Integrated Network Design for Forest Bioenergy Value Chain– decisions support system for the transformation of the Canadian forest industry

Thèse

Foroogh Abasian

Doctorat en génie mécanique
Philosophiae doctor (Ph. D.)

Québec, Canada

Résumé

Les usines de bioénergie devraient jouer un rôle important dans la production d'énergie verte à partir de la biomasse forestière. Pour intégrer l'usine de bioénergie dans la chaîne d'approvisionnement forestière, l'industrie a besoin de nouveaux investissements ainsi que de la conception et de la gestion de la chaîne de valeur. D'un autre côté, les incertitudes associées aux nouveaux produits sur le marché peuvent ajouter des risques supplémentaires à un investissement aussi important dans la chaîne d'approvisionnement forestière instable. Par conséquent, l'objectif principal de cette thèse est d'étudier la conception du réseau de bioénergie forestière dans un contexte déterministe et stochastique.

La première partie de la thèse propose une plate-forme expérimentale pour intégrer la conception et le pilotage de la chaîne de valeur puisque le nouveau design ne sera réalisable que s'il considère au préalable la planification. La plateforme a inclus plusieurs actions collaboratives entre tous les partenaires impliqués dans la chaîne d'approvisionnement. Cette plateforme est la base d'un nouvel outil éducatif appelé jeu de transport. Ensuite, la plate-forme a été utilisée pour concevoir un réseau optimisé de bioénergie forestière. La chaîne d'approvisionnement forestière de Terre-Neuve, composée de quatre acteurs majeurs de l'industrie forestière, a été considérée comme notre étude de cas. La rentabilité de l'ajout de nouvelles installations de bioénergie ainsi que de nouveaux terminaux dans plusieurs emplacements potentiels ont été évalués. Enfin, à la troisième partie de la thèse, nous repensons le réseau bioénergétique en tenant compte de l'incertitude de la demande et des prix de tous les produits finaux de la nouvelle chaîne de valeur. Plusieurs bioprocédés potentiels avec différentes technologies ont été évalués dans notre étude de cas. Pour fournir une solution tenant compte du risque, nous avons développé deux nouveaux modèles de gestion des risques. Les résultats dans les trois parties ont clairement démontré l'impact de la planification intégrée, des usines de bioénergie et de la collaboration sur l'amélioration de la performance de la chaîne d'approvisionnement forestière. En général, le travail accompli dans ce projet permettra une transformation en douceur de la chaîne d'approvisionnement forestière en tenant compte des risques d'investissement. En ce qui concerne les résultats obtenus grâce aux études de cas, nous croyons que la plateforme et les approches proposées dans cette thèse peuvent être considérées comme des outils novateurs et pratiques pour le problème de la conception des réseaux de bioénergie forestière.

Abstract

Bioenergy plants are expected to play an important role in green energy production from forestry biomass. To incorporate bioenergy plant in the forest supply chain, the industry requires new investments as well as new value chain design and management. On the other side, the uncertainties associated with demand and price of new products in the market may add risks to such large investment in current forest supply chain. Hence, the main objective of this thesis is to analyze and to propose new design of the forest bioenergy network in both a deterministic and a stochastic context.

The first part of the thesis has proposed four optimization models for strategic, tactical and operational planning levels of the supply chain. The models have included several collaborative actions between all involved stakeholders of the supply chain. They have been integrated in a new educational tool called hierarchical transportation game. In the second part of the thesis, we have integrated the developed optimization models to propose an integrated value chain design and value chain management optimization model. This model has been used to analyze a forest bioenergy network in Newfoundland. Newfoundland forest supply chain comprising four major stakeholders was considered as our case study. The profitability of adding a new bioenergy plant as well as new terminals in several potential locations have been evaluated. Finally, in a third part of the thesis we have proposed the bioenergy network taking into account uncertainty on demand and price of all final products of a new value chain. Several potential bioprocesses with different technologies have been evaluated for our case study. To provide a risk-averse solution, we have proposed two risk management models. The results from the three parts of the thesis have demonstrated the impact of integrated planning, bioenergy plants and collaboration on improvement of forest value chain. In general, the work in this thesis can support an efficient transformation of the forest supply chain considering investment risks. The optimization models and approaches proposed in this thesis are novel and practical for the forest bioenergy network design problem.

Table of contents

Résumé iii
Abstract iv
Table of contents v
List of tables viii
List of figures ix
Acknowledgments xiii
Foreword xiv
General introduction 1
1.1. Introduction 1
1.2. Problem description 2
1.2.1. Case study 4
1.2.2. The hierarchical transportation game 6
1.3. Literature review 7
1.3.1. Supply chain network design 7
1.3.2. Forest Supply chain 8
1.3.3. Research opportunities and thesis objective 9
1.4. Thesis contributions and organization 9
1.4.1. Chapter 2 10
1.4.2. Chapter 3 10
1.4.3. Chapter 4 11
1.5. Reference 12
Chapter 1 The hierarchical transportation game 17
2.1. Introduction 19
2.2. Game description 20
2.2.1. Game basics and map 20
2.2.2. Phase 1: Selection of supply areas 21
2.2.3. Phase 2: Decide on collaboration through wood exchanging. 22
2.2.4. Phase 3: Assignment of areas to mills 22
2.2.5. Phase 4: Backhaul planning 23
2.2.6. Result presentation 24
2.2.7. Game setup and control 25
2.3. Optimization Models 26

2.3.1. Optimization model for selection phase ... 27
2.3.2. Optimization model for swap phase ... 28
2.3.3. Optimization model for assignment phase ... 29
2.3.4. Optimization model for backhaul phase ... 30
2.3.5. Overall model ... 31
2.4. Examples of running the game ... 32
2.5. Discussion and experience ... 37
2.6. Conclusion ... 38
2.7. Reference ... 38
Chapter 2 Forest Fibre Network Design with Multiple Assortments: a case study in Newfoundland ... 40
3.1. Introduction ... 42
3.2. Problem Formulation and mathematical model ... 44
3.2.1. Optimization model ... 45
3.3. Case study ... 50
3.4. Results ... 54
3.5. Concluding Remarks ... 61
3.6. Acknowledgments ... 62
3.7. References ... 63
Chapter 3 Forest bioenergy network design under market uncertainty ... 65
4.1. Introduction ... 67
4.2. Problem statement ... 69
4.3. Mathematical model and solution methodology ... 70
4.3.1. Solution methodology ... 75
The solution which is found is optimal for master and sub problems4.3.2 Risk management models ... 77
4.4. Case study ... 78
4.5. Results and explanations ... 82
4.5.1. Objective value comparison ... 82
4.5.2. Network design comparison ... 85
4.5.3. General solution evaluation ... 87
4.6. Conclusion ... 88
4.7. Acknowledgments ... 89
4.8. References ... 89
General conclusion and perspectives ... 92

5.1. General conclusion..92
5.2. Recommendation for future work 93

List of tables

Table 2-1. Purchasing, transportation and total cost for optimal 1 and 2 and players performance.. 34
Table 2-2. Student performances in two round plays of the game……………………………….. 37
Table 3-1. Developed scenarios based on the five defined assumptions…………………………. 54
Table 3-2. Size of each scenario using CPLEX directly…………………………………………. 55
Table 3-3. Key performance indicators definition……………………………………..………… 56
Table 3-4. The optimization result for each of the scenarios (revenue, costs and profit are in million…………………………………………………………………………………........ 57
Table 4-1. General potential process information………………………………………………... 80
Table 4-2. Problem size for different models…………………………………………………….. 82
Table 4-3. Expected value and standard deviation for stochastic solution, deterministic for each scenario and deterministic with fixed average design…………………………………………… 83
Table 4-4. Technology assessment………………………………………………………………. 87
Table 4-5. New generated scenarios……………………………………………………………… 87

List of figures

Figure 1-1: Forest bioenergy network design and the flows between network nodes. The dashed circles around terminals and bioenergy plant display their potential locations in the value chain.…….. 3
Figure 1-2: The main contributions of the thesis…………..……………………………………… 4
Figure 1-3: Newfoundland forest map including 18 forestry districts and four stakeholders. The dashed grey areas are Kruger tenure……………………………………………………………. 6
Figure 1-4: The game map, the circles are supply areas and the numbers demonstrate weekly demand of each mill.………………………………………………………………………… 7
Figure 1-5: The necessary modules to comprehensively consider network design problem……… 9
Figure 1-6: Research organization in the first contribution………………………………………. 10
Figure 1-7: Research organization in the second contribution…………………………………… 11
Figure 1-8: Research organization in the third contribution……………………………………… 12
Figure 2-1: Illustration of the game' map. Supply points are demonstrated by circles. The icon of sawmills and pulp and paper mills determines the location of mills for each team. The numbers display demand of each mill. The teams are differentiated by different colors………………….. 20
Figure 2-2: a) A player selection among pulp wood supply nodes. b) A player selection among saw log supply nodes. c) For each node, the interior (exterior) of hexagonal determines the composition of the area as the supplier of saw log (pulpwood). d) The selected resources in a single map for a player ……………………………………………………………………… 21
Figure 2-3: Illustration of an exchange of areas. a) The map demonstrated high load and unload transportation cost before the exchange. b) exchange proposal windows c) the map shows the reduction in transportation cost after exchange of area 22 (saw logs) with area 40 (saw logs)….. 22
Figure 2-4: Illustration of the assignment phase. The arrows show the possible assignment options for the selected mill……………………………………………………………………… 23
Figure 2-5: Illustration of a backhauling concept with 2 units of cost saving in empty driving. The straight and dash lines in the figures demonstrate loaded and unloaded transportation respectively. (a) Two deliveries by direct transportation and total distance of 8. (b) The same deliveries within a backhaul route with total distance of 6……………………………………… 23
Figure 2-6: Backhaul phase. a) Two direct transportation routes. b) The backhaul path with saving cost c) A backhaul route that reduces unload transportation cost (dash lines) by 10 units. 24
Figure 2-7: Results for selection phase. It demonstrates the planning cost for current phase in the first week……………………………………………………………………………………. 25
Figure 2-8: The first page to access to the game. To start, the players should click on "play game" button. Other administration settings can be done in "create a game" and "game administrator" option……………………………………………………………………………………………….. 26
Figure 2-9: The login page of the game; the players should select the game name firstly, then select their team, type their name and afterwards click on GO………………………………….. 26
Figure 2-10: Optimal solution and player performance for the first phase of the game………..... 32

Figure 2-11: Selection phase, the left side maps are players selection for saw log (a) and pulp wood (c) resources; the right side maps are optimal solution for resource selection of saw log (b) and pulp wood (d)………………………………………………………………………………… 33
Figure 2-12: Optimal solution and player performance for the second phase of the game……………………………………………………………………………………………… 34
Figure 2-13: Player areas before exchanging for saw log (a) and pulpwood (c) and after it for saw log (b) and pulpwood (d) in swap phase. Comparing (a) and (b) displays the swap of areas 50 and 9. Comparing (c) and (d) displays swap of areas 38 with 46 and 26 with 56……………………. 35
Figure 2-14: Optimal solution and player performance for assignment phase ………………….. 36
Figure 2-15: Optimal solution and player performance for the fourth phase of the game……………………………………………………………………………………………. 36
Figure 2-16: Comparing results of player with optimal solution during four phases of the game… 36
Figure 3-1: Forest biomass network design and the flows between network nodes. The dashed circles around terminals and biorefineries display their potential location in existing supply chain……………………………………………………………………………………… 45
Figure 3-2: Map of Newfoundland forest industry………………………………………………. 51
Figure 3-3: Potential location for terminals (yellow points) and pellet mill (purple point), the mills are depicted by black points (map is taken from FPInterface™)………………………….. 52
Figure 3-4: The possible backhaul routes: (a) Newfoundland's principle backhaul route without empty driving between Corner Brook Pulp and Paper (CBPP) and Sexton Lumber. (b and c) Backhaul routes with more full load trips rather than empty driving between CBPP, Sexton Lumber and an open terminal……………………………………………………………….. 53
Figure 3-5. Sum of revenue for selling products. The orange line in all figures is the total revenue for the base case scenario. The scenarios are compared in four categories: (a) scenarios without terminal and pellet mill opening assumptions, (b) scenarios with terminal opening assumption, (c) scenarios with pellet mill opening assumption, and (d) scenarios with terminal and pellet mill opening assumptions……………………………………………………………………………… 58
Figure 3-6: Total network cost for each scenario. The brown line in all figures is total cost for the base case scenario. The scenarios are compared in four categories: (a) scenarios without terminal and pellet mill opening assumptions, (b) scenarios with terminal opening assumption, (c) scenarios with pellet mill opening assumption, and (d) scenarios with terminal and pellet mill opening assumptions. The percentage on top of all bars determines the difference between the scenario and the reference line………………………………………………………………… 59
Figure 3-7: Total network profit and profit/m3 for each scenario. The orange and green lines in all figures are total profit and profit/m3 for base case scenario. The scenarios are compared in four categories: (a) scenarios without terminal and pellet mill opening assumptions, (b) scenarios with terminal opening assumption, (c) scenarios with pellet mill opening assumption, and (d) scenarios with terminal and pellet mill opening assumptions. The percentage on top of all bars determines the difference between the scenario and their corresponding reference line…………. 60
Figure 3-8: Selected facilities location in different scenarios (map is taken from FPInterface™)… 61
Figure 4-1: The forest network structure. Dashed lines demonstrate the potential location and flows……………………………………………………………………………………………… 69

Figure 4-2: Newfoundland forest map including 18 forestry districts and four stakeholders. The dashed grey areas are Kruger tenure………………………………………………………… 79
Figure 4-3: Scenario diagram in the condition that all products have faced with uncertainty. The letters M, H and L demonstrated the medium, high and low level of demand for each product category respectively……………………………………………………………………... 81
Figure 4-4: The potential location for terminals and bioenergy plant are displayed by stars and mill signs respectively……………………………………………………………………. 81
Figure 4-5: Scenarios profitability comparison between stochastic solution, deterministic for each scenario and deterministic with fixed average design. ……………………………………….. 84
Figure 4-6: Comparison of objective values with different risk coefficient values……………… 84
Figure 4-7: Frequency of objective value with and without downside risk management……….. 85
Figure 4-8: Network design and resource allocation comparison. a) Network design for deterministic model. b) Network design for stochastic model. c) Network design for variability risk model (risk coefficient equal to 2). d) Network design for downside risk model (target of 10 M$ and fixed risk of 12 M$)……………………………………………………………….. 86
Figure 4-9: Evaluation of network design of average case and stochastic case for four new developed scenarios…………………………………………………………………………. 89

“You can never cross the ocean unless you have the courage to lose sight of shore.”

-Christopher Columbus-

Acknowledgments

I enjoyed every moment of my Ph. D. journey because I had a privilege to work under the supervision of my dear advisor Professor Mikael Rönnqvist, you have been a tremendous mentor for me. I would like to express my heartfelt thanks to you for teaching me on how to conduct high-quality research. I will always remember your priceless advice on research and my life.

I also would like to extend my deepest gratitude to my co-advisor Professor Mustapha Ouhimmou, you gave me endless encouragement, guidance and support. Your level of care always helps me to improve the research work presented in this dissertation.

I am especially thankful to Strategic Network on Value Chain Optimization (VCO) and FORAC Research Consortium for their financial support and the number of workshops, summer schools, and webinars they held during all these years. Special thanks to the administrative and technical support of both networks: Catherine Lévesque, Julie Richard, Catherine Savard, Edith Brotherton, Yan Feng, Philippe Marier and Alexandre Morneau.

I am grateful to the FPInnovations, Newfoundland Centre for Forest Science and Innovation, and all stakeholders in Newfoundland for providing relevant information and technical advice for the development of the case study presented in this thesis.

I am thankful to all my friends Maha, Chourouk, Julie and Jean for the interesting talks about research and life, and for making the time at the office much more enjoyable. I am also very grateful to my dear Patricia for her endless weekly effort during these four years to help me to improve my French.

Crossing the oceans to start a challenging life here in Quebec was impossible without endless emotional support and encouragement of my family. They always trust me and respect my decisions even if it was very painful for them to live far from each other. My hearties thanks to my dearest parents who encourage me to follow my dreams. I am also deeply thankful to my dear sister and my best friend, Fatemeh for her incredible support.

The last but not the least thanks to my dearest Dariush. Your great heart, your high understanding, your endless kindness and your pure love bring me a happy life beside all Ph. D. challenges.

Foreword

This thesis is prepared as an article insertion thesis comprising of five chapters starting with the introduction, chapter 1 and ending with a conclusion, chapter 5. Chapter 2, 3 and 4 regroup the published and submitted articles. Here is the information on the mentioned articles:

Abasian F., M. Rönnqvist, P. Marier, JG. Gill-Couture, D. Fjeld2 (2017). "The hierarchical transportation game**",** submitted on INFORMS transactions on Education.

Abasian F., Rönnqvist, M., Ouhimmou, M. (2017). "Forest Fiber Network Design with Multiple Assortments a case study in Newfoundland"**,** Canadian Journal of Forest Research, https://doi.org/10.1139/cjfr-2016-0504.

Abasian F., Rönnqvist, M., Ouhimmou, M. (2017). "Forest bioenergy network design under market uncertainty**",** submitted on Energy.

Furthermore, in addition to the above-mentioned papers, the results of this work were presented during the following conferences:

Abasian F., Rönnqvist, M., Ouhimmou, M., Forest Bioenergy Value Chain Design under uncertainty. 21st Conference of the International Federation of operational research society, July 17-21, 2017, Quebec, Canada.

Abasian F., Rönnqvist, M., Ouhimmou, M., Forest Biomass Value Chain Design- case study in Newfoundland. Optimization days, May 8-10, 2017, Quebec, Canada.

Abasian F., Rönnqvist, M., Gill-Couture, J.G., Marier, P., Fjeld, D**.,** The hierarchical transportation game. 11th International conference on modeling, optimization and simulation, August 22-24, 2016, Montreal, Canada.

Abasian F., Rönnqvist, M., Ouhimmou, M., Forest Biomass Value Chain Design. 11th International conference on modeling, optimization and simulation, August 22-24, 2016, Montreal, Canada.

Abasian F., Rönnqvist, M., Ouhimmou, M., Forest Biorefinery value chain design with multiple assortment under uncertainty. 58th CORS Annual Conference, May 30- Jun 1, 2016, Banff, Canada.

Abasian, F., Rönnqvist, M., Ouhimmou, M., Design of a forest biomass value chain under uncertainty, 11th International Industrial Engineering Conferences (CIGI), Oct 26-28, 2015, Université Laval, Quebec, Canada.

Abasian, F., Rönnqvist, M., Ouhimmou, M**.,** Design of a forest biomass value chain under uncertainty, Joint International Meeting Canadian Operation Research Society and Institute for Operation Research and Management Science (CORS/INFORMS), Jun 14-17, 2015, Sheraton Hotel, Montreal, Canada.

Abasian, F., Adam, M., Gill-Couture, J.G., Marier, P., Rönnqvist, M., Fjeld, D**.,** Educational game in transportation planning, 56th CORS Annual Conference, May 26-28, 2014, Marriott Hotel, Ottawa, Canada.

General introduction

1.1. Introduction

A supply chain represents a set of organizations that are involved in a network to produce values in the form of products and services from the available resources and given demands. This network is created by four linked processes including procurement, distribution, production and sales. Procurement process includes all subprocesses to provide resources for production. Production is associated with manufacturing or refinement of products. Distribution process creates a bridge between manufacturing plants and customers. The sale process is responsible to use costumer's demand to maximize profit. The ultimate objective of the processes is increasing the network competitiveness through means of supply chain management (SCM). Two board pillars of SCM to achieve supply chain competitiveness are integration (or cooperation) of the involved partners (Stevens 1989, Dainty et al. 2001) and coordination (Simatupang et al. 2002, Stadtler and Kliger 2005).

Integration attempts to link all involved parties of the chain to collaborate on the long-term (Stadtler and Kliger 2005). Wood (1997) reported that 10% cost reduction in integrated supply chain could yield an improvement of 40%-50% pre-tax profit for each partner. The potential outcomes of a real integration are new partnerships, reduced inventory, shorter lead time and better service to customers (Parnell 1998). Integration will be possible only if coordination of information and material exists between all involved partners as well as the supply chain's processes.

To coordinate the information effectively between all aforementioned components of supply chain, decision support system was developed (Ghodsypour and O'Brien1998). It decomposes overall decisions of the supply chain into two or more decision levels to build hierarchical planning for the supply chain. In the concept of hierarchical planning, the higher level decisions restrict the decisions on the lower level (Miller 2012). Anthony (1965) classified the hierarchical planning levels to long, mid and short-term planning that are so-called strategic, tactical and operational planning, respectively. Strategic decisions typically concern the design of the supply chain on which has several year impacts. The tactical decisions comprise material flows within 6 to 24 months. Finally, operational decisions consider all daily activities in detail for immediate execution (Fleischmann et al. 2008).

The success of a supply chain relies on other fundamental aspects including strategic management, logistic and transportation, marketing, etc. (Croom et al. 2000). Hence, an appropriate planning procedure for the supply chain is to include all aforementioned aspects in a decision support system. However, the uncertainties associated with market behavior, technology efficiency and resources availability could affect the efficiency of decisions in the supply chain. These uncertainties have more impacts on the network especially when new products are introduced in the supply chain. In such conditions, we use the value chain term instead of supply chain and the design planning is about finding a set of feasible investments among a collection of possible ones to optimize robustly the specific objectives of the network taking into account all existing uncertainties. We define value chain robustness as the ability of a value chain to resist or avoid change.

The network design problem requires value chain management to execute efficiently the proposed decisions. A system comprising optimization models of all combinations of the process-planning as a single problem could facilitate the integration of value chain design and management. The strategic model in the system evaluates the profitability of adding new products and values to the market with and without uncertainty consideration. The tactical model comprising supply allocation, production level and network flow decisions supports long-term decisions. The integration of models in the system provides a comprehensive model with the objective of robust value chain design and planning. Regarding above-mentioned subjects, the main research questions of this thesis are as follows:

1. How can we plan hierarchically a value chain considering several stakeholders?
2. How can we integrate the value chain design with value chain management in a collaborative environment?
3. How can we design such value chain under uncertainty consideration?

Forest supply chain is a very suitable example of the proposed research questions since it is faced with a new market' demands for green energy that would demand new network design. Therefore, in what follows, we describe the research problem in forest bioenergy value chain. Moreover, we explain why Newfoundland forest supply chain is considered as our case studies. A comprehensive review of the literature on existing approaches addressing hierarchical planning, value/supply chain design models and value/supply chain management with uncertain demand, price and uncontrollable supply is also included. The outline and organization of the thesis have been given at the end of this chapter.

1.2. Problem description

In recent years, the forest industry has been facing several crises, including the global economic recession, rapid decline in commodity demand and strong competition from Asian companies (Mockler and Fairbairn 2009; Mockler and Robichaud 2011). Several countries, including Canada, Sweden, Finland, Chile and New Zealand have been affected by the aforementioned crises. However, the trend of new energy generation from woody biomass creates a great opportunity for the forest industry. Forestry biomass comprises cellulose, hemicellulose, lignin and other extractable parts are all convertible in bioenergy plants to a wide range of products and energies including heat, bio-oil, pellet, ethanol and many others. In order to generate renewable energies from forestry resources, the value chain needs a transformation. This transformation induces additional risks due to the uncertainty of the new markets, new advanced materials, associated technologies and integration with an existing supply chain. Figure 1-1 displays the forest value chain with potential strategic opportunities. To redesign the network three principal steps should be accomplished: first, the current state of the supply chain should be stabilized in a collaborative environment; second, new network design taking into account new bioenergy plant as well as logistic planning should be proposed; third, the impact of uncertainties on the new production process should be analyzed.

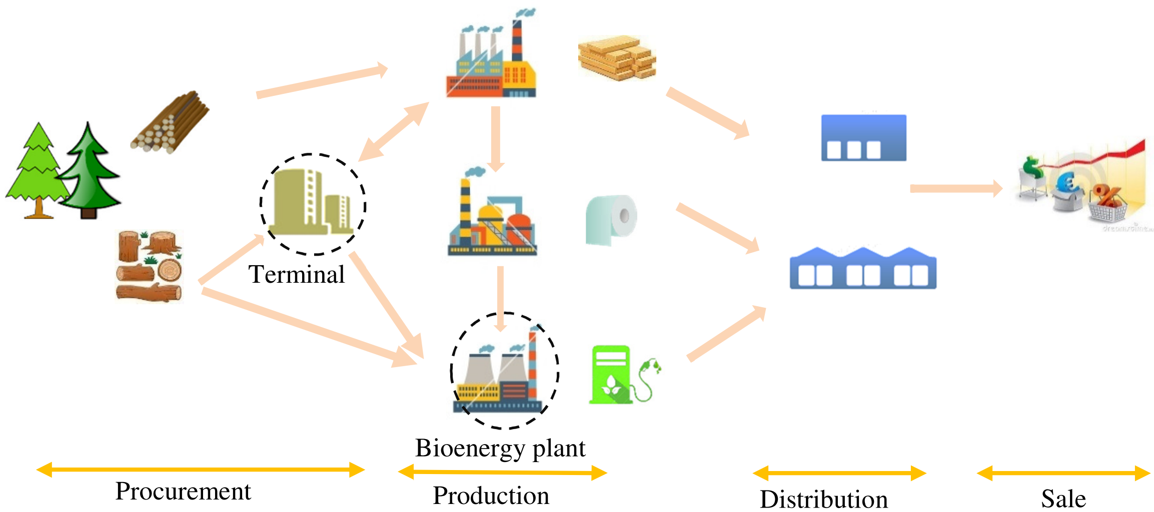


Figure 1-1: Forest bioenergy network design and the flows between network nodes. The dashed circles around terminals and bioenergy plant display their potential locations in the value chain.

In the context of value chain design, we have proposed three contributions. First, we have developed four optimization models pertinent to strategic, tactical and operational planning in the value chain. The tactical and operational models have considered collaborative and non-collaborative planning. The developed models have been integrated to a teaching tool called the hierarchical transportation game.
Second, we have proposed an integrated strategic-tactical optimization model for the forest bioenergy value chain. The developed models in the first contribution have been expanded and have been integrated in this phase in order to be utilized for Newfoundland forest supply chain case study. Several scenarios have evaluated different improvement opportunities for the current situation of the supply chain by assuring the resource availability and minimizing the logistic cost in a collaborative planning. Afterwards, the profitability of adding new assortments including bioenergy and terminals in the current or improved situation has been studied.
The sensitivity analysis of the result has shown that such design is highly sensitive to the input parameters including resource availability, the yield of processes, demand and price of the final products. Hence, the third contribution of this thesis has defined to develop a stochastic optimization model taking into account uncertainty on demand and price of all final products in the forest bioenergy value chain. We have developed several scenarios based on different uncertainties combination. Afterwards, we have reported the network design decision that is optimal on average for all developed scenarios. The current situation of the supply chain, as well as the existing of uncertainty on new market have increased investment risks for adding the new bioenergy plant in the value chain. Hence, we have developed two risk models to manage financial risks. Finally, we have compared the network design of deterministic, stochastic and financial risk models.
Figure 1-2 has demonstrated the accomplished work in each contribution. The presented research in this thesis has started with questions about: How hierarchical planning can optimize the situation of

the entire supply chain? How the collaborative and non-collaborative planning could affect all involved partners of the supply chain? Hierarchical planning models have been proposed for educational transportation game that simulates the procurement planning in the supply chain. Afterwards, we have concentrated on the forest supply chain and we have raised the question about: what are the actions to stabilize the current state of the forest supply chain? How can new forest value chain including new bioenergy plant and terminals improve the value chain situation? An integrated strategic-tactical optimization model has been developed to answer these questions. Finally, we have answered the questions including: what is the best robust bioenergy network design considering uncertainty on demand and price of final products? Which processes bring more profitability and reliability to the network? How to reduce investment risks of new bioenergy plant?

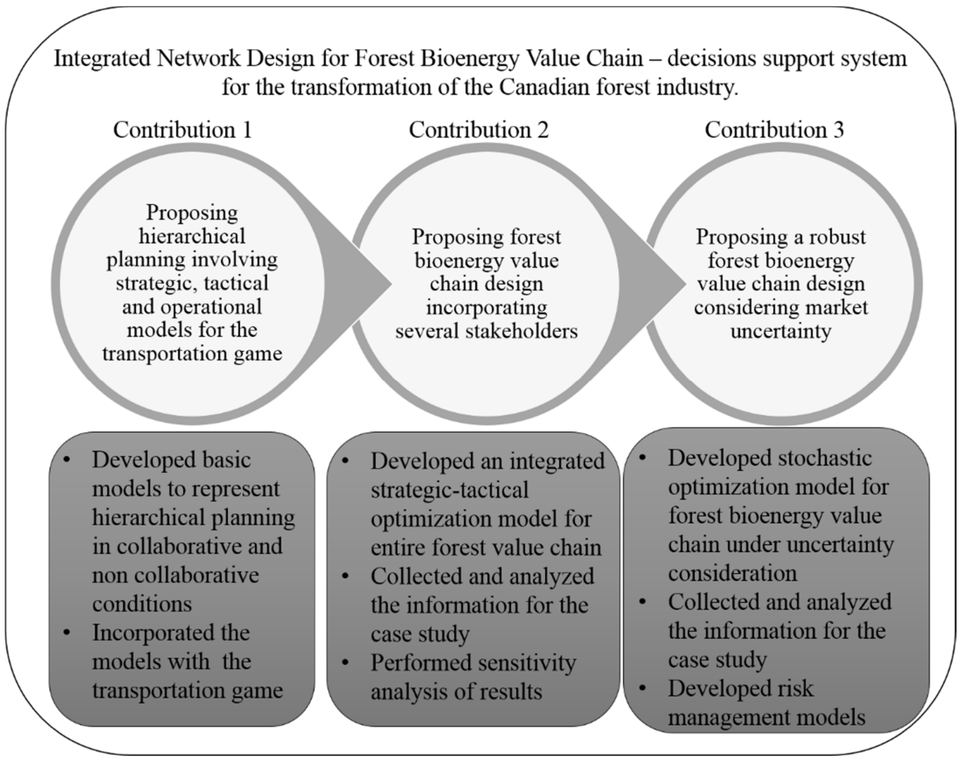


Figure 1-2: The main contributions of the thesis

1.2.1. Case study

Several surveys explored the perspective of forest product supply chain in different countries (Rönnqvist 2003 in Sweden, Martell et al. 1998 in Canada and Epstein et al. 1999 in Chile). In this thesis, we study the Canadian forest supply chain. In 2013, the forest supply chain contributed about $60 billion to Canada's nominal gross domestic product (GDP). This industry comprises five entities described below:

- Forest: the supplier of resources including sawlog, pulpwood and energy wood
- Terminals: in-transit yards for logs between forest and plants
- Pulp and paper mill: the plant to produce pulp and paper
- Sawmills: the plant to produce lumber and wood chip
- Bioenergy plant: new plant to produce bioenergy and biofuel

We have collected information of the aforementioned entities for the Newfoundland forest value chain. Newfoundland is the insular portion of the Canadian province of Newfoundland and Labrador located in the North Atlantic Ocean. It has two million ha of productive forestland, within 18 districts, available or partially available for harvest. The lands are 96% owned by the public and 4% by the private sector. The primary commercial species are black spruce (Picea mariana (Mill.) Britton, Sterns & Poggenb.) and balsam fir (Abies balsamea (L.) Mill.). Each 5 years Newfoundland Centre for Forest Science and Innovation releases detailed information about the annual allowable cut of forest. The information determines the fiber volume, fiber attributes and their exact location in 2 km× 2 km forest blocks. The resources are harvested to satisfy demand of the four existing plants including Corner Brook Pulp and Paper Limited owned by Kruger (capacity 700,000 m3/yr), Burton's Cove Lumber Limited (capacity 70,000 m3/yr), Cottle's Island Lumber (capacity 40,000 m3/yr) and Sexton Lumber (capacity 180,000 m3/yr) respectively from west to east. The final products of the mills are mainly commodity forest products, including lumber, pulp and paper and energy. Corner Brook Pulp and Paper holds timber tenure of 29% of the total public forestlands that is called Kruger tenure. This means other stakeholders are not permitted to harvest Kruger tenure (Sustainable Forest Management 2013). The stakeholders have individual annual agreements with the government that allow them to harvest specific areas. Figure 1-3 displays available forestry resources in the 18 districts and 6505 forest blocks. Kruger tenures are differentiated by dashed gray color in the figure.

Fiber wood availability is one of the most challenging problems in this supply chain, particularly for sawmills with their restricted timber tenure. Two charcterics make this problem problematic. First, Newfoundland has a very acid soil with low fertility, which means vast supply areas with low production. Second, the mills do not receive the quantity and quality of supply they require since the resources are not allocated based on the mills desires. Sorting yards with the goal of delivering the right fiber to the right mill at the right time could significantly improve their current situation.

Furthermore, high transportation costs as well as environmental concerns are two other significant problems for Newfoundland forest supply chain. The large resource distribution increases the transportation distance. The west of the insular area is covered by balsam fir which is a valuable feedstock for Corner Brook Pulp and Paper; and conversely, the eastern part of the island is covered by black spruce, a valuable raw material for the sawmills. The travel from west to east of Newfoundland takes around 8 hours. Moreover, transportation in Newfoundland is operated by several independent organizations under different agreements. As a consequence, the supply delivery to Corner Brook Pulp and Paper is restricted to drivers of a particular organization. This condition severely limits the opportunity for collaboration in the form of backhauling transportation. Hence, introduction of bioenergy to produce green energies and backhaul transportation to reduce the pollution and cost can significantly improve the supply chain situation.

The specific characteristics of biomass in the case study as well as maturity of new bioprocesses constraint the choice of new bio-based product among the diverse ones. We have considered palletization, organic ranking cycle (ORC), internal combustion engine (ICE), combined heat and power (CHP) and fast pyrolysis as potential bio-process to produce electricity and biofuel in the supply chain. It is worth to mention that Corner Brock Pulp and Paper has already CHP process however it could transform to another process in the case of profitability.

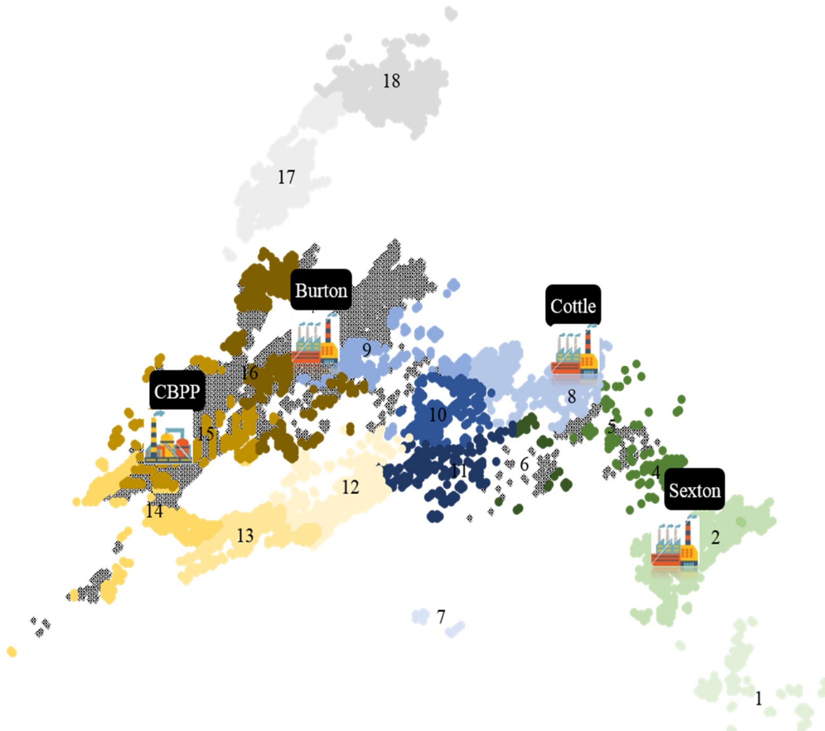


Figure 1-3: Newfoundland forest map including 18 forestry districts and four stakeholders. The dashed grey areas are Kruger tenure.

1.2.2. The hierarchical transportation game

As already mentioned, we have started the thesis with proposing generic hierarchical planning models for the supply chain. The developed models have been incorporated with the transportation game, an educational tool that simulates procurement planning in the supply chain. Although transportation game simplified forest supply chain planning, it has been developed generally enough to utilize as an educational tool to support hierarchical planning in any supply chain. The game runs for three players in simultaneous competition and collaboration in four different stages. Indeed, in some phases, the players compete against each other and in some phases they should collaborate to improve their situation. The game is accessible online and its initial setting is a hexagonal map with 61 potential supply areas and a set of existing mills with demand (Figure 1-4). Each mill is either a paper mill or a sawmill differentiated by the sign and has a given demand for pulp logs (paper mill) or sawlogs (sawmill) each period. The detailed information about game stages and their optimization models have been provided in chapter 2 of the thesis.

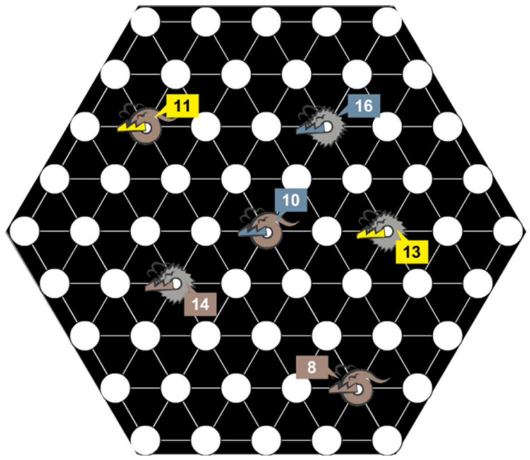


Figure 1-4: The game map, the circles are supply areas and the numbers demonstrate weekly demand of each mill.

1.3. Literature review

1.3.1. Supply chain network design

The history of network design models dates back to 1970s when Geoffrion and Graves (1974) studied the multi-commodity single-period distribution network design problem. These types of studies have been applied to different networks such as transportation, telecommunication, distribution and distributed computer networks. In the 1990s type of research on the location-allocation problems progressed toward designing integrated production-distribution models. Pirkul and Jayaraman (1996) represented a crucial step toward integrated facilities' design combining the issue of product distribution with the issue of interaction of manufacturing plants and warehouses.

Supply chain design and planning is reviewed comprehensively by Melo et al. (2009). They classified studies in this domain based on multi-layer facilities, multiple commodities, single/multiple period(s) and deterministic/stochastic parameters assumptions. Studies that consider all entities of the supply chain are the ones in the category of multiple commodities, multi-layer facilities. In all included studies the planning attempts to configure the supply chain for financial objective including maximizing net present value or minimizing the cost. Jang et al. (2002) proposed a supply network management system comprising four modules of supply chain network design, operation-distribution, management and data management. Detailed logistic planning of supply chain including resource allocation, product flow and transportation mode selection is studied in Cordeau et al. (2003). However, a robust network design requires integrated planning with uncertainty and risk consideration.

Uncertainties exist on several network parameters including demands, prices, exchange rate and raw material/energy costs. A scenario is defined based on the combination of assumed random parameters. To consider scenarios in the planning, proactive approaches including stochastic optimization have been proposed in several studies (Birge and Louveaux 1997; Ruszczynski 2004; Santoso et al. 2005). If the behavior of random parameters during time remains stationary, then two-stage stochastic optimization can be utilized; otherwise multi-stage stochastic optimization is required. Two-stage stochastic optimization was proposed and employed by Tsiakis et al. (2001); Santoso et al. (2005);

Vila et al. (2006) and Azaron et al. (2008). Moreover, it could easily consider the risk metrics (Mulvey et al. 1995; Santoso et al. 2005). One of the promising methodology to solve two-stage model is L-shaped model (Birge and Louveaux 1997; Jeihoonian et al. 2016).

1.3.2. Forest Supply chain

Although supply chain planning has supported the development of involved partners in many supply chains, the challenge of integrated planning in forest supply chain remains open. The hierarchical planning on different processes of the value chain including harvesting, transportation, production, distribution and marketing were studied in many research projects (Rönnqvist 2003; Fleischmann et al. 2008, Flisberg et al. 2012; Carlsson and Rönnqvist 2007). To have a better solution in such planning, collaboration and cooperation could extensively help. Frisk et al. (2010) declared a potential saving of 5-15% by collaboration in the transportation between eight forest companies in Sweden.

Each of forest entities including terminal (Lehoux et al. 2012; Alam et al. 2014; Dramm et al. 2004; Carlgren et al. 2006), pulp and paper mill (Martel et al. 2005; Carlsson et al. 2009; Weigel et al. 2010; Philpott and Everett 2001) and sawmill (Vila et al. 2006) are studied separately in previous research. Recently the importance of green energies to reduce CO2 emissions motivates many researchers to study energy and fuel generation from forestry biomass. This type of problem is named forest bioenergy network design. Bioenergy plants are new facilities that could employ several potential processes including extraction, CHP, ORC, ICE, pelletization, pyrolysis and fermentation to produce electricity, heat, pellet, biofuels and ethanol from forest biomass. Technical and economic analysis of bioenergy technologies have provided by several studies (Marinescu 2012; Dansereau et al. 2014; Natural Resource Canada 2017; Mirkouei et al. 2017; Whalley et al. 2017; Akhtari et al. 2017; Li et al. 2017).

Kim et al. (2011) studied forest biofuel value chain design considering transportation and operating costs. Ekşioğlu et al. (2009) analyzed and managed the design of ethanol value chain from forestry resources. They identified the number, capacity and location of biofuel considering procurement and transportation decisions. The integration of biofuel plant with an existing bioenergy plant considering biomass availability, transportation cost and the local heating price is investigated by Leduc et al. (2010). Cambero et al. (2015) studied strategic optimization of integrated bioenergy and biofuel in the forest industry. Their optimal solution provided the facility location and technology assessment.

As already stated, network design problems are highly subjected to uncertainty on resource availability and characterization, process performance and market. However, the complexity of uncertainty consideration in the bioenergy value chain design attracts less attention compared to the deterministic problem. Kim et al. (2011) considered the uncertainty by performing sensitivity analysis. They developed a general optimization model to select biomass supply locations, candidate sites and capacities for biofuel plants and the logistics of forest biomass. Meanwhile, they did sensitivity analyzes in order to investigate the most important parameters on the overall economy. They extended their work using stochastic optimization to tackle demand uncertainty of biofuels in the biomass value chain (Kim et al. 2011).

Biomass value chain planning in tactical level considering uncertainty has been investigated in few studies (Svensson et al. 2011; Chen and Fan 2012; Tay et al. 2013; Zanjani et al. 2010). Svensson and Berntsson (2011), for instance, investigated the transformation of pulp and paper process to biofuels process considering the uncertain energy market. In forestry, Shabani et al. (2014) studied the tactical planning of forest biomass value chain under supply uncertainty. Moreover, they have optimized risk metrics to reduce solution variability. Uncertainty in designing biofuel supply chain has been reviewed by Awudu and Zhang (2012). Finally, for a comprehensive survey over forest biomass value chain optimization models in deterministic and stochastic contexts, readers are referred to Shabani et al. (2013) and D'Amours et al (2010).

1.3.3. Research opportunities and thesis objective

In the forest supply chain part of the literature review, we first reviewed the forest supply chain design and planning studies. We found that an integrated forest value chain network design model in collaborative environment has been missed in the literature. We have classified all necessary modules to design and plan integrated forest value chain in Figure 1-5. The modules include several separate optimization models in strategic and tactical levels that have been applied for the transportation game. The integration of a bioenergy plant to the forest supply chain requires a network redesigning and planning. However, from reviewing the literature, integrated bioenergy network design considering all supply chain partners and detailed logistic planning have been missed in previous studies. This motivates us to develop a comprehensive model for bioenergy network design planning. The principal contributions of this work are to stabilize the current situation of the forest supply chain and then provide an efficient transformation. The developed model has been applied for the Newfoundland forest supply chain case study.

The last part of the literature review surveyed the studies that considered uncertainty in bioenergy network design. From our best information, stochastic forest bioenergy network design problem in such a comprehensive way has not been considered in the literature. Moreover, the risks associated with new investments have not been studied which is not the case for our assumed problem.

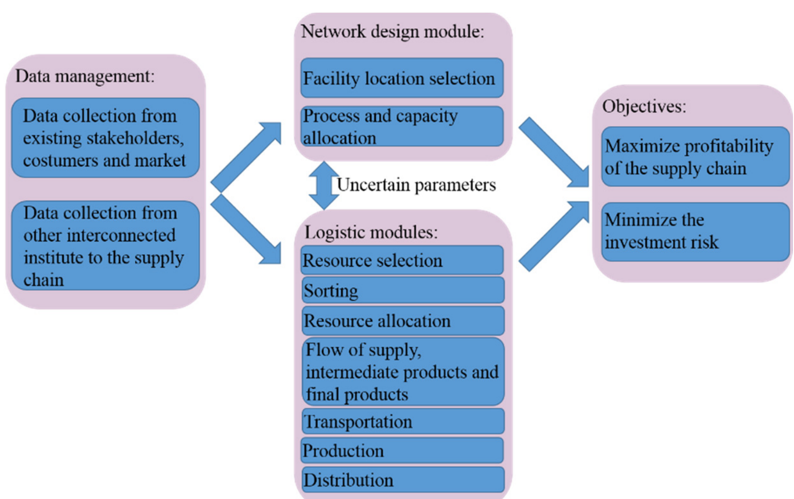


Figure 1-5: The necessary modules to comprehensively consider network design problem

1.4. Thesis contributions and organization

This thesis presents a system to design and plan forest bioenergy network in a deterministic and a stochastic context. The concept development and the experimentation performed for this thesis represent different scientific contributions. The thesis includes three original contributions (presented as three articles), which have been provided throughout Chapters 2 to 4 as follows.

1.4.1. Chapter 2

Following the identification of the research objective in the literature review on the hierarchical planning of the supply chains, we have presented the first paper entitled "*The hierarchical transportation game*". We have developed the educational transportation game that simulates hierarchical planning on the procurement process of the supply chains. The game plays online in a simplified map during four stages. It provides a collaborative environment for hierarchical planning in an educational setting. We have equipped the game with basic hierarchical models. The objective in the game for players is to minimize transportation and purchasing cost. The players' performance in each stage is compared between each other's as well as with the optimal solutions. The contribution organization of the paper has been depicted in Figure 1-6 summarizes the contents of chapter 2.

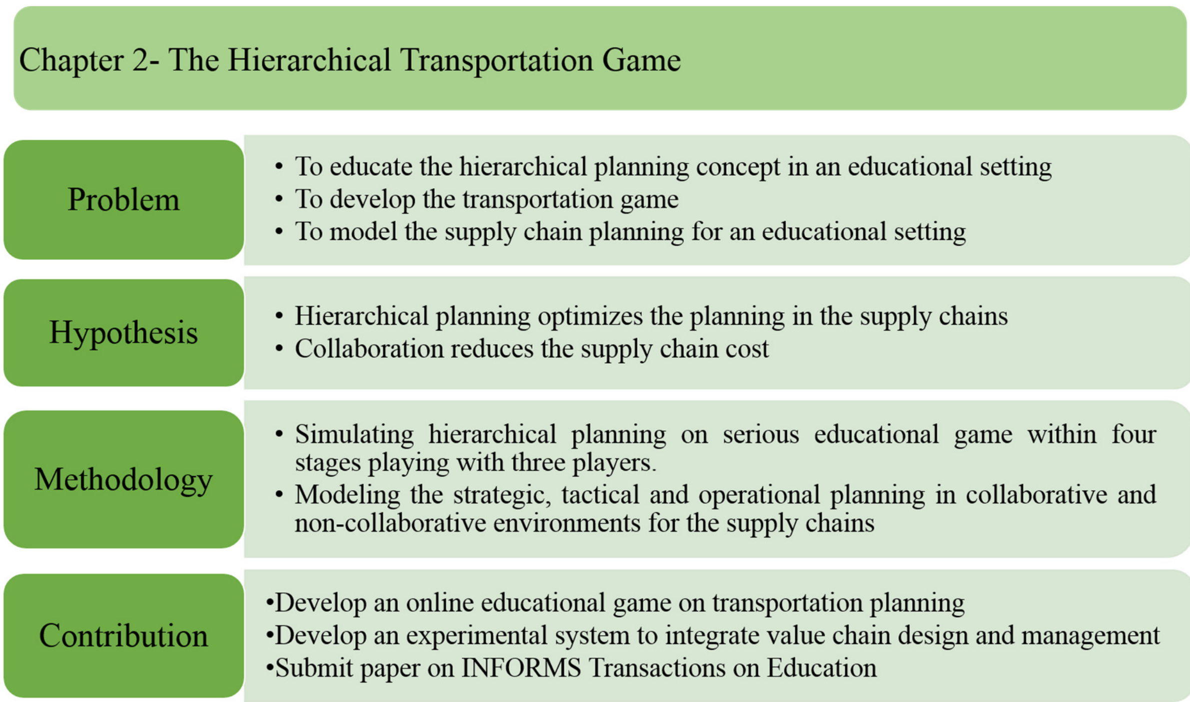


Figure 1-6: Research organization in the first contribution

1.4.2. Chapter 3

The second paper, entitled "*Forest Fibre Network Design with Multiple Assortments: a case study in Newfoundland*", has proposed a new network design that increases the value chain profitability. The principal objective of this chapter is to prepare the forest supply chain for an efficient transformation. The impacts of different improvement opportunities have been evaluated to help the stabilization of the supply chain. Afterwards, we have evaluated the profitability of a new pellet mill. Several key performance indicators have compared the decisions that have been made. Finally, the sensitivity analysis on the result has determined the sensitivity of decisions on specific parameters including demand and price of the final products. The contribution organization of the paper has been shown in Figure 1-7.

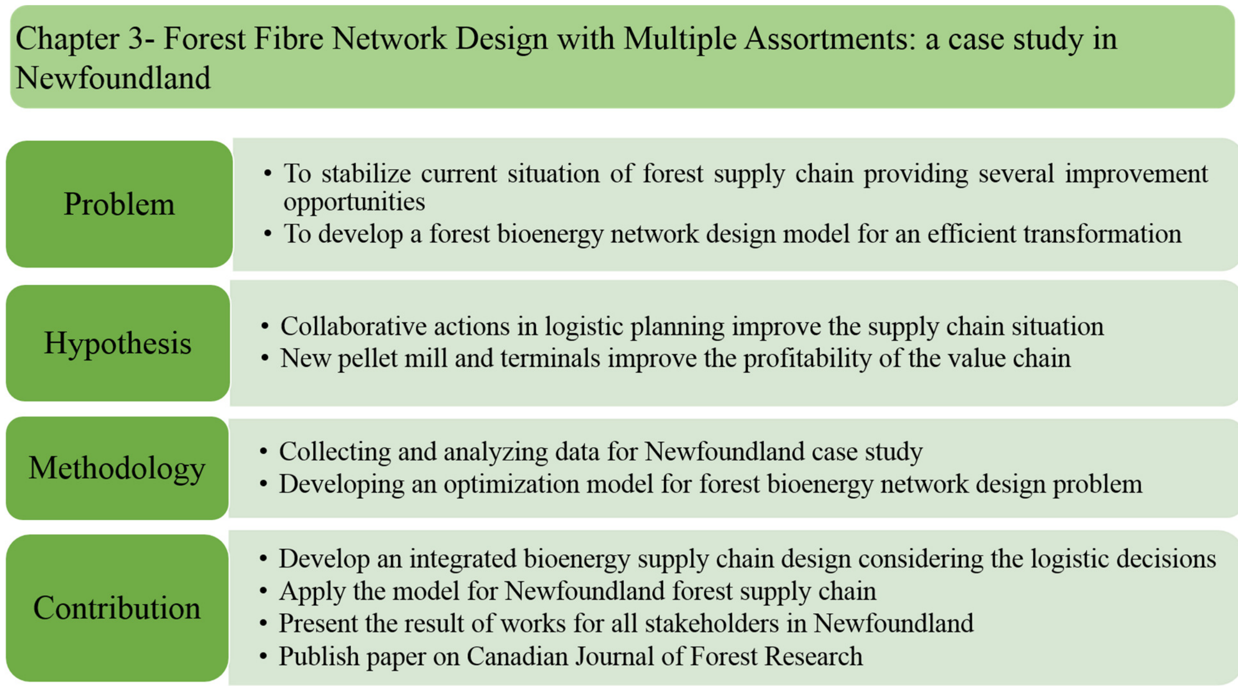


Figure 1-7: Research organization in the second contribution

1.4.3. Chapter 4

The third paper, entitled "*Forest bioenergy network design under uncertainty*", has proposed a robust network design that increases the supply chain profitability. The principal objective is to provide a robust bioenergy network design through optimizing the stochastic optimization model. Firstly, the model has provided an optimal network design for the proposed scenarios. Afterwards, it considered the risk metrics including variability index and downside risk providing the robust solution. Moreover, several bioenergy processes with different processes and capacities have been proposed to the models. All different network designs have been compared in the last part of the chapter. The contribution organization of the paper has been shown in Figure 1-8.

Chapter 4- Forest bioenergy network design under market uncertainty

Problem

- To provide a robust forest bioenergy network design under uncertainty of demand and price of final products
- To develop risk management models to control the investment risks in such design

Hypothesis

- The stochastic solution provides a reliable solution compared to a deterministic
- New bioenergy processes improve the profitability of forest bioenergy value chain

Methodology

- Developing a two-stage stochastic optimization model
- Developing a modified L-shaped method for stochastic model
- Developing a modified L-shaped method for risk models

Contribution

- Develop a stochastic design model for forest bioenergy value chain
- Develop a risk-averse design model for forest bioenergy value chain
- Apply the model for Newfoundland forest supply chain
- Submit paper on Journal of Energy

Figure 1-8: Research organization in the third contribution

1.5. Reference

Akhtari, S., T. Sowlati and V. C. Griess, 2017. Integrated strategic and tactical optimization of forest-based biomass supply chains to consider medium-term supply and demand variations. *Applied Energy*.

Alam, M. B., C. Shahi and R. Pulkki, 2014. Economic impact of enhanced forest inventory information and merchandizing yards in the forest product industry supply chain. *Socio-Economic Planning Sciences,* 48 (3), 189-197.

Anthony, R. N., 1965. Planning and control systems: a framework for analysis. Division of Research, Graduate School of Business Administration, Harvard University.

Awudu, I. and J. Zhang, 2012. Uncertainties and sustainability concepts in biofuel supply chain management: A review. *Renewable and Sustainable Energy Reviews,* 16 (2), 1359-1368.

Azaron, A., K. N. Brown, S. A. Tarim and M. Modarres, 2008. A multi-objective stochastic programming approach for supply chain design considering risk. *International Journal of Production Economics.* 116 (1), 129-138.

Birge, J. R. and F. Louveaux, 1997. Nonlinear Programming Approaches to Two-Stage Recourse Problems. Introduction to Stochastic Programming: 199-232.

Cambero, C., T. Sowlati, M. Marinescu and D. Röser, 2015. Strategic optimization of forest residues to bioenergy and biofuel supply chain. *International Journal of Energy Research,* 39 (4), 439-452.

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

Carlsson, D., S. D'Amours, A. Martel and M. Rönnqvist, 2009. Supply chain planning models in the pulp and paper industry. *INFOR: Information Systems and Operational Research,* 47 (3), 167-183.

Carlsson, D. and M. Rönnqvist, 2007. Backhauling in forest transportation – models, methods and practical usage. *Canadian Journal of Forest Research,* 37 (12), 2612-2613.

Chen, C. W. and Y. Fan (2012). Bioethanol supply chain system planning under supply and demand uncertainties. *Transportation Research Part E: Logistics and Transportation Review***,** 48 (1), 150-164.

Cordeau, J. F., F. Pasin and M. M. Solomon, 2003. Supply Chain Optimization by Benders Decomposition.

Croom, S., P. Romano, and M. Giannakis, 2000. Supply chain management: An analytical framework for critical literature review. *European Journal of Purchasing & Supply management, 6*, 67–83.

Dainty, A. R. J., M. Sarah J. and Geoffrey H. Briscoe, 2001. New perspectives on construction supply chain integration. *Supply Chain Management: An International Journal* 6 (4), 163-173.

D'Amours, S., M. Ouhimmou, J. F. Audy and Y. Feng, (Eds.), 2016. *Forest Value Chain Optimization and Sustainability*. CRC Press.

Dansereau, L. P., M. El-Halwagi, V. Chambost and P. Stuart, 2014. Methodology for biorefinery portfolio assessment using supply-chain fundamentals of bioproducts. Biofuels, *Bioproducts and Biorefining*, 8 (5), 716-727.

Dramm, J. R., R. Govettt, T. Bilek and G. L. Jackson, 2004. Log sort yard economics, planning, and feasibility.

Ekşioğlu, S. D., A. Acharya, L. E. Leightley and S. Arora, 2009. Analyzing the design and management of biomass-to-biorefinery supply chain. *Computers & Industrial Engineering,* 57 (4), 1342-1352.

Epstein, R., R. Morales, J. Seron and A. Weintraub, 1999. Use of OR systems in the Chilean forest industries. *Interface*, 29(1): 7–29.

Fleischmann, B., H. Mayr and M. Wagner, 2008. Supply Chain Management an Advanced Planning - Concept, Models, software and Case Studies. Springer, 4.

Flisberg, P., M. Frisk and M. Rönnqvist, 2012. FuelOpt: a decision support system for forest fuel logistics. *Journal of the Operational Research Society,* 63 (11), 1600-1612.

Frisk, M., M. Göthe-Lundgren, K. Jörnsten and M. Rönnqvist, 2010. Cost allocation in collaborative forest transportation. *European Journal of Operational Research***,** 205 (2): 448-458.

Geoffrion, A. M. and G. W. Graves, 1974. multicommodity distribustion design by Benders Decomposition. *Management Science***,** 20 (5), 822-844.

Ghodsypour, S. H. and C. O'Brien, 1998. A decision support system for supplier selection using an integrated analytic hierarchy process and linear programming. *International journal of production economics*, 56, 199-212.

Jang, Y. J., S. Y. Jang, B. M. Chang and J. Park, 2002. A combined model of network design and production/distribution planning for a supply network. *Computers & Industrial Engineering,* 43 (1), 263-281.

Jeihoonian, M., M. K. Zanjani, and M. Gendreau, 2016. Accelerating Benders decomposition for closed-loop supply chain network design: Case of used durable products with different quality levels. *European Journal of Operational Research*, 251(3), 830-845.

Kim, J., M. J. Realff and J. H. Lee, 2011. Optimal design and global sensitivity analysis of biomass supply chain networks for biofuels under uncertainty. *Computers & Chemical Engineering***,** 35 (9), 1738-1751.

Kim, J., M. J. Realff, J. H. Lee, C. Whittaker and L. Furtner, 2011. Design of biomass processing network for biofuel production using an MILP model. *Biomass and Bioenergy*, 35 (2), 853-871.

Leduc, S., F. Starfelt, E. Dotzauer, G. Kindermann, I. McCallum, M. Obersteiner and J. Lundgren, 2010. Optimal location of lignocellulosic ethanol refineries with polygeneration in Sweden. *Energy*, 35 (6), 2709-2716.

Lehoux, N., P. Marier, S. D'Amour, D. Ouellet and J. Beaulieu, 2012. The value creation network of Canadian wood fibre. *Canadian Forest Service Publications: CIRRELT report*.

Li, Y., P. Tittmann, N. Parker and B. Jenkins, 2017. Economic impact of combined torrefaction and pelletization processes on forestry biomass supply. *Gcb Bioenergy*, 9(4), 681-693.

Marinescu, M. 2012. Technical and Economic Analysis of Bioenergy Technologies at a Sawmill in Hanceville, BC. *FPInnovations: Vancouver, BC, Canada*.

Martel, A., W. M'Barek and S. D'Amours, 2005. International Factors in the Design of Multinational Supply Chains: The Case of Canadian Pulp and Paper Companies. *Document de travail DT-2005-AM-3, Centor, Université Laval, 10.*

Martell, D. L., E. A. Gunn and A. Weintraub, 1998. Forest management challenges for operational researchers. *European Journal of Operational Research*, 104: 1–17.

Melo, M. T., S. Nickel and F. Saldanha-da-Gama, 2009. Facility location and supply chain management – A review. *European Journal of Operational Research,* 196 (2): 401-412.

Miller, T. C., 2012. *Hierarchical Operations and Supply Chain Planning*. Springer Science & Business Media.

Mockler, P. and J. Fairbairn, 2009. The Canadian Forest Sector: Past, Present, Future. *Interim Report of the Standing Senate Committee on Agriculture and Forestry.*

Mockler, P. and F. Robichaud, 2011. The Canadian Forest Sector: A Future Based on Innovation. *Interim Report of the Standing Senate Committee on Agriculture and Forestry.*

Mirkouei, A., K. R. Haapala, J. Sessions and G.S. Murthy, 2017. A review and future directions in techno-economic modeling and optimization of upstream forest biomass to bio-oil supply chains. *Renewable and Sustainable Energy Reviews*, 67, 15-35.

Mulvey, J. M., R. J. Vanderbei and S. A. Zenios, 1995. Robust Optimization of Large-Scale Systems. *Operations Research*, 43 (2), 264-281.

Natural Resources Canada, 2017. A Forest Bioeconomy Framework for Canada.

Natural Resource of Canada, 2013. from http://www.nrcan.gc.ca/forests/innovation/13331.

Philpott, A. and G. Everett, 2001. Supply Chain Optimisation in the Paper Industry. *Annals of Operations Research*, 108 (1-4), 225-237.

Parnell, C., 1998. Supply chain management in the soft goods industry. *Apparel Industry Magazine*, 59 (6).

Pirkul, H. and V. Jayaraman, 1996. Production, Transportation, and Distribution Planning in a Multi-Commodity Tri-Echelon System. *Transportation Science*, 30 (4), 291-302.

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

Putzger, I., 1998. All the ducks in a row. *World Trade*, 11(9), 54-5.

Ruszczynski, A., 2004. Handbooks in Operations Research and Management Science: Stochastic Programming.

Santoso, T., S. Ahmed, M. Goetschalckx and A. Shapiro, 2005. A stochastic programming approach for supply chain network design under uncertainty. *European Journal of Operational Research,* 167 (1), 96-115.

Shabani, N., T. Sowlati, M. Ouhimmou and M. Rönnqvist, 2014. Tactical supply chain planning for a forest biomass power plant under supply uncertainty. *Energy*, 78 (0), 346-355.

Shabani, N., S. Akhtari and T. Sowlati, 2013. Value chain optimization of forest biomass for bioenergy production: a review. *Renewable and Sustainable Energy Reviews*, 23, 299-311.

Simatupang, T. M., A. C. Wright, , and R. Sridharan, 2002. The knowledge of coordination for supply chain integration. *Business process management journal*, 8(3), 289-308.

Stadtler, H. and C. Kliger, 2005. *Supply Chain Management and Advanced Planning*, Springer Berlin Heidelberg.

Stevens, G. C., 1989. Integrating the Supply Chain. *International Journal of Physical Distribution & Materials Management,* 19 (8), 3-8.

Svensson, E. and T. Berntsson, 2011. Planning future investments in emerging energy technologies for pulp mills considering different scenarios for their investment cost development. *Energy*, 36 (11), 6508-6519.

Svensson, E., A. B. Strömberg and M. Patriksson, 2011. A model for optimization of process integration investments under uncertainty. *Energy,* 36 (5), 2733-2746.

Tay, D. H. S., D. K. S. Ng and R. R. Tan, 2013. Robust optimization approach for synthesis of integrated biorefineries with supply and demand uncertainties. *Environmental Progress & Sustainable Energy,* 32(2), 384-389.

Tsiakis, P., N. Shah and C. C. Pantelides, 2001. Design of Multi-echelon Supply Chain Networks under Demand Uncertainty. *Industrial & Engineering Chemistry Research,* 40 (16), 3585-3604.

Vila, D., A. Martel and R. Beauregard, 2006. Designing logistics networks in divergent process industries: A methodology and its application to the lumber industry. *International Journal of Production Economics,* 102 (2), 358-378.

Weigel, G., S. D'Amours, A. Martel and P. Watson, 2010. A Modeling Framework for Maximizing Value Creation in Pulp and Paper Mills. *INFOR: Information Systems and Operational Research,* 47 (3), 247-260.

Whalley, S., S. J. Klein and J. Benjamin 2017. Economic analysis of woody biomass supply chain in Maine. *Biomass and Bioenergy*, 96, 38-49.

Wood, A., 1997. Extending the supply chain: strengthening links with IT. *Chemical Week*, 159 (25): 26.

Zanjani, M., M. Nourelfath, and D. Ait-Kadi, 2010. A multi-stage stochastic programming approach for production planning with uncertainty in the quality of raw materials and demand. *International Journal of Production Research*, 48(16), 4701-4723.

Chapter 1 The hierarchical transportation game

This chapter is earmarked to the article entitled *"The hierarchical transportation game"*. It has been submitted in the journals of *INFORMS Transactions on Education.* The figures and mathematical formulations have been revised to keep the coherence with the thesis.

RÉSUME : Cet article présente un jeu éducatif en ligne sur la planification hiérarchique des achats dans la chaîne d'approvisionnement forestière avec plusieurs entreprises. Le but du jeu est de fournir une compréhension de l'importance des décisions individuelles et de leurs impacts sur l'ensemble de la chaîne d'approvisionnement au fur et à mesure que les décisions sont prises au fil du temps. Le jeu de transport est composé de quatre phases pour simuler la prise de décision hiérarchique lorsque trois entreprises concurrentes (c'est-à-dire des joueurs dans le jeu) prennent des décisions simultanées des ressources disponibles. De plus, chaque phase du jeu nécessite collaboration et compétition en même temps. Les phases sont représentatives des différents niveaux de planification allant de la planification à long terme à la planification à court terme en tenant compte du concept de collaboration dans la chaîne d'approvisionnement. L'objectif de la chaîne d'approvisionnement simulée est de minimiser le coût d'achat des ressources ainsi que les coûts de transport. Le coût d'achat sera réparé après la première phase, mais la possibilité de réduire les coûts de transport est disponible jusqu'à la fin de la partie. Nous développons quatre modèles d'optimisation pour quatre phases du jeu. Une fois le jeu terminé, il compare le résultat des joueurs avec des solutions optimales préparées en amont. Enfin, nous présentons quelques commentaires sur l'expérience du jeu dans différentes salles de classe.

MOTS-CLÉS : Foresterie, Jeu sérieux, Transport, Planification de la chaîne d'approvisionnement, Collaboration

ABSTRACT: This paper presents an online educational game on hierarchical procurement planning in forest supply chain with multiple companies. The purpose of the game is to provide an understanding of the importance of individual decisions and their impacts on the entire supply chain as the decisions are made over time. The transportation game is comprised of four phases to simulate hierarchical decision making when three competing companies (i.e. players in the game) are making simultaneous decisions of the available resources. Moreover, each phase of the game requires collaboration and competition at the same time. The phases are representative of different planning levels from long term to short term planning considering collaboration concept in the supply chain. The objective for simulated supply chain is minimizing resource purchasing cost as well as transportation cost. The purchasing cost will fix after the first phase however the chance to decrease transportation cost is available till the end of the game. We develop four optimization models for four phases of the game. Once the game is finished, it compares the result of players with optimal solutions prepared upfront. Finally, we present some comments about the experience of the game in different classrooms.

KEYWORDS: Forestry, Serious game, Transportation, Supply chain planning, Collaboration

2.1. Introduction

The planning decisions in forest supply chain include procurement, production, distribution and marketing over planning horizon. In the long term, strategic planning should adjust the capacities of harvesting, transportation and production with demand changes over several years. Tactical management deals with annual or monthly changes in transportation capacity or the allocation of new harvest areas. Operational planning manages routing, backhauling and detail scheduling for transportation, production and distribution planning (Rönnqvist, 2003). Moreover, planning may require cooperation between all network entities to be more efficient. To educate the complex concept of hierarchical planning, supply chain processes and logistics planning especially in forestry, transportation game has been developed. The game facilitates the education of coordination, information sharing, negotiation and collaboration to students, managers and planners.

There are many supply chains which require very long term and short term decisions. One example is the forest industry where some strategic planning decisions cover several hundred years and some process control requires online decision making (D'Amours et al., 2008). Hierarchical planning with the goal of proposing a decision-making framework that integrates strategic, tactical and operational planning is a suitable planning method for such industry. This planning is used to deal with the complexity of planning problems with different objectives and time horizons. Indeed, the consistency of planning to ensure the feasible implementation of higher level decisions on lower level planning and preserving costs and benefit values is a critical point. This problem is introduced as an open problem in forestry (Rönnqvist et al. 2015). There are several coordination mechanisms to deal with this concern. One of the common approaches is using anticipation models to implicitly evaluate upper level decisions considering lower level behavior. Beaudoin et al. (2008) proposed an anticipation model to integrate key operational level decision into tactical phase. Another approach is to use bi-level models where the upper level provides policy decisions and the lower level models provide the feedback from potential several independent models. Paradis et al. (2015) utilize bi-level formulation for distributed wood supply planning. Their results verified the impact of this approach on risk mitigation.

Several educational games in the context of forestry have been developed. The online *Wood supply game* (D'Amours et al, 2017) is an adapted version of the popular beer distribution game (Sterman, 1989) and was developed to educate the effect of coordination and information sharing between all stakeholders in a divergent wood supply chain. It focuses on an operational planning environment. Another online educational tool is the Collaboration game (D'Amours and Rönnqvist, 2013). The game focuses on collaboration and negotiation between a set of companies working in the same region. Frisk et al., (2010) developed a game based on a real case study involving eight companies in Sweden. The purpose of the game is to understand basic theoretical principles of collaboration and how they can be used to find efficient partnership which has a potential of high cost savings and simultaneously is stable.

The first version of a hierarchical educational game was the transport game (Fjeld and Hedlinger, 2005). The developed tool was a paper-based game with the goal of minimizing load and unload transportation freight. Although their developed game has a well-defined structure to teach transportation planning, there were some weaknesses including invariant setup, the absence of collaboration concept and an easy way to compute and evaluate the solution directly. This motivated

us to develop the online game presented in this paper. The contribution of the game is to provide a collaborative environment for hierarchical planning that can be evaluated in an educational setting. Moreover, it provides an instructive approach to demonstrate the necessity of optimization in transportation planning to the players. Meanwhile, the online accessibility of the game will definitely facilitate fast computation of the costs and information sharing between the players.
The outline of the paper is as follows. Section 2 provides a description of the game and its four phases. Section 3 presents the optimization models for each phase. Sections 4 and 5 present experiences from some illustrative examples where the game was used and conclusions, respectively.

2.2. Game description

2.2.1. Game basics and map

The game works for three players in simultaneous competition and collaboration within four different phases in a hierarchical planning environment. It can repeat in a chosen number of periods; we often use three periods (weeks). The overall aim is to minimize the cost of a series of coupled decision-planning processes. The cost relates to purchasing of wood products and their hauling and backhauling cost. The initial setting is a hexagonal map with 61 potential supply areas and a set of existing mills with demand. Each mill is either a paper mill or a sawmill differentiated by the sign and it has a given demand for pulp logs (paper mill) or saw logs (sawmill) each period (Figure 2-1). Each of circles in the figure is a supplier of exactly one full truckload of "Saw logs" and one full truckload of "Pulp Wood". The distances between a supply point and a demand point are expressed as the number of links you need to move between them. The four phases that are described below are:

- Phase 1 (strategic): select supply areas and product combination. (all companies involved.)
- Phase 2 (tactical): decide on collaboration through wood exchanging. (all companies involved.)
- Phase 3 (tactical): decide transportation, i.e. allocation between supply and demand points. (each company by itself)
- Phase 4 (operational): decide on backhaul trips (all companies involved)

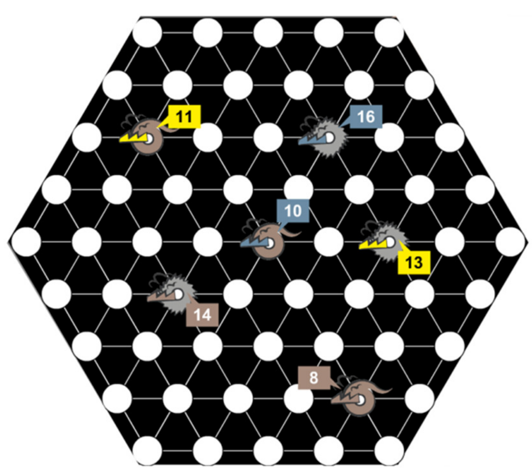


Figure 2-1: Illustration of the game' map. Supply points are demonstrated by circles. The icon of sawmills and pulp and paper mills determines the location of mills for each team. The numbers display demand of each mill. The teams are differentiated by different colors.

2.2.2. Phase 1: Selection of supply areas

The objective of the first phase is to purchase supply areas and products such that they are close to the mills. Hence, the transportation cost can be controlled in the initial phase. Figures 2-2(a) and 2-2(b) display a player selection from pulp woods and saw logs supply nodes respectively. However, to display the player selection in a single map, each supply point is presented as a hexagon with interior and exterior parts that demonstrates supply of saw log and pulp wood respectively (Figure 2-2(c)). Figure 2-2(d) demonstrates the player selection in a single map. If both products are bundled at the supply point, there is a rebate such that it is cheaper to purchase them together than individually. The disadvantage is that the demand may be spread out and the supply of one product is closer than the other product. In the game, each player takes turns to select supply areas and products. In each round, one company can select pre-determined supply points and products. Then the second and third company selects. This process is repeated until all demand is satisfied.

Depending on the configuration of the mills, there will be higher or lower demand for supply points in different regions of the game map. Two obvious principle strategies can be used. One is to select bundled (cheaper) supply areas in the middle of mills or close to one and then hope that there is enough collaboration to improve the situation later. Another is to select supply areas with single products (more expensive) but very close to its own mills so as to keep the transportation cost small. As an example, the resource price is set such that purchasing one area cost 5 for each area and each product. If both products are purchased as a bundle the cost is 8, i.e. a rebate of 2. The transportation cost is 1 for each unit length illustrated by each line on the map. The purchasing cost will be fixed for the rest of the game, however the opportunities to reduce transportation cost are still open. Each player tries to balance the purchasing cost with the distances from its different mills. However, the competition between players does not let them select whatever they desire to have.

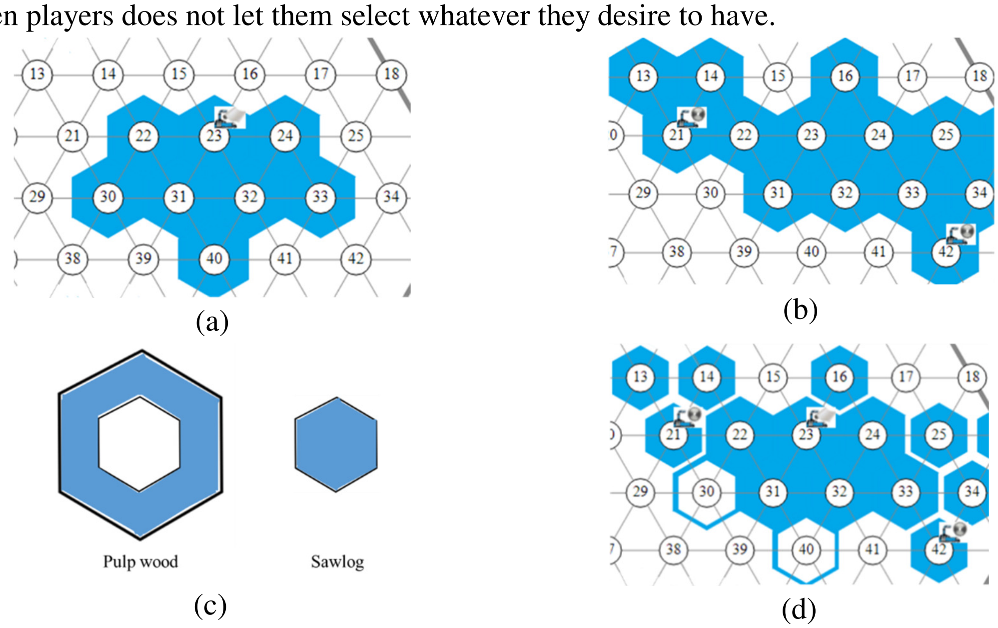


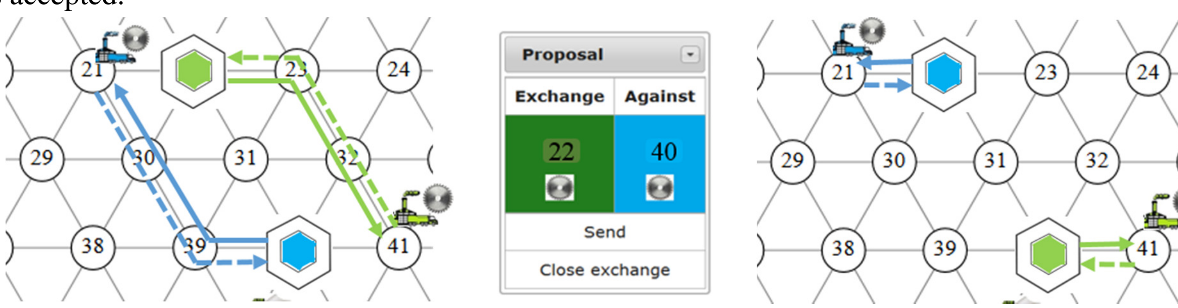
Figure 2-2: a) A player selection among pulp wood supply nodes. b) A player selection among saw log supply nodes. c) For each node, the interior (exterior) of hexagonal determines the composition of the area as the supplier of saw log (pulpwood). d) The selected resources in a single map for a player.

The game is a simplification of the planning process and data in practice. In reality, many companies can select areas which they own themselves, whereas others need to purchase from independent forest owners or through members in forest associations (Bredström et al., 2010). To select supply areas, it is highly important to consider the scheduling of the harvesting operations (Frisk et al., 2016). The costs are often approximated depending on the estimated composition of assortments and volumes and the distance to mills. Some general cases where the costs are nonlinear are described in Kong et al, (2015). The competition between different companies is hard to describe and there is little research published on this specific aspect. The subsequent potential collaboration is, however, described in Phase 2.

2.2.3. Phase 2: Decide on collaboration through wood exchanging.

Following harvest areas selection, a modification tool including wood exchanging between companies can progress the decisions made (Forsberg et al., 2005). In this regard, the game provides the possibility of exchanges between player's areas. This is the first practice of collaboration and negotiation for the players. They should wisely find the areas in a win-win strategy to create advantages for both involved players. Exchange of harvest area does not change the purchasing cost of players from the first phase although it reduces transportation cost.

Figure 2-3 depicts an example of exchange proposal between players. In part (a), assuming the 1 unit of transportation cost per map arcs, the network includes 12 unit costs of round way transportation to from mills to resources in area 22 and 40 and deliver them to player green and blue. Both areas are far away from their associated mill and it would be advantageous to exchange as their distance would decrease. Afterwards, in part (c), the swap of area has reduced the cost to 2 for each and 4 in total. We note that the exchange must be in the same product and the improvements may not be the same for the two players. Hence, there is a need to communicate for exchanges that may span over multiple exchanges. The swap is proposed and is made once the offer is accepted by both involved players. We also note that there may be multiple proposals for the same area and these are removed once a proposal is accepted.



(a) (b) (c)

Figure 2-3: Illustration of an exchange of areas. a) The map demonstrated high load and unload transportation cost before the exchange. b) exchange proposal windows c) the map shows the reduction in transportation cost after exchange of area 22 (saw logs) with area 40 (saw logs).

2.2.4. Phase 3: Assignment of areas to mills

In the third phase there is a need to make the best possible allocation of areas to mills to make sure that the demand is satisfied in least transportation cost. In the previous phases the transportation cost is estimated by the game however in this phase it will be fixed based on player assignment. In practice, this problem is solved using a standard transportation problem with flows between supply areas and mills as decision variables and supply and demand constraints. The assignment phase is an internal planning for each company to reduce its direct transportation cost. It will be available only if there is at least more than one mill per sort of resources for a player. Players choose their mills and then allocate the areas to them. Figure 2-4 depicts a view of this phase.

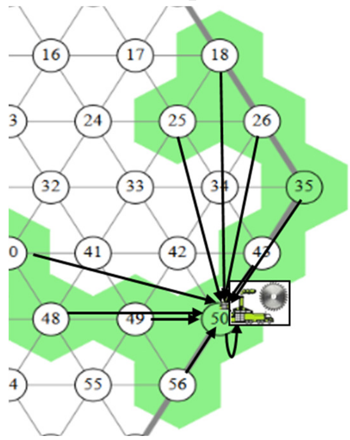
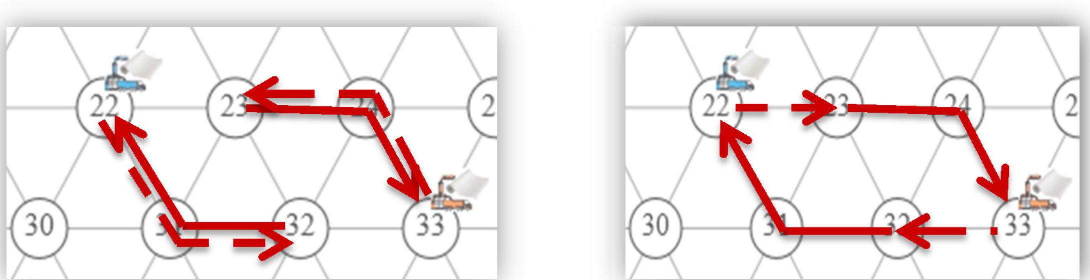


Figure 2-4: Illustration of the assignment phase. The arrows show the possible assignment options for the selected mill.

2.2.5. Phase 4: Backhaul planning

Daily scheduling on routing and backhauling for truck drivers is the primary duty for operational transportation planners. This mission can provide a significant saving by managing backhaul routes (Carlsson and Rönnqvist, 2007) to reduce unload transportation cost. Typically transporters are paid by going back and forth between a supply and a demand point. However, with the backhauling, it is possible to reduce the unload transportation cost (Figure 2-5). In the figure, the cost to transport resources in area 32 to mill 22 is 4, as there are 2 units of loaded transportation cost and 2 units of unloaded transportation cost. The same is true for assigning resource of area 23 to mill 33. However if a backhaul route similar to Figure 2-5(b) is utilized, the unload transportation cost will reduce and hence total transportation cost be reduced from 8 to 6.

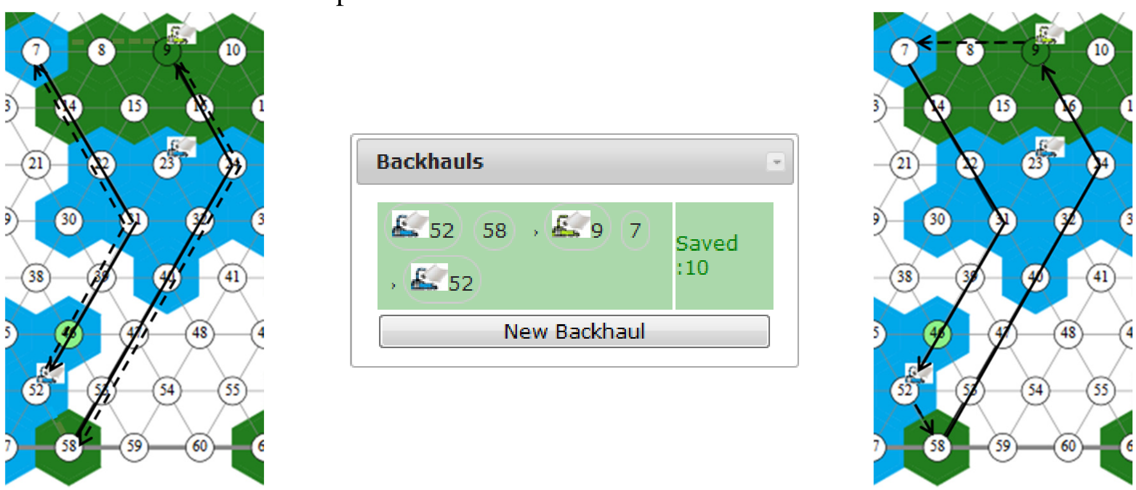


(a)Total distance= 8 *(b)Total Distance = 6*

Figure 2-5: Illustration of a backhauling concept with 2 units of cost saving in empty driving. The straight and dash lines in the figures demonstrate loaded and unloaded transportation respectively. (a) Two deliveries by direct transportation and total distance of 8. (b) The same deliveries within a backhaul route with total distance of 6.

Backhaul creates either within mills of one player or more preferably between all members of the network as cooperation. It may include more than two deliveries. This collaboration divided the unload transportation cost between all involved members and concluded the lowest costs at the end of the day. Any saving cost from backhaul transportation is split between all contributing players to create the backhaul route. For example, if the saving using the backhaul is 10 cost units; each player receives a reduction of 5.

The last phase of this game is played as follows. A player proposes a backhaul route starting from a mill with an empty truck to pick up one unit resource, deliver it to allocated mill and leave the mill empty to pick up again one unit resource to deliver to other allocated mill and continuing to come back to the mill of origin. To consider the proposed route, all involved players should accept it. Figure 2-6 displays an example of backhaul route with 10 units of saving in transportation cost. The unload transportation cost reduced from 13 (Figure 2-6(a)) to 3 (Figure 2-6(c)). The straight and dashed lines depict the load and unload transportation in route.



(a) (b) (c)

Figure 2-6: Backhaul phase. a) Two direct transportation routes. b) The backhaul path with saving cost c) A backhaul route that reduces unload transportation cost (dash lines) by 10 units.

2.2.6. Result presentation

Once each phase is completed, its results are presented in bar charts. Figure 2-7 displays purchasing, transportation and total costs for players after the first phase in the first week. The left-hand side chart demonstrates the aforementioned costs for current week, although the cost per selected territories is demonstrated on the right-hand side chart. Afterwards by clicking on OK, the next phase will start.

Figure 2-7: Results for selection phase. It demonstrates the planning cost for current phase in the first week.

Once all periods have been completed, a summary over all of the weeks is shown to the player. The winner is the player with the overall minimum cost. Moreover, the players with best improvement, best purchasing cost and best transportation cost will get awards.

2.2.7. Game setup and control

The game is accessible online at http://forac-old.fsg.ulaval.ca/TransportGame/Start.aspx. The web interface of the game is built using the Flash technology from Adobe. Each user interaction is communicated to the game server using URL requests. Every 5 seconds, the Flash web interface of any given player communicates with the game server to inquire about new events or status change that may have occurred since the last time it checked. The vb.net web server stores the status of each player within the game into an SQL database. It is also the web server that monitors player actions and changes the game status as needed, for example to change phases or to trigger an event that should be reflected within web user interface (like the display of end game results).

The game link directs the players on the first page of game to play or create a game or do administration setup (Figure 2-8). All initial settings for a new game are managed in “create a game” section. It includes number of mills for each player, the location of mills, the demand, costs, the number of periods. Moreover, this section provides some predefined games to accelerate game setup. The created game could be multiplied or deleted in “Game administrator” part. To start, the players should select “play game” and then they will forward to select their game name (Figure 2-9). Afterwards, they should type their name, select their team and log into the predefined game.

Figure 2-8: The first page to access to the game. To start, the players should click on "play game" button. Other administration settings can be done in "create a game" and "game administrator" option.

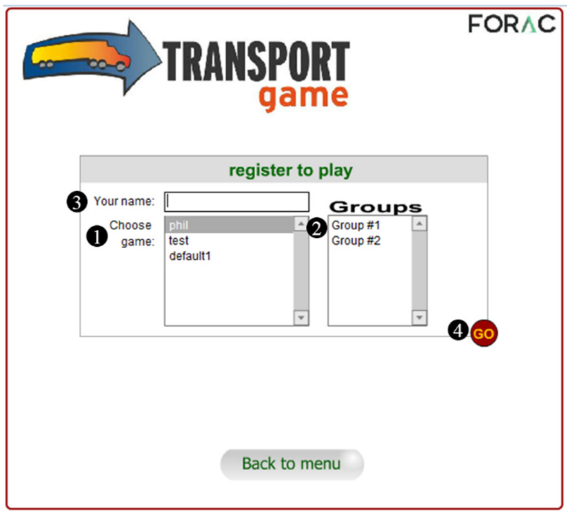


Figure 2-9: The login page of the game; the players should select the game name firstly, then select their team, type their name and afterwards click on GO.

2.3. Optimization Models

In order to evaluate the performance of the players, we make use of four optimization models each representing one phase of the game. For comparison with optimal scenarios with player performance, the open source solver GLPK (stored on the server) is called by the server, passing on the model and the data in the form of flat text files. Optimal results are read back by the server and stored within the SQL database to later be accessed by the user web interface upon request. The optimization models are used to evaluate the performance in each phase but also as a means to find theoretical optimal solutions that can be used in discussions before or after the game. They can also be used in more advanced project assignments for the students before or after the game.

We define some similar indices, sets, parameters and decision variables. The ones that are unique for a phase will be presented in the related phase section.

Indices and sets:

I	set of areas
C	set of players
J_c^s	set of sawmills for players c
J_c^p	set of pulp mills for players c
J	set of all mills ($J = J_c^s \cup J_c^p$)

Parameters:

d_j^s	demand of saw log at mill j
d_j^p	demand of pulp wood at mill j
c_{ij}^{ds}	cost to deliver one unit saw log between area i and sawmill j
c_{ij}^{dp}	cost to deliver one unit pulp wood between area i and sawmill j
c_i^{ps}	cost to purchase one unit saw log from area i
c_i^{pp}	cost to purchase one unit pulp wood from area i
r	rebate if both saw logs and pulp woods are purchased for the same player.

Decision variables:

x_{cij}^s 1 if player c delivers saw logs from area i to mill j, and 0 otherwise

x_{cij}^p 1 if player c delivers pulp woods from area i to mill j, and 0 otherwise

z_{ci} 1 if player c receives a rebate for purchasing both saw logs and pulp woods from area i, and 0 otherwise

2.3.1. Optimization model for selection phase

The mathematical formulation for selection phase is:

$$\min \sum_{i\in I}\sum_{c\in C}\sum_{j\in J_c^s}(c_{ij}^{ds}+c_i^{ps})x_{cij}^s+\sum_{i\in I}\sum_{c\in C}\sum_{j\in J_c^p}(c_{ij}^{dp}+c_i^{pp})x_{cij}^p-\sum_{c\in C}\sum_{i\in I} r z_{ci} \qquad (2\text{-}1)$$

s.t:

$$\sum_{c\in C}\sum_{j\in J_c^s} x_{cij}^s \le 1, \qquad \forall i\in I \qquad (2\text{-}2)$$

$$\sum_{c\in C}\sum_{j\in J_c^p} x_{cij}^p \le 1, \qquad \forall i\in I \qquad (2\text{-}3)$$

$$\sum_{i\in I}\sum_{c\in C} x_{cij}^s = d_j^s, \qquad \forall j\in J_c^s \qquad (2\text{-}4)$$

$$\sum_{i\in I}\sum_{c\in C} x_{cij}^p = d_j^p, \qquad \forall j\in J_c^p \qquad (2\text{-}5)$$

$$z_{ci} \le \tfrac{1}{2}\Big(\sum_{j\in J_c^s} x_{cij}^s + \sum_{j\in J_c^p} x_{cij}^p\Big) \qquad \forall i\in I, c\in C \qquad (2\text{-}6)$$

$x_{cij}^{s}, x_{cij}^{s}, z_{ci} \in \{0,1\} \qquad \forall i \in I, c \in C, j \in J \qquad (2\text{-}7)$

The goal of the model is to minimize the integrated transportation and purchasing costs. Constraint sets (2-2) and (2-3) assure that each harvest area as the source of saw log or pulpwood assigns only one time to a mill. Mills demand satisfies in constraint sets (2-4) and (2-5). Constraint set (2-6) determines whether players are eligible for the rebate or not. Constraint set (2-7) defines binary limits of all decision variables. The model is an integer programming model with binary variables. It has 915 binary variables and 317 constraints.

Since the purchasing cost of players is constant after their selection, our objective functions for the rest of phases consider only transportation cost. Indeed, this fixed purchasing cost will be added as a parameter to the other objective functions. This cost is not the optimal objective value, but it is the one that is calculated in the game after player selection in the first phase. It is shown by F_c defined as follows.

F_c Purchasing cost of players in the first phase of the game.

2.3.2. Optimization model for swap phase

In phase 2, the selected areas for each player is determined. Swap decision variable considering the allowable number of swaps should define for optimization model of this phase. We retrieve the following sets from player performances in previous phases.

Indices and sets:

I_c^s set of selected area for saw log resources of players c

I_c^p set of selected area for pulpwood resources of players c

I^s set of all selected areas as a source of saw log ($I^s = \bigcup_{c\in C} I_c^s$)

I^p set of all selected areas as a source of pulpwood ($I^p = \bigcup_{c\in C} I_c^p$)

Parameters:

B limited number of swaps

Decision variables:

y_{pq}^{s} 1 if a swap for saw logs of area p and q happens, and 0 otherwise

y_{pq}^{p} 1 if a swap for pulpwood of area p and q happens, and 0 otherwise

The mathematical formulation for this phase is:

$$\min : \sum_{c\in C} F_c + \sum_{i\in I}\sum_{c\in C}\sum_{j\in J_c^s} c_{ij}^{ds} x_{cij}^{s} + \sum_{i\in I}\sum_{c\in C}\sum_{j\in J_c^p} c_{ij}^{dp} x_{cij}^{p} \qquad (2\text{-}8)$$

s.t:

$$\sum_{j\in J_c^s} x_{cij}^{s} = 1 - \sum_{q\in I^s \setminus I_c^s} y_{iq}^{s} \qquad \forall i \in I_c^s, c \in C \qquad (2\text{-}9)$$

$$\sum_{j\in J_c^s} x_{cij}^{s} = \sum_{p\in I_c^s} y_{pi}^{s} \qquad \forall i \in I^s \setminus I_c^s, c \in C \qquad (2\text{-}10)$$

$$\sum_{j\in J_c^p} x_{cij}^p = 1 - \sum_{q\in I^p \setminus I_c^p} y_{iq}^p \qquad \forall i\in I_c^p, c\in C \qquad (2\text{-}11)$$

$$\sum_{j\in J_c^p} x_{cij}^p = \sum_{p\in I_c^p} y_{pj}^p \qquad \forall i\in I^p \setminus I_c^p, c\in C \qquad (2\text{-}12)$$

$$\sum_{i\in I} x_{cij}^s = d_j^s \qquad \forall j\in J_c^s, c\in C \qquad (2\text{-}13)$$

$$\sum_{i\in I} x_{cij}^p = d_j^p \qquad \forall j\in J_c^p, c\in C$$

(2-14)

$$y_{pq}^s = y_{qp}^s \qquad \forall p,q\in I^s \qquad (2\text{-}15)$$

$$y_{pq}^p = y_{qp}^p \qquad \forall p,q\in I^p \qquad (2\text{-}16)$$

$$\sum_{p\in I_c^s}\sum_{q\in I^s\setminus I_c^s} y_{pq}^s + \sum_{p\in I_c^p}\sum_{q\in I^p\setminus I_c^p} y_{pq}^p \le B \qquad \forall c\in C \qquad (2\text{-}17)$$

$$x_{cij}^s, x_{cij}^s, y_{pq}^s \in \{0,1\} \qquad \forall i,p,q\in I, c\in C, j\in J \qquad (2\text{-}18)$$

The objective function is to minimize transportation cost given fixed purchasing costs from phase 1. Constraint set (2-9) assigns saw logs of a selected area either to its owner or another player as a swap. If a player exchanges its area of saw log, a new area will be assigned to them in constraint sets (2-10). Likewise, constraint sets (2-11) and (2-12) define swap for pulpwood. The demand of all sawmills and pulp mills will be satisfied in constraint sets (2-13) and (2-14). Constraint sets (2-15) and (2-16) are to consider symmetry of swap of saw logs and pulp wood, respectively. Moreover, they assure the total number of swaps between two teams should be equal. Constraint set (2-17) restricts the number of swaps for each player. Constraint set (2-18) defines binary restriction of all decision variables. The model is an integer programming model with binary variables. It has 5832 binary variables and 5523 constraints considering 5 allowable swaps for each player.

2.3.3. Optimization model for assignment phase

The selected harvest area for each team (i.e. the sets I_c^s and I_c^p) will update after swap phase. Afterwards, the assignment model for this updated set is as follows:

$$\min: \sum_{c\in C} F_c + \sum_{c\in C}\sum_{i\in I_c^s}\sum_{j\in J_c^s} c_{ij}^{ds} x_{cij}^s + \sum_{c\in C}\sum_{i\in I_c^p}\sum_{j\in J_c^p} c_{ij}^{dp} x_{cij}^p \qquad (2\text{-}19)$$

s.t:

$$\sum_{j\in J_c^s} x_{cij}^s = 1 \qquad \forall i\in I_c^s, c\in C \qquad (2\text{-}20)$$

$$\sum_{j\in J_c^p} x_{cij}^p = 1 \qquad \forall i\in I_c^p, c\in C \qquad (2\text{-}21)$$

$$\sum_{i\in I_c^s} x_{cij}^s = d_j^s, \qquad \forall c\in C, j\in J_c^s \qquad (2\text{-}22)$$

$$\sum_{i\in I_c^p} x_{cij}^s = d_j^p, \qquad \forall c\in C, j\in J_c^p \qquad (2\text{-}23)$$

$$x_{cij}^s, x_{cij}^s \in \{0,1\} \qquad \forall i\in I, c\in C, j\in J \qquad (2\text{-}24)$$

Where the model structure is similar to the first phase model however player should assign the area only from their selected ones. The objective function minimizes transportation cost including fixed purchasing cost. Constraint sets (2-20) and (2-21) allocate selected harvest area of each player to its mills. Similarly to previous models, constraint sets (2-22) and (2-23) are for assuring the demand satisfaction of all mills. The variable restriction is given by constraint set (2-24). The model is an integer programming model with binary variables. It has 732 binary variables and 114 constraints.

2.3.4. Optimization model for backhaul phase

To start the optimization, we generate all eligible backhaul routes with two, three and four deliveries with less transportation cost compared with direct transportation. Moreover, we define a series of new parameters as a coefficient for defined backhaul routes. These coefficients determine the included nodes in each backhaul route.

New Set:

L set of all generated backhaul routes

New parameters:

f_l cost of backhaul route l

a_{li}^s 1 if backhaul route l picks up saw log at area i, 0 otherwise

a_{li}^p 1 if backhaul route l picks up pulpwood at area i, 0 otherwise

b_{lj}^s 1 if backhaul route l delivers saw log at sawmill j, 0 otherwise

b_{lj}^p 1 if backhaul route l delivers pulpwood at sawmill j, 0 otherwise

New decision variables:

y_l 1 if backhaul route l is used, 0 otherwise

The mathematical formulation for backhaul phase is as follows:

$$\min: \sum_{c\in C} F_c + \sum_{i\in I}\sum_{c\in C}\sum_{j\in J_c^s} c_{ij}^s x_{cij}^s + \sum_{i\in I}\sum_{c\in C}\sum_{j\in J_c^p} c_{ij}^p x_{cij}^p + \sum_{l\in L_c^a} f_l \, y_l \qquad (2\text{-}25)$$

s.t:

$$\sum_{j\in J_c^s} x_{cij}^s + \sum_{l\in L_c^a} a_{li}^s y_l = 1 \qquad \forall i\in I_c^s, c\in C \qquad (2\text{-}26)$$

$$\sum_{j\in J_c^p} x_{cij}^p + \sum_{l\in L_c^a} a_{li}^p y_l = 1 \qquad \forall i\in I_c^p, c\in C \qquad (2\text{-}27)$$

$$\sum_{i\in I_c^s} x_{cij}^s + \sum_{l\in L_c^a} b_{li}^s y_l = d_j^s, \qquad \forall j\in J_c^s, c\in C \qquad (2\text{-}28)$$

$$\sum_{i\in I_c^p} x_{cij}^p + \sum_{l\in L_c^a} b_{li}^p y_l = d_j^p, \qquad \forall j\in J_c^p, c\in C \qquad (2\text{-}29)$$

$$x_{cij}^s, x_{cij}^s, y_l \in \{0,1\} \qquad \forall i\in I, c,d\in C, j\in J, l\in L \qquad (2\text{-}30)$$

Where the goal, like the other models is to minimize transportation cost including fixed purchasing cost. Constraint sets (2-26) and (2-27) deliver the allocated resource in a direct or backhaul route. The demand of sawmills and pulp mills should satisfy either with direct or backhaul routes considering constraint sets (2-28) and (2-29). Constraint set (2-30) defines all decision variables.

There may be a very large number of backhauls. In our implementation, we limit ourselves to backhauls consisting of 2 to 4 deliveries. The model is an integer programming model with binary variables. The model in phase 4 has 19648 binary variables and 102 constraints.

2.3.5. Overall model

It is also possible to solve an overall problem where all phases are integrated. The model is an integer programming model with binary variables. However, the size of model increases enormously compared to the model of backhaul phase since the areas have not yet been allocated. Carlsson and Rönnqvist (2007) developed a column generation approach to solve such problems.

$$\min: \sum_{i\in I}\sum_{c\in C}\sum_{j\in J_c^s} (c_{ij}^{ds} + c_i^{ps}) x_{cij}^s + \sum_{i\in I}\sum_{c\in C}\sum_{j\in J_c^p} (c_{ij}^{dp} + c_i^{pp}) x_{cij}^p - \sum_{c\in C}\sum_{i\in I} r z_{ci} + \sum_{l\in L_c^a} f_l\, y_l \qquad (2\text{-}31)$$

s.t:

$$\sum_{j\in J_c^s} x_{cij}^s + \sum_{l\in L_c^a} a_{li}^s y_l \le 1 \qquad \forall i\in I_c^s, c\in C \qquad (2\text{-}32)$$

$$\sum_{j\in J_c^p} x_{cij}^p + \sum_{l\in L_c^a} a_{li}^p y_l \le 1 \qquad \forall i\in I_c^p, c\in C \qquad (2\text{-}33)$$

$$\sum_{i\in I_c^s} x_{cij}^s + \sum_{l\in L_c^a} b_{li}^s y_l = d_j^s, \qquad \forall j\in J_c^s, c\in C \qquad (2\text{-}34)$$

$$\sum_{i\in I_c^p} x_{cij}^p + \sum_{l\in L_c^a} b_{li}^p y_l = d_j^p, \qquad \forall j\in J_c^p, c\in C \qquad (2\text{-}35)$$

$$z_{ci} \le \tfrac{1}{2}\left(\sum_{j\in J_c^s} x_{cij}^s + \sum_{l\in L_c^a} a_{li}^s y_l + \sum_{j\in J_c^p} x_{cij}^p + \sum_{l\in L_c^a} a_{li}^p y_l\right) \qquad \forall i\in I, c\in C \qquad (2\text{-}36)$$

$$x_{cij}^s, x_{cij}^s, y_l \in \{0,1\} \qquad \forall i\in I, c,d\in C, j\in J, l\in L \qquad (2\text{-}37)$$

The model is similar to model of selection phase including backhaul deliveries. The objective function minimizes the transportation cost in direct or backhaul routes as well as purchasing cost. Constraint sets (2-31) and (2-32) ensure that each resource of saw log and pulp wood assign maximum one time to a mill. Constraint sets (2-34) and (2-35) satisfy the demand of sawmills and pulp mills through direct or backhaul deliveries. The constraint (2-36), which is similar to the constraint set (2-6), is to calculate rebate on purchasing an area as resources of both saw log and pulp wood.

2.4. Examples of running the game

To illustrate the performance of a typical group of students, we compare them with two sets of optimal solutions. Figure 2-10 shows the optimization result for the first phase in three formats of optimal 1, 2 and players. Optimal 1 shows the optimal solution for each player without any restriction on its selection, i.e. each player can select all its desired areas. This condition is only used to provide a lower bound on the best possible outcome for each single player. Optimal 2 is the result of the optimization model for integrated network. In this solution, the cost for all player is almost the same. However a good mill location of player A economizes more on its cost. It is worth mentioning that optimal 1 and 2 objective values include purchasing and direct transportation costs. Finally, player bar in the chart demonstrates their real performance in a game. The player's cost is included in the exact purchasing cost and estimated transportation cost. We call their transportation cost "estimated" since they haven't assigned the resources yet. The comparison between all results reveals that player could create the more successful network. The visualization of optimal solution and player performance are demonstrated in Figure 2-11.

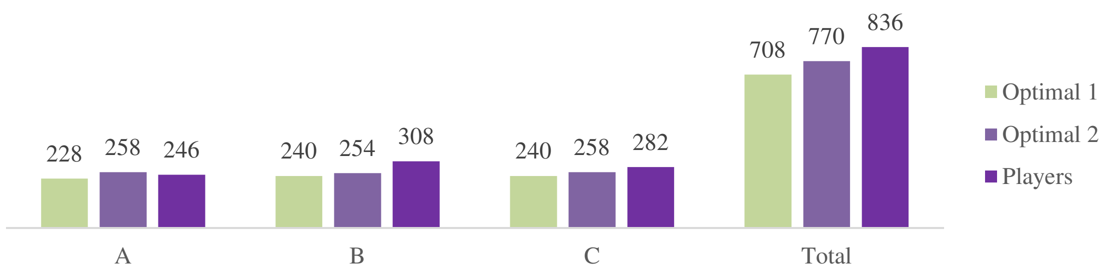


Figure 2-10: Optimal solution and player performance for the first phase of the game

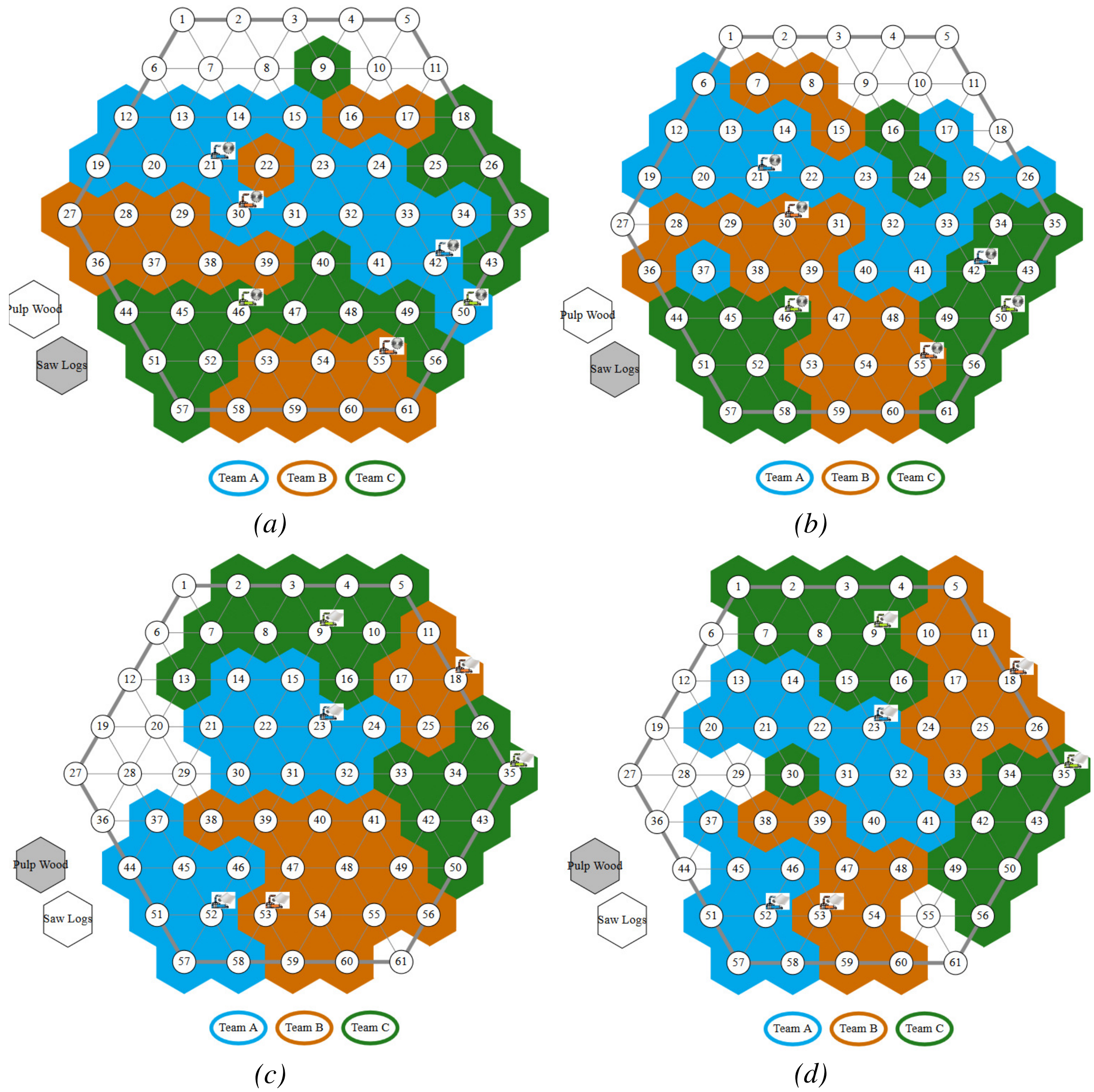


Figure 2-11: Selection phase, the left side maps are players selection for saw log (a) and pulp wood (c) resources; the right side maps are optimal solution for resource selection of saw log (b) and pulp wood (d)

Table 2-1 reports the purchasing costs for optimization models as well as players performance. The player purchasing cost f^p (470) will fix and add to the next phases models. Moreover the transportation cost and total cost have been reported in the table.

Table 2-1. Purchasing, transportation and total cost for optimal 1 and 2 and players performance

	A	*B*	*C*	*Total Purchasing cost*	*Total transportation cost*	*Total cost*
Optimal 1	152	164	158	474	234	708
Optimal 2	152	154	154	460	310	770
Players	154	154	162	470	366	836

Given the selected areas of players in the first phase, the optimization models as well as players start the second phase of the game. Figure 2-12 compares the result of swaps in optimal condition with player performance. Optimal 1 and optimal 2 are defined similar to the first phase definition. The number of eligible swaps is restricted to 5 for each player. The figure reveals a considerable cost reduction especially for team B by doing swaps in optimal ways compared to its real performance. Figure 2-13 displays the network structure before and after players' performance in swap phase. The optimal swaps for pulp wood resources are created by exchange of area 39, 49 and 56 of team B with area 24 of team A and areas 5 and 26 of team C and exchange of area 15 of team A with area 33 of team C, respectively. For saw log resources, the optimal swaps are created by exchange of areas 30, 31 and 50 of team A with area 17 and 16 of team B and 9 of team C. These swaps can save in total 44 (826-782=44) units of cost. It is worth mentioning that some of these exchanges are profitable only for one player. Hence, it is crucially important for players to play as an integrated network rather than individual companies. We call these savings as the effect of collaboration.

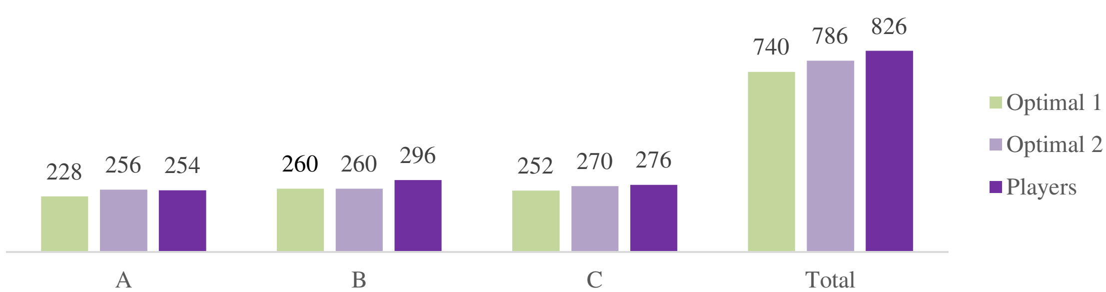


Figure 2-12: Optimal solution and player performance for the second phase of the game

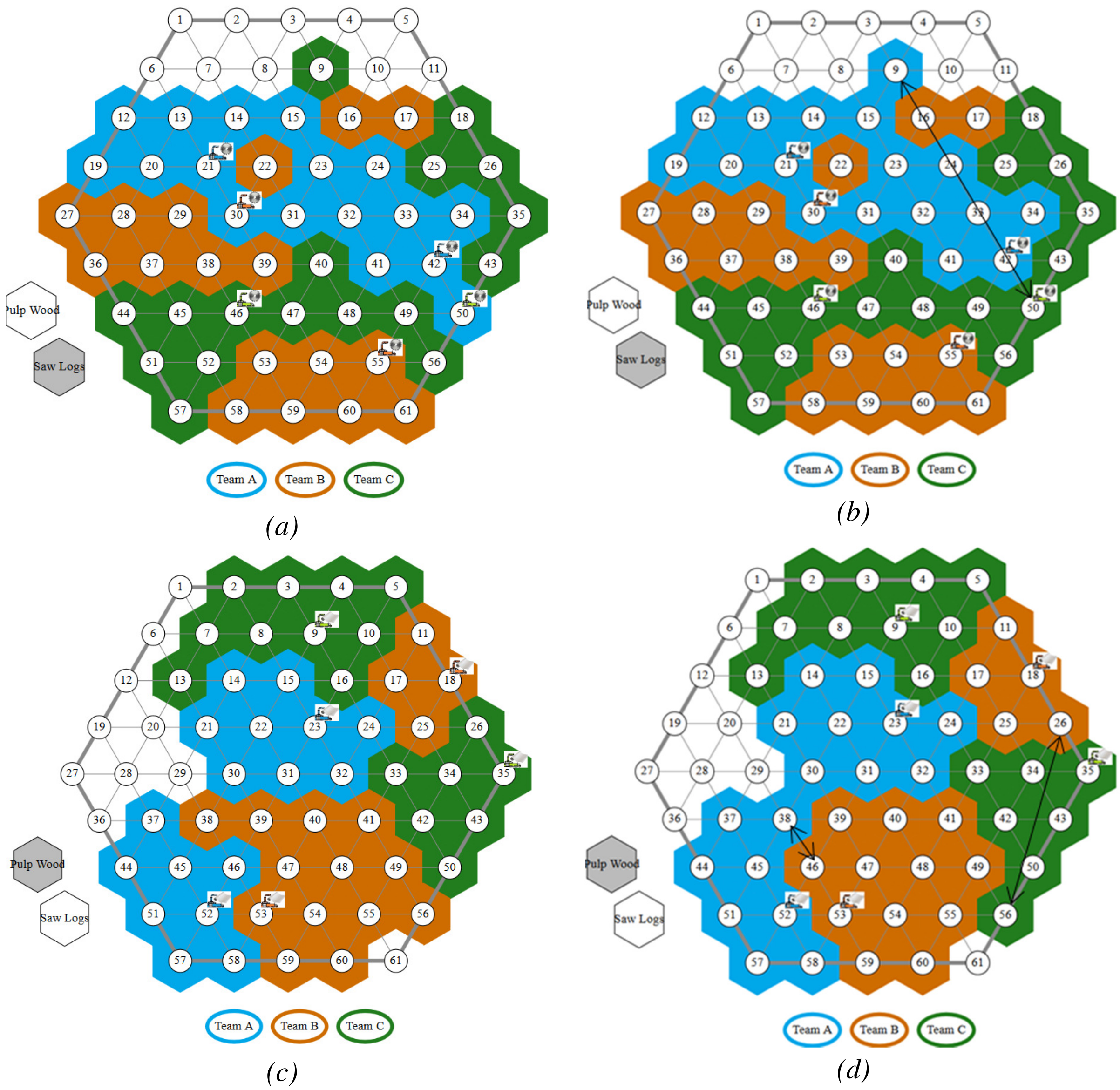


Figure 2-13: Player areas before exchanging for saw log (a) and pulpwood (c) and after it for saw log (b) and pulpwood (d) in swap phase. Comparing (a) and (b) displays the swap of areas 50 and 9. Comparing (c) and (d) displays swap of areas 38 with 46 and 26 with 56.

The third phase of the game is a relatively easy task for players since they should deal with their new selected area after swap phase. Players normally allocate areas to mill in an optimal way. Figure 2-14 displays the result of the optimal solution for all players (optimal 2) and player performance.

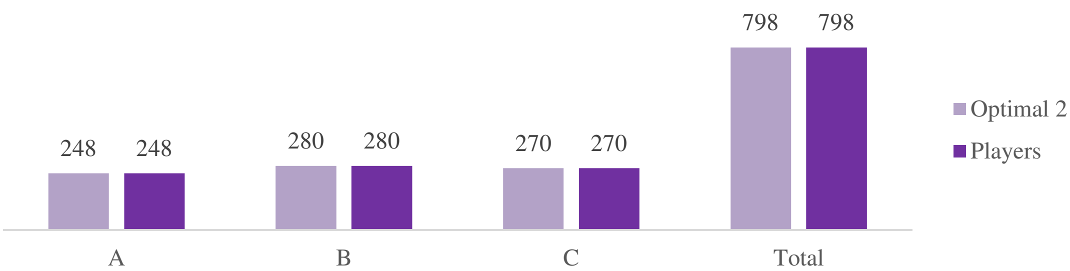


Figure 2-14: Optimal solution and player performance for assignment phase

The backhaul phase is the last chance of players to reduce their transportation cost. A backhaul route in the game is a closed route for a truck starting from a mill and coming back to the same mill. The optimal solution shows that players A, B and C can save 14.2, 36.6 and 26.2 (77 in total) units of transportation cost by using backhauling (Figure 2-15). This saving is created from 10 optimal backhaul routes however the players found only two of them. Backhauling gives the players the opportunity to be close to optimal cost regardless of its first network structure.

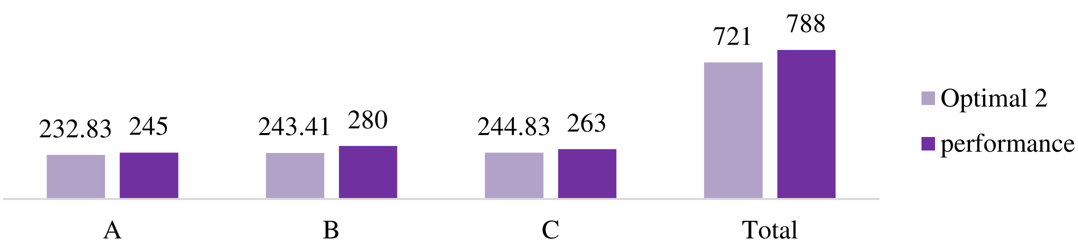


Figure 2-15: Optimal solution and player performance for the fourth phase of the game

Figure 2-16 displays the effect of each phase in cost reduction. It clearly shows appropriate swaps, assignment and backhauling will dramatically reduce costs and create win moves for all players. This could be a great point to prove the importance of integration and collaboration in supply chain planning. For optimal solution each phase is optimized given the player actions in previous phase. That's why optimal solution in phase 2 has higher value compared to phase 1. The transportation cost in phases 1 to 3 is the only direct one although phase 4 has the option of backhaul transportation.

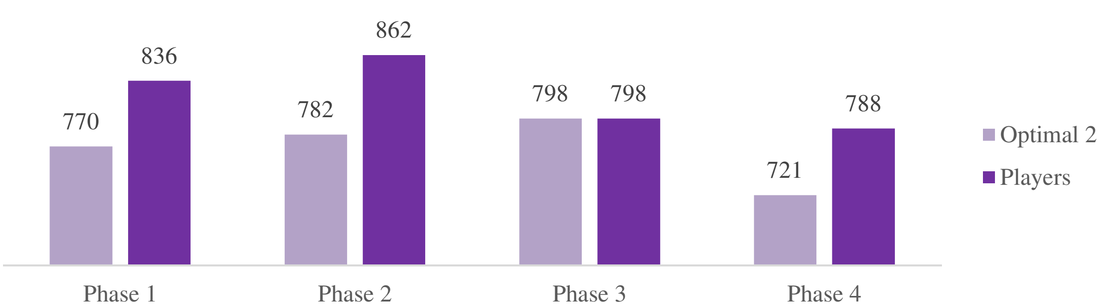


Figure 2-16: Comparing results of player with optimal solution during four phases of the game

Table 2-2 compares the performance of players as well as groups. For instance, for the first run of the game, group 4 with a total cost of 874 was the winner, however in the second run of the game, group

2 with 26% improvement and cost of 774 is the winner. Referring to the performance of group 2 in second run, the enhancement in all player performance and more collaboration moves them toward winning.

Table 2-2. Student performances in two round plays of the game

		A	progress	B	progress	C	progress	Total	progress
Group 1	first run	310	18.7%	294	-3.4%	344	20.6%	948	12.6%
	second run	252		304		273		829	
Group 2	first run	368	31.3%	324	21.6%	354	24.6%	1046	26.0%
	second run	253		254		267		774	
Group 3	first run	269	5.2%	300	10.7%	340	19.4%	909	12.3%
	second run	255		268		274		797	
Group 4	first run	252	5.6%	285	-15.1%	335	8.1%	872	-0.2%
	second run	238		328		308		874	

2.5. Discussion and experience

To be successful in the game several strategies could have been adopted by players. First, they should always collaborate with each other even though they are in competition. It is especially important from the first phase of the game that supply points will be selected. As an example, a successful collaboration is the one that players agree on selecting bundle of supply that has a very low purchasing cost and then propose very good exchange proposals in the next phase of the game. Another strategy could be to play independently from start and have a hierarchical way of thinking. Indeed, the successful independent player is the one who selects the areas in the first phase with very high interest in exchanging. Afterwards, they assign the supply to demand points in the way that will be very interesting for backhauling.

The player will understand the importance of hierarchical planning at the end of the first stage when they visualize how their first stage design could affect their improvement proposals on other stages. Indeed, they could easily see that in each phase they are limited to previous stage decisions. Hence, it is important to run the game at least twice to give the player the chance to use their learning and experience. In this way, they personally visualize how much they could improve their performance by having hierarchical thinking from the beginning.

The experience of game running in the class made us understand it is important to try firstly a short time game with low demand in order to familiarize the students with the interface of the game. Moreover the ongoing surveillance of the student performance will accelerate their understanding about those different phases. The last phase of the game is the most complicated one that certainly needs close observation by tutors to help the players to find a backhaul route. Finally, we follow up the game education with lectures on optimization models and explain how we develop optimization models in each phase.

2.6. Conclusion

Hierarchical transportation planning in forest supply chain attracts much attention from academics and industry experts. Moreover, collaboration as a relatively new introduced concept on forest industry could directly affect this planning. Our online transportation game combines these important aspects. The students are forced to think ahead of the local planning phases to consider also the overall planning problem. Students will realize that one local optimization is not enough to find a coordinated solution for the overall hierarchical problem. Students will also realize the large potential with collaboration through wood exchange and backhauling routes even when they are competitors. The game uses illustrative visualization for each of the phases and it is easy to understand the game rules and costing structure. The resulting generation is clear and informative. The game provides an understanding of planning in different decision levels and a vision of collaboration. Integrated optimization models to game clearly display the effect of optimization on cost reduction, or in another word, good planning. The game is developed based on a forest application but the same planning issues arise in many other industries.

Acknowledgments
The authors would like to thank FORAC research consortium and the Faculty of Engineering and Science at Université Laval for its support in developing the transportation game.

2.7. Reference

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

Bredström, D., P. Jönsson and M. Rönnqvist, 2010. Annual planning of harvesting resources in the forest industry. *International Transactions in Operations Research*, 17 (2), 155-177.

Carlsson, D. and M. Rönnqvist, 2007. Backhauling in forest transportation – models, methods and practical usage. *Canadian Journal of Forest Research,* 37 (12), 2612-2613.

D'Amours, S., PH. Marier, M. Rönnqvist, R. Azouzi and D. Fjeld, 2017. The online wood supply game. INFORMS Transactions on Education**,** 18 (1), 71-87.

D'Amours, S. and M. Rönnqvist, 2013. An Educational Game in Collaborative Logistics. *INFORMS Transactions on Education,* 13 (2), 102-113.

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

Fjeld, D. and C. Hedlinger, 2005. The Transport Game - A Tool for Teaching the Basics of Transport Decision Proficiency. *International Journal of Forest Engineering*, 16 (2), 57-65.

Forsberg, M., M. Frisk and M. Rönnqvist, 2005. FlowOpt - A Decision Support Tool for Strategic and Tactical Transportation Planning in Forestry. *International Journal of Forest Engineering*, 16 (2), 101-114.

Frisk, M., M. Göthe-lundgren, K. Jörnsten and M. Rönnqvist, 2010. Cost allocation in collaborative forest transportation. *European Journal of Operational Research*, 205 (2), 448-458.

Frisk, M., P. Flisberg, M. Rönnqvist and G. Andersson, 2016. Detailed scheduling of harvest teams and robust use of harvest and transportation resources. *Scandinavian Journal of Forest Research,* 31(7), 681-690.

Kong, J., M. Frisk and M. Rönnqvist, 2015. Using mixed integer programming models to synchronously determine production levels and market prices in an integrated market for roundwood and forest biomass. *Annals of Operations Research*, 232 (1), 179-199.

Paradis, G., M. Bouchard, L. Lebel and S. D'Amours, 2015. Bilevel Model Formulation for the Distributed Wood Supply Problem. CIRRELT Research Paper, Quebec, Canada.

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

Rönnqvist, M., S. D'Amours, A. Weintraub, A. Jofre, E. Gunn, R.G. Haight, D. Martell, A.T. Murray and C. Romero, 2015. Operations Research challenges in forestry: 33 open problems. *Annals of Operations Research*, 232 (1), 11-40.

J. Sterman, 1989. Modeling Managerial Behavior: Misperceptions of Feedback in a Dynamic Decision Making Experiment. *Management Science*, 35 (3), 321-339.

Chapter 2 Forest Fibre Network Design with Multiple Assortments: a case study in Newfoundland

This chapter is earmarked to the article entitled *"Forest Fiber Network Design with Multiple assortments: a case study in Newfoundland"*. It has been published in the *Canadian Journal of Foreset Reseach (2017).* The figures and mathematical formulations have been revised to keep the coherence with the thesis.

RÉSUMÉ : L'industrie forestière canadienne est confrontée a` plusieurs défis tels qu'un prix élevé de la fibre, une diminution de la rentabilité des produits de base et de faibles investissements dans des usines de transformation vieillissantes. Pour favoriser la transformation de cette industrie, les innovations sont nécessaires afin de développer des produits a` valeur ajoutée et ainsi évoluer vers une chaîne de valeur intégrée efficace. À cet égard, une meilleure logistique pour améliorer la manipulation de la matière première, utiliser la biomasse forestière et employer de nouvelles technologies sont des avenues prometteuses. Dans cet article, nous proposons un modèle générique de chaîne de valeur qui inclut la localisation de nouvelles cours de triage et de bioraffineries afin de maximiser le profit total de la chaîne de valeur. Ce problème de planification intégrée traite des décisions stratégiques incluant les investissements dans de nouvelles installations et technologies ainsi que les décisions tactiques comprenant le retour a` charge dans le cas du transport et les flux de fibre dans la chaîne de valeur. Pour résoudre un tel problème, nous avons développé un modèle de programmation mixte en nombres entiers pour concevoir le réseau de la chaîne de valeur de la forêt. Ce modèle a été utilisé dans une étude de cas en milieu industriel dans la province de Terre-Neuve au Canada. Nous avons produit et analysé 32 scénarios évalués sur la base de 12 indicateurs de performance prédéfinis. Les résultats démontrent que la collaboration via le retour a` charge, les terminus communs et les nouveaux assemblages constituent des opportunités majeures pour améliorer la profitabilité et l'efficacité de la chaîne de valeur. L'amélioration potentielle par rapport a` la situation actuelle peut être aussi grande que 23% en prenant en compte les actions précédemment mentionnées.

MOTS-CLÉS : biomasse forestière, conception de la chaîne de valeur, retour a` charge, cours de triage, planification stratégique et tactique intégrée.

ABSTRACT: The Canadian forest industry is facing several challenges including high fibre cost, decline in commodity profitability and low investment levels at relatively old manufacturing plants. To enable transformation of the industry, innovations are needed to develop value-added products and to shift to an efficient integrated value chain. In this regard, improved logistics for better handling of raw material, forest biomass utilization and use of new technologies are some promising avenues. In this paper, we propose a generic value chain model which includes locating new sorting yards and biorefineries maximizing the overall profit of the value chain. This integrated planning problem deals with strategic decisions including investments in new facilities and technologies and tactical decisions comprising backhaul transportation and fibre flows across the value chain. To solve such a problem, we developed a mixed integer programming model to design the forest value chain network. This model is used in an industrial case study in the province of Newfoundland, Canada. We have generated and analyzed 32 scenarios evaluated on 12 predefined key performance indicators. The results show that collaboration through backhauling, common terminals and new assortments are important opportunities to improve the profitability and efficiency of the value chain. The potential improvement over the current situation is as high as 23% considering the aforementioned actions.

Keywords: Forest biomass, value chain design, backhaul transportation, sorting yards, integrated strategic and tactical planning.

3.1. Introduction

In recent years, the forest industry crisis has had significant economic and social consequences. Several studies have investigated the causes and effects of these crises on the Canadian forest industry (Mockler and Fairbairn 2009; Mockler and Robichaud 2011). These studies show that the crisis in the industry has been provoked by a rapid decline in commodity demand, the volatile exchange rate of the Canadian dollar as well as strong competition from Asian companies. To deal with the aforementioned challenges, the industry should first stabilize its market conditions, then smoothly transform along four distinct lines: These are market development, operational efficiency, business process change and new product development (Natural Resources of Canada (A) 2016). Among them, new product development, in particular green energy from forest biomass, has been accentuated recently. Such development requires network redesign to introduce new facilities and technologies into the supply chain.

It is often more difficult to redesign a network than to design one from start. There is a need to consider the ongoing operations and to ensure smooth transition between the two designs. Moreover, the reengineering process can become even more complex when there are several stakeholders with their own objectives who have run their operations for many years. In reality, this is often the situation that must be dealt with primarily. Hence, our goal is to develop a decision support tool for all transition phases. The tool first proposes improvement directions for current state of the supply chain. Afterwards, it provides new network design for new transformed industry.

To propose improvement strategies, it is essential to have insights about the entire forest supply chain. D'Amours et al. (2008) presented a global view of Canadian forest supply chain. They characterized the forest supply chain, in particular the Canadian one, as an integrated and divergent supply chain. The forest wood flow starts with harvesting and then continues through sorting, transportation, storage and operating to convert to products comprised of lumber, pulp and paper, energy or new bio-products (Carlsson and Rönnqvist 2005). All final products are distributed to the market. Wood flow planning consdering interactions between all business units was studied by Weintraub and Epstein (2005).

The sorting and transportation parts of wood flow have significant impacts on efficiency and economy of the supply chain. Sorting activities help to reduce variability of supply to the mills that require wood supply with specific properties. Such supply strengthens the competitiveness of the industry since it makes possible high-quality products. In this regard, log sorting yards are among the improvement strategies for the forest economy (Alam et al. 2014). Several objectives including profit making, cost saving, risk reduction and an improved forest management economy could be achieved through strategic and operational planning of sorting yards (Dramm et al. 2004). In spite of its advantages, Carlgren et al. (2006) showed, for a case study, the introduction of demand for a specific log assortment will increase the transportation and sorting costs by up to 6%. However, they noted that backhaul transportation could reduce the cost by up to 25%. Hence, backhaul transportation plays a significant role in cost reduction.

There are several comprehensive studies on developing decision support systems for transportation planning with special consideration for backhauling (Carlsson and Rönnqvist 2007; Forsberg et al. 2005). Effective backhaul routes depend notably on stakeholders' cooperation. Palander and Väätäinen (2005), demonstrated a significant cost saving from backhauling combined with interenterprise collaboration in the Finnish forest industry.

Besides determining improvement directions, our tool has been developed to propose a smooth market transformation. This could happen in forest industry by invaluable forest biomass, which consists of forest residues, non-merchantable woods, sawdust and other non-usable by-products. These homogenous resources have been used for many years to provide forest industry energy. However, with rising environmental concerns, the industry in such resources as a means of producing renewable energies has increased. Frombo et al. (2009) provided a strategic decision model to select an optimal energy-conversion technique that maximizes the selling profit minus collection and transportation costs. Gunnarson et al. (2004) studied tactical planning for forest bioenergy supply chain in which they satisfied the yearly contract-based energy demands. A comprehensive study by Shabani et al. (2013) reviewed all recent researches on forest biomass value chain optimization for bioenergy production.

Furthermore, forest residues are a great alternative to produce biofuels and bio-products because of their wide geographical distribution and availability. Ekşioğlu et al. (2009) developed a mixed integer programming (MIP) model for biorefinery supply chain producing ethanol from agriculture and woody biomass. They proposed a network design for biorefinery location coordinated with harvesting, sorting, transporting and processing decisions. Kim et al. (2011) considered a forest supply chain comprising forest, potential location for biofuel plants and market with objective of determining number, location and size of biofuel plants as well as logistic planning. They performed a sensitivity analysis showing the significant effect of demand variation on network design and profitability.

Integration of bioenergy and biofuel value chain in forest industry has been studied by Cambero et al. (2014). The authors proposed a multi-period optimization model to decide the right period for facility opening considering procurement planning. However, real integration in the supply chain consists in considering all existing partners. Troncoso et al. (2015) compared the integrated forest value chain planning versus decoupled planning for a Chilean case study. The authors reported that the net present value of the value chain increased up to 5% when the proposed integrated solution is implemented.

Feng et al. (2010) clarified the potentiality of integrated forest biomass value chain. The paper proposed a general mathematical programming model to locate new biorefinery, assign technologies to them and allocate resources. New technology could develop in green field sites or existing mills. Dansereau et al. (2012) considered a pulp and paper mill which has facilities for biorefinery products. They considered manufacturing flexibility methodology to reduce the risk of assessing new technologies.

In this paper, we followed the concept of an integrated forest supply chain of Feng et al. (2010) in a more comprehensive way. The main decisions we consider are a) to locate value-adding facilities including biorefineries and sorting yards b) to assign technology and capacity to biorefineries c) to allocate resources to existing and new facilities d) to plan the logistics of supply chain considering transportation, sorting and operating and finally f) to consider the possibility of collaboration between industrial partners including backhaul transportation. Our general problem is motivated by a specific case of the forest industry in the province of Newfoundland, Canada. We propose an MIP model to investigate the aforementioned problem. All required information is collected from stakeholders in the province and FPInnovations, a Canadian non-profit organization in forestry research. The results of this project are reported in the Centre for Forest Science and Innovation of Newfoundland to be utilized as a guideline for industry improvement and competitiveness policies. The main contributions of the paper are the proposed model and its practical test in a real industrial case study setting.

The outline of the paper is as follows: Section 3.2 gives the problem description. Then the detailed case study is described in Section 3.3. Section 3.4 reports the results based on a set of designed scenarios. Finally, we provide some concluding remarks.

3.2. Problem Formulation and mathematical model

Forest supply chain comprises four main entities: the forest, pulp and paper operation units, wood-manufacturing units to produce lumber, panel and engineering wood and transformation units (Lehoux et al. 2012). Each of these entities has its own business plan to maximize its revenue and profit; however, they are all interconnected (Figure 3-1). Manufacturing plants are connected to the forest either directly or through terminals. Sawmills provide intermediate products for pulp and paper mills and transformation mills. Finally, the products are delivered to the market through distribution centers. A short description of each entity is provided in the following.

Forest- Canada has the second largest forest in the world with 396 million hectares. There are 35 different economic important species. Forests and their industries play a vital role in the Canadian economy, society and environment. They support one million jobs, i.e., 5.6 % of the total employment of the country (Natural Resources of Canada (B) 2016).

Terminal- Terminals are in-transit yards for logs from the forest and before their arrival in mills. They can be used as sorting yards, stock-yards or merchandizing yards (Lehoux et al. 2012). Terminals provide a great opportunity for backhaulage for all stakeholders in the network and can extensively increase the existing value of fibre in the network by allocating the right log to the right mill with a minimum cost.

Sawmill- Products and by-products of sawmills have a crucial role in the efficiency of the entire forest supply chain. Wood chips produced in the sawing process are utilized as raw material for pulp and paper mills. Moreover, bark, sawdust and shavings are used as feed for new transformation processes.

Pulp and paper mill- An important part of the industry is the pulp and paper industry. However, the rise of electronic media and the steep decline in paper-based products has affected the main economic contributors of the forest industry. In this regard, their collaboration in the transformation of Canadian forest industry has dramatically increased.

Transformation unit- They are new facilities to start industry transformation. Several processes including extraction, combined heat and power, organic ranking cycle, pelletization, fermentation and lignin precipitation could be employed at these units to produce biofuels, biochemicals, biodegradable plastics, personal care products and industrial chemicals from forest biomass. Among aforementioned processes, pelletization is a mature one with high yield. Moreover, the stable market of pellets, motivates investors towards such a low-risk investment option. In this regard, we consider pelletization as the process of our transformation unit to be included in the value chain network.

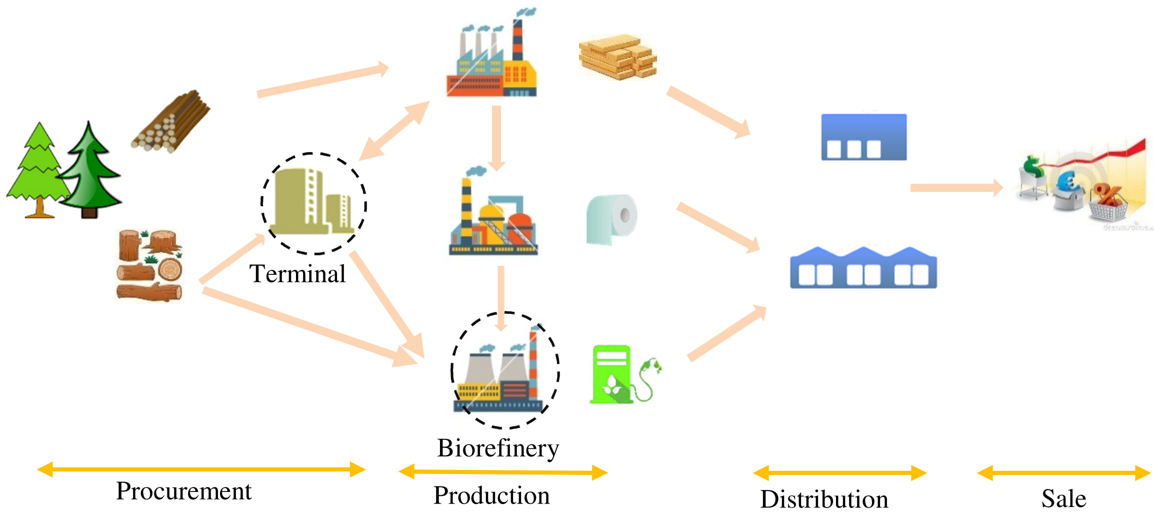


Figure 3-1: Forest biomass network design and the flows between network nodes. The dashed circles around terminals and biorefineries display their potential location in existing supply chain.

3.2.1. Optimization model

We propose an MIP model to find an optimal design for a general forest supply chain considering existing stakeholders, potential terminals and pellet mills and backhaul availability. The model aims to maximize the profit of the network while satisfying a set of constraints such as customer demand, forest supply and mill capacities, existing road network, etc. The following will present the exact formulation of the MIP model including sets and parameters definition, decision variables and constraints.

Defined and supporting sets for the developed model are described in the following.

P^R set of raw and intermediate products

P^F set of final products

P set of all product types $P = P^R \cup P^F$

S set of sort groups

F^P set of piles

F^C set of species

D set of districts

Z set of zones

O set of tenure holders

L^T set of potential terminal locations

L^E set of potential biorefinery locations

M^P set of existing manufacturing plants

N set of all network nodes $N = Z \cup M^{P} \cup L^{T} \cup L^{E}$

R^{i} set of existing and candidate processes for mill i

H set of hauling type

L^{B} set of backhaul routes

Here are some comments on set of sort groups and set of hauling types; We define four sort groups comprising unsorted supply, sort base on wood species, sort base on wood species and their utilization, i.e., sawlogs, studwoods (short sawlogs), pulpwoods and energy woods and sort base on wood species, utilization and dimension. The model allows sorting at different places from higher sort group to lower ones. Moreover, we classify different truck organization within the set of hauling types.

Supporting sets:

I_{izo} set of forest areas indicated by district i, zone z and tenure holder o.

H_{ojh} set of hauling methods for woods belonging to o with truck type h to mill j.

P_{rj}^{R} set of all processes r at mill j.

P_{pr}^{R+} set of input products p to process r.

P_{pr}^{R-} set of output products p from the process r.

W_{lf}^{FS} set of sorted pile f created from sorting pile l.

E_{foj}^{FF} flow of pile f from forest tenure o to mill j.

E_{foij}^{FM} flow of pile f of tenure holder o from mills i to j.

The parameters used to describe harvest areas, costs, values, production at mills and capacities are given below.

k_{izop} annual allowable cut of product p at forest block indicated by $(izo) \in I_{izo}$.

a_{fl}^{FS} proportion of sorted pile f at the pile l.

f_{i} fixed cost to open a new facility i.

v_{pj}^{F} unit selling value of final product p at the gate of mill j.

c_{s}^{I} unit harvesting cost for each sort group s.

c_{sj}^{S} unit sorting cost to group s at mill j.

c_{pr}^{R} unit processing cost of product p at the process r.

c_{izoj}^{HI} unit transportation cost of any product from forest area indicated $(izo) \in I_{izo}$ to mill j.

c_{ijh}^{HM} unit transportation cost of any product between mill i and j by truck type h.

c_{lh}^{ML} unit transportation cost for backhaul route l by truck type h.

a_{lfsoj}^{ML} 1; if backhaul trip l picks u a pile f with a sort group S and owner o at supply point j.

b_{lfsoj}^{ML} 1; if backhaul trip l delivers pile f with a sort group S and owner o to demand point j.

u_{prq}^{R} yield of process r in producing product q while it is fed by product p .

k_{r}^{R+} max capacity of process r.

k_{r}^{R-} min capacity of process r.

k_{jh}^{H} transportation capacity of truck type h for mill j.

M a big value.

To avoid nonlinearity in modeling we assume the proportion of available products in each pile (a_{fl}^{FS}) is known. This value is estimated by average on proportion of available forest resources.

The decision variables used in the models are:

y_{i}^{E} 1; if biorefinery i is open, and 0 otherwise.

y_{i}^{T} 1; if terminal i is open, and 0 otherwise.

x_{izoj}^{A} 1; if forest block indicated by $(izo) \in I_{izo}$ is assigned to mill j, and 0 otherwise.

x_{sizo}^{AP} percentage of harvesting in sort group S from forest block indicated by $(izo) \in I_{izo}$.

$x_{fscizojh}^{FF}$ flow of pile f with sort group S and species c from forest block indicated by $(izo) \in I_{izo}$ to mill j by truck type h.

$x_{fscoijh}^{MF}$ flow of pile f with a sort group S and species c belong to owner o between mills i and j by truck type h.

x_{lh}^{ML} backhaul flow l done by truck type h.

x_{jp}^{E} volume of final product p produced at mill j .

x_{fsoj}^{S} sorting amount of pile f with a sort group S and wood owner o at mill j .

x_{psorj}^{R} volume of inputted product p with sorting group S and wood owner o to process r at mill j.

Most of the decision variables are anticipation variables which are used to evaluate the strategic decisions. As such, these anticipation decisions are not being operated. Instead, shorter-term tactical and operational models will be used to find such operational decisions. Besides, the available data is based on long-term allowable annual cut (AAC) models which essentially describe the available volume per year. As these numbers are the same; it is possible to use only one time period to make strategic decisions. Hence, we do not consider time horizon dimension for decision variables.

The objective function is to maximize the profit (revenue from sales minus costs). The sales value of final products is the revenue of the network. The included costs in the model are harvesting, transportation, sorting, operating and fixed cost to open new terminals and biorefinery.

$$Max\,Z:\sum_{p\in P^F}\sum_{j\in N}(v_{pj}^{F}x_{jp}^{E})-\sum_{s\in S}\sum_{(izo)\in I_{izo}}\sum_{p\in P^R}(c_s^{I}k_{izop}x_{sizo}^{AP})-\sum_{(izo)\in I_{izo}}\sum_{(foj)\in E_{foj}^{FF}}\sum_{s\in S}\sum_{c\in F^C}\sum_{h\in H}(c_{izoj}^{HI}x_{fscizojh}^{FF})-$$
$$\sum_{(foij)\in E_{foij}^{FM}}\sum_{s\in S}\sum_{c\in F^C}\sum_{h\in H}(c_{ijh}^{HM}x_{fscoijh}^{MF})-\sum_{l\in L^B}\sum_{h\in H}(c_{lh}^{ML}x_{lh}^{ML})-\sum_{f\in F^p}\sum_{s\in S}\sum_{o\in O}\sum_{j\in N}(c_{sj}^{S}x_{fsoj}^{S})- \qquad (3\text{-}1)$$
$$\sum_{(pr)\in P_{pr}^{R+}}\sum_{s\in S}\sum_{o\in O}\sum_{(rj)\in P_{rj}^{R}}(c_{pr}^{R}x_{psorj}^{R})-\sum_{i\in L^T}f_i\ y_i^{T}-\sum_{i\in L^E}f_i\ y_i^{E}$$

The model is subjected to a set of constraints for capacity constraints, fibre delivery constraints, balance constraints, flow constraints and demand constraints.

Capacity constraints:

The first set of constraints, harvest capacity constraints, assures the sum of a percentage of harvested products in different sorting groups for each forest block should be less than one.

$$\sum_{s\in S}x_{sizo}^{AP}\leq 1 \qquad \forall(i,z,o)\in I_{izo} \qquad (3\text{-}2)$$

The resource should satisfy mill demand; however each forest area may only be assigned to one mill (constraint set (3-3)).

$$\sum_{j\in N}x_{izoj}^{A}\leq 1 \qquad \forall(izo)\in I_{izo} \qquad (3\text{-}3)$$

Constraint set (3-4) assures that only assigned forest area will be harvested.

$$\sum_{s\in S}\sum_{z\in Z|(izo)\in I_{izo}}x_{sizo}^{AP}\leq\sum_{j\in N}x_{ioj}^{A} \qquad \forall i\in D,o\in O \qquad (3\text{-}4)$$

Constraint set (3-5) considers the restricted capacity of transportation of all transported products to or from a mill.

$$\sum_{(foj)\in E_{foj}^{FF}}\sum_{s\in S}\sum_{c\in F^C}\sum_{(izo)\in I_{izo}}x_{fscizojh}^{FF}+\sum_{(foij)\in E_{foij}^{MF}}\sum_{s\in S}\sum_{c\in F^C}x_{fscoijh}^{MF}+\sum_{l\in L^B}\sum_{(foij)\in E_{foij}^{MF}}\sum_{s\in S}b_{lfsoj}^{ML}x_{lh}^{ML}+$$
$$\sum_{s\in S}\sum_{i\in N}\sum_{f\in P^F}\sum_{(foji)\in E_{foji}^{FM}}\sum_{c\in C}x_{fscojih}^{MF}+\sum_{l\in L^B}\sum_{i\in N}\sum_{(foji)\in E_{foji}^{MF}}\sum_{s\in S}a_{lfsoj}^{ML}x_{lh}^{ML}\leq k_{hj}^{H} \qquad \forall j\in N,h\in H \qquad (3\text{-}5)$$

Flow constraints

The flow of wood in the network will start from the forest; therefore, all harvested resources should be directly forwarded from the forest to mills (constraint set (3-6)).

$$\sum_{p\in P^R}k_{izop}x_{sizo}^{AP}-\sum_{(foj)\in E_{foj}^{FF}}\sum_{c\in F^C}\sum_{(ojh)\in H_{ojh}}x_{fscizojh}^{FF}=0 \qquad \forall(izo)\in I_{izo},s\in S \qquad (3\text{-}6)$$

Moreover, constraint set (3-7) permits all the decision variables related to the biorefinery to have the value 1 if the facilities are open. The same constraint exists for terminals.

$$\begin{aligned}
&\sum_{(foj)\in E^{FF}_{foj}} \sum_{(izo)\in I_{izo}} \sum_{s\in S} \sum_{c\in F^C} \sum_{(ojh)\in H_{ojh}} x^{FF}_{fscizojh} + \sum_{(foij)\in E^{FM}_{foij}} \sum_{s\in S} \sum_{c\in F^C} \sum_{(ojh)\in H_{ojh}} x^{MF}_{fscoijh} + \\
&\sum_{l\in L^B} \sum_{(foij)\in E^{MF}_{foij}} \sum_{s\in S} \sum_{h\in H} b^{ML}_{lfsoj} x^{ML}_{lh} + \sum_{(lf)\in W^{FS}_{lf}} \sum_{s\in S} \sum_{o\in O} (a^{FS}_{fl} x^{S}_{jlso}) + \\
&\sum_{(rj)\in P^{R}_{rj}} \sum_{(fr)\in P^{R-}_{fr}} \sum_{(pr)\in P^{R+}_{pr}} \sum_{s\in S} \sum_{o\in O} (u^{R}_{prf} x^{R}_{psorj}) + \sum_{(foji)\in E^{FM}_{foji}} \sum_{s\in S} \sum_{c\in C} \sum_{(oih)\in H_{oih}} x^{MF}_{fscojih} + \\
&\sum_{l\in L^B} \sum_{(foji)\in E^{MF}_{foji}} \sum_{s\in S} \sum_{h\in H} a^{ML}_{lfsoj} x^{ML}_{lh} + \sum_{f\in F^P} \sum_{s\in S} \sum_{o\in O} x^{S}_{jfso} + \sum_{(pr)\in P^{R+}_{pr}} \sum_{s\in S} \sum_{(rj)\in P^{R}_{rj}} \sum_{o\in O} x^{R}_{psorj} \le M y^{E}_{j}
\end{aligned} \qquad \forall j \in l^E \cup l^T \tag{3-7}$$

Balance constraints:

The balance constraints are defined to assure the equilibrium of inputs and outputs of each mill for different sorting piles. Constraint set (3-8) assures the balance of raw material and intermediate products in the format of different piles at mills. The input flow can be a flow from forest or mills (direct or backhaul), or the output of a sorting process or a process where we consider balance constraint for the intermediate product.

$$\begin{aligned}
&\sum_{(foj)\in E^{FF}_{foj}} \sum_{c\in C} \sum_{(izo)\in I_{izo}} \sum_{(ojh)\in H_{ojh}} x^{FF}_{fscizojh} + \sum_{(foij)\in E^{FM}_{foij}} \sum \sum_{c\in C} \sum_{(ojh)\in H_{ojh}} x^{MF}_{fscoijh} + \\
&\sum_{l\in L^B} \sum_{(foij)\in E^{FF}_{ofj}} \sum_{h\in H} b^{ML}_{lfsoj} x^{ML}_{lh} + \sum_{(lf)\in W^{FS}_{lf}} \sum_{o\in O} (a^{FS}_{fl} x^{S}_{jlso}) + \\
&\sum_{(pr)\in P^{R+}_{pr} \& (fr)\in P^{R-}_{fr}} \sum_{o\in O} \sum_{(rj)\in P^{R}_{rj}} (u^{R}_{prf} x^{R}_{psorj}) - \sum_{(foji)\in E^{MF}_{foji}} \sum_{c\in C} \sum_{(oih)\in H_{oih}} x^{MF}_{fscojih} - \\
&\sum_{l\in L^B} \sum_{(foji)\in E^{MF}_{foji}} \sum_{h\in H} a^{ML}_{lfsoi} x^{ML}_{lh} - \sum_{o\in O} x^{S}_{jfso} - \sum_{(fr)\in P^{R+}_{fr}} \sum_{o\in O} \sum_{(rj)\in P^{R}_{rj}} x^{R}_{fsorj} = 0
\end{aligned} \qquad \forall j \in N, f \in F^P, s \in S \tag{3-8}$$

The balance constraint for final product at mill is formulated in the constraint set (3-9).

$$\sum_{(fr)\in P^{R+}_{fr} \& (pr)\in P^{R-}_{pr}} \sum_{(jr)\in P^{R}_{jr}} \sum_{s\in S} \sum_{o\in O} (u^{R}_{frp} x^{R}_{fsojr}) - x^{E}_{jp} = 0 \qquad \forall j \in N, p \in P^F \tag{3-9}$$

Demand constraints

In our modeling, each process has a minimum and maximum production range capacity (constraint (3-10)). For the energy plants, this constraint depends on the existence of them in our network structure (constraint (3-11)).

$$k^{R+}_{r} \le \sum_{(fr)\in P^{R+}_{fr}} \sum_{s\in S} \sum_{o\in O} x^{R}_{fsorj} \le k^{R-}_{r} \qquad \forall (rj) \in P^{R}_{rj} \tag{3-10}$$

$$k^{R+}_{r} y^{E}_{j} \le \sum_{f\in F^P | (fr)\in P^{R+}_{fr}} \sum_{s\in S} \sum_{o\in O} x^{R}_{fsojr} \le k^{R+}_{r} y^{E}_{j} \qquad \forall r \in R, j \in L^E \mid (rj) \in P^{R}_{rj} \tag{3-11}$$

Variable definition constraints

Finally, variables are defined in constraint sets (3-12) and (3-13).

$$y^{E}_{i}, y^{T}_{i}, x^{A}_{izoj} \in \{0,1\}, x^{AP}_{sizo} \in \{0,1\} \tag{3-12}$$

$$x^{FF}_{fscizojh}, x^{MF}_{fscoijh}, x^{ML}_{lh}, x^{E}_{jp}, x^{S}_{jfso}, x^{R}_{fsorj} \ge 0 \tag{3-13}$$

3.3. Case study

Newfoundland is the insular portion of the Canadian province of Newfoundland and Labrador situated in the North Atlantic Ocean. It has two million ha of productive forestland, within 18 districts, available or partially available for harvest. The lands are 96% owned by the public and 4% by the private sector. The primary commercial species are black spruce (Picea mariana) and balsam fir (Abies balsamea). There are four stakeholders in operation: Corner Brook Pulp and Paper Limited (capacity 700,000 m^3/yr), Burton's Cove Lumber Limited (capacity 70,000 m^3/yr), Cottle's Island Lumber (capacity 40,000 m^3/yr) and Sexton Lumber (capacity 180,000 m^3/yr) respectively from west to east. The final products of the mills are mainly conventional forest products, including lumber, pulp and paper and energy. Corner Brook Pulp and Paper holds timber tenure of 29% of the total public forestlands that has been called Kruger tenure. This means other stakeholders are not permitted to harvest Kruger tenure (Sustainable Forest Managment 2013). They have annual agreements with the government that allow them to harvest specific areas.

A Newfoundland forest map is depicted in Figure 3-2. The green blocks in the picture are harvest areas of 2 km × 2 km size. Newfoundland has 5,888 of such blocks for each, district number, location, timber tenure holder, harvest capacity and fibre attributes are known by the Newfoundland Centre for Forest Science and Innovation. However, such detailed information is not necessary for a strategic tactical planning problem. Hence, we aggregate forest blocks to a larger size called zone as a forest management unit. The same information for blocks is available for each of 520 zones. Afterwards, we identify each harvest area with its district number, zone number and tenure holder.

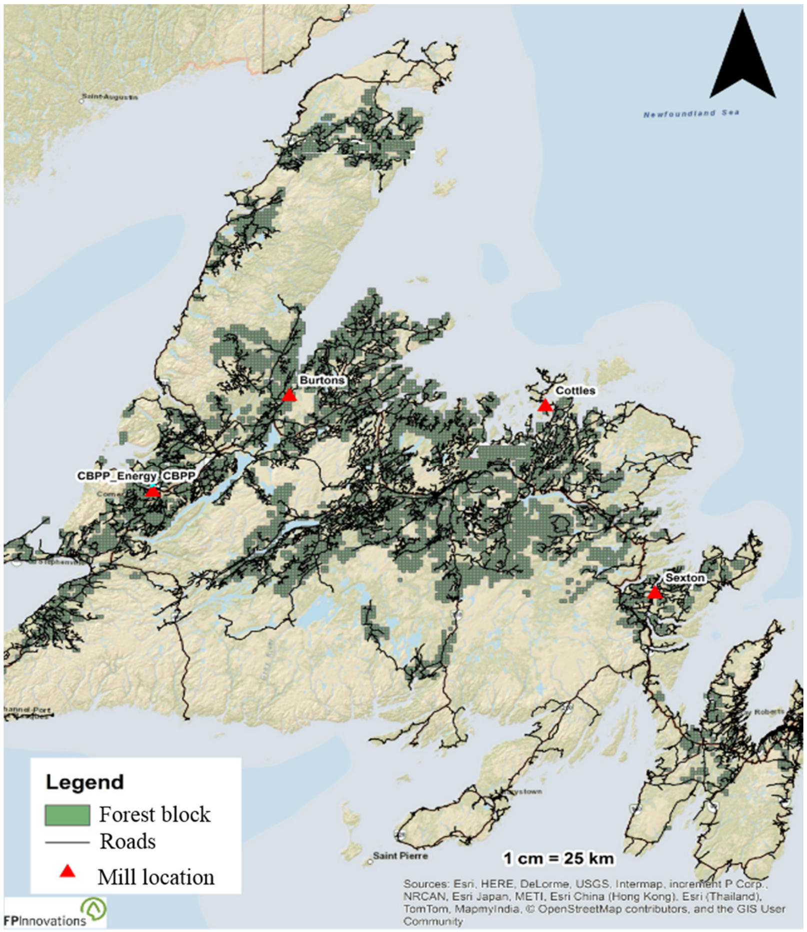


Figure 3-2: Map of Newfoundland forest industry

The transportation cost between all network nodes is calculated by FPInterface™. Information comprising supply, harvesting and purchasing cost, yield of process and operation cost is collected from each stakeholder. All values (revenues) and costs are evaluated as sold at mill gate.
Fibre wood availability is one of the most challenging problems in this supply chain, particularly for sawmills with their restricted timber tenure. Two reasons are the cause of this problem. First, Newfoundland has a very acid soil with low fertility, which means large and vast supply areas. Second, mills do not receive the quantity and quality of supply they require. Sorting yards with the goal of delivering the right fibre to the right mill at the right time could significantly improve the current situation.

On the other hand, high transportation costs as well as environmental concerns are two other significant problems for Newfoundland forest supply chain. The large resource distribution increases the transportation distance. The west of the insular area is covered by balsam fir which is valuable feedstock for Corner Brook Pulp and Paper; and conversely, the eastern part of the island is covered by black spruce, a valuable raw material for sawmills. Moreover, transportation in Newfoundland is operated by several independent organizations under different agreements. As a consequence, the supply delivery to Corner Brook Pulp and Paper is restricted to drivers from a particular organization. This condition severely limits opportunity for collaboration in the form of backhauling transportation.

Backhaul transportation could be a beneficial option to demonstrate the impact of collaboration, to reduce transportation costs and greenhouse gas (GHG) emissions. We have designed three sets of backhaul routes depicted in Figure 3-3. Each backhaul route characterizes the supply and delivery nodes as well as the hauled products and their owner. The total saving in backhaul transportation declared in the figure is calculated by the reduction in empty driving distances. Moreover, we calculate the reduction in GHG emissions by using backhaul transportation in equation (3-14) (Lakshmanan and Han 1997). The equation requires distance travel ($m^3 \times km$), fuel consumption ($\frac{gallon}{(100km)(m^3)}$); and fuel specific factor ($8.887\times10^{-3}\ \frac{metric\ tons}{gallon}$) to calculate metric tons of CO2 emissions.

$$GHG = Distance\ travel \times fuel\ consumption \times fuel\ specific\ factor \tag{3-14}$$

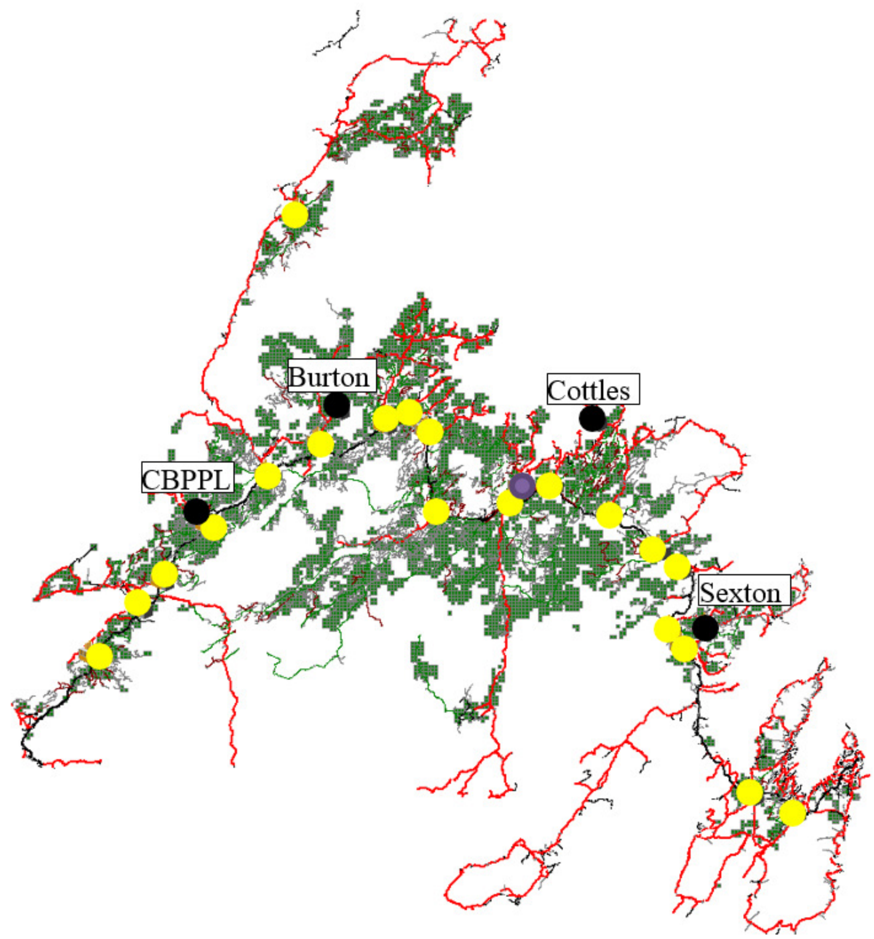


Figure 3-3: Potential location for terminals (yellow points) and pellet mill (purple point), the mills are depicted by black points (map is taken from FPInterface™)

The Newfoundland stakeholders are always searching for new products, processes and markets to increase their profit margin. Investigation of their current state and the availability of wood energy in the forest have identified that new biorefinery are ideal options for improving their profitability

(Melendez Esquivel 2015). The new process could be installed either in green field site or existing mills.

The case study in Newfoundland is a very good test for our proposed model. Twenty potential locations for terminals and one potential location for a biorefinery are considered (Figure 3-4). These locations represent large crossings in the road network and are identified together with government representatives in collaboration with the stakeholders. Moreover, to evaluate the effect of each of the aforementioned actions we develop different scenarios. Each scenario is optimized by the model and analyzed.

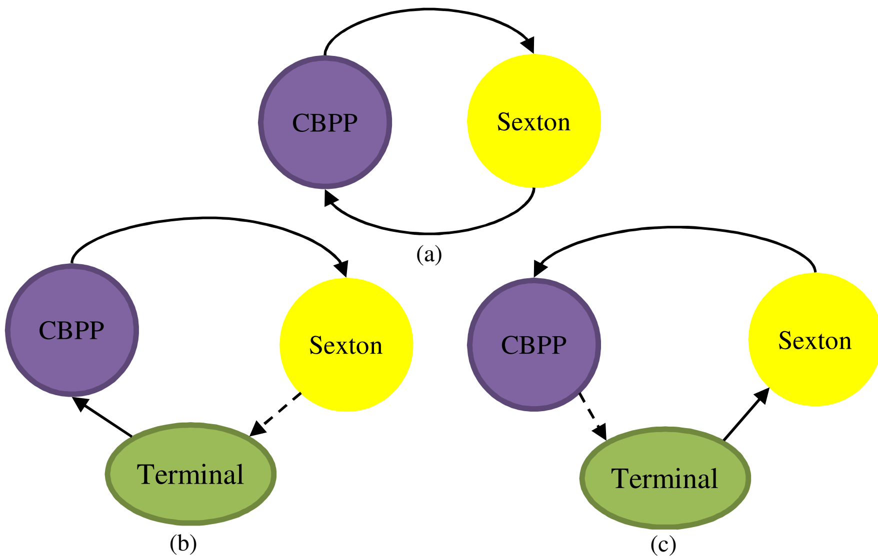


Figure 3-4: The possible backhaul routes: (a) Newfoundland's principle backhaul route without empty driving between Corner Brook Pulp and Paper (CBPP) and Sexton Lumber. (b and c) Backhaul routes with more full load trips rather than empty driving between CBPP, Sexton Lumber and an open terminal.

The scenarios are generated through a combination of assumptions. The assumptions are: 1) allowable wood allocation in forest can be shared between all stakeholders; 2) accessibility of sawmills to supply in the Kruger tenure; 3) possibility of using backhaul availability; 4) terminals can be used; 5) biorefineries can be used. Assumption (1) gives the model the possibility to allocate a harvest zone to more than one stakeholder. It is provided to model by relaxing the constraint set (3). Assumption (2) allows sawmills to harvest and transport from forest zones located in the Kruger tenure to mills. Modification in the matrix of flows permits such wood flows. Backhaul availability, terminals and a pellet mill are applied to model by their decision variable whether they are zero or not. It is worth mentioning that assumption (1) - (3) could be used directly if the stockholders accept collaboration. Hence, any scenario that includes these assumptions represents collaboration concept.

The matrix of the scenarios is provided in Table 3-1. Scenario (1) presents the current situation of the network where none of the aforementioned assumptions exists. The other scenarios, however, are current situations considering one or several assumptions. For instance, in scenario 18, we allow the optimization model to allocate a forest zone to different stakeholders, and to have terminal opening opportunity. The other scenarios are interpreted in the same way considering its active assumptions.

Table 3-1. Developed scenarios based on the five defined assumptions

Assumption* / scenario	1	2	3	4	5	Assumption / scenario	1	2	3	4	5
s_1	-**	-	-	-	-	s_9	-	-	-	√	-
s_2	√***	-	-	-	-	s_{10}	√	-	-	√	-
s_3	-	√	-	-	-	s_{11}	-	√	-	√	-
s_4	-	-	√	-	-	s_{12}	-	-	√	√	-
s_5	√	√	-	-	-	s_{13}	√	√	-	√	-
s_6	-	√	√	-	-	s_{14}	-	√	√	√	-
s_7	√	-	√	-	-	s_{15}	√	-	√	√	-
s_8	√	√	√	-	-	s_{16}	√	√	√	√	-
s_{17}	-	-	-	-	√	s_{25}	-	-	-	√	√
s_{18}	√	-	-	-	√	s_{26}	√	-	-	√	√
s_{19}	-	√	-	-	√	s_{27}	-	√	-	√	√
s_{20}	-	-	√	-	√	s_{28}	-	-	√	√	√
s_{21}	√	√	-	-	√	s_{29}	√	√	-	√	√
s_{22}	-	√	√	-	√	s_{30}	-	√	√	√	√
s_{23}	√	-	√	-	√	s_{31}	√	-	√	√	√
s_{24}	√	√	√	-	√	s_{32}	√	√	√	√	√

*Assumptions are as follows:
1) Allowable wood allocation in forest between all stakeholders; 2) accessibility of sawmills to Kruger tenure; 3) backhaul availability; 4) terminals opening; 5) biorefinery opening.
**Hyphen determines that assumption in the related scenario is inactive
***Check mark determines that assumption in the related scenario is active

3.4. Results

The model is implemented in the modeling language AMPL using CPLEX 12.0 as a solver. For all numerical tests, we have used a standard PC with a 2.6 GHz processor and 42.0 GB RAM. The size of each scenario, its solution time and its gap using CPLEX directly are presented in Table 3-2. The number of binary and linear variables as well as constraints is provided for each scenario. A restricted solution time of 1,800 seconds is considered for each problem. The gap determines the difference between best integer solution and best bound (from the LP relaxation) divided by the best bound. All problems were solvable with a maximum gap of 0.5%.

Table 3-2. Size of each scenario using CPLEX directly

scenario	binary variables	linear variables	constraints	solution time(s)	gap(%)
S_1	13,900	21,345	16,780	0.53	0.00
S_2	1,520	21,345	3,205	0.22	0.00
S_3	13,900	21,823	17,038	0.66	0.00
S_4	13,900	21,385	16,788	0.52	0.02
S_5	1,580	21,823	3,463	0.16	0.00
S_6	13,900	21,930	17,054	0.94	0.04
S_7	0	21,385	1,693	0.02	0.00
S_8	21	176,036	7,355	21.40	0.00
S_9	13,920	162,193	32,768	1800.08	0.13
S_{10}	20	162,193	7,273	11.67	0.00
S_{11}	13,920	162,811	32,846	1800.00	0.18
S_{12}	13,920	167,349	32,772	132.38	0.11
S_{13}	12,000	16,281	19,271	14.59	0.00
S_{14}	13,920	171,843	32,854	221.05	0.12
S_{15}	20	167,349	7,277	24.12	0.22
S_{16}	20	171,843	7,299	1711	0.17
S_{17}	13,901	31,410	21,822	1.4	0.00
S_{18}	1	13,410	6,227	0.69	0.00
S_{19}	13,901	32,028	22,106	1.36	0.79
S_{20}	13,901	31,450	21,830	1.17	0.00
S_{21}	2,101	32,028	8,531	1.39	0.00
S_{22}	13,901	32,108	22,122	1.33	0.17
S_{23}	1	31,450	6,235	1.48	0.00
S_{24}	1	32,108	6,447	0.64	0.02
S_{25}	13,921	166,246	33,318	1800.08	0.46
S_{26}	21	166,246	7,323	17.25	0.00
S_{27}	13,921	167,004	33,422	1801.11	0.16
S_{28}	13,921	171,402	33,322	78.62	0.08
S_{29}	12,521	167,004	19,847	17.04	0.00
S_{30}	13,921	176,036	33,430	834.93	0.05
S_{31}	21	171,402	7,327	35.04	0.00
S_{32}	21	176,036	7,355	22.22	0.00

For each scenario, we report on a set of key performance indicators (KPI). These KPIs, defined in Table 3-3, demonstrate how effectively each mill achieves the business objective and have been identified together with the stakeholders. They are reported for each stakeholder and for each scenario. KPIs RevInt and RevFin calculate respectively the revenue from selling Intermediate and final products at mill gates. KPIs 3 to 9 demonstrate strategic and tactical costs. The profit and total delivered product volume to each mill are calculated by KPIs TotalProfit and TotalIn, respectively. The KPI

Profit/In represents the profit per one m^3 of the proceeded supply. Finally, KPI GHG indicates the saving in GHG emissions using backhauling.

Table 3-3. Key performance indicators definition

Item	KPI	Description
1	RevFin	Revenue from selling products
2	RevInt	Revenue from selling products
3	FixCost	Fixed cost to open terminals or pellet mill
4	HvCost	Harvesting cost for each sort group
5	PurCost	Purchasing cost for each sort group
6	SortCost	Sorting cost for each sort group
7	OperCost	Operating cost for each sort group
8	TransCost	Transportation cost for each sort group
9	TotalProfit	Total profit (revenue – costs)
10	TotalIn	Total m^3 input to mills
11	Profit/In	Profit per m^3 of input products at each mill
12	GHG	Tonnes of GHG emissions reduction by backhaul transportation

Table 3-4 reports total revenue of selling products, fixed cost, tactical cost and profit in millions of CAD dollars. Moreover, it reports total volume incoming product in million cubic meters. The profit per one m^3 of incoming product as a key comparator of the scenarios is calculated in Profit/In column. The GHG column represents reduction of GHG emissions of all stakeholders. The model provides the detailed tactical information including the flow of products, the amount of sorted and operated product and the amount of backhauling for each stakeholder. It is worth mentioning that, tactical cost is the sum of harvesting, purchasing, transporting, sorting and operating costs.

As the table shows, in all of the scenarios, the optimization model supplies the stakeholders up to their maximum requirements, hence the total revenue is almost equal for all scenarios. The revenue of stakeholders will increase in the scenarios which open a pellet mill. For instance, the total revenue of scenarios s_1 and s_{18} has a difference of around \$6.7 million which is principally created by the opening of the pellet mill. On the other hand, the flow of products within the network will reduce in all of the scenarios compared to the base case and according to reduction in tactical costs. Harvesting cost primarily depends on two factors including the accessibility of sawmills to Kruger tenure and having a pellet mill. If the mill demands have not been satisfied by harvesting operation, they will purchase wood supply from other mills.

Table 3-4. The optimization result for each of the scenarios (revenue, costs and profit are in million CAD)

Scen	Total Revenue	FixCost	Tactical cost	TotalProfit	TotalIn	Profit/IN	GHG
s_1	197.32	0.00	129.02	68.30	1.45	47.09	-
s_2	196.78	0.00	128.34	68.44	1.44	47.43	-
s_3	195.36	0.00	126.71	68.64	1.45	47.29	-
s_4	194.55	0.00	122.16	72.39	1.43	50.66	745.6
s_5	189.23	0.00	117.12	72.11	1.26	57.46	-
s_6	193.86	0.00	117.56	76.30	1.43	53.39	731.2
s_7	194.52	0.00	122.00	76.38	1.43	50.74	750.3
s_8	191.04	0.00	114.92	76.12	1.31	57.95	498.3
s_9	199.28	0.50	130.26	69.02	1.53	45.24	-
s_{10}	195.67	0.50	123.75	71.92	1.42	50.55	-
s_{11}	198.36	0.50	129.20	69.16	1.53	45.18	-
s_{12}	194.55	0.00	122.16	72.39	1.43	50.66	745.6
s_{13}	192.32	0.50	119.60	72.72	1.32	55.09	-
s_{14}	193.86	0.00	117.56	76.30	1.43	53.39	731.2
s_{15}	195.68	0.50	122.68	59.26	1.17	50.71	474.7
s_{16}	190.97	0.00	114.86	76.12	1.31	57.95	498.3
s_{17}	197.54	0.00	129.24	68.30	1.45	47.09	-
s_{18}	203.99	1.00	132.71	71.28	1.45	49.28	-
s_{19}	195.36	0.00	126.72	68.65	1.45	47.36	-
s_{20}	194.55	0.00	122.16	72.39	1.43	50.66	745.6
s_{21}	189.29	0.00	117.18	72.11	1.26	57.46	-
s_{22}	194.06	0.00	117.76	76.30	1.43	53.39	731.2
s_{23}	194.52	0.00	122.00	76.38	1.43	50.74	750.3
s_{24}	190.95	0.00	114.83	76.12	1.31	57.95	498.3
s_{25}	199.28	0.50	130.26	68.87	1.54	45.24	-
s_{26}	195.79	0.50	123.87	71.92	1.42	50.55	-
s_{27}	198.18	0.50	129.01	69.17	1.53	45.35	-
s_{28}	194.55	0.00	122.16	72.39	1.43	50.66	745.6
s_{29}	192.46	0.50	119.74	144.89	1.32	55.09	-
s_{30}	193.92	0.00	117.63	76.30	1.43	53.40	731.2
s_{31}	195.68	0.50	122.68	60.14	1.44	50.71	474.7
s_{32}	191.04	0.00	114.92	76.12	1.31	57.95	498.3

As regards value creation, the model suggests the sorting opportunity for all scenarios to create higher value from the fibre. In all scenarios, the solutions supply stakeholders up to their maximum volume requirement; however different total profits are reported. This shows two key points: the first is, even in the base case scenario, the supply chain has the ability to provide secure fibre for all stakeholders; second, with the same input and more collaboration all stakeholders could generate more profit. Revenue, cost and profit for all scenarios are compared in Figures 3-5, 3-6 and 3-7, respectively.

Comparison of Profit/In for different scenarios in Figure 7 presents a potential saving of 23.06% for the entire supply chain which could be created only by collaboration between stakeholders.

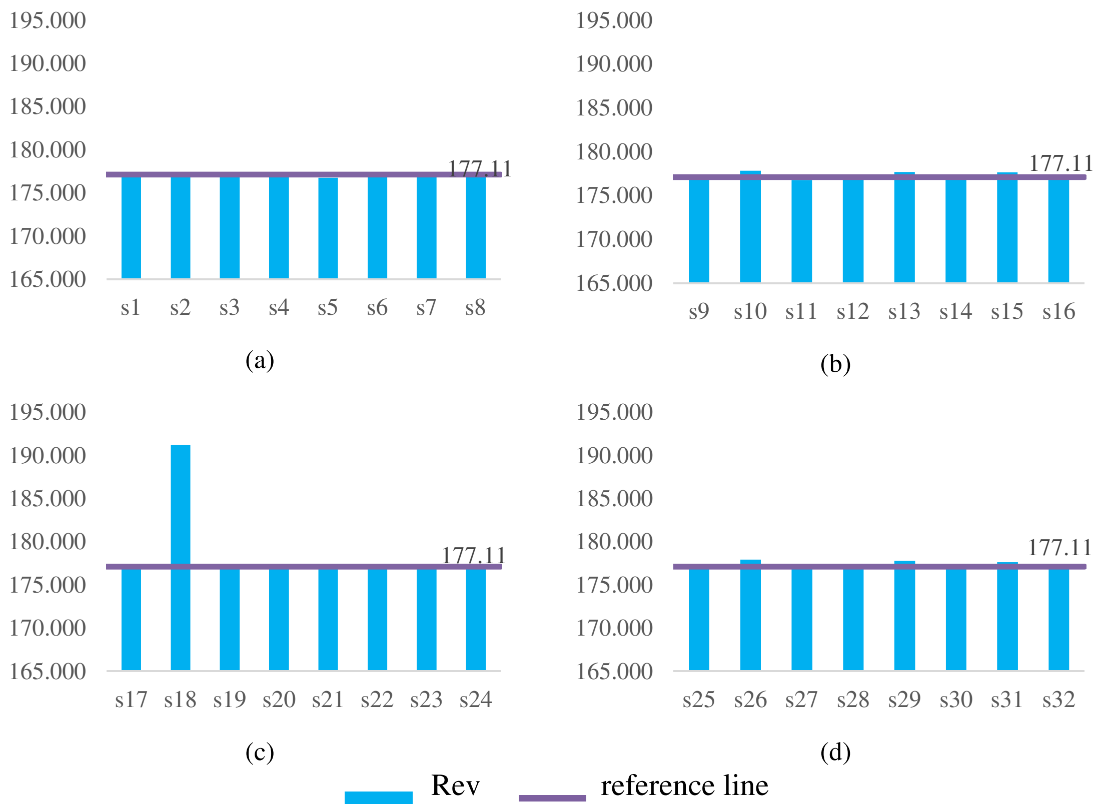


Figure 3-5. Sum of revenue for selling products in million CAD. The orange line in all figures is the total revenue for base case scenario. The scenarios are compared in four categories: (a) scenarios without terminal and pellet mill opening assumptions, (b) scenarios with terminal opening assumption, (c) scenarios with pellet mill opening assumption, and (d) scenarios with terminal and pellet mill opening assumptions.

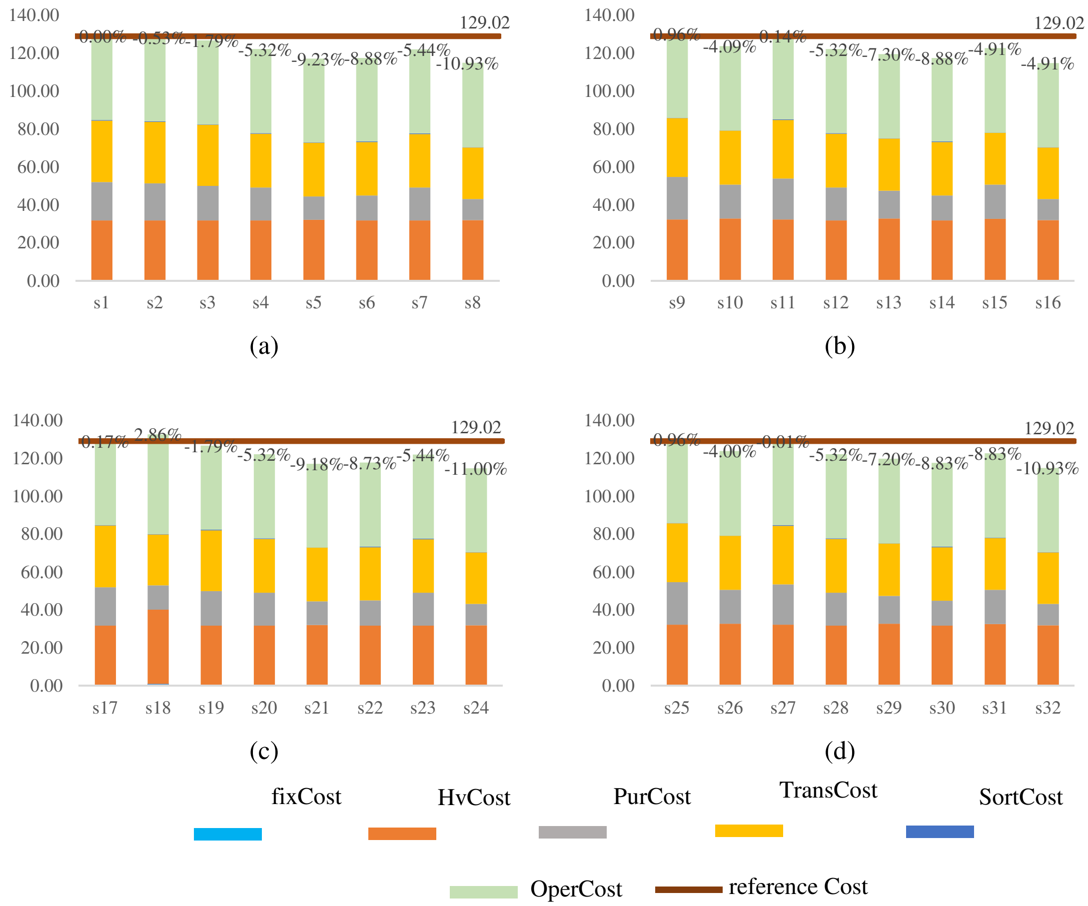


Figure 3-6: Total network cost for each scenario in million CAD. The brown line in all figures is total cost for the base case scenario. The scenarios are compared in four categories: (a) scenarios without terminal and pellet mill opening assumptions, (b) scenarios with terminal opening assumption, (c) scenarios with pellet mill opening assumption, and (d) scenarios with terminal and pellet mill opening assumptions. The percentage on top of all bars determines the difference between the scenario and the reference line.

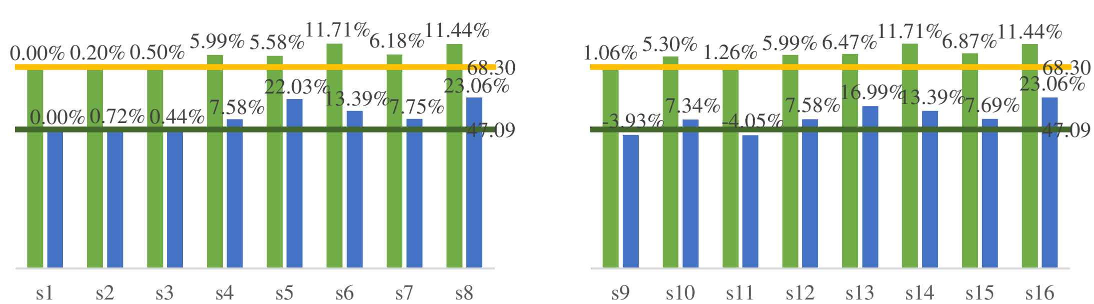


Figure 3-7: Total network profit and profit/m3 for each scenario. The orange and green lines in all figures are total profit and profit/m3 for base case scenario. The scenarios are compared in four categories: (a) scenarios without terminal and pellet mill opening assumptions, (b) scenarios with terminal opening assumption, (c) scenarios with pellet mill opening assumption, and (d) scenarios with terminal and pellet mill opening assumptions. The percentage on top of all bars determines the difference between the scenario and their corresponding reference line.

The overall localization decisions of the model are to open one terminal in the west of Newfoundland or the one in the east central region (Figure 3-8). The terminal in the West will facilitate the transportation to Corner Brook Pulp and Paper by their hauling fleets, and from that terminal to all stakeholders, the possibility of backhauling by other drivers will be provided. Moreover, in all scenarios with the possibility of wood exchange, all harvested pulp logs will be delivered directly to the terminal and then to Corner Brook Pulp and Paper. The terminal located in East is preferable if sawmills have accessibility to Kruger tenures. In this way, the decision supporting tool suggests harvesting the centre of Newfoundland and delivering to terminals in the centre, and then distributing the products. The pellet mill is a profitable decision when sawmills have access to Kruger tenure, otherwise the restriction on resources will prevent such investment. The location of selected terminals is also in accordance with the expectations of all stakeholders.

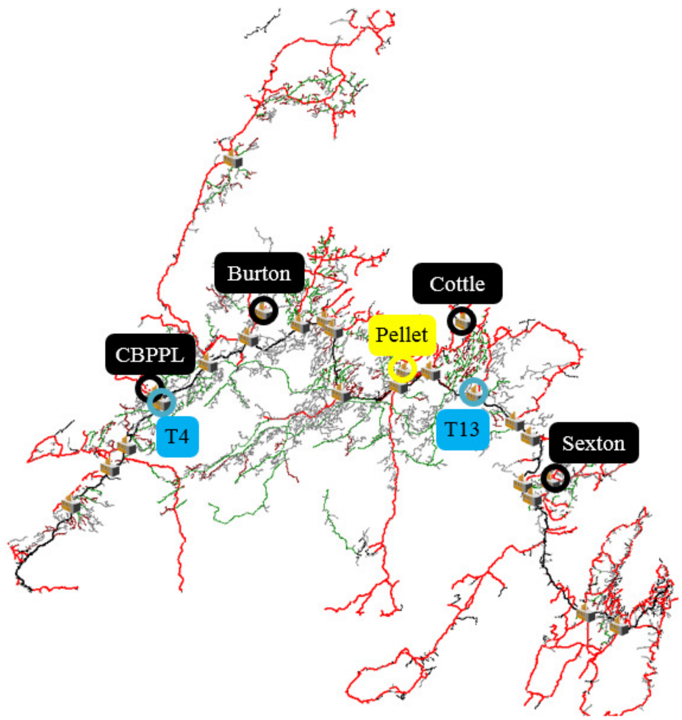


Figure 3-8: Selected facilities location in different scenarios (map is taken from FPInterface^{TM})

3.5. Concluding Remarks

We have developed an MIP model to design a forest biomass value chain with special consideration of fibre value creation. Our developed model covers important strategic and tactical decisions at the same time. The strategic decisions include locating new terminals and a pellet mill. The network flows, harvesting, purchasing, transporting and sorting costs are considered in the model to support a sustainable strategic decision. The backhauling transportation opportunity is considered to reduce cost and GHG emissions.

Our generic model was validated with a real case study in the context of the Newfoundland forest industry and has provided guidelines for this supply chain to progress. Two special conditions of the case study including truck hauling regulation and timber tenure holders have considerable effect on profitability of the industry. Moreover, the significant effect of collaboration on network profitability has been reported.

Our developed optimization model has the ability to consider a new bio-process in its modeling. However, a comprehensive market study is required to design a good product-process portfolio. A fact in such a new market is the uncertainty about availability of resources, performance of new processes and the market of new products. In this regard, uncertainty consideration in such areas could be very interesting to study and to compare with the current findings. Moreover in the new designed value chain the individual stakeholder saves differently, hence a study on sharing profit mechanisms could introduce an applicable future work.

3.6. Acknowledgments

The author would like to acknowledge FORAC research consortium (Université Laval) and NSERC Strategic Network on Value Chain Optimization for supporting this research. Moreover, special thanks to FPInnovations' Mr. Dave Lepage, and the Centre for Forest Science and Innovation Newfoundland's Mr. Bill Dawson, for providing data to validate our developed model. We also sincerely thank the co-operation of the stakeholders: Mr. David Chamberlain, Corner Brook Pulp and Paper Ltd; Mr. Fred Osmond, Burton's Cove Ltd; Mrs. Lorie Philpott, Cottle's Island Ltd; and Mr. Kevin Sexton and Mr. Neil Greening, Sexton Lumber Ltd.

3.7. References

Alam, M. B., Shahi, C. and R. Pulkki, 2014. Economic impact of enhanced forest inventory information and merchandizing yards in the forest product industry supply chain. *Socio-Economic Planning Sciences,* 48**,** 189-197.

Cambero, C., T. Sowlati, M. Marinescu and D. Röser, 2014. Strategic optimization of forest residues to bioenergy and biofuel supply chain. *International Journal of Energy Research, 39, 439-452*.

Carlgren, C. G., D. Carlsson and M. Rönnqvist, M. 2006. Log sorting in forest harvest areas integrated with transportation planning using backhauling. *Scandinavian Journal of Forest Research,* 21**,** 260-271.

Carlsson, D. and M. Rönnqvist, 2005. Supply chain management in forestry—case studies at Södra Cell AB. *European Journal of Operational Research,* 163**,** 589-616.

Carlsson, D. and M. Rönnqvist, 2007. Backhauling in forest transportation – models, methods and practical usage. *Canadian Journal of Forest Researh,* 37**,** 2612-2613.

D'amours, S., M. Rönnqvist and A. Weintraub, 2008. Using Operational Research for supply chain planning in the forest product industry. *INFOR: Information Systems and Operational Research,* 46**,** 47-64.

Dansereau, L. P., M. M. EL-Halwagi and P. R. Stuart, 2012. Value-Chain Planning in the Forest Biorefinery: Case Study Analyzing Manufacturing Flexibility. *Journal of Science and Technology for Forest Products and Processes,* 2**,** 60-69.

Dramm, J. R., R. Govettt, T. Bilek and G. L. JACKSON, 2004. *Log sort yard economics, planning, and feasibility,* Gen. Tech. Rep. FPL-GTR-146. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Ekşioğlu, S. D., A. Acharya, L. E. Leightley and S. Arora, 2009. Analyzing the design and management of biomass-to-biorefinery supply chain. *Computers & Industrial Engineering,* 57**,** 1342-1352.

Feng, Y., S. D'amours, M. Nourelfath and L. Lebel, 2010. Integrated Forest Biorefinery Supply Chain Network Design Using Mathematical Programming Approach. *In:* Stuart, P. R. & EL-Halwagi, M. M. (eds.) *Integrated Biorefineries: Design, Analysis, and Optimization.* CRC Press/Taylor & Francis.

Forsberg, M., Frisk, M. & Rönnqvist, M. 2005. FlowOpt - A Decision Support Tool for Strategic and Tactical Transportation Planning in Forestry. *International Journal of Forest Engineering,* 16, 101-114.

Frombo, F., Minciardi, R., Robba, M., Rosso, F. & Sacile, R. 2009. Planning woody biomass logistics for energy production: A strategic decision model. *Biomass and Bioenergy,* 33**,** 372-383.

Gunnarsson, H., Rönnqvist, M. & Lundgren, J. T. 2004. Supply chain modeling of forest fuel. *European Journal of Operational Research,* 158**,** 103-123.

Kim, J., M. J. Realff, J. H. Lee, C. Whittaker and L. Furtner, 2011. Design of biomass processing network for biofuel production using an MILP model. *Biomass and Bioenergy*, 35, 853-871.

Lakshmanan, T. R. and X. Han, 1997. *Factors underlying transportation CO2 emissions in the U.S.A.: A decomposition analysis*. Transportation Research Part D: Transport and Environment, 2, 1-15.

Lehoux, N., PH. Marier, S. D'amours, D. Ouellet and J. Beaulieu, 2012. The value creation network of Canadian wood fibre. *In:* Natural Resources of Canada (ed.). Canadian Forest Service Publications: CIRRELT report, 210 p.

Melendez Esquivel, J.A. 2015. Biomass procurement cost minimization for implementation of a retrofit biorefinery in a pulp and paper mill. P.hD. thesis, Department of Chemical Engineering, École Polytechnique de Montréal, Montréal, Québec, Canada.

Mockler, P. and J. Fairbairn, 2009. The Canadian Forest Sector: Past, Present, Future. *In:* Forestry, A. A. (ed.), Intern report of the standing senate comittee on agricalture and forestry.

Mockler, P. and F. Robichaud, 2011. the Canadian forest sector: a future based on innovation. The Canadian Forest Sector: a Future Based on Innovation. Ottawa: Queen's Printer of Canada.

Natural Resources of Canada (A). 2016. *Industry transformation* [Online]. Available from http://www.nrcan.gc.ca/forests/industry/overview/13311.

Natural Resources of Canada (B). 2016. *Statistical data* [Online]. Available from http://cfs.nrcan.gc.ca/statsprofile.

Palander, T. and J. Väätäinen, 2005. Impacts of interenterprise collaboration and backhauling on wood procurement in Finland. *Scandinavian Journal of Forest Research,* 20**,** 177-183.

Shabani, N., S. Akhtari, and T. Sowlati, 2013. Value chain optimization of forest biomass for bioenergy production: A review. Renewable and Sustainable Energy Reviews, 23, 299-311.

Sustainable Forest Managment. 2013. Www.sfmcanada.org/images/Publications/EN/NL_ info_Provinces_and_territories_EN.pdf.

Troncoso, J., S. D'amours, P. Flisberg, M. Rönnqvist and A. Weintraub, 2015. A mixed integer programming model to evaluate integrating strategies in the forest value chain — a case study in the Chilean forest industry. *Canadian Journal of Forest Research,* 45**,** 937-949.

Weintraub, A. and R. Epstein, 2005. The Supply Chain in the Forest Industry: Models and Linkages. *In:* Geunes, J., Pardalos, P. M. & Romeijn, H. E. (eds.) *Supply Chain Management: Models, Applications, and Research Directions.* Boston, MA: Springer US.

Chapter 3 Forest bioenergy network design under market uncertainty

This chapter is earmarked to the article entitled *" Forest bioenergy network design under market uncertainty"*. It has been submitted to the *Energy*. The figures and mathematical formulations have been revised to keep the coherence with the thesis.

RÉSUMÉ: L'industrie forestière se transforme pour favoriser le développement de nouveaux produits en utilisant la biomasse forestière. Cependant, l'instabilité du marché de tous les types de produits forestiers a des répercussions importantes sur l'approche de transformation de l'industrie. La transformation fluide dépend fortement de la stabilisation de l'état actuel du réseau. À cet égard, nous proposons un modèle d'optimisation stochastique en deux étapes pour évaluer la compétence d'ajouter de nouveaux assortiments incluant les terminaux et la bioénergie à la chaîne d'approvisionnement forestière existante, en tenant compte de l'incertitude de la demande et du prix des produits finaux. Le modèle évalue les processus optimaux de bioénergie ou de biocarburants parmi les potentiels. Une méthode de décomposition multicoupe est mise en œuvre pour fournir une conception de réseau rentable pour tout scénario futur. Enfin, le modèle et l'algorithme proposés sont démontrés par une étude de cas à Terre-Neuve, au Canada. Le résultat montre que la solution stochastique crée une valeur supérieure à celle déterministe. De plus, les paramètres de risque, y compris l'indice de variabilité et le risque de baisse, sont quantifiés afin de fournir une vision claire aux décideurs averses au risque.

MOTS-CLÉS : bioénergie, biocarburant, biomasse forestière, conception de la chaîne de valeur, optimisation stochastique, gestion des risques

ABSTRACT: The forest industry is transforming itself in order to foster new product development by utilizing forest biomass. However, market instability of all types of forestry products has significant impacts on the transformation approach of the industry. Smooth transformation highly depends on stabilizing the current state of the network. In this regard, we propose a two-stage stochastic optimization model to evaluate the proficiency of adding new assortments including terminals and bioenergy to existing forest supply chain, taking into account uncertainty of demand and price of final products. The model assesses the optimal bioenergy or biofuel processes among the potentials. A multicut L-shaped decomposition method is implemented to provide a profitable network design for any future scenario. Finally, the proposed model and algorithm are demonstrated through a case study in Newfoundland, Canada. The result shows that the stochastic solution creates a higher value compared to deterministic one. Moreover, risk metrics including variability index and downside risk are quantified to provide a clear vision for risk-averse decision makers.

Keywords: bioenergy, biofuel, forest biomass, value chain design, stochastic optimization, risk management

4.1. Introduction

The forest supply chain, especially the Canadian one, is faced with a serious challenge due to reduction in its commodities demand leading to very low interest in investment in this industry. In such situation, forestry biomass creates many opportunities for the supply chain. There are very good alternatives available for the production of several renewable energies and products that could significantly protect the environment from global warming. In this regard, forest supply chain has started a smooth transformation of its industry in order to utilize new feedstocks in new technologies and enter new markets. However, uncertainty about the availability of biomass resources, their quality and characteristics, the maturity of new technologies and new markets bring many difficulties to this transformation. Technology and product selection are strategic level decisions that need to be supported with tactical level decisions and risk consideration. Hence, we study integrated strategic-tactical forest bioenergy supply chain under uncertainty of demand and price of final products while some risk metrics have been considered. Forest biomass including wood chips, sawdust and forest residues are very good substitutes for fossil fuel in terms of carbon emissions reduction (Hal 2002; Ahtikoski et al. 2008 and Saidur et al. 2011). The study of Gunnarsson et al. (2004) was among the first researches on supply chain modeling of forest fuels. They determined the best location for preparing forest biomass for transport to heating plants for energy production. Afterwards, D'Amours et al. (2008) demonstrated an overall forest supply chain taking into account new facilities to produce energy including electricity, heat and pellets. Alam et al. (2012) developed a woody biomass assessment tool for bioenergy production which increases 0.6% productivity of harvest area in northwestern Ontario, Canada. Flisberg et al. (2012) developed a decision support system for allocating forestry biomass to biofuels. Optimal planning of biofuel supply chain to produce ethanol, biodiesel, and hydrogen considering environmental aspects is studied in a multi-objective optimization model of Santibañez-Aguilar et al. (2011). In a comprehensive review Shabani et al. (2013) concluded that to maximize the profit of forest power plant supply chain, key factors are quality and quantity of biomass, transportation cost, and technology.

Supply chain design considering biofuel process and transportation and operation cost has been studied in Kim et al. (2011b). They determined the optimal location for biofuel process to satisfy all customer demand. Ekşioğlu et al. (2009) analyzed and managed the design of ethanol supply chain from forestry resources. They identified the number, capacity and location of biofuel considering procurement and transportation decisions. The integration of biofuel plant with an existing bioenergy considering biomass availability, transportation cost and local heating price is investigated in Leduc et al. (2010). Cambero et al. (2015) studied strategic optimization of integrated bioenergy and biofuel in forest industry. Their optimal solution provided the facility location and technology assessment for new plants. Abasian et al. (2017) developed an integrated strategic tactical model considering different new types of assortments including pellet mills and terminals. They proposed several improvement actions for the entire supply chain including optimal backhauling routes, possible collaborating actions as well as optimal location for assortments.

Network design problems are often highly subjected to uncertain parameters including, resource availability and characterization, process performance and market. However the complexity of considering uncertainty in such problems reduces the contribution of researchers in this field. Kim et al. (2011b) considered uncertainty by performing sensitivity analysis. They developed a general optimization model to select biomass supply locations, candidate sites and capacities for biofuel plants and the logistics of forest biomass. Meanwhile they did sensitivity analysis to identify the most effective parameters on the overall economics. They extended their work using stochastic optimization to tackle demand uncertainty of biofuels in biomass value chain Kim et al. (2011a).

Biomass value chain planning in tactical level considering uncertainty has been investigated in a few studies (Svensson et al. 2011a; Chen et al. 2012 and Tay et al. 2013). Svensson et al. (2011b), for instance, investigated the transformation of pulp and paper making process to biofuels process considering uncertain energy market. In forestry, Shabani et al. (2014) studied the tactical planning of forest biomass value chain under supply uncertainty. Moreover, they have optimized risk metrics to reduce solution variability. Uncertainty in designing biofuel supply chain has been reviewed by Awudu et al. (2012). Finally, for a comprehensive survey of forest biomass value chain optimization models in deterministic and stochastic contexts, readers are referred to Shabani et al. (2013).

Standard stochastic solution neglects the variability over different solutions. Indeed, its solution is a risk neutral. However, supply chain planning is concerned with involved risks especially when a large investment must be made to change the current configuration of such supply chain. Risk should be controlled based on decision makers' preference. Risk metrics comprising variance, upper partial mean, variability index, probabilistic financial risk, downside risk, conditional value at risk and etc. can manage the variability from different points of view. Kazemzadeh et al. (2013) studied stochastic biofuel supply chain design optimizing conditional value at risk (CVaR) to control demand shortage. Gebreslassise et al. (2012), proposed an optimal design and planning of hydrocarbon biorefinery supply chain under supply and demand uncertainty. Their developed optimization model was a multi-objective optimization framework considering financial risk metrics. Their major biomass resources were agricultural residues, energy crops and wood residues. Awudu et al. (2012) considered the downside risk and variability index for a tactical planning of forest bioenergy supply chain.

We believe forest bioenergy value chain design under demand and price uncertainty considering the financial risk metrics has not been studied before. We have supported our network design decisions with tactical decisions in an integrated form. We locate value-adding facilities including bioenergies and sorting yards and assign technology and capacity to them in way that the design will be optimal on average against any fluctuation in the market. Afterwards, resources will be allocated to existing and new facilities and the logistics planning of supply chain considering transportation, sorting and operating will be taken as the recourse actions while the uncertainties will be revealed. The general problem is motivated by a specific case of the forest industry in the province of Newfoundland and Labrador, Canada. We propose a two-stage stochastic optimization model to investigate the aforementioned problem. To manage investment risk on value chain design, we have considered downside risk and variability index. All required information of the supply chain has been collected from stakeholders in the province and FPInnovations, a Canadian non-profit organization in forestry research. Moreover, some information about new process has been collected from CamnetEnergy (Natural Resources of Canada). The contributions of the paper are the proposed model for biomass network design under uncertainty, the solution methodology, the proposed risk management models, the considered large case study and analyzing the result in a comprehensive way that demonstrates the optimal decision in different conditions.

The outline of the paper is as follows: Section 2 gives the problem description. Then the mathematical models and solution methodologies are presented in Section 3. Section 4 contains the detailed case study description. Section 5 reports the results and explanations based on a set of designed scenarios. Finally, Section 6 provides some concluding remarks.

4.2. Problem statement

We have considered a forest supply chain including five entities described below:

- Forest: the supplier of the supply chain with allowable annual cut for the next 5 years
- Pulp and paper mill: the producers of pulp and paper with possibility of new process extension
- Sawmills: lumber and wood chips producer
- Bioenergy: a set of potential locations, processes and capacities to produce bioenergy and biofuel
- Terminals: a set of potential locations for collecting and sorting the supply.

Figure 4-1 displays the overall structure of the network. Our goal is to develop an optimization model that evaluates the proficiency of having new bioenergy plants and terminals, taking into account uncertainty on the market of all final products. The model proposes a new network design with detailed logistic planning for assumed future scenarios.

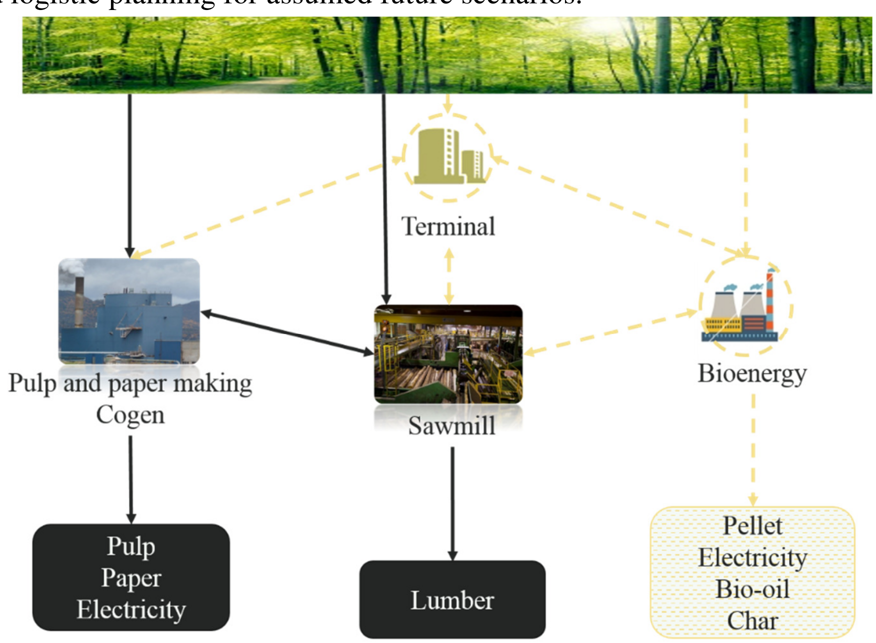


Figure 4-1: The forest network structure. Dashed lines demonstrate the potential location and flows.

To develop the stochastic model, first we need a deterministic version of such model. We use the model in Abasian et al. (2017) that considered forest bioenergy network design. Information related to different potential bioenergy processes as well as scenario development based on demand and price uncertainty need to be added to the model. The decisions in the new stochastic model are taken in two phases of strategic and tactical levels. That's why we called the stochastic model two-stage model. Since the two-stage optimization model should be solvable for large case studies we have utilized benders decomposition with some accelerating cuts. Afterwards we have developed multi-objective stochastic optimization considering risk metrics. The solution has been evaluated to prove its efficiency in any unforeseen future.

4.3. Mathematical model and solution methodology

We propose a stochastic optimization model for our forest bioenergy network design problem. The following will present the exact formulation of the model including sets and parameters definition, decision variables, objective function and constraints.

Defined and supporting sets for the developed model are described in the following. The specific set for the stochastic version of model is set of scenarios.

U	set of scenarios
P^R	set of raw and intermediate products
P^F	set of final products
P	set of all product types $P = P^R \cup P^F$
S	set of sort groups
F^P	set of piles
F^C	set of species
D	set of districts
Z	set of zones
O	set of tenure holders
L^T	set of potential terminal locations
L^E	set of potential biorefinery locations
M^P	set of existing manufacturing plants
N	set of all network nodes $N = Z \cup M^P \cup L^T \cup L^E$
R^i	set of existing and candidate processes for mill i
K^r	set of existing and candidate capacities for process r
H	set of hauling type
L^B	set of backhaul routes

Here are some comments on set of sort groups; we define three sort groups comprising preliminary, medial and complete sorting. Preliminary sorting classifies the resources based on the wood species. The medial creates groups of resources with similar wood species and utilization i.e. whether they are pulpwood, sawlog or energy wood. Finally, complete sorting categorizes the resources with same wood species, utilization and dimension. The model allows sorting at different places to different groups. Regarding set H, it is worth mentioning that we classify different types of transportation in this set. It includes the transportation with different regulations.

Supporting sets:

I_{izo} set of forest areas indicated by district i, zone z and tenure holder o.

H_{ojh} set of hauling methods for woods belonging to o with truck type h to mill j.

P_{rj}^{R} set of all processes r at mill j.

$P_{pr}^{\mathrm{R}+}$ set of input products p to process r.

$P_{pr}^{\mathrm{R}-}$ set of output products p from process r.

W_{lf}^{FS} set of sorted pile f created from sorting pile l.

E_{foj}^{FF} flow of the pile f from forest tenure o to mill j.

E_{foij}^{FM} flow of the pile f of tenure holder o from mills i to j.

The parameters used to describe harvest areas, costs, values, production at mills and capacities are given below.

k_{izop} annual allowable cut of product p at forest block indicated by $(izo) \in I_{izo}$.

a_{fl}^{FS} proportion of sorted pile f at pile l.

f_i^{o} fixed cost to open new facility i.

f_i^{c} fixed cost to close an existing facility i.

v_{pju}^{F} unit selling value of final product p at the gate of mill j for scenario u.

c_s^{I} unit harvesting cost for each sort group s.

c_{sj}^{S} unit sorting cost to group s at mill j.

c_{pr}^{R} unit processing cost of product p at the process r.

c_{izoj}^{HI} unit transportation cost of any product from forest area indicated $(izo) \in I_{izo}$ to mill j.

c_{ijh}^{HM} unit transportation cost of any product between mill i and j by truck type h.

c_{lh}^{ML} unit transportation cost for backhaul route l by truck type h.

a_{lfsoj}^{ML} 1; if backhaul trip l picks up pile f with sort group s and owner o at supply point j.

b_{lfsoj}^{ML} 1; if backhaul trip l delivers pile f with sort group s and owner o to demand point j.

u_{prq}^{R} yield of process r in producing product q while it is fed by product p.

$k_r^{\mathrm{R}+}$ max capacity of process r.

$k_r^{\mathrm{R}-}$ min capacity of process r.

d^{F}_{pju} demand for final product p at the gate of mill j for scenario u .

k^{H}_{jh} transportation capacity of truck type h for mill j.

p_u probability of scenario u .

M a large value.

To avoid nonlinearity in modeling we assume the proportion of available products in each pile (a^{FS}_{fl}) is known. This value is estimated by average of proportion of available forest resources.

The decision variables used in the models are classified in two categories: first-stage decisions and second-stage decisions. The former is not dependent on scenarios while the latter are tactical decisions for each scenario (depend on scenarios).

First-stage decision variables are:

y^{E}_{i} 1; if bioenergy i is open, and 0 otherwise.

y^{T}_{i} 1; if terminal i is open, and 0 otherwise.

y^{MP}_{i} 1; if existing manufacturing plant i is continuing to work, and 0 otherwise.

y^{R}_{irk} 1; if process r with capacity k assigns to mill i , and 0 otherwise.

Second-stage decision variables are:

x^{A}_{sizoju} percentage of sort group s at forest block indicated by $(izo)\in I_{izo}$ that is assigned to mill j for scenario u

$x^{\mathrm{FF}}_{fscizojhu}$ flow of the pile f with a sort group s and species c from forest block indicated by $(izo)\in I_{izo}$ to mill j by truck type h for scenario u .

$x^{\mathrm{MF}}_{fscoijhu}$ flow of pile f with sort group s and species c belong to owner o between mills i and j by truck type h for scenario u .

x^{ML}_{lhu} backhaul flow l done by truck type h for scenario u .

x^{E}_{jpu} volume of final product p produced at mill j for scenario u .

x^{S}_{fsoju} sorting amount of pile f with a sort group s and wood owner o at mill j for scenario u .

x^{R}_{psorju} volume of inputted product p with sorting group s and wood owner o to process r at mill j for scenario u .

Tactical decision variables are anticipation variables that are used to evaluate and support strategic decisions. However, they will be determined in short-term tactical and operational models while the uncertainties have been revealed. On the other hand, the available supply data is based on long-term forest management plans models that essentially describe the available volume per year (annual allowable cut). As these numbers are the same (volume is constant over time); it is possible to use only one time period to make strategic decisions. Hence, we do not consider time horizon dimension for the decision variables in the current model.

The objective function is to maximize the average profit (revenue from sales minus costs) for all scenarios (4-1). The sales value of final products is the revenue of the network. The included costs in the model are harvesting, transportation, sorting, operating, and fixed costs to close existing mills or to open new terminals and bioenergy. All revenues and costs except fixed costs vary per scenario and the model aims to maximize the expected value of scenarios.

$$\begin{aligned} Max\,Z: & \sum_{u\in \mathrm{U}} p_u \Big(\sum_{p\in \mathrm{P^F}} \sum_{j\in \mathrm{N}} (v^{\mathrm{F}}_{pju} x^{\mathrm{E}}_{jpu}) - \sum_{s\in \mathrm{S}} \sum_{(izo)\in I_{izo}} \sum_{p\in \mathrm{P^R}} \sum_{j\in \mathrm{N}} (c^{\mathrm{I}}_{s} k_{izop} x^{\mathrm{A}}_{izoju}) - \\ & \sum_{(izo)\in I_{izo}} \sum_{(foj)\in E^{\mathrm{FF}}_{foj}} \sum_{s\in \mathrm{S}} \sum_{c\in \mathrm{F^C}} \sum_{h\in \mathrm{H}} (c^{\mathrm{HI}}_{izoj} x^{FF}_{fscizojhu}) - \sum_{(foij)\in E^{\mathrm{FM}}_{foij}} \sum_{s\in \mathrm{S}} \sum_{c\in \mathrm{F^C}} \sum_{h\in \mathrm{H}} (c^{\mathrm{HM}}_{ijh} x^{\mathrm{MF}}_{fscoijhu}) - \\ & \sum_{l\in L^{\mathrm{B}}} \sum_{h\in \mathrm{H}} (c^{\mathrm{ML}}_{lh} x^{\mathrm{ML}}_{lhu}) - \sum_{f\in \mathrm{F^p}} \sum_{s\in \mathrm{S}} \sum_{o\in \mathrm{O}} \sum_{j\in \mathrm{N}} (c^{\mathrm{S}}_{sj} x^{\mathrm{S}}_{fsoju}) - \sum_{(pr)\in P^{\mathrm{R+}}_{pr}} \sum_{s\in \mathrm{S}} \sum_{o\in \mathrm{O}} \sum_{(rj)\in P^{\mathrm{R}}_{rj}} (c^{\mathrm{F}}_{pr} x^{\mathrm{R}}_{psorju}) \Big) - \\ & \sum_{i\in MP} f^{\mathrm{c}}_i (1 - y^{\mathrm{MP}}_i) - \sum_{i\in L^T} f^{\mathrm{o}}_i y^{\mathrm{T}}_i - \sum_{i\in L^E} f^{\mathrm{o}}_i y^{\mathrm{E}}_i \end{aligned} \qquad (4\text{-}1)$$

The model is subjected to a set of network design constraints, adjacency constraints, capacity constraints, fiber delivery constraints, balance constraints, flow constraints and demand constraints.

Network design constraints:

The first set of constraints (4-2) assesses maximum one potential process with specific capacity to the open bioenergy. The same constraint is considered for existing mills.

$$\sum_{r\in R^i} y^{\mathrm{R}}_{irk} \le y^E_i \qquad \forall (ri)\in P^R_{ri}, k\in \mathrm{K}^{\mathrm{r}} \qquad (4\text{-}2)$$

Adjacency constraint:

Adjacency constraint restricts the model to harvest two nearby blocks (4-3). This is a specific restriction for the case study.

$$\sum_{j\in \mathrm{N}} x^{\mathrm{A}}_{izoju} \le 1 - \sum_{j\in \mathrm{N}} \sum_{z'\in \{z-1, z+1\}} x^{\mathrm{A}}_{iz'oju} \qquad \forall\, i\in \mathrm{D}, o\in \mathrm{O}, u\in \mathrm{U} \qquad (4\text{-}3)$$

Capacity constraints:

Harvest capacity constraints (4-4) assure that flow of specific sort group of resources from any forest block to any mill is less than available capacity.

$$\sum_{(foj)\in E^{\mathrm{FF}}_{foj}} \sum_{c\in \mathrm{F^C}} \sum_{z|(izo)\in I_{izo}} x^{\mathrm{FF}}_{fscizojhu} \le \sum_{z|(izo)\in I_{izo}} k_{izof} x^{\mathrm{A}}_{izoju} \qquad \begin{aligned} &\forall i\in \mathrm{D}, o\in \mathrm{O}, \\ &s\in \mathrm{S}, f\in \mathrm{P}, u\in \mathrm{U} \end{aligned} \qquad (4\text{-}4)$$

Constraint set (4-5) considers the restricted capacity of transportation of all transported products to or from a mill.

$$\begin{aligned} & \sum_{(foj)\in E^{\mathrm{FF}}_{foj}} \sum_{s\in \mathrm{S}} \sum_{c\in \mathrm{F^C}} \sum_{(izo)\in I_{izo}} x^{\mathrm{FF}}_{fscizojhu} + \sum_{(foij)\in E^{\mathrm{MF}}_{foij}} \sum_{s\in \mathrm{S}} \sum_{c\in \mathrm{F^C}} x^{\mathrm{MF}}_{fscoijhu} + \sum_{l\in L^{\mathrm{B}}} \sum_{(foij)\in E^{\mathrm{MF}}_{foij}} \sum_{s\in \mathrm{S}} b^{\mathrm{ML}}_{lfsoj} x^{\mathrm{ML}}_{lhu} + \\ & \sum_{s\in \mathrm{S}} \sum_{i\in \mathrm{N}} \sum_{f\in \mathrm{P^F}} \sum_{(foji)\in E^{\mathrm{FM}}_{foji}} \sum_{c\in \mathrm{C}} x^{\mathrm{MF}}_{fscojihu} + \sum_{l\in L^{\mathrm{B}}} \sum_{i\in \mathrm{N}} \sum_{(foji)\in E^{\mathrm{MF}}_{foji}} \sum_{s\in \mathrm{S}} a^{\mathrm{ML}}_{lfsoj} x^{\mathrm{ML}}_{lhu} \le k^{\mathrm{H}}_{hj} \end{aligned} \qquad \begin{aligned} &\forall\, j\in \mathrm{N}, h\in \mathrm{H}, \\ &u\in \mathrm{U} \end{aligned} \qquad (4\text{-}5)$$

Each process has a minimum and maximum production range capacity (constraint (4-6)). For the bioenergy plant, this constraint depends on their existence in our network structure (constraint (4-7)).

$$k_r^{R+} \leq \sum_{(fr)\in P_{fr}^{R+}} \sum_{s\in S} \sum_{o\in O} x_{fsorj}^{R} \leq k_r^{R-} \qquad \forall (rj)\in P_{rj}^{R}, u\in U \qquad (4\text{-}6)$$

$$k_r^{R+} y_j^{E} \leq \sum_{f\in F^{P} | (fr)\in P_{fr}^{R+}} \sum_{s\in S} \sum_{o\in O} x_{fsojr}^{R} \leq k_r^{R+} y_j^{E} \qquad \forall r\in R, j\in L^{E} | (rj)\in P_{rj}^{R}, u\in U \qquad (4\text{-}7)$$

Flow constraints

The flow of wood in the network will start from the forest; therefore, all harvested resources should be directly forwarded from the forest to mills (constraint set (4-8)).

$$\sum_{p\in P^{R}} k_{izop} x_{izoju}^{A} - \sum_{(foj)\in E_{foj}^{FF}} \sum_{c\in F^{C}} \sum_{(ojh)\in H_{ojh}} x_{fscizojhu}^{FF} = 0 \qquad \forall (izo)\in I_{izo}, s\in S, u\in U \qquad (4\text{-}8)$$

Moreover, constraint set (4-9) permits all the decision variables related to the biorefinery to have the value 1 if the facilities are open. The same constraint exists for terminals and existing mills.

$$\begin{aligned}
&\sum_{(foj)\in E_{foj}^{FF}} \sum_{(izo)\in I_{izo}} \sum_{s\in S} \sum_{c\in F^{C}} \sum_{(ojh)\in H_{ojh}} x_{fscizojhu}^{FF} + \sum_{(foij)\in E_{foij}^{FM}} \sum_{s\in S} \sum_{c\in F^{C}} \sum_{(ojh)\in H_{ojh}} x_{fscoijhu}^{MF} + \\
&\sum_{l\in L^{B}} \sum_{(foij)\in E_{foij}^{MF}} \sum_{s\in S} \sum_{h\in H} b_{lfsoj}^{ML} x_{lhu}^{ML} + \sum_{(lf)\in W_{lf}^{FS}} \sum_{s\in S} \sum_{o\in O} (a_{fl}^{FS} x_{jlsou}^{S}) + \qquad \forall j\in l^{E}, u\in U \qquad (4\text{-}9) \\
&\sum_{(rj)\in P_{rj}^{R}} \sum_{(fr)\in P_{fr}^{R-}} \sum_{(pr)\in P_{pr}^{R+}} \sum_{s\in S} \sum_{o\in O} (u_{prf}^{R} x_{psorju}^{R}) + \sum_{(foji)\in E_{foji}^{FM}} \sum_{s\in S} \sum_{c\in C} \sum_{(oih)\in H_{oih}} x_{fscojihu}^{MF} + \\
&\sum_{l\in L^{B}} \sum_{(foji)\in E_{foji}^{MF}} \sum_{s\in S} \sum_{h\in H} a_{lfsoj}^{ML} x_{lhu}^{ML} + \sum_{f\in F^{P}} \sum_{s\in S} \sum_{o\in O} x_{jfsou}^{S} + \sum_{(pr)\in P_{pr}^{R+}} \sum_{s\in S} \sum_{(rj)\in P_{rj}^{R}} \sum_{o\in O} x_{psorju}^{R} \leq M y_j^{E}
\end{aligned}$$

Balance constraints:

The balance constraints are defined to assure the equilibrium of inputs and outputs of each mill for different sorting piles. Constraint set (4-10) assures the balance of raw material and intermediate products in the format of different piles at mills. The input flow can be a flow from forest or mills (direct or backhaul), or the output of a sorting process or a process where we consider balance constraint for the intermediate product.

$$\begin{aligned}
&\sum_{(foj)\in E_{foj}^{FF}} \sum_{c\in C} \sum_{(izo)\in I_{izo}} \sum_{(ojh)\in H_{ojh}} x_{fscizojhu}^{FF} + \sum_{(foij)\in E_{foij}^{FM}} \sum_{c\in C} \sum_{(ojh)\in H_{ojh}} x_{fscoijhu}^{MF} + \\
&\sum_{l\in L^{B}} \sum_{(foij)\in E_{ofj}^{FF}} \sum_{h\in H} b_{lfsoj}^{ML} x_{lhu}^{ML} + \sum_{(lf)\in W_{lf}^{FS}} \sum_{o\in O} (a_{fl}^{FS} x_{jlsou}^{S}) + \qquad \forall j\in N, f\in F^{P}, \\
&\sum_{(pr)\in P_{pr}^{R+} \& (fr)\in P_{fr}^{R-}} \sum_{o\in O} \sum_{(rj)\in P_{rj}^{R}} (u_{prf}^{R} x_{psorju}^{R}) - \sum_{(foji)\in E_{foji}^{MF}} \sum_{c\in C} \sum_{(oih)\in H_{oih}} x_{fscojihu}^{MF} - \qquad s\in S, u\in U \qquad (4\text{-}10) \\
&\sum_{l\in L^{B}} \sum_{(foji)\in E_{foji}^{MF}} \sum_{h\in H} a_{lfsoi}^{ML} x_{lhu}^{ML} - \sum_{o\in O} x_{jfsou}^{S} - \sum_{(fr)\in P_{fr}^{R+}} \sum_{o\in O} \sum_{(rj)\in P_{rj}^{R}} x_{fsorju}^{R} = 0
\end{aligned}$$

The balance constraint for final product at mill is formulated in constraint sets (4-11).

$$\sum_{(fr)\in P_{fr}^{R+} \& (pr)\in P_{pr}^{R-}} \sum_{(jr)\in P_{jr}^{R}} \sum_{s\in S} \sum_{o\in O} (u_{frp}^{R} x_{fsojru}^{R}) - x_{jpu}^{E} = 0 \qquad \forall j\in N, p\in P^{F}, u\in U \qquad (4\text{-}11)$$

Demand constraints

The constraint set (4-12) assures that demand of final products in each scenario should be satisfied.

$$x_{jpu}^{E} - d_{pju}^{F} y_{j}^{E} = 0 \qquad \forall j\in N, p\in P^{F}, (jr)\in P_{jr}^{R}, (pr)\in P_{pr}^{R-}, u\in U \qquad (4\text{-}12)$$

Variable definition constraints

Finally, variables are defined in constraint sets (4-13) and (4-14).

$$y_i^{E}, y_i^{T}, y_i^{MP} \in \{0,1\} \qquad (4\text{-}13)$$

$$x_{fscizojhu}^{FF}, x_{fscoijhu}^{MF}, x_{lhu}^{ML}, x_{jpu}^{E}, x_{jfsou}^{S}, x_{fsorju}^{R} \geq 0, 0 \leq x_{izoju}^{A} \leq 1 \qquad (4\text{-}14)$$

4.3.1. Solution methodology

If the behavior of random parameters during time planning is stationary, then two-stage stochastic optimization with recourse action could be implied as decision process. In such planning, strategic decisions (first-stage decisions) are made in the first stage, followed by tactical decisions (second-stage decisions). First-stage decisions are here-and-now type of decisions that consider all upcoming scenarios with their probabilities. Second-stage decisions are recourse actions that will be revealed once the uncertain parameters have been revealed. They are decisions related to network flows, sorting, transportation and operating. First and second stages are called master and sub problems, respectively. To facilitate explanation of two-stage model, we have presented a general formulation (4-15) and (4-16) as first and second models respectively.

$$\underset{y\in\{0,1\}}{Max}\, Z : \sum_{u\in U} p_u F_u - fy \qquad (4\text{-}15)$$

Where F_u is:

$$\begin{aligned} &\underset{u\in U, x\in \mathbb{R}^{+}}{Max}\, F_u = v_u x_u - c^{T} x_u \\ &\quad s.t: \\ &\quad Ax_u - ky \leq b \\ &\quad Tx_u \leq h_u \end{aligned} \qquad (4\text{-}16)$$

where y and x_u are first and second-stage decision variables, respectively. Since the recourse function is convex (Laport and Louveaux 1993), the formulation of (4-15) could be written as formulation (4-17):

$$\begin{aligned} &\underset{y\in\{0,1\}}{Max}\, Z = fy + \theta \\ &\quad s.t: \\ &\quad \theta \leq \sum_{u\in U} p_u F_u \\ &\quad \theta \geq 0 \end{aligned} \qquad (4\text{-}17)$$

To accelerate the solving time of large-scale two-stage stochastic optimization models, decomposition methods including L-shaped method are useful methodologies (Laport and Louveaux 1993; Tang and Zhao 2003). The general idea is smoothly converging to optimal solution by adding feasibility or optimality cuts to the master problem. The methodology commences with solving the master problem. In next iteration, considering first-stage decision variables, sub problems should find the optimal solution for each scenario. However, two different cases may occur for sub problems; they have either feasible solutions or at least one of them encounters infeasibility. In the first case, the expected value of dual of sub problem's objective function will be added as optimality cut to the master problem. In the second case, the infeasibility array multiplied by dual of sub problem's objective function will be added as a feasibility cut to the master problems in order to prevent this infeasibility in the next iterations. Afterward, the process will start over again until first-stage solution doesn't change (Rei et al. 2009). The following steps explain the structure of such methodology. In order to accelerate converging process we have relaxed binary restriction of master problem and solve the problem following L-shaped method. Afterward, we have saved all optimality cuts in the master problem and solve the problem again considering integrality (Rei et al. 2009).

Step 0- Initializing: Set $\theta'_u = -\infty$, where θ'_u is the objective value of each scenario u .

Step 1- solving master problem Z and calculate y^* and θ^* (4-18):

$$
\begin{aligned}
& Max\, Z = \theta - fy \\
& \quad s.t: \\
& \quad \theta \leq \sum_u p_u \theta'_u
\end{aligned}
\tag{4-18}
$$

Where f is fixed cost for the network design decisions displayed by y , and p_u is probability of each scenario.

Step 2- solving sub problem per scenarios and calculate x_u^* (4-19):

$$
\begin{aligned}
& Max\, F(\text{u}) = v_u^F x_u - c^T x_u \\
& \quad st. \\
& \quad Ax_u - ky \leq b_u \quad (\lambda_{1u}) \\
& \quad Tx_u \leq h_u \qquad (\lambda_{2u})
\end{aligned}
\tag{4-19}
$$

Where x_u is decision variable of second stage for each scenario. λ_{1u} and λ_{2u} are dual variables of the constraints in optimality condition. If sub problems are feasible, go to step 3, else go to step 4.

Step 3- adding optimality cut:

let $\theta'_u = \lambda_{1u} \times (b_u - ky\ ) + \lambda_{2u} \times (h_u - Tx_u^*)$ and calculate θ_u^* by substituting y by y^*.

If $\theta^* \leq \sum_u p_u \theta_u^*$ then go to step 5, else add optimality cut of $\theta \leq \sum_u p_u \theta'_u$ to master the problem and go to step 1.

Step 4- adding feasibility cut:
Since in our proposed model demand has always considered less than capacity, we may not be faced with non-feasibility in our sub problems. Go to step 1.
Step 5- end of algorithm:

The solution which is found is optimal for master and sub problems

4.3.2 Risk management models

Stochastic optimization could not manage the deducted risk of solution variation since it considers only their expectations. However, the risk-averse decision makers would like to optimize the profit as well as risks. This needs multi-objective programming to maximize the profit and minimize the risk. Mulvey et al. (1995) suggested robust optimization approach to control the mean value and variance of the objective functions in stochastic programs. Ahmed et al. (1998), proposed alternative formulation for standard two-stage stochastic optimization which penalizes solution variability. You et al. (2009) incorporated risk measures with stochastic programming approach in a mid-term planning. They have compared four risk models and concluded that downside risk management and probabilistic financial risk management models are the most effective ones. In this paper, we select the variability index and downside risk to control solution variability in different ways. The first metric manages any variation from expected value however the latter is concerned with the extremes of the cost spread (You et al. 2009).

4.3.2.1. Variability index

In order to minimize the variability of solution from stochastic optimization, we not only need to optimize the expected value but also minimize the variance. However the variance calculation will add a quadratic term to the problem which makes the problem nonlinear. Moreover, variance will penalize all scenarios who have the value lower and upper the average although for example in a maximization problem the scenarios with the value above expected value should not be penalized. Hence instead of variance, we consider variability index which minimizes the undesirable deviation (positive deviation in the case of minimization problem) between the objective value and expected value. Variability index is a non-negative variable which is defined by Δ_s for each scenario Mulvey et al. (1995). Hence, the master problem will be updated as formula (4-20), and all steps of the aforementioned algorithm will be followed as described above.

$$\begin{aligned} &Max\, Z = \theta - fy - \zeta \sum_{u \in \mathrm{U}} P_u \Delta_u \\ &\quad s.t: \\ &\quad \theta \le \sum_{u \in \mathrm{U}} p_u \mathrm{F}_u \\ &\quad \Delta_u \ge \theta - \mathrm{F}_u \\ &\quad \Delta_u \ge 0 \end{aligned} \tag{4-20}$$

Where ζ is the weight associated with the variability index. The output of such model provides a solution with balancing expected value and variability.

4.3.2.2. Downside risk

An efficient way to manage the risk is to have high probability for high profit and low probability for low profit. Downside risk metric minimizes the probability that the real profit is less than a defined target (Γ). The difference between the target and scenarios objective values is calculated for each scenario. Downside risk is the average of these differences. We set the risk equal to a reasonable amount and then solve the problem. The new master problem model will be updated as formula (4-21):

$$
\begin{aligned}
& Max\, Z = \theta - fy \\
& \quad s.t: \\
& \quad Risk = \sum_{u \in U} p_u \Omega_u \\
& \quad \theta \leq \sum_{u \in U} p_u F_u \\
& \quad \Omega_u \geq \Gamma - F_u \\
& \quad \Omega_u \geq 0
\end{aligned}
\qquad (4\text{-}21)
$$

4.4. Case study

We apply our developed model to a case study in Newfoundland, Canada, located in the North Atlantic Ocean. This island has around 1.8 million productive forestlands within 18 districts. The main wood species are soft woods including black spruce (Picea mariana (Mill.) Britton, Sterns & Poggenb.) and balsam fir (Abies balsamea (L.) Mill.). Every 5 years Newfoundland Centre for Forest Science and Innovation releases detailed information about annual allowable cut of all species. The information determines the fiber volume, fiber attributes and their exact location in 2 km× 2 km forest blocks. The resources are harvested to satisfy demand of four existing plants including Corner Brook Pulp and Paper Limited (capacity 700,000 m^3/year), Burton's Cove Lumber Limited (capacity 70,000 m^3/year), Cottle's Island Lumber (capacity 40,000 m^3/year) and Sexton Lumber (capacity 180,000 m^3/year). Corner Brook Pulp and Paper Limited (CBPP) holds tenure of 29% of public forest lands and it is called Kruger tenure. The rest of the forestlands are called Crown tenure. Sawmills can only harvest resources from Crown tenure. Figure 4-2 displays available forestry resources in the 18 districts and 6505 forest blocks. Kruger tenures are differentiated by dashed grey colors in the figure.

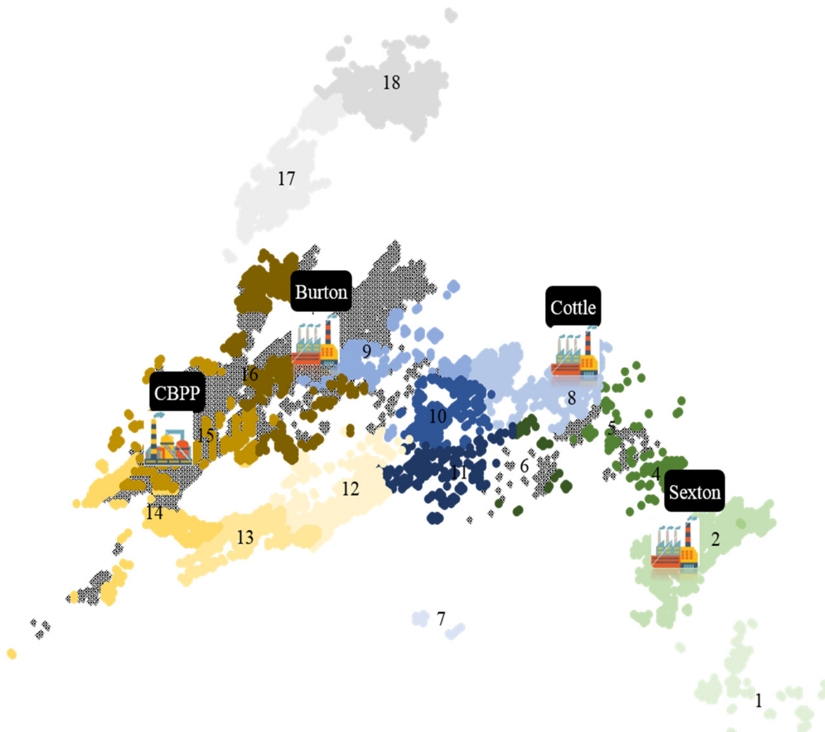


Figure 4-2: Newfoundland forest map including 18 forestry districts and four stakeholders. The dashed grey areas are Kruger tenure.

Since forest block sizes are very small for the scale of our developed strategic-tactical model, we have created forest management zones that are aggregations of forest blocks. Hence each supply point is indicated by district number, tenure holder and zone number. Regarding the logistic costs, transportation cost between all network nodes is calculated by FPInterface™ software. Other information comprising supply harvesting and purchasing cost, yield of process and operation cost is collected from each stakeholder of the supply chain.

Newfoundland supply chain has plenty of unutilized forest biomass that could be used by new processes whether in existing mills or in a greenfield site. However, the specific characterization of biomass in the supply chain as well as maturity of new bioprocesses restrains the choice of new bio-based products among the diverse products. We have considered pelletization, organic ranking cycle (ORC), internal combustion engine (ICE), combined heat and power (CHP) and fast pyrolysis as potential bio-process to produce electricity and biofuel in the supply chain. It is worth mentioning that Corner Brook Pulp and Paper already has CHP process, however it could be transformed to other processes in the case of proving their profitability.

Demand for electricity always exists for residential and commercial uses. Hence the energy generation process including ORC, ICE and CHP are very interesting to consider [13]. Pelletization is a mature process with high production yield and a high-demand market. Hence it is very interesting to consider this process as one of the potential options. Fast pyrolysis process works perfectly with softwood chips and its final product has a growing market in the next decades. Hence we have considered this process among the potential processes options. Pyrolysis process information is collected from a software called I-BIOREF developed by Natural

Resources Canada. All considered potential processes have almost reached their maturity. In this regard we are safe to not consider uncertainty on processes (yield). Table 4-1 displays the detailed information for each process.

Table 4-1. General potential process information

Process (output)	capacity	Efficiency*	Fixed cost** ($)	Variable cost ($/m^3)
Biomass oil heater +ORC	5 MW	0.36 (MWH/m^3)	42,334	1.64
	7 MW		58,808	1.28
	9 MW		75,283	0.91
	11 MW		91,757	0.54
	13 MW		108,231	0.18
	15 MW		124,705	0.18
	17 MW		141,180	0.18
Biomass gasifier + ICE	5 MW	0.58 (MWH/m^3)	30,654	3.79
	7 MW		46,370	2.82
	9 MW		62,085	1.86
	11 MW		77,800	0.89
	13 MW		93,515	0.89
	15 MW		109,231	0.89
	17 MW		124,946	0.89
Biomass boiler + CHP	17 MW	0.87 (MWH/m^3)	-***	0.82
pelletization	15000 m^3	89%	19,631	7.80
	30000 m^3		43,739	10.06
	45000 m^3		54,475	8.62
	60000 m^3		50,000	7.18
Pyrolysis	30000 m^3	0.45 (ton/m^3)	21,519	63.5

*Efficiency of a process depends on the capacity and input products. Hence, the value here is average efficiency for different capacities and inputs.

**The real fixed cost is 10 times more, however since we consider only one year of planning we divide the fixed cost to 10.

***Since CBPP already has this process, we don’t consider the process fixed cost.

In order to consider the fluctuation on market of final products, we have assumed an inverse relation between price and demand of final products following law of demand. The law indicates that in the perfect economy condition, if the consumer’s demand for the good or service increases, its price will decrease and vice versa. We have considered four categories of products: paper, lumber, pellet, energy and biofuel. For each, their demand could vary between 0 to 100% and the price in range of ±20%. We have discounted this variation into three levels of high, average and low. Hence when the demand is high for specific product its price is low. Considering 4 product categories and 3 different market status, we will have 3^4=81 scenarios. Part of scenario diagram is depicted in Figure 4-3. A scenario is a situation where all four product categories have specific demand/price levels.

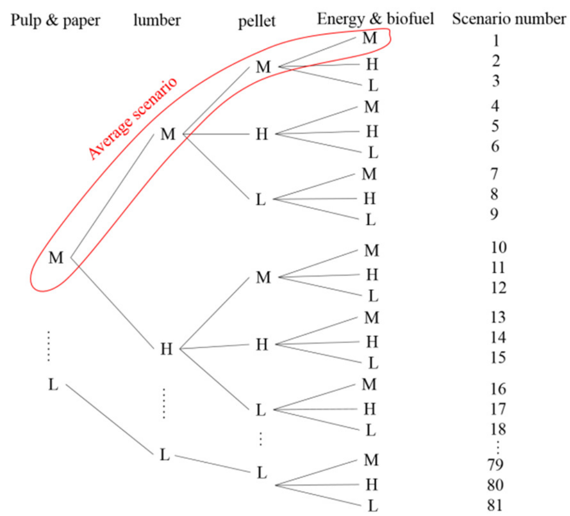


Figure 4-3: Scenario diagram in the condition that all products have faced with uncertainty. The letters M, H and L demonstrated the medium, high and low level of demand for each product category respectively.

The goal of this work is to design a robust forest bioenergy value chain considering aforementioned scenarios. We have evaluated the proficiency of adding new terminals and bioenergy to an existing supply chain considering market fluctuation. We have considered twenty potential locations for terminals and one for bioenergy (Figure 4-4). The potential processes and capacities are proposed for the open bioenergy.

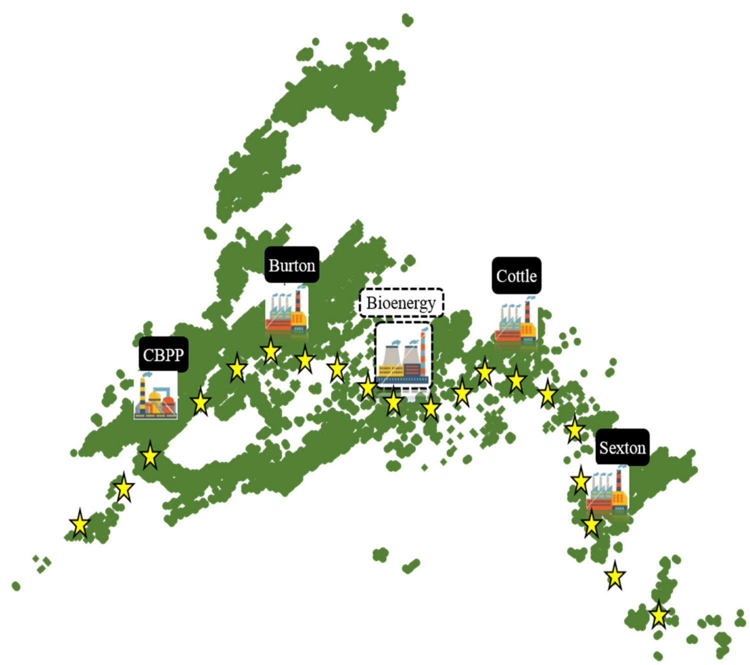


Figure 4-4: The potential location for terminals and bioenergy plant are displayed by stars and mill signs respectively.

4.5. Results and explanations

We implemented our stochastic model with risk metrics with the modeling language AMPL using CPLEX 12.0 as a solver. For all numerical tests, we have used a standard PC with a 2.6 GHz processor and 42.0 GB of RAM. The gap determines the difference between best integer solution and best bound (from the LP relaxation) divided by the best bound. All problems were solvable with a maximum gap of 0.5% in a reasonable time. The stochastic solution will propose a network design that is optimal on average for all the 81 developed scenarios. In order to evaluate the efficiency of the stochastic solution compared to the deterministic solution and displaying the importance of uncertainty consideration we have calculated expected value of perfect information (EVPI) and value of stochastic solution (VSS). The former displays the amounts that decision makers are willing to pay to have perfect information. The latter precisely measures the proficiency of stochastic solution compared to average problem. Afterwards we resolve stochastic solution considering variability index and downside risk. Different levels of risk consideration change the strategic decisions of the model. We have compared the network design structure in deterministic or stochastic condition with or without risk consideration. The size of each problem, its solution time and the number of iterations to converge to optimality are presented in Table 4-2. Finally, we have evaluated the network design structures with four new generated scenarios. These scenarios have not been considered in the network design decision making however they may happen in the future.

Table 4-2. Problem size for different models

	# binary variables	# linear variables	# constraints	# L-shaped iteration to converge	solution time
Stochastic model	64	18,929,296	8,864,558	27	13 h
variability index model	64	18,929,377	8,864,639	44*	22 h
downside risk model	64	18,929,377	8,864,720	54**	27 h
deterministic model	64	233,695	109,493	1	0.2 h

* The number is dependent on the coefficient of variability index

** The number is dependent on the risk level that we have fixed for downside risk model

4.5.1. Objective value comparison

Stochastic optimization model is an extension of the deterministic one while it considers several scenarios instead of only one average scenario. Indeed, deterministic model is the simplest version of stochastic solution with only average scenario consideration. However output of deterministic model is not very profitable for any other scenario that may occur. Indeed it is very important to make a strategic network design decision with the best possible profit for any other future scenarios. To evaluate the efficiency of stochastic solution we have solved the problem with three methods. The first that we called deterministic with fixed average design solves the deterministic model for average scenario and fixed the network structure and then solves sub problems for scenarios one by one to calculate tactical profit for each scenario. Stochastic problem is the second method that provides a network design considering all scenarios. The third method we called deterministic for each scenario solves an MIP model for scenarios one by one.

The results for each scenario demonstrate optimal network design only if this scenario happens in the future. Table 4-3 displays the expected value and standard deviation for the three methods. Based on the data of the table we are able to calculate EVPI and VSS values. The difference between expected value of deterministic for each scenario solution and stochastic solution showed EVPI and the difference between expected value of deterministic with fixed average design and stochastic solution provide VSS. The EVPI and VSS calculation are equal to \$12,665,898 and for \$6,496,002 for our case study. Hence, the first conclusion is that if the network has a stable situation in the future, its transformation will be easier with fewer uncertainty impacts. Standard deviations of the cases clearly demonstrate that solutions are not robust for all scenarios. However, the reason for large standard deviation is interpretable with Figure 4-5 that scenarios with low demand have negative profit. Hence, the difference between positive and negative profit creates such huge variation.

Table 4-3. Expected value and standard deviation for stochastic solution, deterministic for each scenario and deterministic with fixed average design.

	Deterministic with fixed average design	Stochastic solution	Deterministic for each scenario
Expected value	\$ 12,210,544	\$ 18,706,545	\$ 31,372,443
Standard deviation	\$ 52,505,990	\$ 52,269,442	\$ 31,222,533

Figure 4-5 is deployed to visually compare the profitability of the three approaches for each scenario. The first 27 scenarios are in the condition that current market is in good state. Hence the network has high profitability with low variation, which is interesting for investors. However, the sudden changes in scenarios 27 and 54 in the figure clearly display the importance of pulp and paper mill for the supply chain. Scenario 27 is the one with high paper demand and scenario 54 is the scenario with zero paper demand. Scenarios with zero demand of pulp and paper always have negative profit. This is because high quantity of forest residues and chips that could produce added-value products has not been used. However there are bioenergy processes as potential options for utilizing forest biomass and chips, their assumed capacity is not as high as the existing pulp and paper mill. Even in deterministic cases the low demand level of pulp and paper may cause sawmill closure that will have a negative impact on the industry. Thus, it is very important to keep the current stakeholders open and prepare the entire supply chain to smoothly add new processes to utilize the forest biomass feedstocks.

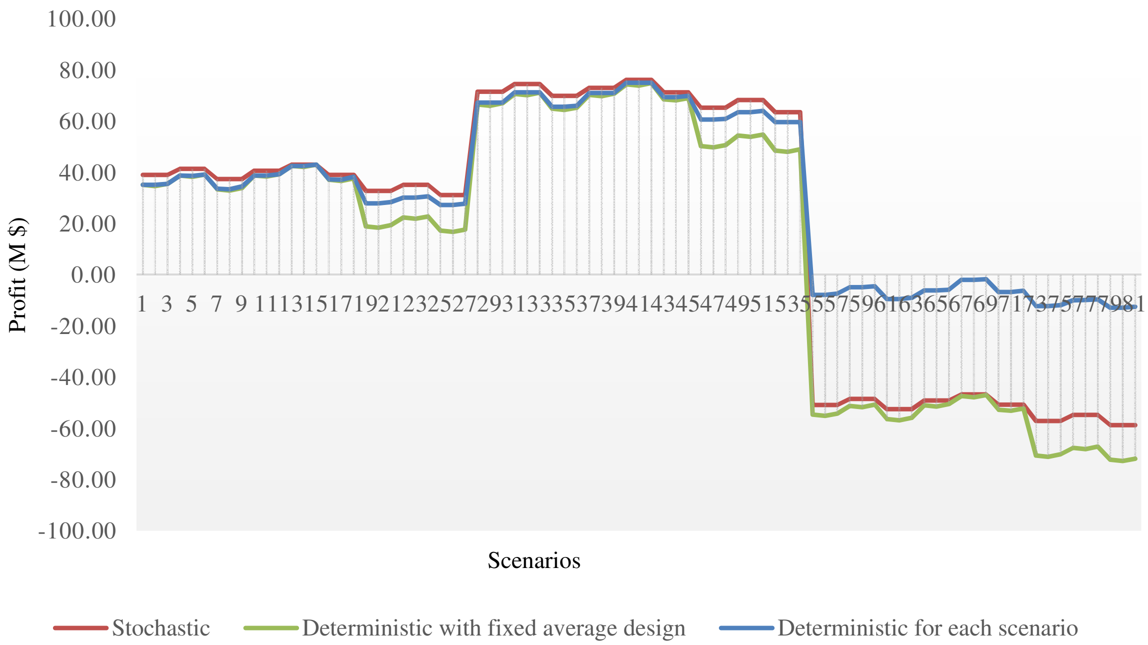


Figure 4-5: Scenarios profitability comparison between stochastic solution, deterministic for each scenario and deterministic with fixed average design.

To reduce sensitivity of stochastic solution to data fluctuation, we have considered variability index. The weight associated to the variability index has direct effect on the solution. Stochastic solution is the case when the coefficient is equal to 0. Figure 4-6 displays the expected profit and standard deviation for scenarios when different risk coefficient is considered. Decision makers choose the coefficient in order to find the most suitable one.

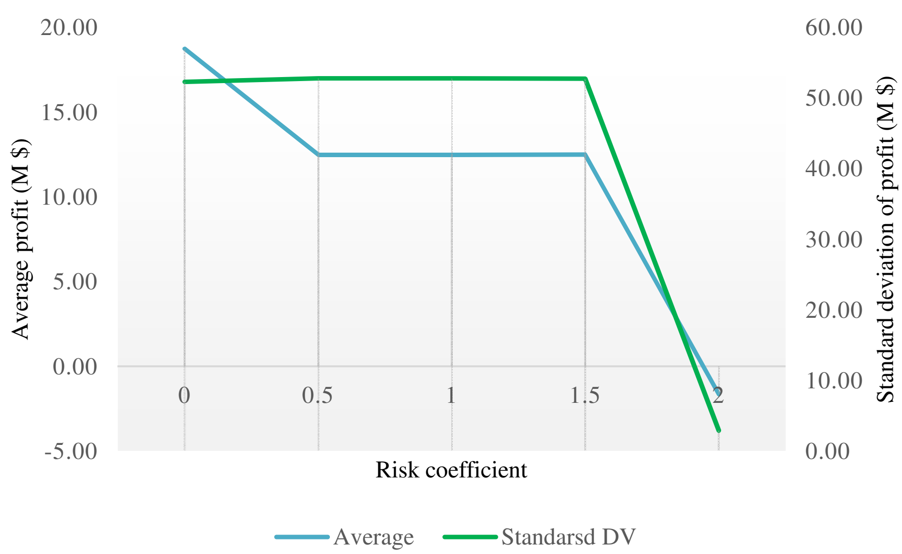


Figure 4-6: Comparison of objective values with different risk coefficient values.

The other interesting risk metric is downside risk which will control the extreme loss for our model. For our considered case study even in deterministic condition, we will be faced with loss for some of the scenarios (check Figure 4-5). The stochastic solution without risk consideration has average value of 18 M$ which is set as a target and the risk is calculated as 23.60 M$. We set the target of 10 M$ and solve the stochastic solution with fixed risk of 12 M$. Figure 4-7 displays the changes on the frequency of objective value before and after applying this. The figure clarified that downside risk management reduces the possibility of extreme loss for different scenarios.

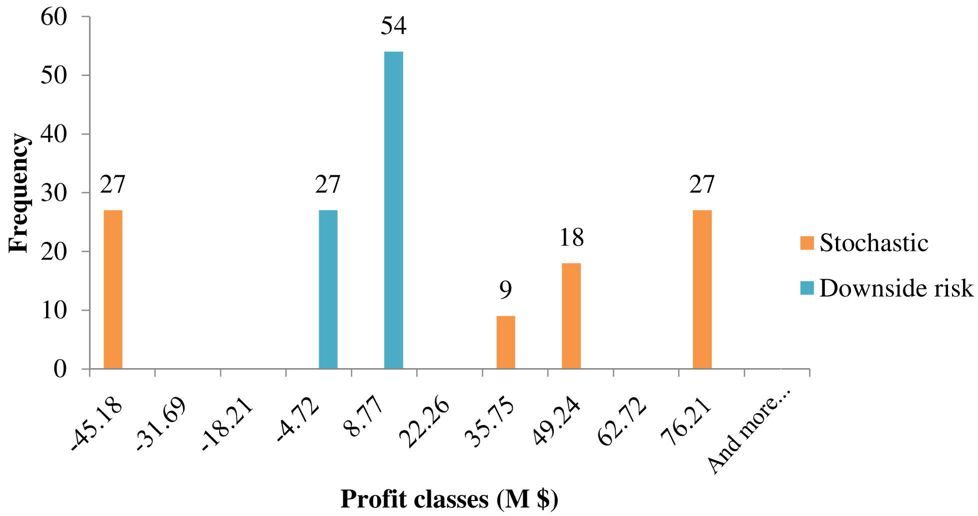


Figure 4-7: Frequency of objective value with and without downside risk management.

The risk in blue bars with fixed target of 10 M$ has been fixed at 12 M$, while the risk for stochastic optimization considering the average objective value as target is 23.60 M$.

4.5.2. Network design comparison

Besides objective value, the network design as an important strategic decision varies per assumed condition of the problem whether it included uncertainties or risk metrics. In this regard, we have compared network design decisions of deterministic, stochastic, variability index and downside risk models in Figure 4-8. Moreover, the figure displays the allocation of resources for average scenario while the network design in each method is fixed. New technology assessment for each solution is summarized in Table 4-4.

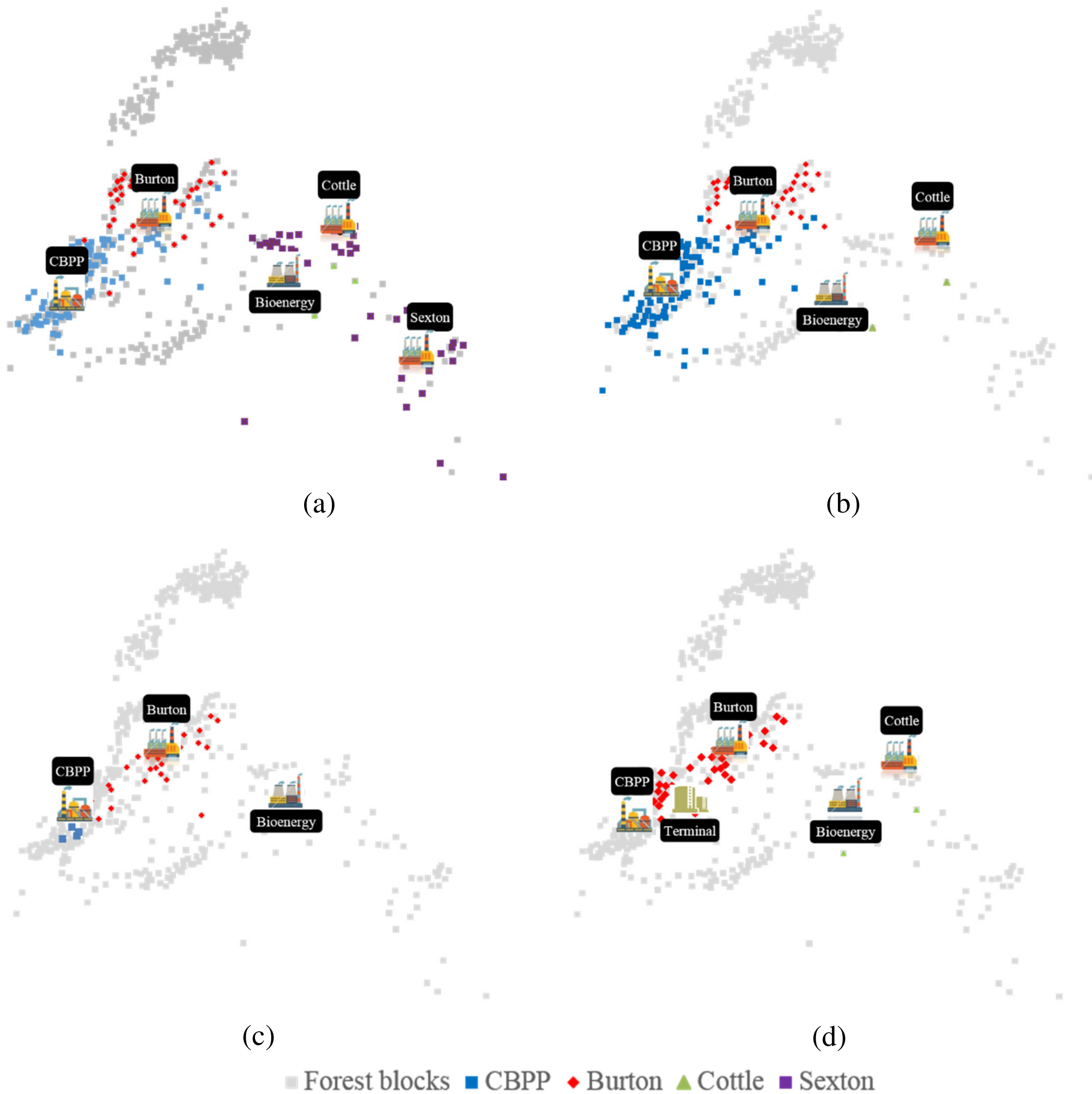


Figure 4-8: Network design and resource allocation comparison. a) Network design for deterministic model. b) Network design for stochastic model. c) Network design for variability risk model (risk coefficient equal to 2). d) Network design for downside risk model (target of 10 M$ and fixed risk of 12 M$).

The decision to open a pellet mill in the center of Newfoundland was taken in all methods, which demonstrates the robustness of such decision (pellet mill). The mill is located in the same location as the previously closed mill, which is very interesting for the local community. Moreover, it is close to all sawmills and harvest areas to receive chips and residues. Deterministic model for average scenario has decided to transform the existing CHP process of CBPP to pyrolysis process since it has more capacity. Moreover, there is no mill closure in this method since all parameters are assumed in average levels. Stochastic network design decides to close one of the largest sawmills on the island and that could be a serious warning for the entire supply chain stakeholders. If scenarios with zero demand of pulp and paper and lumbers have been neglected, this industry closure will not happen in stochastic model. The variability model similarly to deterministic model forces the pulp mill to transform to pyrolysis process. However the high risky condition (coefficient of 2) and uncertainty of parameters caused several mill closures on its solution. Finally, downside risk model decides to close pulp making process at pulp mill and continue with energy generation at the mill. Moreover it has opened a terminal and bioenergy with only pyrolysis process and opened a terminal close to CBPP. Terminal in this design will help stakeholders to respect the specific transportation regulation of the insular. However, it helps to reduce transportation cost by using backhauling.

Table 4-4. Technology assessment

Solving method	CBPP		Bioenergy		Terminal
	process	capacity	process	capacity	
Stochastic model	CHP	17 MW	Pelletization	60 000 m^3	-
Variability model	Pyrolysis	30 000 m^3	Pelletization	60 000 m^3	-
Downside model	CHP	17 MW	Pelletization	60 000 m^3	yes
Deterministic	Pyrolysis	30 000 m^3	Pelletization	60 000 m^3	-

4.5.3. General solution evaluation

In order to prove the efficiency of stochastic solutions we have generated 4 new scenarios and have compared their solutions while we have stochastic solution with and without risk consideration and deterministic solution. The new scenarios are presented in Table 4-5. As the table showed they don't follow demand law. The pessimistic scenarios consider a worst case scenario for forest industry. The transformation scenario is the one that demand for energy, biofuel and pellet is created and the commodities don't have good market. Stable scenario could be a great situation for current stakeholders since they still have good market for their commodities and excellent opportunities for investment in new products. Finally, optimistic scenarios are the ideal conditions for the future, both for stakeholders and for investors.

Table 4-5. New generated scenarios.

	pessimistic	transformation	stable	optimistic
Energy & biofuel	L*(M)**	M(H)	H(M)	H(H)
Pellet	M(M)	M(H)	H(M)	H(H)
Lumber	L(M)	L(L)	M(M)	M(M)
Pulp & paper	L(M)	L(L)	L(M)	M(M)

*L, M and H are abbreviation for low, medium and high level respectively.

**The first letter in the table displays demand levels and the letter in parentheses shows the price level.

Figure 4-9 demonstrates network design performance for new defined scenarios. As the figure shows stochastic design is more profitable for pessimistic and transformation scenarios compared to average design. Variability model design provides very good solution for worst-case scenarios and vice versa for good scenarios. Downside model design has very low profit for all scenarios with very low solution variation. The result proved again the low variability of stochastic solution compared to deterministic solution. Moreover, the level of risk consideration definitely changes the solution.

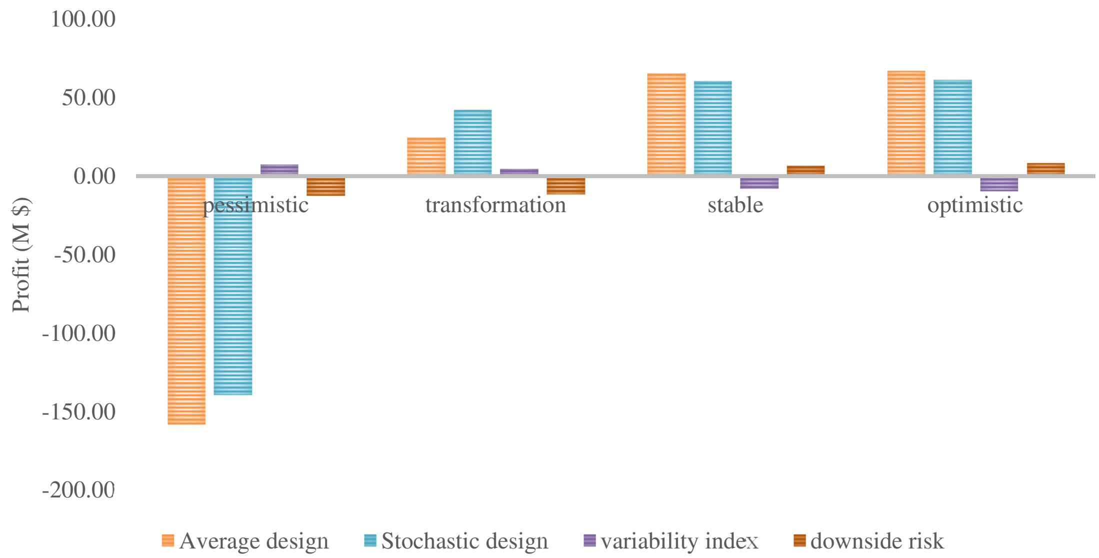


Figure 4-9: Evaluation of network design of average case and stochastic case for four new developed scenarios

4.6. Conclusion

We have developed a two-stage stochastic optimization model taking into account variability and downside risk metrics to design a forest bioenergy value chain under market uncertainty. The bioenergy potential processes including CHP, ORC, ICE, pelletization and pyrolysis with different potential capacities have been proposed to the developed models. Moreover, to stabilize the current structure of the network and to reduce the transportation cost we proposed 20 potential locations for terminals. Different network designs are reported depending on decision criteria. The methods were compared from difficulty, objective value and network design points of view. The results clearly show that level of risk consideration directly affects the network design decisions.

Our developed optimization model has the ability to consider a new bio-process in its modeling. However, a comprehensive market study is required to design a good product-process portfolio. Facts in such a new market is the uncertainty about availability of resources, performance of new processes and the market for new products. The more uncertainty consideration the more accurate results will be provided by the model. The uncertainty could be considered in multi-period models which are closer to reality. Moreover, social and environmental impacts of strategic decisions are necessary to be considered for a sustainable transformation. Finally, study of robust network design and comparison with stochastic solution could provide clear insight for decision makers.

4.7. Acknowledgments

The author would like to acknowledge the support of FORAC Research Consortium (Université Laval) and NSERC Strategic Network on Value Chain Optimization. Moreover, special thanks to FPInnovations' Francis Charette, the Centre for Forest Science and Innovation Newfoundland's Bill Dawson and Natural Resource of Canada (CamnetEnergy) Marzouk Benali and Louis-Alexandre Lapointe Pelletier for providing data to validate our developed model. We also sincerely thank the co-operation of the stakeholders: David Chamberlain, Corner Brook Pulp and Paper Ltd; Fred Osmond, Burton's Cove Ltd; Lorie Philpott, Cottle's Island Ltd; and Kevin Sexton and Neil Greening, Sexton Lumber Ltd.

4.8. References

Abasian F., M. Rönnqvist and M. Ouhimmou, 2017. Forest Fibre Network Design with Multiple Assortments: a case study in Newfoundland. *Canadian Journal of Forest Research*.

Ahmed S. and N. V. Sahinidis NV, 1998. Robust Process Planning under Uncertainty. *Industrial & Engineering Chemistry Research,* 37 (5), 1883-1892.

Ahtikoski A. J. Heikkilä, V. Alenius and M. Siren, 2008. Economic viability of utilizing biomass energy from young stands—The case of Finland. *Biomass and Bioenergy*, 32 (11):988-996.

Alam M. B., R. Pulkki and C. Shahi, 2012. Woody biomass availability for bioenergy production using forest depletion spatial data in northwestern Ontario. *Canadian Journal of Forest Research*, 42 (3), 506-516.

Brige J. R. and F. Louveaux, 2011. *Introduction to Stochastic Programming*. Springer Science & Business Media.

Cambero C., T. Sowlati, M. Marinescu and D. Röser, 2015. Strategic optimization of forest residues to bioenergy and biofuel supply chain. *International Journal of Energy Research*, 39 (4), 439-452.

Chen C. W. and Y. Fan, 2012. Bioethanol supply chain system planning under supply and demand uncertainties. *Transportation Research Part E: Logistics and Transportation Review*, 48 (1), 150-164.

D'Amours S., M. Rönnqvist, A. Weintraub, 2008. Using Operational Research for supply chain planning in the forest product industry. *INFOR: Information Systems and Operational Research,* 46 (4), 47-64.

Ekşioğlu S. D., A. Acharya, L. E. Leightley, S. Arora, 2009. Analyzing the design and management of biomass-to-biorefinery supply chain. *Computers & Industrial Engineering*, 57 (4), 1342-1352.

Flisberg P., M. Frisk and M. Rönnqvist, 2012. FuelOpt: a decision support system for forest fuel logistics. *Journal of the Operational Research Society*, 63 (11), 1600-1612.

Gebreslassie B. H., Y. Yao and F. You, 2012. Design Under Uncertainty of Hydrocarbon Biorefinery Supply Chains: Multiobjective Stochastic Programming Models, Decomposition Algorithm, and a Comparison Between CVaR and Downside Risk. *AIChE Journal,* 58 (7), 2155-2179.

Gunnarsson H., M. Rönnqvist, J. T. Lundgren, 2004. Supply chain modeling of forest fuel. *European Journal of Operational Research,* 158 (1), 103-123.

J. P. Hall, 2002. Sustainable production of forest biomass for energy. *The Forestry Chronicle,* 78 (3), 391-396.

Kazemzadeh N. and G. Hu, 2013. Optimization models for biorefinery supply chain network design under uncertainty. *Journal of Renewable and Sustainable Energy*, 5 (5), 53-125.

Kim J., M. J. Realff and J. H. Lee, 2011a. Optimal design and global sensitivity analysis of biomass supply chain networks for biofuels under uncertainty. *Computers & Chemical Engineering,* 35 (9),1738-1751.

Kim J., M. J. Realff, J. H. Lee, C. Whittaker and L. Furtner, 20011b. Design of biomass processing network for biofuel production using an MILP model. *Biomass and Bioenergy*, 35 (2), 853-871.

Laporte G. and F. V. Louveaux, 1993. The integer L-shaped method for stochastic integer programs with complete recourse. *Operations research letters*, 13 (3),133-142.

Leduc S., F. Starfelt, E. Dotzauer, G. Kindermann, I. McCallum, M.Obersteiner and J. Lundgren, 2010. Optimal location of lignocellulosic ethanol refineries with polygeneration in Sweden. *Energy.* 35 (6), 2709-2716.

Mulvey J.M., R. J. Vanderbei and S. A. Zenios, 1995. Robust Optimization of Large-Scale Systems. *Operations Research,* 43 (2), 264-281.

Rei W, Cordeau JF, Gendreau M, Soriano P. Accelerating Benders Decomposition by Local Branching. INFORMS Journal on Computing. 2009;21(2):333-345.

Saidur R., E. A. Abdelaziz, A. Demirbas, M. S. Hossain and S. Mekhilef, 2011. A review on biomass as a fuel for boilers. *Renewable and Sustainable Energy Reviews*, 15 (5), 2262-2289.

Santibañez-Aguilar J. E., J. B. González-Campos, J. M. Ponce-Ortega, M. Serna-González and M. M. El-Halwagi, 2011. Optimal Planning of a Biomass Conversion System Considering Economic and Environmental Aspects. *Industrial & Engineering Chemistry Research*, 50 (14), 8558-8570.

Shabani N., S. Akhtari and T. Sowlati, 2013. Value chain optimization of forest biomass for bioenergy production: A review. *Renewable and Sustainable Energy Reviews,* 23, 299-311.

Shabani N., S. Akhtari and T. Sowlati, 2013. Value chain optimization of forest biomass for bioenergy production: A review. *Renewable and Sustainable Energy Reviews,* 23, 299-311.

Shabani N., T. Sowlati, M. Ouhimmou and M. Rönnqvist, 2014. Tactical supply chain planning for a forest biomass power plant under supply uncertainty. *Energy*, 78 (0), 346-355.

Svensson E., A. B. Strömberg and M. Patriksson, 2011. A model for optimization of process integration investments under uncertainty. *Energy*, 36 (5), 2733-2746.

Svensson E. and T. Berntsson, 2011. Planning future investments in emerging energy technologies for pulp mills considering different scenarios for their investment cost development. *Energy*. 36 (11), 6508-6519.

Tang H. and Y. Zhao, 2003. L-shaped algorithm for two stage problems of stochastic convex programming. *Journal of Applied Mathematics and Computing*. 13 (1-2), 261-275.

Tay D. H. S., D. K. S. Ng and R. R. Tan, 2013. Robust optimization approach for synthesis of integrated biorefineries with supply and demand uncertainties. *Environmental Progress & Sustainable Energy*. 2013;32(2):384-389.

You F., J. M. Wassick and I. E. Grossmann, 2009. Risk management for a global supply chain planning under uncertainty: Models and algorithms. *AIChE Journal*, 55 (4), 931-946.

General conclusion and perspectives

5.1. General conclusion

We studied a value chain design that was the result of strategic investment and management actions. Since the uncertainty associated with supply, production and market of value chain may affect the strategic investment decisions, we managed the effect of uncertainties as well as the investment risks. We found this study very suitable for forest bioenergy value chain since new strategic decisions under market uncertainty should be made. Hence, our generic network design optimization models in deterministic and stochastic context were applied to Newfoundland forest supply chain. From the application perspective, this work has included an in-depth analysis of the forest supply chain at Newfoundland. The supply chain had initially the serious challenge of secure fiber that has been resulted in many mill closures. On the other side, the supply chain has a great opportunity for new bioenergy plant at the location of a closed mill in the center of Newfoundland. Our developed optimization model has provided a guideline for their resource allocation and cost reduction to improve their current situation and also has proposed some new opportunities. The analysis of results including the effect of collaboration, backhaul transportation, new terminals and bioenergy plants on stakeholders' profitability have been presented to them. Moreover, by considering the risk metrics, we have proposed a robust bioenergy value chain design for forest bioenergy value chain.

The thesis has started with the first research question on: How can we plan hierarchically a value chain considering several stakeholders? To respond this question we have developed strategic to operational planning models which have been connected to each other's. Indeed the outputs of higher level decision have inputted as the parameters to lower level model. The models have been integrated with transportation game. The incorporated optimization system in the game has been provided a clear vision for students about the importance of hierarchical planning and optimization models in all supply chains, especially in forestry. The game includes many collaborative actions comprising backhaul transportation and wood exchange between stakeholders that evaluated the importance of collaboration in supply chain planning. The players make strategic, tactical and operational planning sometimes in co-competition and sometimes in collaboration condition to minimize supply chain costs. Moreover, the level of their collaboration is compared with the optimal level of collaboration presented by the optimization system.

Afterwards, we have concentrated on second research question about: How can we integrate the value chain design with value chain management in a collaborative environment? For this question, we have developed a network design model for forest bioenergy network taking into account tactical planning and all involved stakeholdres. The model has addressed all particular challenges of adding new bioenergy plant in an existing supply chain including fiber availability and stakeholder's collaboration for the new partnership. The proposed model supports the strategic decisions with tactical decisions and it is also applicable to large-scale case study. Some possible modification in the planning including backhaul transportation, wood exchange between partners and adjustments in harvesting rule of the supply chain have been analyzed through scenario analysis of the model. The impacts of each of these changes have been evaluated by 7 key performance indicators on Newfoundland forest supply chain. The KPIs have calculated improvement in profit as well as reduction in costs and greenhouse gas emissions associated with each of the modifications. The result has showed even in the current situation of Newfoundland supply chain, new planning has the ability to provide secure fibre for all stakeholders. Moreover, with the same input volume and more collaboration, all stakeholders could generate more profit. Backhaul transportation could reduce the GHG emission up to 750 metric tons per year. New pellet mill and terminals could increase the profitability up to 4.36% and 7.69%, respectively. Finally, all improvement opportunities could create a potential 23% increase in network profitability. However, the sensitivity of the solution to input parameters could increase the investment risk in such project.

In the third part of the thesis, we have developed a stochastic optimization model to deal with third research question on: How can we integrate the value chain design with value chain management in a collaborative environment under uncertainty consideration? We have considered again the forest bioenergy network design problem considering all involved stakeholders under uncertainty on the demand and price of final products. New partnership in the forest value chain has been evaluated with our developed optimization model. The stochastic solution has brought a potential of $6.5 million improvement in the Newfoundland case study. Several bioenergy processes have been considered and depend on the assumption of the problem, pyrolysis, palletization and CHP have been selected for the new processes. Financial risk models have provided different network design with lowest risk metrics. The results have showed the conservative approaches decide on the closure of some mills. Moreover, the importance of existing stakeholders on the future success of the forest supply chain has been highlighted. Hence, the decision makers need to create a trade-off between risk and investment.

5.2. Recommendation for future work

Our developed network design model could be improved with the incorporation of biomass characterization and/or other products. This would require a detailed product-process portfolio design. An analyzing on market of new product considering the geographical situation of the supply chain could create a new contribution in this field. The model could add the customer's location and transportation cost for product distribution into consideration. The capacity of the market for new products could be calculated by a comprehensive survey of different markets zones.

Another area for further research is to include other uncertainties including supply availability and process yield. After the transformation of forest supply chain the demand for forestry residues will increase hence the uncertainty on the availability of resources will increase. Moreover, the new technologies to produce new products have the uncertainty on their production yield. After such studies a comparison between different networks' designs take into account different uncertain parameters will reduce the risk of investment.

Further analysis could involve the incorporation of operational planning in the decision making process. In this regards, the optimization model should consider shorter time planning. In such detailed planning, the uncertainty of new products could consider for each period and a multi-stage stochastic optimization model should be developed. Several solution methodologies including the heuristic or simulation could be developed to deal with such the problem.

Our developed optimization model in deterministic and stochastic context could apply for other forest industry case studies. Each case study has specific regulations that need to be adjusted in the constraints. Moreover, the research that concentrates on operational planning of similar problems could utilize the strategic and tactical decisions of our developed model and then develop their own operational planning models.

Finally, to have sustainability criteria in bioenergy supply chain design, it is necessary to consider social and environmental impacts of the new design. Such studies not only provide a sustainable result but could also motivate the stakeholders so that they could present the social and environmental advantage of their investments. A very good example of environmental impact is the reduction of CO_2 emission. The result of multi-objective optimization model should be embedded into a decision support system to compare any combinations of objectives and their advantages.