preparedness, in term of policies, investments and management practices, for the present day economic realities. Managers now face a challenge to ensure that the industry continues to provide economic and social benefits for Canadians under increased forest conservation requirements. Innovation must be sought, not just in the development of higher value products and new uses of forest fibre, but also in forest management practices. This thesis explores one such innovative method. It provides managers with a tool to make better decisions that ensure greater economic benefits in the face of uncertainty while also respecting environmental and social concerns.

5.4. LITERATURE CITED

FPAC. 2011. The New Face of the Canadian Forest Industry, The Emerging Bio-Revolution, The Bio-Pathways Project. Forest Products Association and Canada. 12pp.

Gauthier, S, Vaillancourt, M., Leduc, A. Grandpré, L., Kneeshaw D., Morin H, Drapeau P., Bergeron Y. 2009. Ecosystem management in the boreal forest. PUQ. In Ecosystem management in the boreal forests, Press de l'Université du Québec.

Groot, A., Gauthier, S., & Bergeron, Y. (2004). Stand dynamics modelling approaches for multicohort management of eastern Canadian boreal forests. *Silva Fennica*, 38(4), 437-448.

Haley, D., & Nelson, H. (2007). Has the time come to rethink Canada's Crown forest tenure systems?. *The Forestry Chronicle*, 83(5), 630-641.

Hanna, K. 2010. Transition and the need for innovation in Canada's forest sector. Chapter 10. In Mitchell B. Resource and Environmental Management in Canada, Addressing Conflict and Uncertainty. Oxford University Press, Fourth Edition.

Leavengood, S., & Bull, L. (2013). Innovation in the global forest sector. In chapter 16 chapter Hansen, E., Panwar, R., & Vlosky, R. The Global Forest Sector: Changes, Practices, and Prospects. CRC Press.

McAfee B and Malouin C. 2008. Implementing Ecosystem-based Management Approaches in Canada's Forests. Natural Resources Canada. 112pp.

Raymond, P., Bédard, S., Roy, V., Larouche, C., & Tremblay, S. (2009). The irregular shelterwood system: review, classification, and potential application to forests affected by partial disturbances. *Journal of Forestry*, 107(8), 405-413.

Thomas, V., Treitz, P., McCaughey, J. H., & Morrison, I. (2006). Mapping stand-level forest biophysical variables for a mixedwood boreal forest using lidar: an examination of scanning density. *Canadian Journal of Forest Research*, 36(1), 34-47.