A Generic Decision Support Model for Analysing the Sustainable Integration of New Products: An Application to the Forest Value Chain

by

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A GENERIC DECISION SUPPORT MODEL FOR ANALYSING THE SUSTAINABLE INTEGRATION OF NEW PRODUCTS: AN APPLICATION TO THE FOREST VALUE CHAIN

Louis-Alexandre LAPOINTE PELLETIER

ABSTRACT

By inspecting the industrial environment of a region, it is possible to distinguish the actors, the strategies employed regarding their product portfolio, their production-distribution network and how they improve their competitiveness using innovation. Inevitably, their actions affect the economic vectors of the region and create a distinctive network with particular characteristics. What is meant by economic vectors is all of the intangible synergies formed in a given region in regard to the strategic assets, commodities, and innovations used by the companies to generate value. When a company evaluates the possibility of introducing new products into a network, the assessment of their impact has to be conducted to ensure the best selection. Competition, synergies, and sustainability have to be taken into consideration to position the strategy of a company, where the product portfolio can be evaluated accordingly.

Consequently, even though a good analysis can be conducted on a small network, it becomes almost infeasible at a regional scale to properly assess the introduction of new products into a complex network without a decision support tool. This situation results in hesitations as to which appropriate combination of products/technologies should be chosen, when to strategically implement them, and what would be the extent of their impact on the existing network. To help organizations with these challenges, the development of a strategic decision support tool to assess the impact of integrating new products into an existing network is brought forward. The generic tool allows a mathematical representation of a given network composed of manufacturing processes, bill of materials and distribution nodes. The model is applied to a realistic case study in the Mauricie region (Quebec) Canada, where the introduction of new products is evaluated for the forest value chain considering the concept of forest biorefinery. Accordingly, scenarios around the potential integration of four prospective processes (i.e. pressurized hot water extraction, fast pyrolysis, organosolv fractionation, and lignin recovery platform) are designed to evaluate the introduction of eight bioproducts. Kraft lignin and crude bio-oil are shown to have the best financial return in the Mauricie region.

Keywords: New products integration, product portfolio diversification, production-distribution network, divergent process network, sustainable forest supply chain, forest value chain, value creation network, mixed integer linear programming.

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UN OUTIL GÉNÉRIQUE D'AIDE À LA DÉCISION POUR L'ANALYSE DE L'INTRODUCTION DE NOUVEAUX PRODUITS EN CONSIDÉRANT LE DÉVELOPPEMENT DURABLE : UNE APPLICATION À LA CHAÎNE DE VALEUR FORESTIÈRE

Louis-Alexandre LAPOINTE PELLETIER

RESUMÉ

En inspectant le tissu économique d'une région, il est possible de distinguer les acteurs, les stratégies adoptées relatives à leur portefeuille de produits, leur réseau de production-distribution et comment ils améliorent leur compétitivité utilisant l'innovation. Inévitablement, leurs actions affectent les vecteurs économiques régionaux et créent ainsi un réseau distinctif arborant des caractéristiques particulières. Ce que l'on entend par vecteurs économiques, c'est l'ensemble des synergies générées par les actifs stratégiques, les matières premières et les innovations utilisées par les entreprises pour générer de la valeur. Lorsqu'une entreprise étudie la possibilité d'introduire de nouveaux produits à un réseau, l'évaluation de leur impact doit être effectuée pour assurer une sélection optimale. De plus, la concurrence, les synergies et le développement durable doivent être considérés afin de positionner la stratégie d'une entreprise, où le portefeuille de produits peut être évalué en conséquence.

De la sorte, bien qu'une analyse précise puisse être effectuée sur un petit réseau, il devient pratiquement impossible à l'échelle régionale d'évaluer correctement l'introduction de nouveaux produits dans un réseau complexe sans outil d'aide à la décision. Cette situation se traduit par des hésitations quant à la combinaison appropriée de produits/technologies à choisir, quant à leur mise en œuvre stratégique et quant à leur impact potentiel sur le réseau existant. Pour aider les organisations confrontées à ce défi, le développement d'un outil d'aide à la décision stratégique est mis de l'avant pour évaluer l'impact de l'intégration de nouveaux produits dans un réseau existant. L'outil générique permet une représentation mathématique d'un réseau donné composé de processus de fabrication, de nomenclatures et de nœuds de distribution. Le modèle est appliqué à une étude de cas réaliste dans la région de la Mauricie (Québec) au Canada, où l'introduction de nouveaux produits est évaluée pour la chaîne de valeur forestière. Le concept de bioraffinerie est avancé où l'intégration potentielle de quatre procédés prospectifs (c'est-à-dire le procédé d'extraction à l'eau chaude, la pyrolyse rapide, le fractionnement organosolv et la récupération de la lignine) sont étudiés pour évaluer l'introduction de huit bioproduits. La lignine kraft et la bio-huile brute démontrent le meilleur potentiel financier pour la région de la Mauricie.

Mots-clés : Intégration de nouveaux produits, diversification du portefeuille de produits, réseau de production-distribution, processus divergent, chaîne d'approvisionnement forestière durable, chaîne de valeur forestière, réseau de création de valeur, programmation linéaire mixte en nombre entiers.

TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF ABREVIATIONS

BCS	Base Case Scenario
BMMB	Bureau de Mise en Marché des Bois *(Timber Sales Office)*
BDMT	Bone Dry Metric Ton
BtoB	Business-to-Business
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
FAO	Food and Agriculture Organization of the United Nations
FBR	Forest Biorefinery
FMU	Forest Management Unit
GHG	Greenhouse Gases
GMT	Green Metric Ton
GMV	Gross Merchantable Volume
IFBR	Integrated Forest Biorefinery
MERN	Ministère de l'Énergie et Ressources Naturelles du Québec *(Quebec Ministry of Energy and Natural Resources)*
MFFP	Ministère des Forêts, de la Faune et des Parcs *(Ministry of Forests, Wildlife and Parks)*
MILP	Mixed Integer Linear Programming
NPV	Net Present Value
NRCan	Natural Resources Canada
OSB	Oriented Strand Board
PAFIT	Plan d'Aménagement Forestier Intégré Tactique *(Tactical Integrated Forest Management Plan)*
PHWE	Pressurized Hot Water Extraction
PDC	Production-Distribution Center
SME	Small and Medium-sized Enterprise
TMP	Thermomechanical Pulp
TRL	Technology Readiness Level

INTRODUCTION

Behind the scene of successful sales, logistics networks are planned by organizations towards the end goal of making profits through well-defined product portfolios. Nevertheless, these structures, as complex as they can get, are built over raging water on a thin layer of ice. The question is neither if it will break nor when, but rather how to be proactive about the life-threatening factors that turmoil under businesses. Unstable markets, erratic trade agreements, a growing global population, newly industrialized and emerging markets, increase preoccupations with land use and pollution, technological advancements, the persistent growth of products and energy consumption – businesses are evolving in an economy deeply affected by global development. These deep cuts alter and transform the market behaviors and companies that omit to improve are often thrown back to the drawing board. In fact, the capacity of a company to adapt to an increasingly complex world might be jeopardized by its lack of innovation.

Driven by competition, companies have now to work harder to satisfy customers' demand around the globe which must be satisfied by the right product, price, location, and time to be fulfilled. This is not a simple task, and one company must take all the initiatives to sustain its competitive advantages. One of them is to create the maximum value out of its production and distribution network by taking in consideration innovative elements. Innovations that can be introduced to the production-distribution network are for instance the concepts of circular economy, of sustainable development, of industry cluster and the diversification of the product portfolio with novel products. However, innovation is intrinsically a double edged-knife; it has the potential to create robust competitive advantages as well as consequential drawbacks. Therefore, companies have to thoughtfully evaluate the effects of going through the process of integrating innovation. In this regard, we propose in this thesis a mean to redesign an existing network where the introduction of new products can be evaluated considering competition, synergies, and sustainability.

The industrial environment of a region is wrought by the actions of companies through their strategies, their product portfolio, their production-distribution network, and how they improved their competitiveness using innovation. Inevitably, their actions affect the economic vectors of the region and create a distinctive network with specific characteristics. The economic vectors can be interpreted as all of the intangible synergies formed in a given region in regard to the strategic assets, commodities, and innovations used by the companies to generate value. Those characteristics drive the regional economy and when correctly supported, may develop into an industry cluster within which stakeholders may benefit from the synergies. The notion of industry cluster can be synthesized as a group of similar and related stakeholders in a region and where innovative businesses concentration may lead to innovation spillover and employment growth (Delgado et al. 2014). The structure of an industry cluster may be formed by governmental programs and incentives, research and development led by non-profit organizations or even from companies closely tied to a regional resource. Hence, to take advantage from an industry cluster, competition and synergies have to be taken into consideration and where a company's product portfolio can be evaluated accordingly. The efficient selection and integration of products have the potential to produce strong competitive advantages. The product portfolio is created by a company to target specific market needs, to lower market risks and to ensure stable inputs of incomes. Nevertheless, its configuration must be redesigned every so often to improve the organization competitiveness and to adapt to new market requirements. The introduction of novel products into an existing network can be accomplished through the integration of appropriate production/distribution technologies which might have consequential effects on the industry cluster. In fact, the simple act of diversifying a product portfolio has an impact on the existing flows and the synergies of the network, from a micro to a macro perspective. By definition, a network is a system composed of entities that are interconnected and in which, every action incurred by one may have an impact on the others. For instance, if a company enters a regional network and requires large quantities of raw materials, the availability, quality and price of the raw materials may differ and subsequently affect the other companies of the region. Consequently, the integration of technologies to a network has a disruptive potential to alter the raw materials and products flows and ultimately transform

the dynamic of the system. However, even if product flows are altered, without an efficient integration of the transformative technologies, the modification might lack the potential to create value, or even to drastically lower the current competitiveness of the network. If a modification occurs, the company must ensure that the access to the required workforce and raw materials/products are available in the region and at a competitive level. Accordingly, synergies between new and existing production-distribution technologies must be assessed as well as the supply chain structure. In the occurrence where stakeholders are closely bounded to a regional resource, the flows and synergies created from the raw material availability outline the network potential. Consequently, when a company evaluates the possibility of introducing new products into a network, the assessment of their impact has to be conducted to ensure the best selection. Even though a good analysis can be conducted on a small network, it becomes almost infeasible at a regional scale to properly assess the introduction of new products into a complex network without a decision support tool. This situation results in hesitations as to which appropriate combination of products/technologies should be chosen and when to implement them. Therefore, a decision support tool to assess the impact of introducing new products to a network may help to mitigate the intrinsic risk incurred by companies.

A good candidate to test this kind of decision support tool is the Canadian forest industry that for years has omitted to innovate and upgrade their model. Pioneer of the wood based newsprint paper, the Canadian forest industry inaction towards innovation is hard to blame; the industry had indispensable commodities and was evolving throughout the decades in a favorable and predictable market. The industry was trapped in the illusion of static competitive advantages in terms of the abundance of raw materials, of a skilled labor pool, of their field expertise, and of their shares of a market that seemed immutable. Inevitably, shifts in the markets' needs and global competition made all of those advantages easily reproducible by foreign competitors or replaced by alternative products. To put the problem into perspective, the Canadian forest has a significant economic potential, is an important pillar of the Canadian Gross Domestic Product (GDP), and sustains 47,000 million cubic meters of growing stock on 3.5 million square kilometers of forest land. Nonetheless, in the

last decade, the sector's labor force has decreased by 30 percent, representing 90,000 direct jobs lost, and the sector’s contribution to the GDP has decreased by one percent (Statistics Canada [1]). This drawback resulted from an amalgamation of events that ended to be detrimental to the old forest industry. For instance, a global phenomenon contributing to this situation can be followed as the digitization of the newspaper industry. The Canadian forest industry is a major international actor in the production of newsprint paper. On the east coast, the province of Quebec had a vast network of thermomechanical pulp and paper mills based on low electricity cost and smaller log sizes. With the surge of electronic media, the demand for newsprint paper decreases and by the same way removed non-competitive producers.

One disadvantage of the Canadian forest is the fibre growth rate which is substantially slower than in warmer regions. The rotation of harvesting areas is challenging and has to be planned on a horizon of many decades resulting in high logistics costs. The production of newsprint paper is not viable anymore with the current aging structure and the production and distribution network has to be rethought. Forest companies have now to adapt by changing their product portfolio and have to consider the economic composition of a region which affects their inputs availability, their processes, and their outputs. To do so, knowledge intensive industry must be created to convert the static disadvantages into dynamic advantages. A particularity of the sector is their main raw material: the wood. Wood is a highly versatile product that can be transformed and used in many ways and one dynamic advantage that can be promoted is the fibre particular characteristics engendered by its slow growth rate. For instance, while the pulp and paper industry is striving to survive, studies demonstrate the potential value of the chemical composition of northern wood species to create new sources of revenue. This avenue opens a wide range of possibilities and the necessary amendments to include these new productions have to be evaluated. A transition could be made without overlooking the fierce competition among products/technologies to access specific fibre quality where the end goal is to maximize the fibre value. For instance, in replacement of the newsprint paper production in the Mauricie region, would it be more beneficial to introduce the production of biofuel, biochemical, carbon fibre, bioplastic, natural sweetener, etc.?

In view of that, the questions investigated in this thesis can be formulated as follow: considering the concept of sustainable development and the economic vectors of a network, is it possible to improve the overall value of an industry cluster by introducing new products? In parallel, what would be the impact of introducing a new product on the different stakeholders' revenues? How would that introduction affect the existing flows of raw materials, of by-products and of energies? What would be the environmental effects of such reorganization? And will this perturbation create or remove jobs in the region? Prior to answering these questions, an analysis of the context encompassing the problem must be conducted in order to develop a generic framework that reflects authentically the phenomenon under study.

The phenomenon can be illustrated by a stone dropped into still water, when the pebble touches the water, a disruptive effect occurs and creates ripples all around the impact point. Introducing a novel product into an existing network is similar; it creates ripples in the system. So, by emulating those ripples, we are able to study the extent of their repercussions and thus, evaluate the impact of introducing new products to an existing regional network. The key challenge here is how to configure both new and existing technologies within the regional cluster, considering synergies, competition, and resources availability in order to produce sustainable value. Creating sustainable value means to take economic, environmental and social aspects into account in the strategic decisions and thus contributing to regional economic development. To do so, the supply chain optimization may help in saving on the costs of a logistics structure regarding the fulfillment of customer demands (Chopra and Meindl 2012) and the introduction of new potential products may create new opportunities. In the context of a regional economy, the allocation of natural resources and their products between stakeholders might generate better global profit using value chain optimization. Thus, by optimizing the resources value through production and distribution technologies, different combinations of products and technologies can be evaluated to offer the most appropriate fit to benefit the overall value of the network.

Within the scope of this thesis, we focus our attention on the impact of introducing new products to an existing network. Network sizes may range from a manufacturing plant to a regional network. To properly assess the effect of altering the economic vectors of a network, a generic mathematical framework is proposed as a decision support tool. The mixed integer linear programming (MILP) model evaluates strategical level decisions of a production-distribution system where the objective is to maximize the value-creation while considering sustainable development, synergies, and competition. To guide and design the development of the decision support tool, the Canadian forest industry is considered due to its extensive and complex value chain network. Hence, an overlook of the industry is presented in the in CHAPTER 1 prior to the literature review (CHAPTER 2). In CHAPTER 3, a methodology approach is deliberated and leads to the development of the MILP model. The model is then applied in CHAPTER 4 to a realistic case study in the region of Mauricie, (Québec) Canada, where the introduction of seven new bioproducts is evaluated for the forest value chain. Finally, experimentations and results are presented and discussed in CHAPTER 5 in regards to the four (4) scenarios elaborated.

CHAPTER 1

THE FOREST INDUSTRY AND ITS VALUE CHAIN

1.1 Introduction

It all starts with the forest; a rich, complex, but also fragile ecosystem. Home of thousands of wildlife species, the forest has evolved throughout the ages offering shelter, protection, and prosperity to its inhabitants. Human populations have thrived on the forest bountiful wealth, and from one of its prominent resources (i.e. the wood), have developed an array of tools and construction materials to explore and shape the world. Over the centuries, a rise of the environmental awareness occurred and sustainable measures were undertaken. Nowadays, forest management and operations are carefully planned to perpetuate a stable harvest cycle, making the sector sustainable and strongly positioned to be part of the green economy. Nonetheless, some challenges remain to be solved as for how the industry can play a role in a low pollution based economy and what could be the successful pathways. Undeniably, developments and applications centered on the innovative use of wood have to be conducted implying high capital investments and risk-oriented management. This chapter is an introduction to how the Canadian forest industry is structured to define the context in which the case study conducted in this thesis evolves in.

1.2 The Canadian forest industry

Known around the world for its abundant quality products, the Canadian forest industry accounted in 2015 for seven (7) percent of the Canadian total exports, representing nine (9) percent of Canada's manufacturing gross domestic product (Natural Resource Canada [2]). It goes without saying that the forest industry is an important emblem of Canada's economy. Yet, the sector is affected by deep cyclical trends and market shifts that increasingly disturb its traditional foundation. While the last years were more clement, the notoriously difficult 2003-2009 period shook the industry and closed more than 450 mills across Canada. Up to this day, the sector has not fully recovered. On the other hand, the forest industry keeps

strong economic potential and uses this adversity to bring new ways of generating sustainable value through innovative products and technologies. Henceforward, Canada invests in its capacity to diversify the traditionally based sector by promoting the research and development of new products to secure new markets. Thus, in order to have a better understanding of the challenges, an overview of Canada's forest governance framework is presented, followed by a presentation of the Canadian forest value chain and its product portfolio. Finally, the sustainable aspects and their impact in today's economy are explored.

1.2.1 The governance framework

With a superficies of 9.985 million square kilometers, Canada is the second largest country in the world. Surprisingly, 35 percent of the country's superficies is covered by forest, of which 75 percent is in the boreal zone. To sustainably manage the exploitation of this profuse resource, a Canadian forest governance structure is developed to delineate power and establish the key roles. Interestingly, 94 percent of forest land in Canada is publicly owned and only four (4) percent is owned by the federal government [2]. In fact, provinces and territories have jurisdiction over most of the resource and together manage 90 percent of the total Canadian's forest by developing and enforcing laws, regulations, and policies.

The Canadian governance framework set rules, procedure, and informational guidelines to guide the industry and enforce the sustainable management of the forest. Laws and international agreements set or signed by the federal government have to be overlapped by provincial and territorial governments' legislations. Overall, the federal legislation helps international trades by ensuring customers that the Canadian products are legally and sustainably produced. Thus, to properly assess a regional forest value chain network, two aspects have to be further explored: what defines sustainability in forestry and how does the provincial and territorial jurisdiction affect the forest industry. To help understand the extent of these aspects, the definition of the forest value chain and its product portfolio is first conducted.

1.2.2 The forest value chain and product portfolio

The forest value chain is a large and complex system fashioned by an extraordinary versatile feedstock. The wood has the potential to create value from single and multi-stage processes where transformation wastes can be further processed creating a business-to-business (BtoB) circular economy. To model such a particular supply chain, one critical aspect originating from the intrinsic nature of wood transformation has to be considered. This aspect is the divergence incurred by the processes (i.e. divergent processes). What is meant by divergent processes is the capacity to transform one principal feedstock into many products. Supply chains based on this characteristic are for instance in the petroleum, sugar or the forest industries. Alternatively, convergent processes are seen mostly in manufacturing industries that converge many products to produce one final merchandise, for instance in the car, electronic, and machinery industries. This aspect wrought the forest supply chain and creates a network with its own specificities, and where vertically integrated companies are prevalent. In the following paragraphs, the Canadian forest value chain is described where traditional and novels products are overviewed.

1.2.2.1 Value chain network

When processed, wood is parted into various physical and chemical forms offering a wide range of possible interactions, where sets of processes can be formed and synergies developed. The forest industry has an extensive value chain starting at the harvesting area, followed by layers of production-distribution centers (PDC), and finally up to the customers. To support this complex network, stakeholders across the supply chain play important roles and their actions are directly or indirectly correlated to the value created. Traditionally, the forest industry was divided into three main segments: forestry and logging, pulp and paper product manufacturing, and solid wood product manufacturing. Over the years, developments in these segments have brought more performant products such as composite wood, high strength packaging paper, torrefied wood, etc., but the structure remained the same without any fundamental change. Generating quantities of waste, pulp mills and sawmills started to burn them as a source of heat and energy, to a point where combined heat and power plant became of commercial interest. This approach is of interest in the more

recent context due to its capacity to reduce our dependency to fossil fuel and improve the processes efficiency. Nowadays, the bioprocessing of the lignocellulosic biomass is of interest because of its potential to enhance the value extracted from the fibre using biochemical and thermochemical conversion processes. In Figure 1.1, a concept of the forest product industry value chain is presented with a consideration for the new bioproduct and chemical manufacturing segment and the expansion of the heat and energy production segment. The introduction of forest biorefineries (FBRs) to the conventional forest industry has a disruptive potential to fundamentally change the forest value creation network. Indeed, unexploited feedstock such as forest residues could be transformed into new sources of incomes, useful biochemicals could be extracted from toxic wastes, polymers could be extracted from the wood prior to being processed into paper, etc.

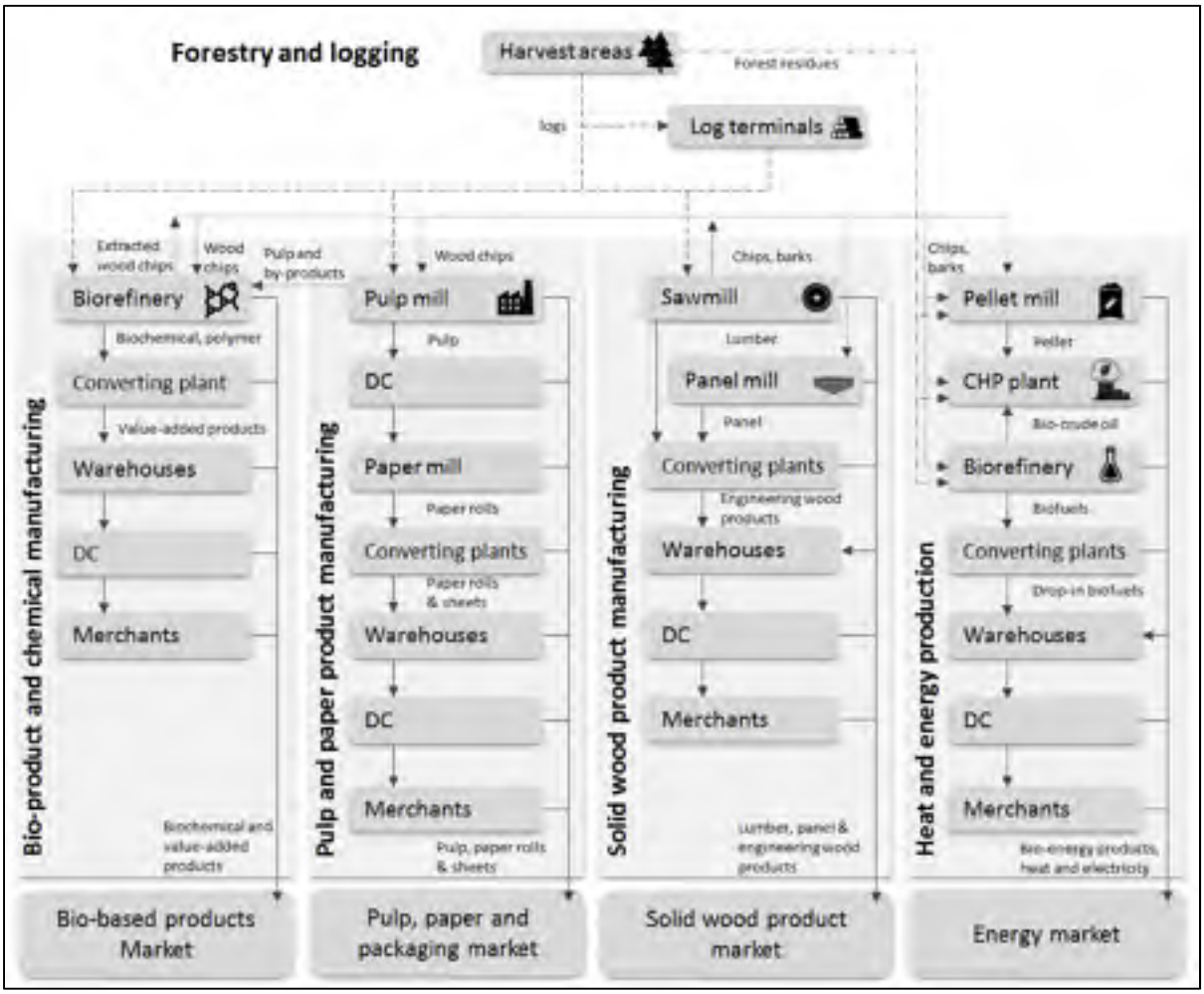

Figure 1.1 Forest product industry value chain – Adapted from D'Amours et al. (2008)

These avenues bring a new complexity to the traditional forest industry where new synergies could be created between the FBRs and the existing mills to promote value creation from the fibre. A biorefinery is basically a set of processes to transform biomass into various bioproducts and chemicals. Annexing a biorefinery to an existing mill to profit from the existing flows of heat, steam, energy, and products has also an interesting potential to reduce cost. This route is what makes the difference between an integrated forest biorefinery (IFBR) versus a standalone forest biorefineries. For an in-depth understanding of the forest value chain prior to the FBRs consideration, the author recommends the extensive review of the Canadian forest value creation network directed by Lehoux et al. (2012).

1.2.2.2 Traditional products

As previously mentioned, traditional products can be divided into three main sectors that are the pulp and paper industry, the solid wood industry and the forestry and logging industry. Together, these sectors contribute to the Canadian forest products trade balance. Basically, a balance of trade is the difference in value between a country's imports versus its exports. In Figure 1.2, the balance indicates that the Canadian forest industry is strongly oriented towards the exportation but then again, took an important downturn in the last decade.

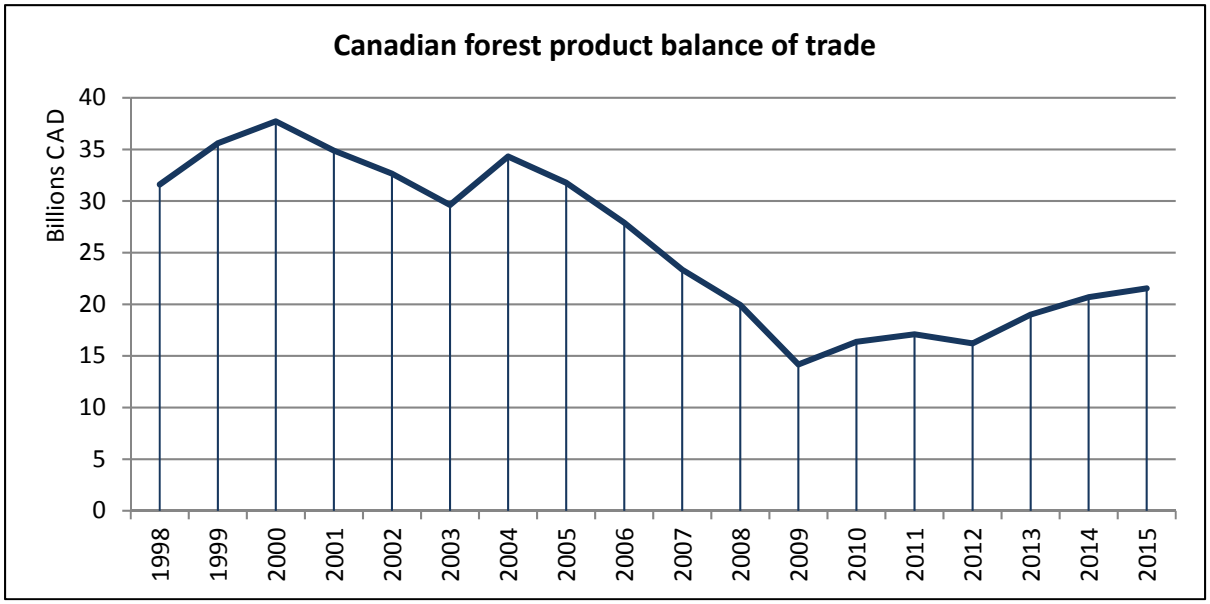

Figure 1.2 Canadian forest product balance of trade (Data Source: NRCan)

In 2015, the pulp and paper industry and the solid wood industry represented together 96 percent of the total export value, where three products contributed 55 percent of the total: softwood lumber, wood pulp (kraft pulp), and newsprint paper. The softwood lumber is highly correlated to the construction sector and was the most affected by the 2008 financial crisis with its largest export market being the United-States (U.S.). On another hand, kraft pulp (referring to Northern Bleached Softwood Kraft Pulp), was less affected by the financial crisis and remains a strong component of the forest value chain with good potential on the international market. Thus far, the Canadian forest economy strongly relies on the newsprint paper industry and is still today the world largest producer. Yet, demand for newsprint paper is continually declining ever since the year 2000 and its North American market has fallen by more than 65 percent. A summary of the forest domestic exports is presented in Figure 1.3.

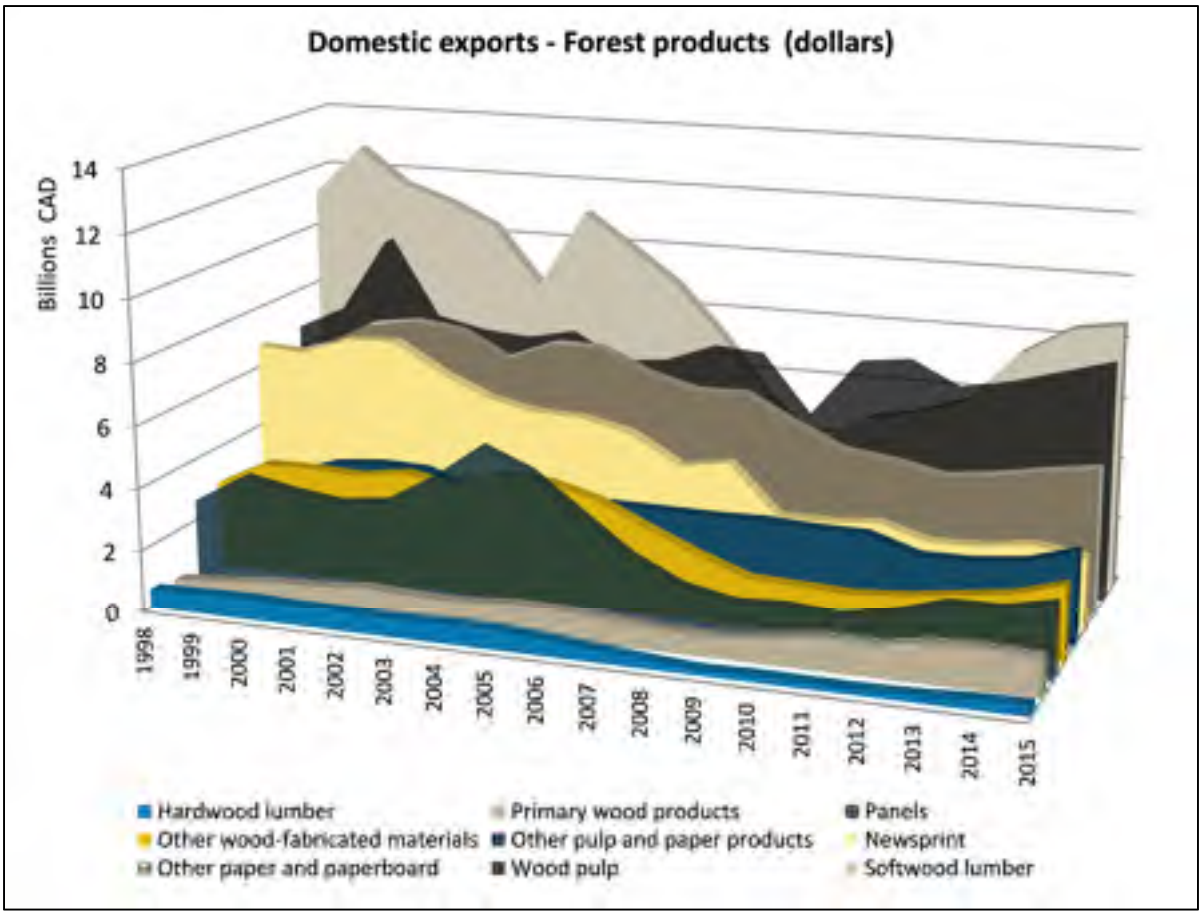

Figure 1.3 Domestic exports - Forest products (Data source: NRCan)

Overall, the analysis of the domestic exports specific to the forest products unveils that structural products such as panels (oriented strand board, plywood, fiberboard, particleboard, etc.) and other engineered woods compose a significant portion of the total exports and are highly influenced by the construction industry. Pulp, paperboards, and other paper products are stable commodities while the newsprint paper has lost a considerable market share with an average annual decreasing rate of five (5) percent in the last 15 years, leaving room for the integration of new productions. Another factor that influences the performance of the sector is where the forest products are exported. Prior to 2009, the majority of the forest product exportations were directed to the U.S., Europe, and Japan (See Figure 1.4). The U.S. is still today the most important segment while Europe and Japan thinned out. Nevertheless, Japan remains an important purchaser of high-value structural lumber for the construction industry. Interestingly, today's second largest segment of the forest product exportations goes to China with a persistently growing share. The market also starts to enlarge towards new needs and products and is now constituted of timber, high-value structural lumber and wood pulp which represent today more than 35 percent of the total Canadian pulp exports.

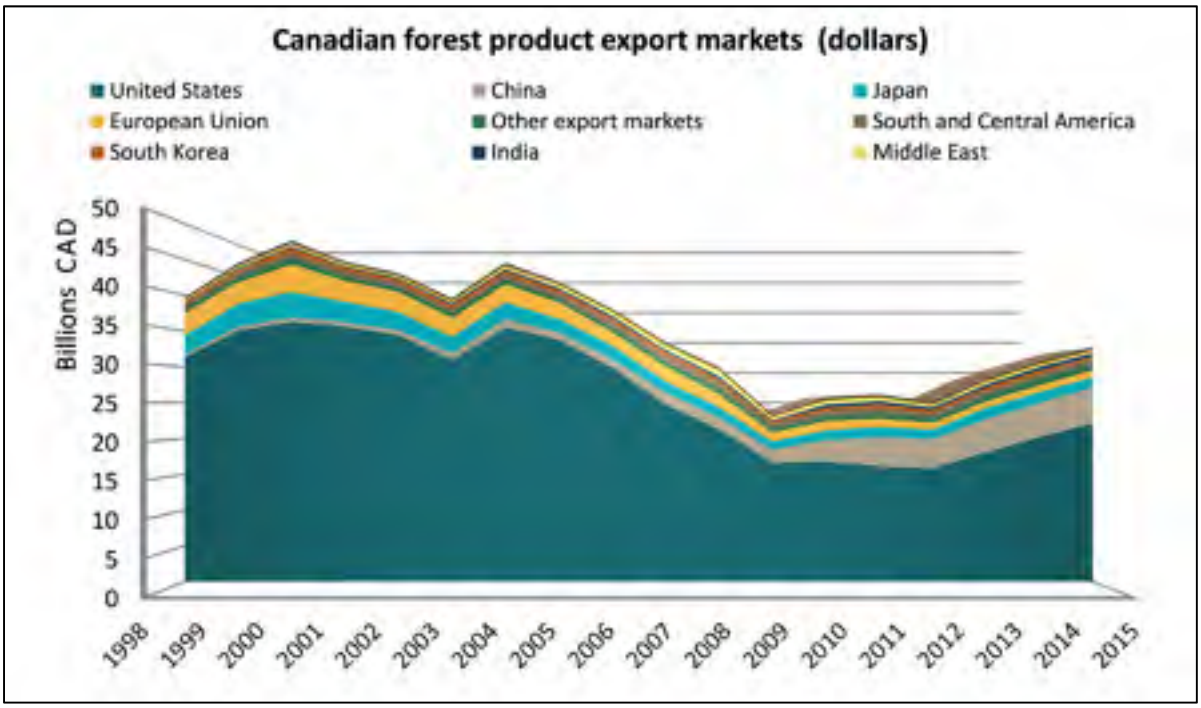

Figure 1.4 Canadian forest product export markets (Data source: NRCan)

Lastly, the domestic market plays a key role as a source of demand for the Canadian forest industry, whether it is locally, regionally or at a national level. Even though the Canadian domestic market has also succumbed to the financial crisis, the effects were milder and better controlled. The lumber and structural products industry represent nowadays more than 70 percent of the domestics consumption (based on the tonnage), and has an average annual growth rate of one (1) percent since 2005. In contrast, the pulp and paper industry has recorded an average annual negative growth rate of six (6) percent since 2005 and a diminution of the consumed volume in all sectors is denoted (see Figure 1.5).

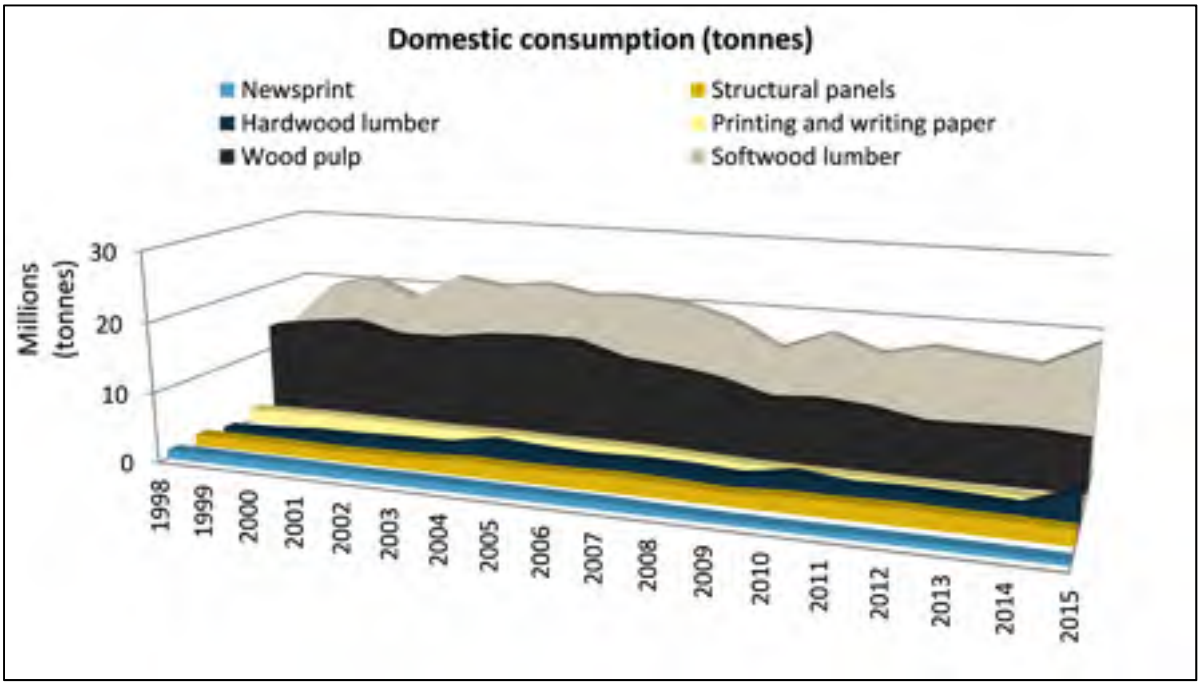

Figure 1.5 Domestics forest product consumption (Data source: NRCan)

1.2.2.3 Innovative products

Affected by economic trends and market shifts, the traditionally based forest product portfolio copes with adversity. From this situation, ingenuity combined to the industry's tenacity brings possibilities to transform the forest product manufacturing to a new revolutionary landscape. By diversifying productions and markets, the industry will be able to mitigate market risks and contribute to the fibre value creation network. One concept

vastly under study is the integration of FBRs. An extensive range of bioproducts can be extracted and produced from the wood fibre. While some processes have long been known, innovations in regard to their yield and cost offer now more viable options and enable competitive entry to the market. To help in this endeavor, research and developments applied to the bio-revolution have been supported by governments and industrials. The Bio-pathways Project has been launched by Forest Products Association of Canada (FPAC), FPInnovations, NRCan and many economic and scientific experts to offer a comprehensive overview of FBRs integration in the Canadian forest industry. In 2011, results from the second phase of the project identified a range of viable products with a global market opportunity of $200 billions. Many prospective products were featured in the report such as the transformation of dissolving pulp to rayon, the production of nanocrystalline cellulose from the old thermomechanical pulp (TMP) plant as a high value composite that can be use in the aerospace industry, the replacement or blend of petroleum base plastic with biodegradable bio-plastic, the use of lignin in tires fabrication, the production of drop-in bio-fuel from forest waste, and many other applications in the medical, pharmaceutical, food, and building sectors. In Figure 1.6, existing and future forest market segments are presented.

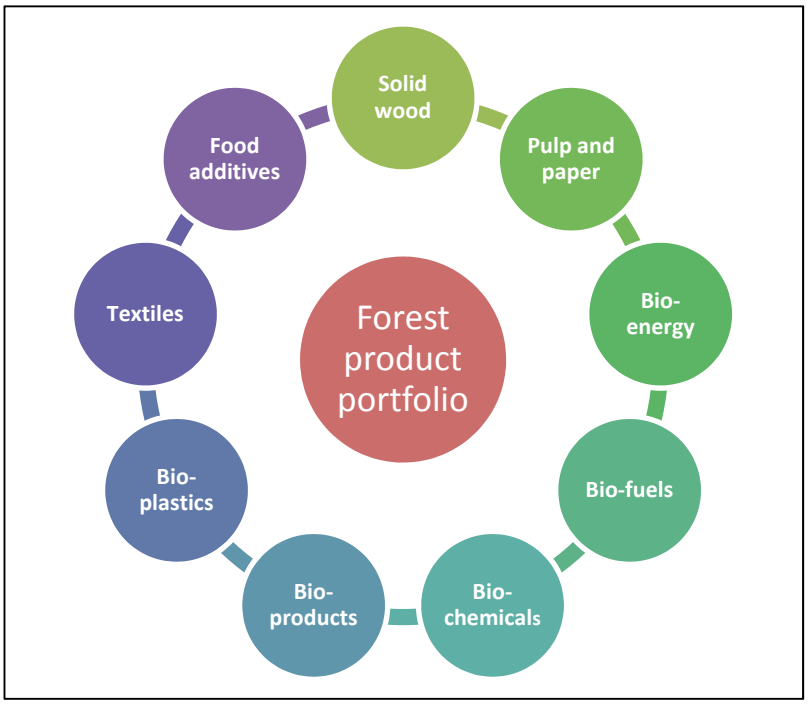

Figure 1.6 The forest product portfolio diversification

These avenues offer an occasion to maximise the value created from the fibre and to establish a well-grounded strategy for the future of the industry. Nevertheless, to access these new markets, challenges are still to be overtaken and the requirements to transform the industry have to be carefully calculated and coordinated. For instance, would it be more beneficial to integrate commodities, specialty products, or a combination of the two? When evaluating the feasibility of a project, three categories of challenges are to be considered: 1) how to produce the desired product and what is the technology readiness level (TRL) of the different options? 2) Is it viable to integrate this production considering the regional context? And 3) what would be the best market penetration strategy to adopt? If these three categories are answered favorably, then a risk calculated transition can be conducted. If enough projects are performed, the industry could be fundamentally changed not only economically, but also environmentally and socially.

1.2.3 Key considerations of sustainable practices

The characteristics of a forest value chain can be divided into four primary aspects: technical, economic, environmental, and social. On one hand, the technical and economic aspects were for a long time considered as the sole characteristics to develop strong businesses and industries, and are still today the key elements to consider in the evaluation of a project feasibility. On the other hand, the public and industries' awareness towards sustainability increases and environmental and social aspects are now known to be correlated to the industries long-term performance as well as to the regional development. Therefore, these aspects have to be measured in accordance with the strategic decisions to ensure the integration of sustainable practices. The integration of sustainable practices means to standardize and perform set of processes and procedures in regard to financial goals without any detrimental environmental or social effect. Accordingly, the organization of the technical aspects is here of importance to connect the influence of the physical operations to the economic, environmental and social considerations. These considerations are together the metrics that compose sustainability. In view of that, brief descriptions of these aspects are presented in the following paragraphs to put an emphasis on the elements that define sustainability in the forest industry.

1.2.3.1 The economics of a green industry

The economic aspect plays a great influence on how industries evolve, innovate and adapt to the increasingly complex world. Forest companies are torn between global competitions, changes in market needs, volatile exchange rates, unreliable trade agreement, and profitability. Fact is, forest companies are resource-dependent and standard determinants of competitiveness such as the labor cost, interest rates and economies of scale are insufficient to support their competitiveness on the international market. Furthermore, production-distribution centers and supply chains around the world are now more efficient and oriented towards low-cost operations, transforming what used to be a competitive advantage into a prerequisite. Consequently, Canadian forest companies have now to position their strategies in regard to future market drivers to gain new competitive advantages. The forest industry is composed of large multinational organizations and also small and medium-sized enterprises (SMEs), and both have now to use innovation and market orientation to strengthen the industry. The economic development of the forest industry has come to a crossroad where traditionally volume-oriented strategy has to be mixed with high value-oriented strategy. This approach facilitates the access to one of the major future drivers that is the international market. A study conducted by DeLong et al. (2007) has set forth that mainly multinational businesses are under the globalization pressure, and that the SMEs' largest consumers were the local markets. These conclusions are suggesting that while SMEs are not fully overwhelmed by foreign competitors, there is a large opportunity to expand markets. Yet, old manufacturing approaches and products have to be revised to ensure competitiveness on future market drivers such as the advent of the green economy. Here, the green economy is the accomplishment of all of the necessary activities to satisfy the customers' demands, from the resource extractions to the disposal of the products, by enforcing sustainable practices. This approach is a means to rectify the market failure that is the high toxicity and waste oriented production era that is destroying eco-systems and future generations' potential to have a similar level of life. From this new economic driver, products' business cycle will be altered and adjusted and the forest industry is well positioned to benefit from this development. One economic driver identified by Dasmohapatra (2009) is originating from the intrinsic nature of the resource: its renewability. Promoting forest bioproducts, material,

and chemicals to environmentally conscious consumers will be key of future international trade. Small environmental footprint products, eco-friendly construction developments, and sustainable practices are today's important considerations to take part of the bio-revolution. Thereby, oriented marketing coupled with innovative products and efficient supply chain structure will be the key ingredients for the Canadian forest industry to perform on the future green international trade.

1.2.3.2 Environmental concerns

Forests are the lungs of the planet; a renowned sentence used by many to remember the importance of this resource. It refers to its capacity to balance the earth's carbon dioxide (CO_2) supply and exchange, a vital component of life on earth. While this critical aspect help to understand the importance of the forests, many more aspects are as much essential to sustain good balance on earth, whether it is in connection with the soil conversion, the biodiversity, and the hydrological regimes (NRCan). Forests are complex ecosystem and their depletion might have long term effects on climate and drives climate change (National Geographic [3]). Many questions arise on the consequences of harvesting this precious resource and as matter of fact, poorly planned forestry operations have certainly a negative impact on the environment and wildlife. On the other hand, forests are renewable and have the potential to replace highly polluting commodities such as steel, concrete, and plastics. As described by Patrick Moore, co-founder of Greenpeace, in an essay written in 1999 [4], the forest is the most sustainable primary industry known to the world; it is the most formidable sun converting facility and is more sustainable than any steel mills, concrete works, or oil refineries. In point of fact, the forestry can not be categorized as deforestation, it is simply a renew of the forest. The real cause of deforestation is rather originated from the need of agricultural lands and urban sprawl. The author also advances that the management of forest may results in better overall forest health by reducing chances of disease, by preventing and lessening wild fires, and by accelerating growth and biodiversity through forest rejuvenescence. Nevertheless, and as stated by the Food and Agriculture Organization of the United Nations (FAO) [5], complete information on whether well-managed forestry operations has positive or negative environmental impact are not available due to the sheer

complexity of the system. One main consideration and metric used to interpret the sustainability of industrial activities is related to the emissions contributing to the greenhouse effect. In the context of deforestation, that is to say, the removal of the forest with the intent to use the land for another purpose, the capacity of the trees to absorb CO_2 is then canceled leading to greenhouse gas (GHG) emissions. What is meant by the capacity of trees to absorb CO_2 refers to the plant's ability to capture and store CO_2, known as biological carbon sequestration. Then again, if proper management of forestry operations are conducted, it has the potential to absorb more CO_2 than the operations produce. According to the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* report by the United States Environmental Protection Agency [6], the largest source of man-made GHG emissions comes from the combustion of fossil fuels to power industries and transportation, while the forestry and land use had an offset of 11.8 percent of the 2015 U.S. GHG emissions. There is an opportunity to use this advantage to convert traditionally polluting sector by mixing and adding forest based bioproducts, biofuels, biochemicals, and bio-materials. This transformation can be supported by the life-cycle sustainability assessments of the industries to promote the forest industry and to sustain, convert and return lands to forest, where biodiversity and economy can flourish sustainably.

1.2.3.3 Socially beneficial, but also morally accepted

When foresters look into the Canadian forest industry, they might see progress, decent management, and potential. Alternatively, public opinion seems to be far harsher and may perceive it as the cause of deforestation, of the destruction of beautiful landscapes, and as an ecological disaster. A major challenge related to the social aspect is to rally the perceptions dichotomy related to forestry activities between the public and the industry. Forest industry's stakeholders must understand the extent of their actions and carefully value what are the repercussions on forest-dependent communities, aboriginals' rights and culture, landscapes, and peoples' health and well-being. Favorable public opinion is crucial to develop a strong forest economy. Therefore, the emphasis on the environmental issues through proactive green marketing could tilt the balance towards bioproducts originating from the forest. This approach has been proposed by Kärnä et al. (2003), where a competitive advantage could be

fashioned with green values, environmental marketing strategies, structures, and functions where the forest can not only be socially beneficial, but also morally accepted and promoted by the public. To explore the connections between the industry and the public, a study on the social impacts of forestry conducted by Dhubháin et al. (2008) divided forest stakeholders into three categories (i.e. producers, consumers, and decision makers). Then, they interviewed representatives of each category and extracted the common emerging themes. Employment, landscape, and communication were the considerations commonly brought forward. Employment opportunities are the first most considered criteria to assess the social aspect and is a key driver of the economy. However, the automating of most processes reduce and remove jobs and modern mills are able to run with a minimal staff. On one side, companies and governments say that the industry creates direct and indirect jobs opportunities, while on the other side, the workforce reports that the industry generates little local employment. Another preoccupation is the effect of forest operations (i.e. harvest, silviculture, thinning, etc.) on the landscape. When forest operations are conducted, heavy equipment has to be transported, and once on the site, the objective is to maximise the profitability of the operation within environmental boundaries. These operations drastically change the landscape and it is the citizens that are left with the visual results. The last theme is of importance because of its capacity to unite the stakeholders in the management of the public forest. Communication has the power of giving voice to events, to value what is cherished and to understand the point of view of all stakeholders. Accordingly, the Canadian forest regime considers the opinion of all stakeholders. This approach is a means to transform the industry not only to be environmentally friendly but also to be socially valuable, where the forest may be beneficial to many purposes (e.g. forestry, non-timber related economic activities, outdoor activities, wildlife observation, recreation, etc.). Nevertheless, compromises in all camp have to be accorded and a considerable work of sensitization is required to change the subjective conceptions. Together, these three themes (i.e. employment, landscape, and communication) may represent the foundation to unite stakeholders where each faction is consenting to promote sustainable forest practices. These requirements are necessary to build and develop sustainability throughout the forest value chain and may help in the transformation of the industry.

1.3 Quebec's forest jurisdiction

The commitment of the Canadian government to sustainable forest management principles is key to succeed in the oncoming green economy, to ensure the development of an environmentally friendly industry, and to benefit Canadians across the country. The required management to accomplish this objective is then conveyed to provinces and territories, which have jurisdiction over the vast majority of the public forests. By integrating federal laws and regulations to theirs, the provinces and territories structure, manage, plan and allocate forest resources on the behalf of the population allowing economic development and sustainability. Therefrom, to correctly model the Mauricie, the region considered for the case study, a presentation of the Quebec's forest regime and structure is explored in the following paragraphs.

It is in 1972 that the first forest regime appeared in the province of Quebec. This forest regime was intended to replace the concessions based management to a more holistic governmental management of the public forest. The aim was to satisfy the rapidly growing commercial requirements of wood taking in consideration the underutilized fibre supply of the public forests. The justification of a forest regime originated from the observation that companies are short-term profit-oriented entities and that the forest is a slow paced system that requires long-term management. The regime was proven unsustainable and a new regime was deposed in 1986 where the management of the forest was returned to the companies under the timber supply and forest management agreement (TSFMA).

In 2013, the Sustainable Forest Development Act is passed as a new and more sustainable forest regime which takes into consideration the participation of the aboriginal communities, municipalities, and takes an integrated regional development approach. The objective of this new regime is to enhance and diversify the socioeconomic development of the public forest by facilitating the access to fibre. Thereby, the government take under its responsibility the forest management activities and establishes the guarantee of supply in replacement of the TSFMA. To do so, a Chief Forester is nominated to determine the annual allowable cut

(ACC) of the regions. Each region has a *Commission régionale sur les ressources naturelles et le territoire* that define the orientations by creating the integrated resource development plan. Every region is divided into a number of forest management units (FMU), where the *Ministère des Forêts, de la Faune et des Parcs* (MFFP) has the responsibility to develop the *Plan d'aménagement forestier intégré tactique* (PAFIT) for each of FMU. This tactical planning has to follow the federal and provincial laws and regulations, the sustainable forest management strategy, and the public land plan. The PAFIT has then to be confirmed by public consultations. The tactical management of the land resources is conveyed by the *Conférence régionale des élus* (CRE). On the operational level, the MFFP develop the *Plan d'aménagement forestier intégré opérationnel* (PAFIO) which is then used by the industry. To access to the fibre, a non-transferable supply guarantee is provided to wood processing companies each year under the annual program. Besides, there is also a possibility to acquire fibre by an auctions system organized by the *Bureau de mise en marché des bois du Québec* (BMMB).

1.4 Conclusion

The forest's intrinsic wealth is of an amazing complexity and its role in the balance of life is of great importance. With conscientious forest management and operations, the sustainable use of this resource may be key to a greener economy. With this philosophy in mind, the definition of what compose sustainability in forestry has been defined in this chapter. A brief exploration of the forest value chain was conducted with an emphasis on the traditional and potential products. Finally, the Quebec's forest jurisdiction structure overviewed to understand how the allocation of fibre is managed. In the following chapter, a literature review is elaborated to guide and structure the development of a generic mathematical model that can be applied to a specific value creation network, for instance, the forest value chain.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In the previous section, the Canadian forest industry is presented where the confrontation between opportunities and challenges is brought forward. Novel products, technologies, and sustainability are today's driving force of the industries development, and their effect has to be carefully evaluated. This section presents a literature review to agglomerate the knowledge around the subject proposal: *A generic decision support model for analyzing the sustainable integration of new products: An application to the forest value chain*. Thereby, the general concept of a value chain is explored to identify the key elements that compose and structure of such a network, and afterwards, its application to the forest industry. Subsequently, the production-distribution design approach is considered for the development of a generic mathematical framework where the impact of product integration can be evaluated. Finally, an outlook on how the economics, environmental and social aspects can be modeled is explored.

2.2 Value creation network

Including the value chain as key foundation of the decision support model is established on the principle that the concept considers a broad spectrum of a network's aspects. First defined by Michael E. Porter in 1985, the notion of a value chain is then synthetized as the strategic activities performed by an organization to improve its competitiveness. With the aim of creating value, companies structure their processes to accomplish the organization's competitive scope, where primary activities are subjected to their support activities. The concept of value chain network, also known as value-creation network or value chain architecture, has been well defined throughout the years and complete knowledge of the value chain concept and modeling have been regrouped and structured by Shapiro (2007) and by Kannegiesser (2008). When first defined, the concept of value chain had the limit of

considering only intra-organization value generation. To promote an inter-organization approach, the notion of supply chain is added to the value chain concept, where the logistics costs are minimized and the value maximised (Holweg and Helo, 2013). As a result, the value chain complemented by the supply chain network concept offer an inter-organization design where company internal value chain contains procurement, production, distribution and sales, and is subsequently connected to other companies' value chain considering location and transportation. By creating a network of value chains, cooperation, competition and synergies can then be considered, and therefore, the assessment of product integration monitored. The use of strategic inter-organizational network may also help in gaining competitive advantages and production efficiency (Talluri et al., 1999). The consideration of the value chain may be a solution for the fast integration of products keeping a low cost and high quality by using the strength of the existing network, where network organization and the creation of partnership can be evaluated. As explained by Bosch-Mauchand et al. (2010), the unceasingly growing constraints imposed by the customers force the organizations to be more and more performance oriented. The consideration of the costs is not enough anymore due to its lack of consideration of other aspects. This is why the value-based approach is a more balanced mean to gain competitive advantages. Accordingly, the maximization of the value enables the development of potential synergies and a better utilization of the resources.

An interesting use of the value chain concept applied to the forest industry is proposed by Weigel et al. (2009), who present a model in which the fibre supplies are considered in order to maximize the value created in the Canadian pulp and paper sector. The mixed integer linear programming model developed corresponds to the activity of a single integrated pulp and paper plant. The classification and allocation of the fibre is introduced in the supply chain into two parallel strategies. The first strategy is to assign the fibre types to the best suited end-product and the second strategy is to select a portfolio of end products and generate the maximum value out of the available fibre supply. Additionally, the selection of the appropriate production technologies and capacity are considered. This research demonstrates that the value chain could increases the potential profit by considering fibre types, creating a competitive advantage. However, a limit denoted is the lack of consideration

for the other stakeholders in the network, removing potential synergies, cooperation, and competition factors. The network structure become of importance when considering virtual value chain business model, where cooperative innovation between stakeholders can be created from synergies that is not available considering a company's structure alone (Walters and Rainbird, 2007). By combining processes and product innovation in a holistic supply chain structure, potential value is engendered and the efficiency of the network enhanced. In this work, the forest value creation network is studied and analyzed to identify the potential value. One concept vastly under study is the integration of biorefinery to the forest value chain where new commodities and value-added specialty products are introduced as potential complements. In the following section, the concept of forest biorefinery is reviewed.

2.3 Biorefinery

A biorefinery is a set of processes to transform biomass into various bioproducts and bio-chemicals. The concept offers a great potential to transform the forest industry through the introduction of commodities and specialty products to the forest product portfolio. Nowadays, this approach is of high interest because of its capacity to create competitive value. When considering the integration of biorefineries, the techno-economic, market, and sustainability criteria necessarily have to be evaluated (Téguia et al., 2017). Notwithstanding, the incorporation of new products is a complex problem and the integration of biorefinery processes to an existing organization involve an enterprise transformation. The product portfolio definition and management become then of critical importance and offer an opportunity for companies to improve their business model (Chambost et al., 2008). This opportunity has the potential of rejuvenating declining industries such as the newsprint paper industry, and to reinforce the position of competitive industry. The identification of strategies to transform existing industry is studied and potential pathways identified. For instance, a study on how biorefineries can reinforce the existing thermomechanical pulp mills has been conducted by Jeaidi and Stuart (2011), where the identification and design of step-wise implementation strategies are developed. The investigation on whether it would be more advantageous to strongly integrate the biorefinery to the existing process, or integrate it

parallel to the process is conducted by the authors. When considering the integration of new products, it becomes of importance to have a supply chain adapted to the products characteristics. Thereby, the evaluation of the bioproducts in regard to their supply chain requirements and potential has to be conducted (Dansereau et al., 2014). A study proposed by Ekşioğlu et al., 2009 helps in assessing the logistic challenges to structure and optimize the supply of biomass to biorefinery, considering the number, size, and location of the biorefineries. In the model, a supply chain design is considered, where the strategic and tactical decisions are coordinated. Nevertheless, a strong supply chain network design is not guaranteed of success without the proper biorefinery process design. Thereby, the connection of the supply chain to the processes may offer a more robust approach to the problematic. A study conducted by Mansoornejad et al. (2011) integrates the concept of supply chain to the process integration strategy of a forest biorefinery considering a flexible design. Design alternatives performances are then evaluated considering different market conditions. While most effort put on the forest biorefinery have been based on the techno-economic analysis, the process design, and biomass logistics, Dansereau et al. (2012) advanced that products research and integrated planning may help in the product portfolio diversification decision and management. A study by Sharma et al. (2011) proposed a similar concept where the technology integration and product portfolio assessment is conducted in a multi-product multi-platform biorefinery. A MILP model is developed with a utility function aiming to maximize the stakeholder value. The consideration of the feedstock, technologies and associated capacities are considered, and costs and credit related to environmental implications are included.

One particularity of the biorefinery is the capacity to generate value from waste produced by traditional forest operations. The waste can be processed to produce biofuel and bioenergy, and their flows have to be considered when considering the forest value creation network. A model considering the flows of energies and residues was developed by Feng et al. (2010), where the model considered the maximization of the supply chain value using the net present value (NPV) of an integrated biorefinery. The model takes facility location, capacity allocation and technology selection into consideration in a multi-period, multi-product and

multi-echelon design. Another study conducted by Cambero et al. (2014a) continues in the same direction and justifies that there is an opportunity to create value from throwaways (tree tops, branches, leaves, non-merchantable stems) and mill waste which are generally left in the forest, burned or disposed in landfill. In addition to the previous article, the model allows the positioning of plants throughout the periods. These models take in consideration the supply chain potential in combination to the technologies selection to maximize the network value. The use of waste in the production of biofuel and bioenergy is a potential alternative to fossil fuel where beneficial impact on the environmental and social aspects can be denoted. The importance of these two aspects is growing and the consideration of strictly oriented economic value is now insufficient in the assessment of projects (Shabani et al., 2013). Accordingly, the following section presents the criteria considered to assess the sustainability of a project.

2.4 Sustainability

The sustainable consideration in today's industry is growing in importance. Approaches and technics are now investigated to take in consideration the impact of economic oriented objectives on the environmental and social aspect. The development of mutli-criteria decision making (MCDM) model is introduced in the forest industry to identify potential solution respecting sustainable consideration. A model developed by Mendoza and Prabhu (2000) proposes a MCDM model for the Indonesian forest concession where sustainable forest management is studied. The criteria considered were based on the social, ecology, policy and production category. Another approach is the consideration of sustainable aspects in a multi-objective optimization, where the profit is maximised and the environmental impact minimized. Santibañez-Aguilar et al. (2011) takes this approach where the environmental impact measurement is based on the life cycle analysis methodology. The authors used the eco-incator-99 which can be categorized into three main category of environmental impact: 1) damage to the human health, 2) damage to the ecosystem quality, and 3) damage to the resource. An extensive literature review on the forest biomass sustainability assessment was conducted by Cambero and Sowlati (2014b). Conclusions of the review indicate that while

the life cycle assessment studies were widely used, their consideration does not allow a complete sustainable evaluation of the forest biomass utilization. A new trend is to consider the integration of economic, environmental and social aspects in the assessment and optimization of the value chain. Nevertheless, the emergence of multi-criteria objective and LCA is an interesting avenue to consider. In most of the article reviewed, the environmental indicator is mainly tied to the GHG emission and where social impact is limited to the employment. A model developed by Sharma et al. (2011) takes sustainable development into account in the product portfolio assessment of a biorefinery where the environmental aspect is tied to greenhouse gas emissions and waste streams, and where the social aspect is tied to the impact on local communities. A forest biomass supply chain optimization model proposed by Cambero and Sowlati (2016) take in consideration a multi-objective approach of based on the economic, environmental and social aspects. The model is solved using a Pareto-generating method where the net present value is optimised considering job creation and greenhouse gas emissions. Lastly, the concept of industrial cluster and circular economy is brought forward where the remanufacturing engineering help to save resource and to protect the environment (Sima and Wang, 2011). This approach can also be used for the revalorisation of waste generated by a production-distribution network, a network design explored in the following paragraph.

2.5 Production-distribution network design

The production-distribution network design approach has been well studied over the years. A good literature review of the early fundamental writings by Vidal and Goetschalckx (1997) proposes an extensive review of global supply chain modelling. From location, capacity acquisition, technology selection to multi-echelon, multi-period and multi-product models, the literature is expanding towards a more complex concept of the supply chain network. Here, the development of such a network is considered to assess the integration of new products, where the potential impact of technology integration in regard to the existing product portfolios of companies has to be evaluated. The introduction of new product that are not compatible to a company strategy may lead to negative impact (Bruch and Bellgran,

2013), and a decision support tool may help to mitigate this risk. A framework proposed by Jugend and Luis da Silva (2014) identify three main criteria that influence the product portfolio management performance that are the methods, the organization and the strategy employed. Thereby, an approach to consider is the holistic perspective of the product portfolio where limited resource and projected returns have to be evaluated. Accordingly, three concepts subjacent to the production-distribution network have to be considered: the location, the technology selection and the supply chain structure. Considering all of these aspects, a model developed by Paquet et al. (2004) present a generic algorithm with a focus on the production function. The notion of technology selection decisions is then added to a manufacturing network that produces several products with non-trivial bills of material (BOM). In line with this work, Martel (2005) presents a general multinational production-distribution model with convergent manufacturing processes. Vila et al. (2006) subsequently expanded the model to divergent manufacturing processes where facility location and capacity options were considered in an optimization of the global profit after tax.

In this work, the concept of facility and technology location is critical. Location problem is a well-established research area in operational research and models of this type have been applied in many industrial contexts (i.e. automotive, chemicals, food, forestry, hardware, etc.). A literature review of the facility location problem in the context of supply chain management was conducted by Melo et al. (2008). The authors pointed out that one interesting factor to consider in the location problem is the resource allocation that may have a consequential effect on the result. More criteria that can be considered are the capacity, inventory, procurement, production, routing, and the transportation modes. Therefore, to properly assess the impact of these criteria, the supply chain structure has to be included. An interesting literature review of the upstream logistics optimization of the forest biomass in the purpose of producing biofuel was completed by De Meyer et al. (2014). The authors stated that in the optimization of the upstream biomass supply chain, the interrelationship between all supply operations and their location highly influences the outcomes. Furthermore, the sustainability concept in the supply chain management needs to be considered to develop competitive network where economic, environmental and social

objectives are included. Thus, to overcome the challenges, biomass supply chain optimization is essential. Different programming methods are available and for tactical and strategic planning problems, the mixed integer linear programming method can be used. One inconvenience of the method is the large number of decisions variables required to emulate a complex supply chain. With a different approach to the problematic, an analysis covering the biomass processing, from the biomass supply to the bioenergy production was conducted by Cozzi et al. (2013). In the analysis, the biomass availability, harvesting, transportation, and distribution were considered under technical and economic measures. The economic metrics used are the NPV, internal rate of return (IRR) and payback period. One correlation identified by the authors was the effect of biomass density and distances to the harvesting and transportation costs. Conclusions of the analysis indicated that the conversion of forest residues to biofuel can have a payback period of less than ten (10) years without the help of incentives, and had a strong potential to increase regional employment.

2.6 Conclusion

The integration of biorefineries to the forest value chain has the potential to rejuvenate the industry and to contribute to the development of a sustainable economy. In this chapter, four (4) concepts are explored to identify the key elements to assess the impact of integrating new products to an existing network. To the best of our knowledge, no one has addressed the problem of products integration assessment into a value chain composed of stakeholders. More precisely, the impact on the profitability, the products flow, and the sustainability of a production-distribution network considering divergent processes with BOM. In the following chapter, the methodology approach and the formulation of a generic MILP model are presented.

CHAPTER 3

METHODOLOGY APPROACH AND MODEL FORMULATION

3.1 Introduction

Driven by economic objectives, companies seek competitive advantages through the development of strategies tailored to their organization. By considering a holistic approach around the economic vectors of a region, companies may gain a more comprehensive view of the existing potential and the impact incurred by their strategies. In the previous chapter, a literature review was elaborated to define concepts and prospective approaches to guide the development of a decision support tool with the aim of assisting decisions makers in the context of products integration. In this section, a methodology approach is first proposed and a mathematical model developed.

3.2 Methodology approach

To assess the impact of integrating new products to an existing network on the economic, social and environmental aspects, variations have to be applied to the parameters that constitute the technical aspect. The technical aspect is the one that defines, structure and bound the potential of a network. It takes into accounts all of the connections required to satisfy the customer's demand and has a direct effect on the outcomes of the other aspects. Moreover, the identification of the synergies may be enabled by structuring the information about the stakeholders' activities and thereby, allow the assessment of the impact of introducing new products. Certainly, a wide range of effects can result from the modifications carried out on the existing network. It is then necessary to define the key parameters and to measure their influence in order to identify the avenues of improvement. When looking into the structure of a region, the first consideration has to be the identification of the factories and their specificities. For instance, to which companies are these factories belonging to? What are the core business products? What are the requirements in terms of chemicals, utilities, energies, and feedstock? What are the production and distribution

technologies and their associated capacities? What is the efficiency of the mills? How are they disposing of their wastes? How many employees are required? It goes without saying that many questions have to be well-thought-out but in doing so, the establishment of the necessary constraints can be organized to offer a better understanding of the existing network. These considerations become of importance bearing in mind that the integration of new product may alter the flows and subsequently affects existing synergies. When studying the product integration process, the flows of the raw materials and products in the regional network can be assessed to determine whether it is more beneficial to directly buy the feedstock, to replace an existing product, or to connect the supply requirement to a process by affecting or not an existing production. When processed, raw materials are fragmented into components of which many products can be derived. Hence, when a process requires only some of the feedstock constitutive elements, by-products can then be promoted. In addition, the flows of by-products and wastes resulting from the production processes may hold a strong economic potential. Here, the concept of business-to-business circular economy can be applied where value-added products are developed from the waste. To explain this statement, we have to perceive a regional network as a potential value creation network, where the aim is to maximise the resources value. Therefore, to identify the potential, three questions can be examined: What are the available natural resources and which products are they transformed into? Are there any wastes generated and how are they disposed or reused? And what kind of energies are used and/or produced? Furthermore, to properly assess the integration of new products to a network, the potential impact has to be evaluated through sustainable metrics. In this work, the environmental and social aspects do not influence directly the utility function and only their associated costs are included (i.e. emissions, wastes disposal, salaries). Nevertheless, their monitoring is essential to properly assess the sustainability of the proposed production, and metrics are included, and control over their cost enable. Then, it becomes possible to take into account the economic vectors by configuring the interactions in the network in order to enhance the global profitability. Thereby, to maximise the value, the utility function has to consider the economic aspect. The economic aspect is required to evaluate the scenarios and is the base referential to assess the impact of products integration. By optimizing the overall value generated, the model is

selecting the most suitable options considering existing and potential activities. Accordingly, all of the acquisitions, connections, and transformations must be associated with a cost as well as all of the necessary structure around these processes. The capital costs and the variable costs (production, distribution, transport, waste disposal, and emission) are taken into account to calculate economic metrics for the companies' options, and further, for the value chain network. The economic metrics that can be used are for instance the net present value (NPV), the internal rate of return (IRR), the return on capital employed (ROCE), the return on investment (ROI), the earnings before interest, taxes, depreciation, and amortization (EBITDA), etc. In the utility function, the net present value is chosen as the optimization metric. The NPV is best suited in the product assessment because it allows comparing investment options, where time frame, cost of capital, and risk factors can be included. Here, the multiple period assessment is important because new products have initially low or difficult market accessibility. Consequently, the consideration of the demand on a multi-periods basis enables the use of the compound annual growth rate (CAGR) annexed to specific products which could influence on the opening of the technologies.

One challenge in the development of the mathematical framework is to keep a general approach to model as many types of value chain as possible, and to enable the consideration of several value chains simultaneously (e.g. forestry and mining value chains). The purpose of the model is to help in the process of evaluating which products have the most desirability to a specific network. Therefore, to keep a generic structure and to enable the recreation of a value chain, a production-distribution network approach is considered following a multi-echelon, multi-product, and multi-period design. The model is structured in two levels. First, it employs strategic level decisions to find optimality where an aggregated tactical level is used to generate data and keep the interactions as true to reality as possible. The formulation of the model follows a mixed integer linear programming method to optimise the net present value of the value chain. The model is divided into three segments (i.e. inbound logistics, production processes, and outbound logistics). The multi-echelon design integrates the complexity of the location-allocation problem considering the road network, where acquisition sources are connected to the production-distribution centers, and then to the final

delivery nodes. By creating a mathematical representation of a chosen regional network, the user is able to optimize the value-creation where the impact of potential products can be assessed. The model developed does not, however, offer a precise supply chain solution due to aggregation used and the sheer scale of the problems considered. In Figure 3.1, the framework of the decision support model is presented and structured around the forest value chain. As inputs, the information on the existing network is sent to the model where potential products, production and distribution technologies and market trends are structured. The model takes this information into a deterministic structure and maximizes the NPV of the production-distribution network. As outputs, information on the economic, environmental and social aspect is then extracted.

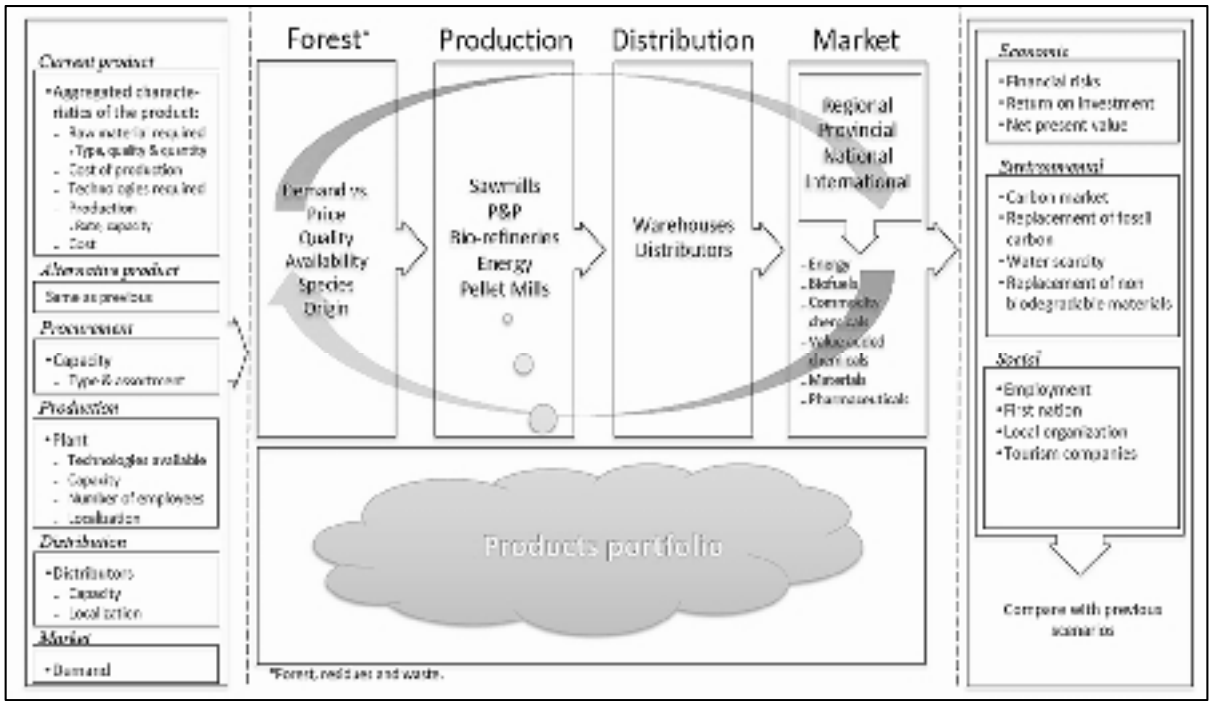

Figure 3.1 Data process framework

To develop the production-distribution structure, the concept of SIPOC (supplier - Input - Process - Output - Customer) is applied to each center. Those centers are then interconnected through a defined network to reflect the holistic approach required. One particularity developed in the model is the capacity to take many inputs and to process them into many outputs. To do so, the concept of bill of materials is combined with the divergent process

approach. Thereby, to manufacture a product prompted by the demand, the model has to use recipes. In the inputs, raw materials, chemicals, energies, man-hour, equipment durability, water consumption, and many more criteria can be considered. In the outputs, manufactured products, by-products, waste, and emissions are returned to the production-distribution network. When returned to the network, outputs that are not directly connected to the demand (e.g. wood chip, black liquor, etc.) are reintroduced to processes to optimize the value and to reduce the waste produced. Here disposal costs can have a critical impact on the solution (e.g. water treatment, landfill of solid waste, carbon tax, etc.). To control the production and to balance the flows of raw materials, products, and waste, an extensive flow equilibrium constraint is required. A visual representation of the aspects, nodes, and connections is presented in Figure 3.2. The flow equilibrium has to consider the flows from the raw materials to the final delivery points, where resources are introduced to processes forming new and altered products.

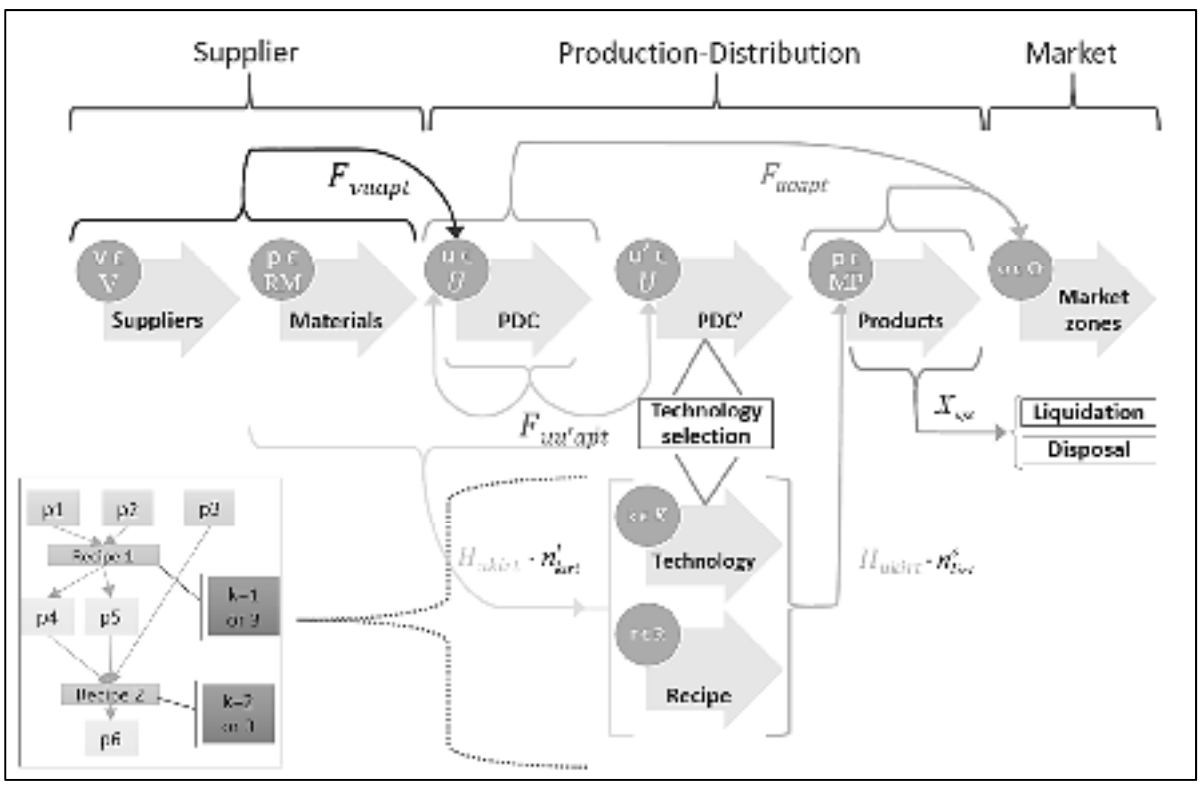

Figure 3.2 Flow equilibrium constraint

3.3 Model formulation

The following generic model is a means to emulate a production-distribution network by considering potential and existing sites $s \in S$ (i.e. from supplier $v \in V \subset S$ to customer zone $o \in O \subset S$) to allocate effectively product $p \in P$. The value creation is assessed by combining technologies $k \in K$ and recipes $r \in R$ in a production-distribution center $u \in U \subset S$. The requisite indexes, sets, parameters, and decision variables are presented below.

3.3.1 Indexes

$p \in P$	Product families.
$s \in S$	Potential network sites.
$r \in R$	Potential recipes.
$k \in K$	Potential production and distribution technologies.
$i \in I$	Potential production and distribution technology improvement levels.
$a \in A$	Potential transport modes.
$t \in T$	Time periods.

3.3.2 Set

$RM \subset P$	Raw material families.
$MP \subset P$	Manufactured product families.
$P_a \subseteq P$	Set of products able to be transported by transport mode $a \in A$.
$S_a \subseteq S$	Set of network sites where transport mode $a \in A$ is available.
$V \subset S$	Potential supplier sites.
$U \subset S$	Potential production-distribution center sites.
$U^c \subseteq U$	Production-distribution center sites that can be closed.
$U^o \subseteq U$	Potential production-distribution center sites that can be opened.
$O \subset S$	Potential customer zones.
$R_p \subseteq R$	Set of recipes able to produce product $p \in MP$.
$K_r \subseteq K$	Set of technologies able to produce recipe $r \in R$.
$K_a \subseteq K$	Set of technologies required to use transport mode $a \in A$.

$k^c \subseteq K$ Set of technologies that can be closed.

$k^o \subseteq K$ Set of potential technologies that can be opened.

3.3.3 Parameters

d_{opt}^{max} Maximum demand of customer zone o ∈ O for product $p \in MP$ in time period $t \in T$.

d_{opt}^{min} Minimum demand of customer zone o ∈ O for product $p \in MP$ in time period $t \in T$.

v_{opt} Price of product $p \in MP$ sold to customer zone o ∈ O in time period $t \in T$.

v_{pt} Price of product $p \in MP$ sold at a liquidation price at time period $t \in T$.

g_{ut}^{o} Initial payment to open production-distribution center $u \in U$ in time period $t \in T$.

g_{ut}^{a} Annual payment after opening production-distribution center $u \in U$ in time period $t \in T$.

g_{ut}^{c} Fixed cost to close production-distribution center $u \in U$ in time period $t \in T$.

n^p Period defined by user to disable the ability to open or close a production-distribution center.

a_{ut} Fixed operating cost for production-distribution center $u \in U$ in time period $t \in T$.

e_u Total space capacity of production-distribution center $u \in U$.

u^m Upper bound on the number of production-distribution centers in the network.

q_{ukit}^{o} Initial payment to open improvement level $i \in I$ of technology $k \in K$ at production-distribution center $u \in U$ in time period $t \in T$.

q_{ukit}^{a} Annual payment after opening improvement level $i \in I$ of technology $k \in K$ at production-distribution center $u \in U$ in time period $t \in T$.

q_{ukit}^{c} Fixed cost to close improvement level $i \in I$ of technology $k \in K$ at production-distribution center $u \in U$ in time period $t \in T$.

n^k Period defined by user to disable the ability to open or close a technology.

n_{kit} Enable the ability to open an improvement level $i \in I$ for technology $k \in K$ in time period $t \in T$.

e_{ki} Required space to use improvement level $i \in I$ of technology $k \in K$.

$\mathrm{b_{uki}}$ Available production capacity of improvement level $i \in I$ of technology $k \in K_r$ at production-distribution center $u \in U$.

b_{ki}^{d} Available distribution capacity of improvement level $i \in I$ of technology $k \in K_a$.

n^{o}_{kirp} Amount of components $p \in MP$ produced by using recipe $r \in R_p$ using improvement level $i \in I$ of technology $k \in K_r$.

n^{i}_{kirp} Amount of components $p \in RM \cup MP$ required to use recipe $r \in R$ using improvement level $i \in I$ of technology $k \in K_r$.

j_{kir} Manufacturing time to make recipe r ϵ R using improvement level $i \in I$ of technology $k \in K_r$.

c^{m}_{ukir} Production cost for recipe r ϵ R using improvement level $i \in I$ of technology $k \in K_r$ at production-distribution center $u \in U$.

c^{o}_{ukir} Over time production cost for recipe r ϵ R using improvement level $i \in I$ of technology $k \in K_r$ at production-distribution center $u \in U$.

l_{ukit} Over time capacity using improvement level $i \in I$ of technology $k \in K_r$ at production-distribution center $u \in U$ in time period $t \in T$.

c^{d}_{ukip} Distribution cost for product $p \in P$ using improvement level $i \in I$ of technology $k \in K_a$ at production-distribution center $u \in U$.

$c_{uu'pt}$ Price of product $p \in MP$ sold by production-distribution center $u \in U$ to production-distribution center $u \in U$ in time period $t \in T$.

c_{pt} Cost to dispose of product $p \in MP$ at time period $t \in T$.

b_{vpt} Capacity of supplier $v \epsilon V$ for product $p \in MP$ at time period $t \in T$.

c_{vpt} Procurement cost of product $p \in RM$ sold by supplier $v \epsilon V$ in time period $t \in T$.

$l_{ss'}$ Distance (unit of length) from site $s \in V \cup U$ to site $s \in U \cup O$.

c_{apt} Transport cost per length unit for product $p \in P$ using transport mode $a \in A$ in time period $t \in T$.

c^{e}_{apt} Cost of GHG emissions for one unit of length for product $p \in P$ using transport mode $a \in A$ in time period $t \in T$.

σ_p Measurement unit of product $p \in P$.

λ_{uat} Capacity of transport mode $a \in A$ at production-distribution center $u \in U$ in time period $t \in T$.

δ_{ut} Available budget at production-distribution center $u \in U$ in time period $t \in T$.

α Cost of capital.

3.3.4 Decision variables

H_{ukirt} Total quantity of recipe $r \in R$ produced using improvement level $i \in I$ of technology $k \in K$ at production-distribution center $u \in U$ in time $t \in T$.

X_{upt} Quantity of product $p \in MP$ produced at production-distribution center $u \in U$ in time period $t \in T$ that is not prompted by a demand.

L_{ukirt} Total over time of improvement level $i \in I$ of technology $k \in K$ producing recipe $r \in R$ at production-distribution center $u \in U$ in time $t \in T$.

B_{ukit} Distribution capacity usage of improvement level $i \in I$ of technology $k \in K$ at production-distribution center $u \in U$ in time period $t \in T$.

$F_{ss'apt}$ Total quantity of product $p \in P_a$ transported from site $s \in V \cup U$ to site $s \in U \cup O$ using transport mode $a \in A$ at time period $t \in T$.

$P_{ss'at}$ Binary variable equal to 1 if transport mode $a \in A$ is used from site $s \in V \cup U$ to site $s \in U \cup O$ in time $t \in T$, else 0.

Y_{ut} Binary variable equal to 1 if production-distribution center $u \in U$ is used in time $t \in T$, else 0.

W^{o}_{ut} Binary variable equal to 1 if production-distribution center $u \in U$ is opened in time period $t \in T$, else 0.

W^{c}_{ut} Binary variable equal to 1 if production-distribution center $u \in U$ is closed in time period $t \in T$, else 0.

Z_{ukit} Binary variable equal to 1 if improvement level $i \in I$ of technology $k \in K$ is used at production-distribution center $u \in U$ in time $t \in T$, else 0.

W^{o}_{ukit} Binary variable equal to 1 if improvement level $i \in I$ of technology $k \in K$ is opened at production-distribution center $u \in U$ in time period $t \in T$, else 0.

W^{c}_{ukit} Binary variable equal to 1 if improvement level $i \in I$ of technology $k \in K$ is closed at production-distribution center $u \in U$ in time period $t \in T$, else 0.

3.3.5 Utility function

The objective of this mixed integer linear program model is to maximize the net present value (NPV) of the value chain network as shown in Equation (3.1):

$$MAX\ NPV = \sum_{t \in \mathrm{T}} \frac{1}{(1+\alpha)^t} (\mathrm{Total\_Revenue}_t - \mathrm{Total\_Cost}_t) \tag{3.1}$$

The total revenue (Eq. (3.2)) is calculated by multiplying the quantity of each product transferred to each customer zone by the selling price in addition to the liquidation at period t.

$$\mathrm{Total\_Revenue}_t = \sum_{u \in U_a} \sum_{o \in \mathrm{O}_a} \sum_{a \in A} \sum_{p \in MP_a} F_{uoapt}\, v_{opt} + \sum_{u \in U} \sum_{p \in MP} X_{upt} v_{pt} \tag{3.2}$$

The total cost (Eq. (3.3)) can be divided into seven sub-sections. First, opening and closing costs of production-distribution centers and technologies are added aswell as their resulting annuities. Secondly, if a production distribution center is open, fixed operating costs may apply. Next, production costs apply depending on the amount of recipe $r \in R$ using improvement level $i \in I$ of technology $k \in K$ that is produced, and disposal costs may apply relative to the wastes generated by the recipes. Lastly, distribution, procurement and transportation costs are considered.

$$\mathrm{Total\_Cost}_t = \tag{3.3}$$

(Production-distribution centers – opening/closing costs and annuities)

$$\sum_{u \in U^c} g^c_{ut}\, W^c_{ut} + \sum_{u \in U^o} g^o_{ut} W^o_{ut} + \sum_{u \in U} g^a_{ut} Y_{ut} +$$

(Technologies – opening/closing costs and annuities)

$$\sum_{u \in U} \sum_{k \in K^c} \sum_{i \in I} q^c_{ukit} W^c_{ukit} +$$

$$\sum_{u \in U} \sum_{k \in K^o} \sum_{i \in I} q^o_{ukit} W^o_{ukit} +$$

$$\sum_{u \in U} \sum_{k \in K} \sum_{i \in I} q^a_{ukit} Z_{ukit} +$$

(Fixed operating costs)

$$\sum_{u \in U} a_{ut} Y_{ut} +$$

(Production costs)

$$\sum_{u \in U} \sum_{k \in K_r} \sum_{i \in I} \sum_{r \in R_p} c^m_{ukir} H_{ukirt} + c^o_{ukir} L_{ukirt} +$$

(Waste disposal costs)

$$\sum_{u \in U} \sum_{p \in MP} X_{upt} c_{pt} +$$

(Distribution costs)

$$\sum_{u \in U} \sum_{k \in K} \sum_{i \in I} \sum_{p \in P} B_{ukit} c^d_{ukip} +$$

(Transportation costs including GHG and product costs)

$$\sum_{v \in V_a} \sum_{u \in U_a} \sum_{a \in \mathrm{A}} \sum_{p \in RM_a} (l_{vu} (c_{apt} + c^e_{apt}) + c_{vpt}) F_{vuapt} +$$

$$\sum_{u \in U_a} \sum_{u' \in U_a} \sum_{a \in A} \sum_{p \in MP_a} (l_{uu'} (c_{apt} + c^e_{apt}) + c_{uu'pt}) F_{uu'apt} +$$

$$\sum_{u \in U_a} \sum_{o \in O_a} \sum_{a \in A} \sum_{p \in MP_a} l_{uo} (c_{apt} + c^e_{apt}) F_{uoapt}$$

3.3.6 Constraints

The model is subject to theses constraints in order to balance the flows and capacities:

Equations (3.4) to (3.6) are necessary to tie up the customers' demands back to the supply of raw materials. Equation (3.5) is a derived formula from Paquet et al. (2004) and ensures the flow equilibrium and prompts the production.

$$d_{opt}^{\min} \leq \sum_{u \in U_a} \sum_{a \in A} F_{uoapt} \leq d_{opt}^{\max} \quad \forall o \in O, p \in MP_a,\ t \in T \tag{3.4}$$

$$\begin{aligned} &\sum_{k \in K_r} \sum_{i \in I} \sum_{r \in R_p} H_{ukirt}\, n_{kirp}^{o} + \sum_{u' \in U_a} \sum_{a \in A} F_{u'uapt} - \\ &\sum_{u \in U_a} \sum_{a \in A} F_{uu'apt} - \sum_{k \in K_r} \sum_{i \in I} \sum_{r \in R_p} H_{ukirt} n_{kirp}^{i} - \\ &\sum_{o \in O_a} \sum_{a \in A} F_{uoapt} = \mathrm{X}_{upt} \quad \forall\ p \in MP, u \in U, t \in T \end{aligned} \tag{3.5}$$

$$\begin{aligned} &\sum_{v \in V_a} \sum_{a \in A} F_{vuapt} = \sum_{u \in U} \sum_{k \in K_r} \sum_{i \in I} \sum_{r \in R} H_{ukirt}\, n_{kirp}^{i} \\ &\qquad \forall\ p \in RM,\ u \in U, t \in T \end{aligned} \tag{3.6}$$

Equations (3.7) to (3.15) are capacity constraints:

Equation (3.7) makes sure that the outputs from a supplier are less or equal to its capacity. Equation (3.8) limits the production to the capacity of the technology and Equation (3.9) limits the overtime usage. Equation (3.10) ensures that proper distribution capacity is opened.

$$\sum_{u \in U_a} \sum_{a \in A} F_{vuapt} \leq b_{vpt} \quad \forall v \in V_a, p \in RM_a \tag{3.7}$$

$$\sum_{r\in R} j_{kir} H_{ukirt} \le b_{uki} Z_{ukit} + \sum_{r\in R} L_{ukirt} \qquad \forall u\in U, k\in K_r, i\in I, t\in T \tag{3.8}$$

$$\sum_{r\in R} L_{ukirt} \le l_{ukit} Z_{ukit} \quad \forall\, u\in U,\ k\in K,\ i\in I,\ t\in T \tag{3.9}$$

$$\sum_{p\in P} B_{ukipt} \le b^{d}_{ki} Z_{ukit} \quad \forall\ u\in U, k\in K, i\in I, t\in T \tag{3.10}$$

Equation (3.11) regulates the distribution capacity. Equation (3.12) ensures that every transport modes' capacity is respected. Equation (3.13) specifies the budget allowed at time period $t \in T$ and Equation (3.14) controls the space capacity of a production-distribution center if opened. Finally, Equation (3.15) bounds the maximum number of centers to be opened in the system.

$$\sum_{v\in V_a}\sum_{p\in RM_a} F_{vuapt}\sigma_p + \sum_{u'\in U_a}\sum_{p\in MP_a} F_{uu'apt}\sigma_p + \sum_{o\in O_a}\sum_{p\in MP_a} F_{uoapt}\sigma_p \le \sum_{k\in K_a}\sum_{i\in I}\sum_{p\in P} B_{ukipt} \qquad \forall\, a\in A, u\in U_a, t\in T \tag{3.11}$$

$$\sum_{v\in V_a}\sum_{p\in RM_a} F_{vuapt}\sigma_p + \sum_{u'\in U_a}\sum_{p\in MP_a} F_{uu'apt}\sigma_p + \sum_{o\in O_a}\sum_{p\in MP_a} F_{uoapt}\sigma_p \le \lambda_{uat} \quad \forall\, a\in A, u\in U_a, t\in T \tag{3.12}$$

$$a_{ut}Y_{ut} + g^{c}_{ut}\, W^{c}_{ut} + g^{o}_{ut} W^{o}_{ut} + \sum_{k\in K^c}\sum_{i\in I} q^{c}_{ukit}\, W^{c}_{ukit} + \sum_{k\in K^o}\sum_{i\in I} q^{o}_{ukit}\, W^{o}_{ukit} \le \delta_{ut} \qquad \forall\, u\in U,\ t\in T \tag{3.13}$$

$$\sum_{k \in K} \sum_{i \in I} e_{ki} Z_{ukit} \leq e_u Y_u \quad \forall u \in U, t \in T \tag{3.14}$$

$$\sum_{u \in U} Y_{ut} \leq u^{\mathrm{m}} \quad \forall t \in T \tag{3.15}$$

Equations (3.16) to (3.18) control the opening and closing of production-distribution centers and Equations (3.19) to (3.21) control the opening and closing of technologies. Equation (3.22) ensures a proper integration of technology improvement levels.

$$-Y_{ut-1} + Y_{ut} \leq W_{ut}^{o} \quad \forall u \in U, t \in \{1..n^p\} \tag{3.16}$$

$$Y_{ut-1} - Y_{ut} \leq W_{ut}^{c} \quad \forall u \in U, t \in \{1..n^p\} \tag{3.17}$$

$$Y_{ut} = Y_{u,n^p} \quad \forall u \in U, t \in \{n^p..T\} \tag{3.18}$$

$$-Z_{ukit-1} + Z_{ukit} \leq W_{ukit}^{o} \quad \forall u \in U, k \in K, i \in I, t \in \{1..n^k\} \tag{3.19}$$

$$Z_{ukit-1} - Z_{ukit} \leq W_{ukit}^{c} \quad \forall u \in U, k \in K, i \in I, t \in \{1..n^k\} \tag{3.20}$$

$$Z_{ukit} = Z_{ukin^k} \quad \forall u \in U, k \in K, i \in I, t \in \{n^k..T\} \tag{3.21}$$

$$Z_{ukit} \leq Z_{uk(i-1)(t-n_{ki})} \quad \forall u \in U, k \in K, i \in \mathrm{I}, t \in T \tag{3.22}$$

Equations (3.23) to (3.25) link the flows to the transport mode considering the distribution technologies required.

$$\sum_{p \in P_a} F_{ss'apt} \leq M \, \mathrm{P}_{ss'at} \quad \forall s \in V_a \cup U_a, \; s' \in U_a \cup O_a, \\ a \in A, \; t \in T \mid M = \max(\sum_{p \in P_a} b_{vpt}, \sum_{p \in P_a} d_{opt}^{\max}) \tag{3.23}$$

$$\sum_{k \in K_a} \sum_{i \in I} Z_{ukit} \geq \mathrm{P}_{usat} \quad \forall u \in U_a, \; s \in U_a \cup O_a, \\ a \in A, \; t \in T \tag{3.24}$$

$$\sum_{k \in K_a} \sum_{i \in I} Z_{ukit} \geq \mathrm{P}_{suat} \quad \forall s \in V_a \cup U_a, \; u \in U_a, \\ a \in A, \; t \in T \tag{3.25}$$

Finally, Equations (3.26) to (3.29) are the non-negativity constraints and Equations (3.30) to (3.36) are the binary constraints of the model.

$$X_{upt} \geq 0 \quad \forall u \in U, p \in MP, t \in T \tag{3.26}$$

$$H_{ukirt} \geq 0 \quad \forall u \in U, k \in K, i \in I, r \in R, t \in T \tag{3.27}$$

$$L_{ukirt} \geq 0 \quad \forall u \in U, k \in K, i \in I, t \in T \tag{3.28}$$

$$F_{ss'apt} \geq 0 \quad \forall (ss'p) \in V \times U \times RM \cup U \times \\ U' \times MP \cup U \times O \times MP, t \in T \tag{3.29}$$

$$\mathrm{P}_{ss'at} \in \{0,1\} \quad \forall s \in S_a,\ s' \in S_a,\ a \in A,\ t \in T \tag{3.30}$$

$$Y_{ut} \in \{0,1\} \quad \forall u \in U, t \in T \tag{3.31}$$

$$Z_{ukit} \in \{0,1\} \quad \forall u \in U, k \in K, i \in I, t \in T \tag{3.32}$$

$$W_{ut}^{o} \in \{0,1\} \quad \forall u \in U,\ t \in T \tag{3.33}$$

$$W_{ut}^{c} \in \{0,1\} \quad \forall u \in U,\ t \in T \tag{3.34}$$

$$W_{ukit}^{o} \in \{0,1\} \quad \forall u \in U, k \in K, i \in I, t \in T \tag{3.35}$$

$$W_{ukit}^{c} \in \{0,1\} \quad \forall u \in U, k \in K, i \in I, t \in T \tag{3.36}$$

3.4 Conclusion

The impact of integrating new products into an existing network has a disruptive potential to change the performance of a network. Accordingly, the holistic assessment of product integration may help organizations in the selection of appropriate products, where competitive advantages may be obtained. In this chapter, a methodology approach and a generic MILP model are developed to assess the sustainable integration of new products into an existing value chain network. In the following section, a realistic case study in the Maurice region is presented where the integration of eight (8) bioproducts are evaluated through four (4) potential production technologies.

CHAPTER 4

THE MAURICIE'S FOREST VALUE CHAIN NETWORK: A CASE STUDY

4.1 Introduction

The mathematical model developed in the previous section is intended to help decision makers by identifying the trends that occur when new products are introduced into an existing network. As previously mentioned, the ideal scope is between a manufacturing plant and regional network. To use and validate the decision support tool, a realistic case study has been applied to the region of Mauricie in the province of Québec, Canada. Accordingly, this chapter presents the development of the case study and is divided into three segments. First, the forest industry of the region is presented to uncover the underlying foundation and trends that form the network to subsequently help develop the second segment that is the extensive data compilation to emulate the existing system. In the third and final segment, alternative scenarios are explored to propose new products that have a potential to fill prospective market gaps.

4.2 The Mauricie region

4.2.1 A socio-economic perspective

The Mauricie region, represented by the area four (04) in Figure 4.1, is located between the two major cities in the province of Québec (i.e. Montréal and Québec city). Stretching itself to the north of Trois-Rivières, the region reaches a total superficies of 39,924 km^2 that is mostly held by public ownership and where the forest area covers 33 800 km^2. Home of two native reserves, members of the Attikamek nation, the region exhibits an astonishing wildlife that attracts near 250,000 visitors each year for its variety of outdoors activities and represents an important economic component of the region. Classified as a resource region, its economy strongly relies on agriculture and on the activities associated with the natural resources that are mainly the forestry, hydroelectricity and minor mining operations. In 2014,

the contribution of the Mauricie region to the Quebec's GDP was 2.5 percent with a total population of 266,794 inhabitants, accounting for 3.2 percent of Quebec's population. Ominously, the 2014/2010 average annual growth rate (AARG) of the region was 1.6 percent compared to the Quebec's AARG of 2.8 percent and the region's AARG for the goods-producing industry was -0.2 percent compared to 2.2 percent for the province (Institut de la Statistique Québec [8]). Numerous temporary, partial and permanent mill closures have hit the region in the last decade, notably the Resolute Laurentide mill, the Rio Tinto Alcan mill, the Manac manufacturing plant, the Saputo mill, etc. One conclusion to be done is that in spite of the natural wealth of the region, the regional economy stagnates and new investments and developments are anticipated.

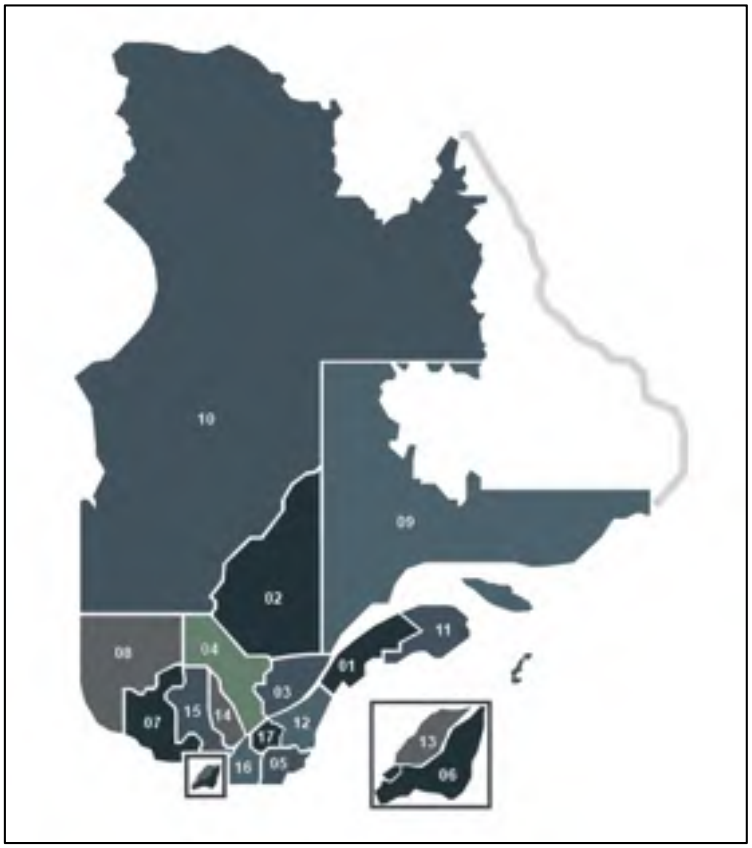

Figure 4.1 Maurice management unit
(Source: Government of Quebec)

Considering that the forest industry is one of the core constituents of the region, the Ministère de l'Énergie et Ressources Naturelles du Québec (MERN) explained that "the regional economy has undergone profound changes and become more diversified. By placing the emphasis on value-added products, the Mauricie region will be able to ensure its economic growth in the near future, and the ongoing viability of business activities based on natural resources." [7] Essentially, the hypothesis stated by the MERN is that a regional economic growth may be accomplished by diversifying the regional production, for instance by introducing value-added products based on the natural resources. This situation takes place in an environment where the economy is centered on slowly deteriorating traditional production, where innovative productions are hoped to economically revive the region. This situation is far from being only an observation and companies and governments work together to accomplish the necessary transition.

A project that is highly representative of this new trend is the cellulose filaments demonstration plant that opened in Trois-Rivières in 2014. Guided by the company Kruger and the nonprofit organization FPInnovations, the biorefinery is able to produce up to five (5) tons per day of cellulose filaments, a product extracted from the wood fibre. Having many potential applications in high-value products, the small production is used as a launching pad to promote the product and to conduct further research and developments. At a cost of 43 millions dollars, the project financing includes many stakeholders, of which there are the provincial and federal government, a non-profit organization, private equities and banks. The project illustrates the will of the stakeholders to revive not only the region but also in broader aim to transform the Canadian forest industry using state-of-the-art technology. Another development announced by Kruger in 2015 is the conversion of one of its newsprint machine to produce recycled lightweight linerboard at the Trois-Rivières mill. With the support of the provincial government, the investment of 250 million dollars is a means to ensure that the 270 jobs will stay, and to take part of the growing demand in the packaging industry. Using cutting-edge technologies, the production will start in 2017 with an annual capacity of 360,000 metric tons. Notwithstanding, Kruger remains one of the largest newsprint producers in North America. Finally, there is another type of production that has been largely

deliberated in the region: the production of crude bio-oil and bio-diesel. Many projects have been presented in different locations (e.g. La Tuque, Parent, etc.) and in various scales (i.e. from 10 to 600 millions dollars investment). In 2017, only an experimental platform has been deployed in Parent from a partnership between Groupe Rémabec and Pyrobiom Énergies. Groups of industrials and researchers are still trying to demonstrate the viability of the production at a commercial scale.

Inevitably and as stated by the MERN, the Mauricie economy is affected by profound changes that will alter the socio-economics dynamic of the region. The questions that remain are: 1) are the introduction of these new production capacities has the disruptive potential to positively change the bioeconomy and to create sustainable value?, and 2)
Alternatively, are there other potentials productions that may benefit better the region considering the synergies and the competition already in place? Therefore, the analysis around the selection and integration of those value-added products can be conducted with the help of our decision support tool to ensure the viability of the projects and the sought after economic growth. Also, the tool may be helpful for governments that are investing in those projects in order to take into consideration the impact on the current production-distribution network and how their incentives may be beneficial or detrimental to other stakeholders in the region. In view of that, we think relevant to develop a case study around the forest industry in the Mauricie region integrating scenarios of potential production. Thus, in the following paragraphs, an extensive development of the structure of the forest industry will be presented to subsequently propose potential orientations.

4.2.2 The forestry industry

Since the 1850s, the Mauricie have relied on the forest sector to develop and stimulate the regional economy. Throughout the decades, the Mauricie forestry industry has evolved following the market trends and the ever growing constraints. Altered by human activities, forest fires, and cyclical pest epidemic, the forest composition keeps renewing itself and continues to remain a cornerstone of the Mauricie. The territory can be separated into two types of forest covers. In the south, a mixed forest composition near the Saint-Laurent River

where hardwood stands and mixed stands coexist (sugar maple-basswood stands, sugar maple-yellow birch stands, and balsam fir-yellow birch stands) and stepping to the north, a notable transition to the boreal forest can be observed and where softwood stands are prominent (spruce-moss forest). To effectively manage the fibre supply and its sustainability, the region is divided into five forest management units (FMU). These FMUs offer an average guarantee of supply of 2.5 millions cubic meters per annum from the public forest, and an average of one (1) million cubic meters is available through the BMMB. These allocations combined with the fibre supply from private forests and external FMUs upkeep the production of the 21 mills in the region, including 3 large pulp mills. Currently, the forest sector in the region sustains approximatively 11,000 jobs and represents 7.8 percent of the forestry activities of the Québec's GDP (Institut de la Statistique Québec [8]). Nonetheless, the last decade has been difficult for the sector and the need to diversify the production has been acknowledged to mitigate the risk tied to the market behaviors. In this line of thoughts, this section will present an in-depth exploration of the current Mauricie's forest industry to understand the assortment of processes that form the regional network, from the fibre acquisition to the customers. By this mean, the data acquired will be used to generate a representative structure where the application of scenarios will be possible. The information is presented in three distinctive sections: basically the mills' upstream connections, the productions, and the mills' downstream connections.

4.2.2.1 The fibre supply

The first consideration to properly assess the introduction of new products is the impact of its feedstock requirement. Where some productions may only use first transformation wood waste (e.g. chips, shavings, sawdust, etc.), others require larger feedstock supply and thus have to tap into the raw material source (i.e. the forest). Nonetheless and even being a renewable natural resource, the forest capacity to feed the industry has its limits and restrictions are enforced to ensure sustainable practices. Therefore, when valuing the potential introduction of a new production, the fibre requirements in terms of quality, quantity, and type have to be evaluated in accordance with the location and the current fibre allocation. To do so, this section explores the details of the regional fibre supply chain and

how to formulate the data structure to emulate properly the fibre acquisition considering the available public harvesting volume, the harvesting costs, and the transportation costs. Basically, four ways of acquiring the fibre by the companies can be distinguished in the province: from the public forest, the private forest, the BMMB auctions, and from the wood processing plants. The fibre availability relies on these acquisition sources that are not necessarily constrained to the region. For instance, companies may buy wood waste from plants outside the region, logs can be bought from another region or country, and auctions and allocations of forest parcels are not necessarily restricted to the regional needs. Those circumstances create a complex upstream network and assumptions are taken to properly represent the fibre supply chain in the region. Three critical assumptions have been considered to keep the model feasible and manageable: 1) all wood by-products acquisitions are completed within the region (see Figure 4.2); 2) private forest has a limited capacity with fixed acquisition costs; 3) auctioned forest parcels are not allocated.

Figure 4.2 Intraregional wood by-products acquisitions assumption

Availability

To determine the regional wood fibre availability considering the previous assumptions, information is collected from public data and from calculations. To calculate fibre requirement, the analysis of the regional consumption is conducted by evaluating the mills'

production capacities. Subsequently, consultation of governmental publications helps to confront the supply and demand and to estimate the private forest contribution to the balance. Conversely to the private forest, information on the public forest is easily available where annual allowable cut and allocation are presented for each FMU of the region considered. Accordingly, the five FMUs present in the Mauricie region are FMU 041-51, 042-51, 043-51, 043-52 and 026-51, illustrated in Figure 4.3. To be noted that FMU 026-51 is not represented in the figure. Its location is the section north of Gouin Reservoir.

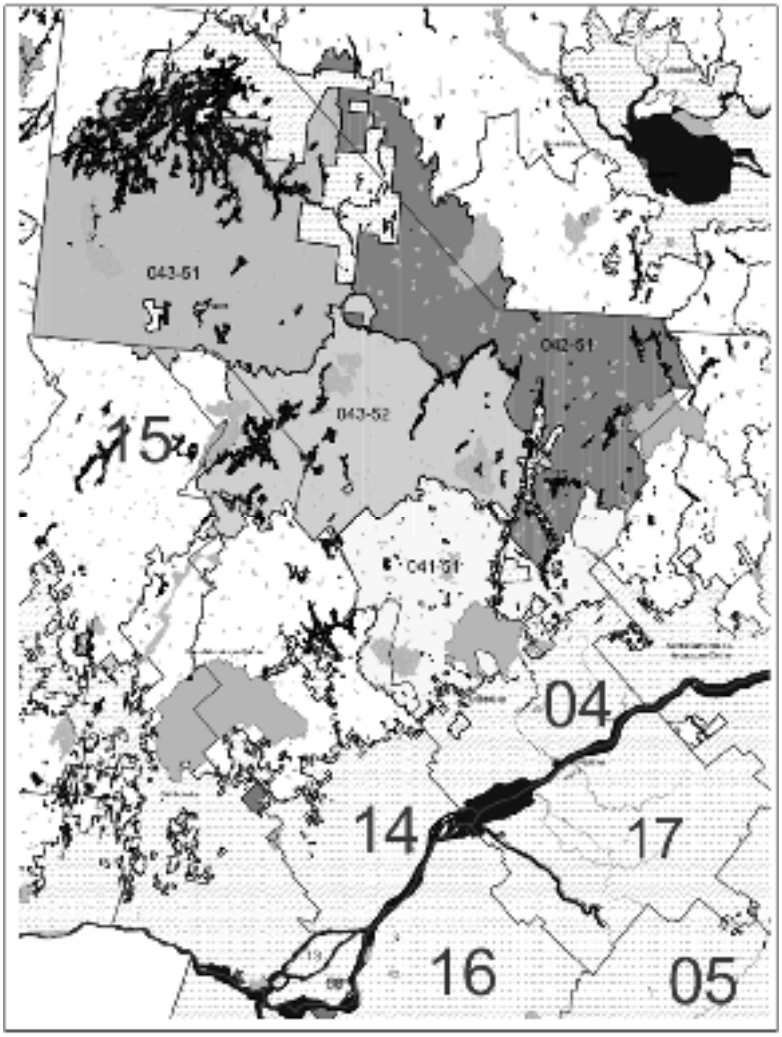

Figure 4.3 Forest Management Units in Mauricie
(Source: MFFP)

The volume attributions in the region are associated to the *Plan d'aménagement forestier intégré tactique* (PAFIT) 2013-2018 of each FMU published by the *Ministère des Forêts, de la Faune et des Parcs* (MFFP). The summary of the available volume is presented in Table 4.1. Because the case study is on a longer time frame than the 2013-2018 PAFITs, the adjustment of the available volume has been completed with the regional synthesis 2018-2023 for the Mauricie region published by the Bureau du Forestier en Chef. Also, all periods following the year 2023 will remain equivalent to the last update. A synthesis of the available gross merchantable volume (GMV) is presented in
Table 4.2.

Table 4.1 Available gross merchantable volume 2013-2018

Species	Available gross merchantable volume (m3 / year) per FMUs [2013-2018]					
	026-51	041-51	042-51	043-51	043-52	Total
Softwood	148100	374500	510500	634700	587200	2255000
Northern white cedar	0	33200	6200	0	7400	46800
Hemlock	0	1900	0	0	0	1900
White and red pines	0	15800	5600	0	6800	28200
Poplar	7700	68700	99400	134600	181200	491600
White birch	13400	106900	203800	194200	262600	780900
Yellow birch	0	66400	65800	2300	43900	178400
Maple	0	99700	37500	1300	37500	176000
Other Hardwood	0	14200	1400	0	2100	17700
TOTAL	169200	781300	930200	967100	1128700	3976500

Table 4.2 Available gross trading volume 2018-2023

Species	Available gross merchantable volume (m3 / year) per FMUs [2018-2023]					
	026-51	041-51	042-51	043-51	043-52	Total
Softwood	151100	514900	734400	791200	681900	2873500
Northern white cedar	0	35100	7900	0	7800	50800
Hemlock	0	1700	0	0	0	1700
White and red pines	0	20900	6700	100	19900	47600
Poplar	7900	63600	118300	121100	163100	474000
White birch	13700	114300	183400	214300	266000	791700
Yellow birch	0	58900	77500	200	38300	174900
Maple	0	85100	40700	4100	28700	158600
Other Hardwood	0	11700	1600	0	1200	14500
TOTAL	172700	906200	1170500	1131000	1206900	4587300

An interesting adjustment to be observed is the 15 percent increase of the regional GMV in the 2018-2023 PAFIT where softwood volume rises but hardwood volume decreases. To be noted that the GMV presented includes the volume auctioned by the BMMB as well as the guaranty of supply offered to the mills outside of the region. Missing in the tables, the supply coming from the private forest has also been included in the development of the case study. Because little information on the matter is available, the calculation of the amount has been estimated by subtracting the regional mills' consumption to their allocated volume available in the *Répertoire des Bénéficiaires de Droits Forestiers sur les Terres du Domaine de l'État* published in September 2016 by the MFFP. Therefore, a total of 1.7 million cubic meters is added to the network with a composition of softwood, poplar, and white birch. Another important aspect to consider is the fibre types. Due to the range of species, the selection and aggregation of the fibre varieties were required to properly run the model. Prior to aggregate the species and fibre types into categories, a careful exploration of the existing and potential technologies of the region has been carried out. The identification of groups of fibre and species has been selected to depict the mills and technologies requirements and where chemical processes made a great influence. After analysis, the aggregation made by the PAFIT for the region was considered as a good starting point and only minor adjustments were applied. Thus, the designed categories are depicted in Table 4.3.

Table 4.3 Feedstock categories

Category	Symbol	Species
Softwood	SFW	Balsam fir, spruce, jack pine, larch, hemlock
White Birch	WTB	-
Yellow Birch	YLB	-
Northern white cedar	NWC	-
Red and White Pines	RWP	-
Poplar	POP	-
Hardwood	HDW	Maple And all other hardwoods

Further organizational technics are used by researchers to properly characterize the fibre, for instance, the decomposition of the resource as sawlogs sizes, pulpwood and energy wood (Lepage and Haddad, 2015). However, to keep the model at a reasonable size, the dimension

of the trees has not been considered. This assumption might have an influence on the distribution and transportation costs but does not have a critical effect on the strategic level analysis taking in consideration that the prospective productions are not affected by the log sizes.

A substantial new consideration that arises in the sector is the utilization of forest residues. Currently left on the road side and in the harvest areas, the forest residues detain interesting potential as feedstock in modern biorefineries. Without competition in its procurement, the annual volume presented by the Bureau du Forestier en Chef in its publication *Estimation de la biomasse générée par les activités de récolte prévues aux possibilités forestières 2013-2018 – Modification 2014* has been estimated at 1,86 million green metric tons (see Table 4.4). Available volume subsequent to 2018 has been increased by 15% to consider the following PAFITs. To convert the feedstock from green metric ton (GMT) to bone dry metric ton, the conversion factors used are 0.5 for softwood and 0.6 for hardwood (BDMT).

Table 4.4 Available annual volume of forest residues

	Forest residues -Available Green Metric Ton (GMT) per year		
FMU	Branches	Leaves	Total
026-51	36510	32310	68820
041-51	241080	171920	413000
042-51	263560	196440	460000
043-51	225390	180450	405840
043-52	293670	214910	508580
Mauricie	1060210	796030	1856240

Procurement and transportation

The fibre availability now defined, the next step is the development of the structure within which the fibre will be brought to the mills. Accordingly, the two major elements that have to be defined are 1) how the mills acquire the fibre? and 2) how fibre is conveyed to them? Even though the model is at a strategic level, the use of tactical information has to be done to

keep realistic trends. Since the cost of procurement and transportation of fibre has a considerable impact on the companies' profitability, the arrangement of harvesting areas and the mapping of the road network had to be considered to represent the upstream supply chain. To help in the development of the fibre procurement, a collaboration with FPInnovations has been deployed to generate accurate harvesting areas and to position them in the road network.

An illustration of the network generated by the software FPInterface is presented in Figure 4.4 where the line colors determine the road type and where cutting blocks are represented by the red zones.

Figure 4.4 Quebec road network (Source: FPInterface™)

It has been judged that the incorporation of the harvesting operations in the model was not an imperative aspect, but that the characteristics produced by the various factors surrounding the operations were. For that reason, the transfer point had to be set and the data specific to the

fibre acquisition up to this point had to be included. Thus, the starting point of the fibre procurement has been set at the roadside. Here, log terminals are not considered, the assumption of a direct connection between the roadside pick-up points and the PDCs is taken. Based on the 2014 harvest season, 1998 cutting blocks have been identified and further aggregated to 57 cutting blocks with a 5 kilometers proximity constraint. The information considered to determine the roadside cost where the dimension of the cutting block (ha), the forest type (mixedwood or softwood), the species, the available volume (m^3), the cut type (partial cutting with protection or clearcut), the felling cost ($\$/m^3$), the harvesting cost ($\$/m^3$), the supply cost, and the skidding/forwarding cost ($\$/m^3$). Also, information on the GHG emissions related to the harvesting operations is included. Finally, the connection between the roadside feedstock and the mills has to be established in relation to the road network. Having more than 30,000 kilometers of forest roads, the movement of wood becomes emblematic of the resource region. Flowing in various forms across the region, the fibre has several routing options which have a direct influence on the transportation costs from factors such as the road types, speed limits, road curvature, etc. However, the strategic nature of the optimization requires aggregation and the extensive routing structure cannot be fully integrated into the scenarios. Hence, a viable option is to take the transportation costs per specie ($\$/m^3$), for all of the origin-destination pairs, by using the best routes associated costs from FPInterface. To be noted that only road transportation are considered in this segment of the model since the wood transported from outer regions has a fixed acquisition cost that includes the transport (mill gate cost).

4.2.2.2 The production-distribution network

The second consideration to properly mimic the existing system is the production-distribution network. Steered by existing flows and synergies, the network operates under specific conditions that create a unique system. To properly replicate these conditions, the mills' information has been gathered from the available public data. Due to their complexity, the depiction of the pulp mills has been further processed in the software I-BIOREF. While the physical structure of the network is easily reproducible, the flows are more difficult to reproduce and assumptions are undertaken in regards to the existing interactions. The first

step to replicate the interactions of a system is to identify the manufacturing companies and then to guide wanted trends so that the model adopts similarities with the real system, for instance, the competition among companies. Thereby, this section presents the structure of the production and distribution network that, once connected with the fibre supply, will be able to emulate the regional forest industry.

The manufacturing companies

The region is characterized by a multitude of wood processing mills from various sizes, types, and belonging. Using the document *Index des Usines de la Mauricie (04) - Édition Janvier 2017* by the MFFP, which is a directory of the factories in the region, the necessary information to identify and categorize the mills across the region were collected. To accurately model the pulp mills in I-BIOREF, the information on the production, capacities, and utilities requirements were taken from the *2014 Pulp and Paper Canada Annual Mill Directory* published by Big Magazines LP. Subsequently, specific information about the production capacities, the operating cost, the production cost, the disposal cost, the annuities, the intra-regional prices of products, etc., had to be collected when available or calculated. Arranged by companies, the mills considered and their aggregated information are presented below.

WestRock

The largest pulp mill in the region is owned by WestRock, an international company that produces a variety of paper and packaging. Located in La Tuque, the mill produces up to 425 kilo tons per annum of kraft pulp to produce white top linerboard and containerboard. (See ANNEX I – Table A - I - 1)

Resolute forest products

Established in seven states in the U.S., in two provinces in Canada and in South Korea, Resolute Forest Products is versed into many productions such as pulp and paper, wood products, tissue, and energy. In 2014, the closure of one the oldest pulp mill of the region occurred, affecting 275 workers and leaving Resolute FP with almost no influence in the region. Interestingly, Resolute FP accused an unfair competition from a government

subsidized mill located in Nova Scotia where both mills were competing on the thin market for specialty paper. The location of the mill is considered in the case study even though it has been partly sold to Nemaska Lithium in 2015. Nevertheless, the company is integrated into the case study due to its 93.2 percent holding of a softwood sawmill located in La Tuque and its potential involvement in new projects. (See ANNEX I –Table A - I - 2)

Commonwealth plywood

Born from the Second World War effort, the Commonwealth plywood company is now the Canadian leading manufacturer of hardwood veneering. Having two mills in the region, their production includes veneering, plywood, and flooring. (See ANNEX I –Table A - I - 3)

Arbec and Groupe Remabec

Groupe Remabec is the most prominent stakeholder of the region and is one of the largest woodlands operators in Quebec. Since Arbec Inc. detain 50 percent of Groupe Remabec and to lighten the case study, both companies are considered as the same group. Thus, the group accounts for seven mills throughout the region which are mainly oriented toward the production of lumber. Yet, they also produce specialty products such as oriented strand board (OSB), pop sticks, and pallet wood. New developments in green energy are also deployed by the group elsewhere in the province, notably the $72 million dollars fast pyrolysis project in Côte-Nord in collaboration with Ensyn technologies Inc. One closed mill in Saint-Tite is also considered as a potential location for potential production. (See ANNEX I – Table A - I - 4)

Kruger

Kruger Inc., one of the largest manufacturers of newsprint in North America, has two pulp and paper mills in the region. The first one is a kraft pulp mill that combines its kraft pulp to TMP to produces coated paper, and the second one is a TMP mill that produces newsprint paper. As mentioned earlier, the production of newsprint paper has recently decreased to partly convert their production to recycled linerboard in their TMP mill. However, since the project is not accomplished and no data are available, it becomes a source of high uncertainty for the model that had to be withdrawn. On the other hand, an analysis with the decision

support tool developed in this work would be highly appropriate to assess the impact of this integration on the network. (See ANNEX I – Kruger mills' informationTable A - I - 5)

Other

Finally, eight more independent mills are included in the case study. Their production ranges from standards sawmilling to hardwood pellet mills and soundproofing panels. (See ANNEX I – Table A - I - 6). Altogether, the mills positioning in relation to the fibre supply network is presented in Figure 4.5.

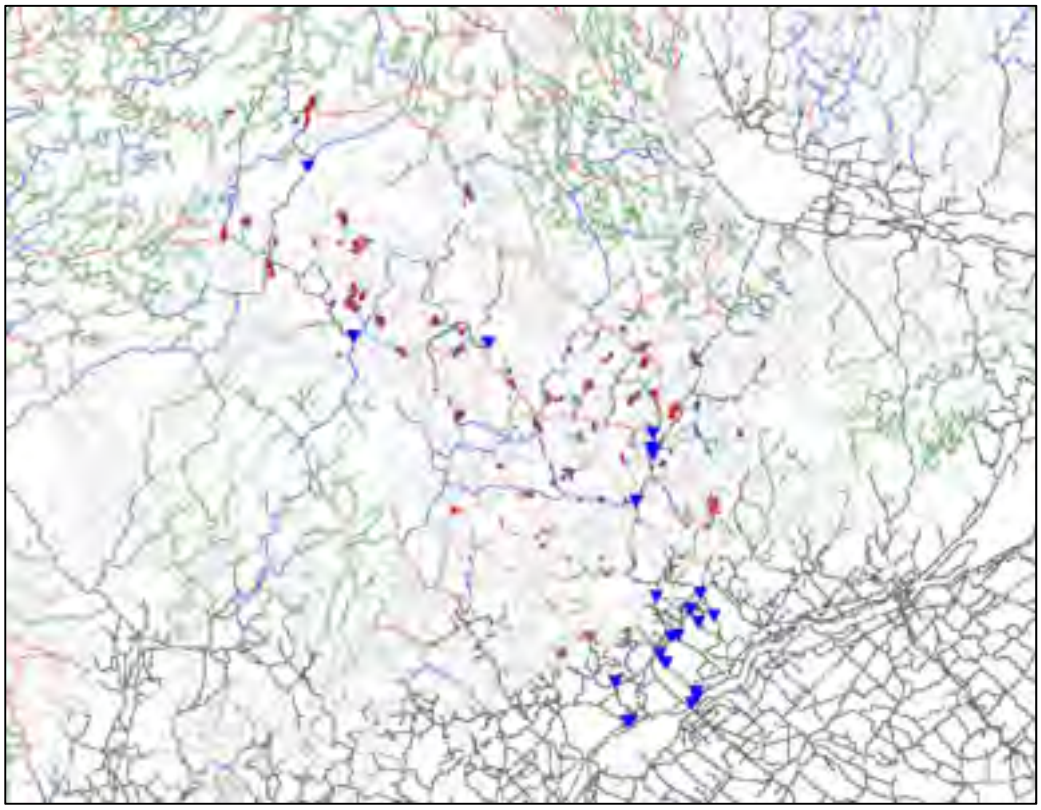

Figure 4.5 Juxtaposition of the mills to the regional fibre supply network

Products, technologies and recipes

The mills now identified, the decomposition of their production into primary elements has to be conducted to allow the proper development of the manufacturing processes. To obtain a specific product, a combination of sequential processes has to be performed with the right amount of inputs to yield the looked-for products and where by-products and waste are

created concurrently. The key challenge here is how to design and aggregate the processes enough to keep the model feasible without losing potential synergies. Thus, 12 production technology sets and 32 recipes have been established and integrated into the base case model. The aggregated information on the subject is presented below in Table 4.5, and the exhaustive information on the combination of technology sets and recipes including the yield is presented in ANNEX IV.

Table 4.5 Production technology sets

PRODUCTION TECHNOLOGY SETS	AVAILABLE RECIPES
Chipping set	10
Hardwood sawmilling set	1
Softwood sawmilling set	1
Veneering set	1
Stranding set	1
Hammermilling set	8
Kraft pulping set	1
Thermomechanical pulping set	1
Papermaking set	3
Pelletisation set	1
Panel Pressing set	3
Drying and planing set	1

Table 4.6 Base case raw materials and manufactured products

INPUTS	INTERMEDIATE PRODUCTS	FINAL PRODUCTS	WASTE
Electricity (MW)	Bark and residues (bdmt)	HDW green lumber (bdmt)	Solid waste (mt)
Water (kmt)	HDW debarked wood residues (bdmt)	SFW green lumber (bdmt)	Effluent (kmt)
Natural Gas (KW)	SFW debarked wood residues (bdmt)	NWC green lumber (bdmt)	GHG (mt CO_2 eq.)
Forest Residues (mt)	POP debarked wood residues (bdmt)	KRAFT (other) (mt)	
HDW (bdmt eq.)	WTB and YLB debarked wood residues (bdmt)	Newsprint paper (mt)	
SFW (bdmt eq.)	HDW chips (bdmt)	Coated paper (mt)	
NWC (bdmt eq.)	SFW chips (bdmt)	Containerboard and packaging paper (mt)	
POP (bdmt eq.)	POP chips (bdmt)	Pellets (mt)	
WTB (bdmt eq.)	WTB and YLB chips (bdmt)	Fiberboard (mt)	
YLB (bdmt eq.)	Veneers (bdmt)	Plywood (mt)	
Kraft chemicals (mt)	Pulverized Fibre (bdmt)	Oriented Strand Board (mt)	
TMP chemicals (mt)	Strands (bdmt)	Boards (bdmt)	
Panel chemicals (mt)	Chipped residues (bdmt)		
Man-hour	KRAFT pulp (mt)		
	TMP (mt)		
	Black liquor (mt)		

These production technology sets have been designed to match the existing regional product portfolio by transforming raw materials into manufactured products. What is qualified as raw materials are all of the inputs in terms of feedstock, chemicals, energies, utilities, and man-hours required to fulfill a specific recipe. Once a recipe completed, three types of manufactured products are produced: intermediate products, final products, and the waste (see Table 4.6).

The inputs

Two main characteristics can be applied to the inputs: whether they originate directly from the public forest with the starting point at the roadsides where transportation cost is considered, or from external suppliers where transportation is included in the acquisition cost. The first category is the fibre supply from the public forest presented previously. The second category is all of the other inputs, including fibre from the private forest, that are required to enable the production (i.e. chemicals, energies, utilities.). Two types of energies have been considered in the base case: electricity and fossil fuel. The electricity requirement has been matched to the grid supplied by Hydro-Quebec, and adjustments have been made for the electricity producing mills considering their higher resell cost. All fossil fuel consumptions have been replaced by their equivalence in natural gas. Regarding the water consumption, no constraint nor cost have been applied since all major sources of acquisition are from the rivers alongside the mills. Three groups of chemicals are considered: Kraft chemicals are sodium sulfate, sodium hydroxide, sodium chlorate, sulfuric acid, calcium quick lime, methanol, and oxygen; TMP chemicals are hydrogen peroxide, sodium hydroxide, and sodium bisulfite; and the panel chemical considered for the production of OSB, plywood and fiberboard panels is the phenol formaldehyde resin. Finally, required workforce to accomplish the production is added via an input called man-hour, where one employee represents 2,672 hours per annum (334 days per year, 8 hours a day).

The manufactured products

The manufactured products are the results of intra-processed items that can be divided into three categories. For instance, if a log is processed in a sawmill, the desired outputs of the operation will be the green lumber (final product), but to achieve the result, bark, and

debarked wood residues are produced (intermediate products) and GHG are generated (waste). Hence, the final products can be described as "ready to sell" merchandises that exit in the system when completed, where the only exception is the green lumber that can be sold as is or further processed through drying and kiln to create boards. The intermediate products can be classified as unfinished products or residual by-products. The unfinished products can be seen as work-in-progress materials that can be processed in the same plant where it has been created or sent elsewhere in the system to be transformed to another stage or to be completed. On another hand, the residual by-products are far from being wastes and are often re-circulated into the system to be re-valued. To estimate the production of basic wood by-products, the yield information of selected wood transformation industries, excluding the bark, has been collected from a study published by the FAO, presented in Table 4.7. The bark production has been calculated using the following conversions (0.075 bdmt/m^3 for softwood log and 0.095 bdmt/m^3 for hardwood log) issued by the MFFP in its 2005 publication *Pistes ayant pour but d'atténuer la diminution des volumes d'écorces du groupe SEPM au Québec.* Finally, the wastes are divided into three classes where associated costs are linked to their disposal (i.e. solid waste burying and water treatment costs) or as a penalty (i.e. GHGs via carbon fee).

Table 4.7 Residues production – excluding bark (Source: FAO)

	Sawmilling %	**Plywood Manu.** %	**Particleboard Manu.** %	**Integrated Operations** %
Finished product (range)	45-55	40-50	85-90	65-70
Finished product (average)	50	47	90	68
Residues/Fuel	43	45	5	24
Losses	7	8	5	8
Total	100	100	100	100

Distribution technologies and transport modes

To connect mills to each other and to deliver the goods to the customers, a realistic distribution network has to be structured. Two components are considered to properly move the products: distribution technologies which are the handling means and the transport modes. As for the production, the aggregation of the distribution technologies and the transport modes had to be conducted. Overall, three transportation methods have been selected: road, rail and direct. Road transportation is the leading means of transport for feedstock and intermediate products in the region. On another side, rail transportation is particularly efficient for long distances and is often used to deliver the products near the customer where the final deliveries are done by trucks. The third transport mode named direct is when the distance between two nodes are too close to use conventional transportation, for instance between two areas in the same mill. Additional subclasses are attached to the defined transportation methods to specialize them to transport standardized packaged units, dry bulk, and liquid bulk. Accordingly, distribution technology sets have been created to correctly handle the products considering the mean of transport. Following the same procedure as presented in the upstream supply chain, the transportation costs between each mill (origin-destination) have been identified. For international customers, the delivery point is set to FOB Port de Montreal.

4.2.2.3 The market zones

Finally, the last consideration is the demand and its market. To replicate the existing network, the production capacity of each mill has been set as the commercial volume sold to customers. Since clients and products' prices are generally well kept by the companies, assumptions about the prices have been set, where the selling price of merchandises produced in the region is equal to its bulk price in the market zones, therefore, transportation costs have to be subtracted from the price. To define de markets zones, statistics about the shipments of wood products by destination has been used from *The Quebec Economic Plan - Budget 2016-2017 – Competitiveness in the Quebec forest industry,* issued by the Government of Quebec. These statistics, presented in Figure 4.6, are then distributed to the following identified market zones: local, regional, Canada, United-States, Europe, and Asia.

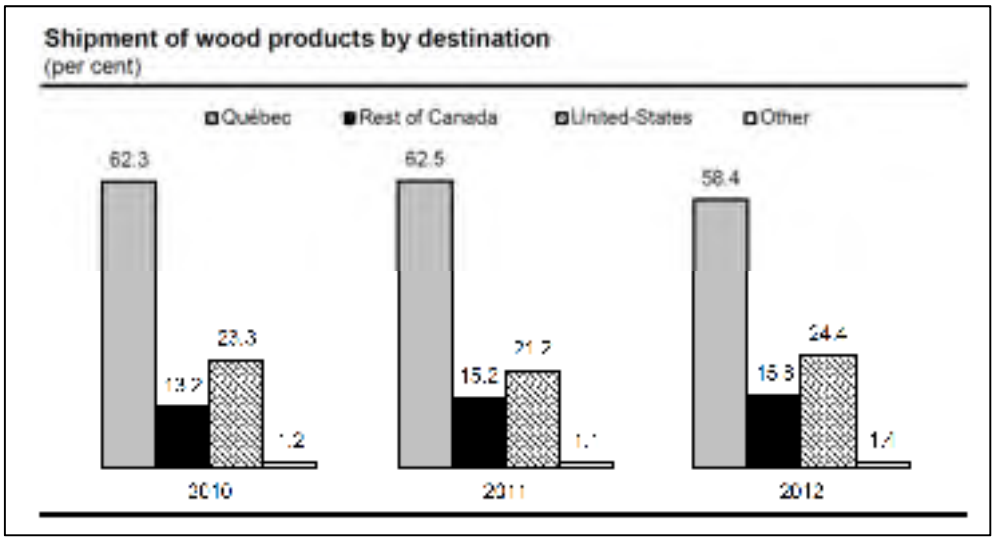

Figure 4.6 Shipment of wood products by destination
(Source: Gouvernment of Quebec)

In Table 4.8, the prices of end products are presented in Canadian dollars and the exchange rates used to convert foreign currency to Canadian dollar (CAD) are presented in Table 4.9. The products' compound annual growth rates (CAGR) have all been set to zero except for the newsprint paper with a negative CAGR of five percent, and different annual price increases have been considered.

Table 4.8 Base case scenario product prices

Prices ($CAD) per metric ton	HWD green lumber	SFW green lumber	NWC green lumber	Crude sulfate turpentine	Tall oil soap	Newsprint paper	Coated paper	White top linerboard	Containerboard	Hardwood pellets	Fiberboard	Plywood	Oriented Strand Board	Boards (Kiln dried and planed)
MIN	345	216	432	214	128	756	1,485	860	540	196	405	392	274	1,013
MAX	378	242	483	944	142	810	2,160	1,296	851	270	432	473	331	1,283
Annual increase (%)	0.5	0.5	0.5	2.0	2.0	0.0	1.3	2.5	2.7	3.0	2.0	0.5	2.5	2.5

Table 4.9 Exchange rates to CAD

Currency	USD	GBP	EUR	CNY	INR
Conversion rate	$ 0.75	£ 0.57	€ 0.66	¥ 5.10	₹ 48.00

4.3 The case study development

The Mauricie's forest industry now accurately modeled, the techno-economic analyses of prospective biorefinery technologies applied to the region can be elaborated. We present in this section, the comparisons of potential products are explored where some products may be produced by different processes or even compared to similar market oriented products. Subsequently, a structure is developed around the integration of the selected product to frame a set of scenarios where the assessment of their integration may be possible.

4.3.1 The exploration of alternative routes: The bio-pathways

The conversion of lignocellulosic biomass to a variety of value-added products have to follow techno-economic analyses to 1) ensure the availability of the required feedstock, 2) validate the technology readiness level (TRL), and 3) to ensure the market penetration potential and possibilities. From these criteria, four (4) technology sets have been identified, of which eight (8) products are derived. In Figure 4.7, a representation of the selected bioproducts and associated technologies show the competing bio-pathways considered. A presentation of the technology sets and bioproducts are afterward presented prior to the generation of the scenarios.

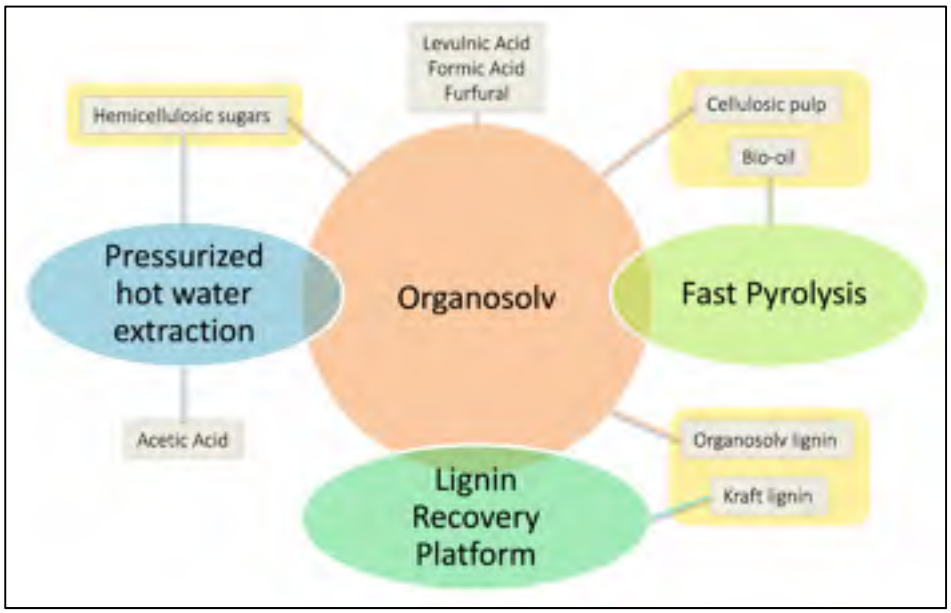

Figure 4.7 Bioproducts selection and competing technologies

4.3.1.1 The proposed technology sets

In collaboration with CanmetEnergy, a division of the Canadian Department of Natural Resources – Natural Resources Canada (NRCan), relevant prospective processes to the Mauricie's regional economy has been selected and their information processed with the software I-BIOREF. Within the framework of the case study, four groups of processes are proposed that are the pressurized hot water extraction (PHWE), fast pyrolysis, organosolv fractionation and the lignin recovery platform. Below, descriptions of the technology sets are briefly discussed.

Pressurized hot water extraction

The PHWE is an extraction method used to fractionate the main compounds in biomass (e.g. hemicellulose from wood). The technique uses water as extractant where it is heated above its atmospheric boiling point by increasing the pressure. Thereby, the water temperature may range from 100° Celsius at the standard atmospheric pressure up to its critical point of 374° Celsius at 22.1 MPa (Plaza and Turner, 2015), which makes it a subcritical water extraction method. Above this temperature, the process is then known as supercritical water extraction, a method that is not covered in this case study. Hardwoods are considered as the process requisite feedstock due to their high content in acetyl groups and where softwoods do not perform as well (Garrote et al., 1999). The products engendered are the hemicellulosic crude sugars (mainly C5) and the acetic acid. Once the process completed, one main by-product remaining is the hot water extracted biomass (i.e. sawdust, chips, or strands). This HWE biomass can then be used in normal application such as pellets, OSB or even as feedstock in pulp mills. The existing regional value chain network has two hardwood pellet mills, one OSB mill and one pulp mill that use hardwood, which create good potential synergies with the proposed technology. Moreover, studies indicate that many benefits are linked to the use of HWE biomass. For instance, the use of HWE biomass in pellets help to lower the ash content and make them less hydrophilic (Amidon et al. 2011) and increase their strength and surface energy content (Oporto et al., 2012). Also, its use in OSB panel increases the physical and mechanical properties while reducing the weight of the panel (Paredes et al. 2009). The technology set considered is based on a standalone biorefinery.

Fast pyrolysis

The second method considered is the biomass pyrolysis process, which is a thermochemical decomposition of organic matters by applying elevated temperature at a specific residence time in the absence of oxygen. The outputs of the process are organic vapor, generally condensed to crude bio-oil, chars, and gases (5% H2, 23% CH4, 27% CO, 40% CO2, and others at 773 Kelvin) (Yamamiya et al, 2003). The temperature and residence time are important parameters to consider since yield may differ accordingly. For instance, fast pyrolysis has temperature ranging around 450-600° Celsius with a residence time of one to three seconds which gives a yield of 75 percent liquid, 12 percent solid and 13 percent gas (75L/12S/13G) (Bridgwater, 2012). If the residence time is increased to 10-30 seconds (intermediate pyrolysis), the yield is then 50L/25S/25G. With temperature higher than 700° Celsius, the process becomes biomass gasification where the syngas produced is collected with a controlled amount of oxygen or steam and the yield is 5L/10S/85G. By decreasing the temperature slightly below 300° Celsius and increasing the residence time, the process then becomes torrefaction with a yield of 0L/80S/20G. In this case study, only the fast pyrolysis process is considered with crude bio-oil as the main product and where the chars and gases by-products are used internally by the process. The feedstock can be hardwood, softwood, or even forest residues which are currently unused. The technology set considered is based on a standalone biorefinery.

Lignin recovery platform

The lignin recovery platform system is a process that extracts lignin from the black liquor produced from the kraft pulping process. The technology can be integrated to kraft pulp mill where a potential revenue stream may be created from the lignin, but also as a potential mean to offloads the recovery boilers that are often the bottleneck in the production of kraft pulp (Kouisni et al, 2012). In 2011, a pilot-plant at the Resolute Forest Product mill in Thunder Bay (Ontario) have been tested. In 2014, the first industrial scale lignin recovery platform was announced in the in the West Fraser pulp mill in Hinton (Alberta).

Organosolv fractionation

Invented in the late 1970s, the organosolv process has been developed with the aim to replace the more pollutant alternatives in the pulp sector. Until now, only a few mills have adopted the technology which makes it still a marginal process. Nevertheless, its use becomes of interest in the context of biorefinery due to its capacity to fractionate the core components of the biomass in an un-degraded form (i.e. high purity lignin, c5 and c6 sugars, and cellulosic pulp). The organosolv process enables the fractionation of the extractives of biomass using an organic solvent (e.g. ethanol) at an elevated temperature ranging from 170 to 200° Celsius (Sannigrahi et al, 2013), and where the solvent is recycled in the process. Pilot and demo lignocellulosic biorefineries are in production in Europe to develop biofuel and high-performance materials based on the organosolv fractionation. In this study, the technology set considered is based on a standalone biorefinery.

4.3.1.2 The bioproducts

From the aforementioned technology sets, the products manufactured are now investigated as for their uses, demand, and price. Due to the novelty of their proposed production methods, significant uncertainties originate from their market potential and viability. Therefore and prior to making the necessary assumptions, the following analysis concisely explain the orientation of the products as for the market penetration considered.

Lignocellulosic sugars

Lignocellulosic biomass can be defined as the dry matter of plants (e.g. trees, grasses, bushes, etc.). The dry matter of wood is essentially divided into three core components that are cellulose (40-50%), hemicellulose (15-25%), and lignin (15-30%). From this structure, cellulose and hemicellulose can be extracted from the lignin to form sugars. These sugars are carbohydrate polymers that contain sugar monomers which can be transformed into a multitude of biochemical, biofuel and polymer products. Basically, the hemicellulose is a polymer of mainly five-carbon sugars (xylose) and the cellulose is a polymer of six-carbon sugar (glucose). The processes to extract these polymers covered in this case study are the

following: the pressurized hot water extraction for the extraction of the hemicellulose, or the organosolv fractionation for the extraction of hemicellulose, cellulose, and lignin.

Cellulosic pulp

Currently, C6 sugars (glucose) are highly used in the production of the first-generation biofuel (e.g. ethanol) and mostly from the starchy crops (e.g. corn, wheat), sugar cane and sugar beets 143[9]. This production occurred to reduce our dependence on fossil fuel and to strategically transfer our energy requirements to sustainable means. However, this first-generation fermentation technology creates concerns as of its use of arable lands and its potential impact on the global food supply. In this regard, the development of the second-generation biofuel using the cellulosic materials (wood, paper waste, food and crops residue, etc.) is anticipated. On the other hand, the conversion of cellulosic pulp to biofuel is still considerably more expensive than the first-generation biofuel and its integration must be well thought. Thereby, the market considered for this case study is for the non-alcohol based products which represent a global volume of 14.5 million metric tons per year with a CAGR of 6.5 percent (Deloitte, 2014). By removing the bioethanol demand, a more restrictive market penetration occurs to take into consideration the maturity curve of the second-generation fermentation technology focusing on high-value products. The price of fermentable cellulosic sugars ranges from $150 to $370 USD per metric ton.

Hemicellulosic sugars

Unlike cellulose that is only composed of hexoses (C6 sugars), hemicellulose consists of two types of building blocks that are hexoses and pentoses (C5 sugars). Even though it is possible to transform hemicellulose into ethanol using the process of fermentation, its concentration in pentoses makes it more difficult and further technological advancement have to be realized to ensure the profitability of the transformation. Nevertheless, cost-effective avenues are undergoing such as the production of xylitol and furfural. Xylitol is a natural low-calorie sweetener that can be used for several applications such as pharmaceuticals industry and food industry (chewing gums, confectionery, beverages, and processed food). The increase in health awareness and concerns in regard to the use of synthetic materials in food makes a great opportunity for xylitol. Therefore, the market size for hemicellulosic sugars is based on

the potential of these two chemicals with good long term potential. An evaluated market size of 220 kilo tons is considered with a CAGR of 4.5 percent (Christopher, 2012). The price for the hemicellulosic crude sugars has been set to 275$ CAD per metric ton.

Lignin

For a long time considered as an inconvenience in the pulp and paper industry, lignin has intrigue researchers around the world who have proven the extreme versatility of the aromatic compound over and over. Being the cause of yellowing in the paper, lignin is removed prior to the bleaching process to produce a quality paper. To date, instead of being isolated, high lignin content waste have mostly been used in the kraft pulp mills as internal energy. The sulfite pulping process, on another hand, does not degrade as much the lignin which has enabled its use in numerous applications (e.g. foams, dust control, paper, chemicals, battery, fuel, heat, grease, dispersants, agriculture, cement and concrete, animal feed pellets, adhesives, fertilizers, ore processing, etc.) This by-product, the lignosulfonate, currently represents 88 percent of the lignin market with a CAGR of 1.4 percent. However, the quality of the lignin restricts its usage and potential markets are still to be tapped. For instance, a study conducted by Lignimatch, a joint industry-academic-project, has proposed a potential roadmap for the new lignin based products on the international market where three products have been identified as good avenues: activated carbon, carbon fibers and phenols. These products are required in large market production and conclusions indicate a favorable transition. Thereby, two processes are under study for the extraction of quality lignin. The first technology is a lignin recovery platform that recovers the lignin from the black liquor produced by the kraft pulping process, and the second is the organosolv fractionation process which produces the high purity lignin. The kraft lignin market has a CAGR of 3.2 percent and the organosolv lignin a CAGR of five (5) percent. These two markets represent a combined global production of 143 kilo tons per annum where 91 percent is lignin recovered from the black liquor, and nine (9) percent from the organosolv fractionation [10]. The price of kraft lignin ranges from $350 to 650 USD and the organosolv lignin ranges from $500 to 650 USD per metric ton [11].

Acetic acid

The acetic acid is a mild acid that can be found in household vinegar. Its usage varies from industrial processes as components in plastics, paints, and glues to the medical and food industries. Mainly produced synthetically from methanol carbonylation in Asia, the global market size is around 6.5 million metric tons per year with a CAGR of 6 per cent [12]. The biological production of acetic acid from fermentation represents currently ten (10) percent of the market and is mostly used in the food industry. The price range varies from $425 to $1250 USD per metric ton [13]. The technology set considered for the production of acetic acid is the PHWE.

Furfural

The production of furfural is considered in this case study as of its impressive CAGR of 13.10 percent and market size of 470 kilo tons per year [14]. The compound can be converted in high yield from the PHWE hemicellulose using a solid acid catalyst or directly created from the organosolv fractionation. Furfural is an organic compound that has various applications in the petrochemicals industry, foundry industry and as a pharmaceutical ingredient. Furan derivatives have a promising future with its usage in a high-volume market and the rapid industrialization of emerging economies. The price ranges considered of furfural is between $1000 and $1500 USD per metric ton.

Levulinic Acid

As a potential output of the organosolv fractionation, levulinic acid has a small global demand of 3200 metric tons with a CAGR of 4.8 percent [15]. Agricultural and pharmaceutical currently represent the main usage of the acid and has a price tag of $1300 USD per ton. New applications of levulinic acid are anticipated to grow the market size including usage in products such as pesticides, solvent, plastics, and cosmetics.

Formic acid

Secreted and used as a defense by some insects, formic acid was discovered in the 17th century by distilling large quantities of ants. Centuries later, the acid is nowadays used in various end-industries (e.g. leather, textile, rubber, chemical, pharmaceutical and agriculture) and has a global market of nearly 1 million metric tons per annum. Formic acid has an

interesting CAGR of 4.9 percent but can be vulnerable to emerging cost effective substitutes, more specifically in the animals' feeds sector. The production of formic acid is done within the framework of this case study by the organosolv fractionation process. The price range varies from $775 to $900 USD per metric ton.

Crude bio-oil

The production of bio oil considered in this case study comes from the process of fast pyrolysis (i.e. pyrolysis oil). Long seen as not economically viable, the production of crude bio-oil starts to appear in moderate commercial scale around the globe. The global production is estimated at 320 kilo tons, and current sites under construction will raise the capacity to 500 kilo tons by 2018 (District Energy). A valid entry point for the bio product is as replacement of the heating oil used in industrial heat and power production and residential application. This option does not require complex transformation of the oil and has the advantage of entering a large and stable market where a transition to greener products would be beneficial. Nonetheless, market potential arises with the development of economically viable processes to upgrade the pyrolysis oil to drop-in transportation fuels with use in commercial diesel and maritime bunker fuel. Another avenue is to convert the bio oil in the existing refineries to make green gasoline and diesel, a method coveted by Ensyn for instance. As a result, the CAGR of the crude bio-oil considered in the study is 17.7 percent [16]. In regard to the price, few information is available. Thus, the price has been estimated based on the energy content of the crude bio-oil compared to crude oil price per barrel (i.e. $50 USD, HHV = 20 GJ/t). Thereby, the price considered is 230 $ CAD mt^{-1} (i.e. 32 $ CAD $barrel^{-1}$).

4.3.2 Case study structure

The technology sets and potential products now identified, the development of scenarios comprising the latter can now be structured (i.e. the bio-pathway scenarios). Accordingly, the first segment of this section is on the integration of the technology sets to the existing network. It is in this segment that the connections between the existing and potential processes are created and where synergies can be promoted. The second segment concerns

the analysis of the market where the potential production capacity of the Mauricie region is defined. This segment has a considerable influence on the scenarios development as well as on the solutions returned by the model. Finally, the final segment presented is the analysis of the technologies capacities and their respective costs in regard to the market analysis conducted.

4.3.2.1 The network development

The technology integration is a critical step in the scenario development. Indeed, most of the synergies considered by the model originate from this elaboration which leads to the meticulous task of processes aggregation. The aggregated processes are developed to take account of the potential flows and synergies created by the integration of the new technologies. Thus, in Figure A - II - 1 and Figure A - II - 2 of ANNEX II, the diagram of the aggregated processes flow network is visually represented and represents how the model is structured considering the inputs and outputs of each process based on the recipes presented in ANNEX IV.

4.3.2.2 Market and production assessment

The evaluation of the market possibilities is another critical step in the case study development due to its uncertainties. Many factors are not considered in the case study framework (e.g. marketing, agreements, contracts, political statements, alliances, R&D platforms, etc.). Therefore, assumptions on the market possibilities had to be settled based on the analyses of the bio products. In Table 4.10, ratios of the global market are scaled to estimate the market possibilities. For instance, the acetic acid has a well-established production in Asia with an efficient process which makes the market possibilities more restricted. Nonetheless, it has been deliberated that since the proposed process creates a non-synthetic acid and that the global market is considerable with a CAGR of 6 percent, 0.2 percent of the market could be grasped by a regional production. On another hand, newer productions as Crude bio-oil have a small global market but highly interesting CAGR, then the market possibilities can reach up to five (5) percent of the market.

Table 4.10 Bio-pathway scenario - Market potential

Products	Market possibilities (mt)						Global market (mt/y)	CAGR
	0.002	0.005	0.01	0.02	0.05	0.1		
Acetic acid	13000	32500	65000	130000	325000	650000	6,500,000	6.00%
Hemicellulosic Sugars	440	1100	2200	4400	11000	22000	220,000	4.50%
Cellulosic pulp	29700	74250	148500	297000	742500	1485000	14,850,000	6.50%
Kraft lignin	260	650	1300	2600	6500	13000	130,000	3.20%
Organosolv lignin	27	67	133	266	665	1330	13,300	5.00%
Levulinic Acid	6	16	32	64	160	320	3,200	4.80%
Furfural	940	2350	4700	9400	23500	47000	470,000	13.10%
Formic Acid	1894	4735	9470	18939	47348	94696	946,958	4.90%
Crude bio-oil	1000	2500	5000	10000	25000	50000	500,000	17.70%

A visual representation of the potential and existing regional productions is available in ANNEX III.

4.3.2.1 Production technologies: Costs and capacities

The markets possibilities assessed, the production capacity can be evaluated accordingly. Here, the production capacity determined by the technology sets. To open a technology set, companies have to pay an initial down payment equivalent to 20 percent of the capital expenditure (CAPEX) and pay afterward annuities based on a 20 years loan at a six (6) percent interest rate. It was considered that companies don't have all the same financial capacity, consequently, budgets have been developed based on the past annual profit of the organizations. Furthermore, two potential sites are available to open in the first year (i.e. Saint-Tite and Shawinigan), and the threshold to open or close a technology is set at the third year. To restrict the model to probable capacities, the technology sets outputs have been bounded between a minimum volume which is set by the technologies break-even point and the maximum volume set by the market possibilities. From these analyses, two capacities have been selected for each technology set based on their inputs volume. To be noted that a technology set can open in many sites and not necessarily tied to only one company. In Table 4.11, the production capacities have been elaborated using a scale of inputs amounts, where greyed numbers indicate an overcapacity compared to the demand.

Table 4.11 Bio-pathway scenario - Production capacity assessment

Products	Woody biomass inputs (bdmt/d)					
	100	200	500	1000	2000	3000
PHWE						Outputs (mt/y)
Acetic acid	-	1470	3674	7348	14696	22044
Hemicellulosic Sugars	-	4434	11086	22172	44344	66516
Organosolv Fractionation						
Cellulosic pulp	-	-	45391	90781	181562	272344
Hemicellulosic Sugars	-	-	33500	67000	134000	201000
Organosolv lignin	-	-	33233	66466	132932	199298
Levulinic Acid	-	-	235	471	942	1413
Furfural	-	-	964	1927	3854	5782
Formic Acid	-	-	105	210	421	631
Lignin recovery platform						
Kraft lignin	822	1643	4109	8217	16434	24651
Fast Pyrolysis						
Bio-oil	19472	38944	97361	194722	389444	584166

The following capacities are evaluated:

- The pressurized hot water extraction set opens with an input of 200 bdmt per day with a capital expenditure of 37 M$, and an increase of 100 bdmt per day is available adding 6 M$, creating a maximum inputs capacity of 300 bdmt per day (100,200 bdmt per annum).

- The organosolv has its first opening at 500 bdmt per day and a proportional increase is available considering a CAPEX of 206 M$ for the former, and a CAPEX of 106 M$ for the latter.

- The lignin recovery platform is considered as an integrated system where the inputs considered are those of the host site. Consequently, the two capacities considered are 1000 and 3000 bdmt per day with CAPEX of 18 M$ and 30.5 M$ respectively.

- The fast pyrolysis set has a first capacity of 200 bdmt per day with a CAPEX of 107 M$, and a similar expansion size at a cost of 86 M$.

4.4 Conclusion

Closely tied to the Mauricie history, the forest industry may have the potential to invigorate the regional economy by integrating novel products. The change from petroleum based products consumption to bioproducts is a necessary step towards a sustainable economy and the transformation of non-food biomass might be a key element of this transition. In this section, the base case scenario and the bio-pathway scenario have been elaborated to recreate at first, an accurate representation of the existing regional network, and to secondly offer a framework in which the impact of integrating novel products can be assessed. Thereby, four production technology sets have been identified to produce eight bioproducts. The scenarios development has been presented, and even though a voluminous amount of data is not shown, a comprehensive view of the case study structure and of the assumptions is accessible. In the following section, experimentations are conducted to evaluate the regional opportunities and results are presented.

CHAPTER 5

EXPERIMENTATIONS AND RESULTS

5.1 Introduction

Characterized as a resource-region, the Mauricie has relied on the forest to support and develop the regional economy. Over the decades, a strong forest value creation network has been established with an axis on high volume commodities. In the recent years, the forest sector economy has been affected by various factors tarnishing the ancestral lust of the industry. This situation has created an urged to revive the sector and innovative avenues are now put forward. In the previous segment, the Mauricie's forest value chain network has been presented in regard to the socioeconomic perspective and the current forest regime. Also, new bio-pathways have been identified to promote the conversion of lignocellulosic biomass to a variety of value-added products. In this chapter, four (4) scenarios are explored to confront the impact of introducing new products to the existing regional value chain network. The scenarios elaborated in this section are 1) all bioproducts are enabled to be open, 2) the provincial government enacts a law to support the production of renewable diesel, 3) the pressurized hot water extraction is force-opened, and 4) the organosolv is force-opened. A base case scenario (BCS) emulating the current Mauricie's forest value chain is initially presented to guide the evaluation of the subsequent scenarios. All of the scenarios were solved using Lingo 16.0 optimizer and Microsoft Excel as the database. The program was run on an Intel i7-5600 CPU @ 2.60GHz with 8.00 GB of RAM.

5.2 Base case scenario: The Mauricie "as is"

To create a representative regional network, the BCS is developed from the analysis conducted in section 4.2.2, where the Mauricie is portrayed considering the fibre availability, the PDCs and the market size. Due to the complexity of the regional network, assumptions were settled and stated in CHAPTER 4. The MILP model generated 2 079 890 decision variables, of which 106 260 are integers and 4 276 715 constraints, and solved within 30

minutes. The regional NPV based on a ten (10) years spent is 3 299 M $ following a regional production presented in Figure 5.1. The regional NPV considers all of the 21 active mills' activities from the fibre acquisition to the final deliveries and is comparable to the Mauricie's GDP specific to the wood and paper products. The cost of capital (α) used is eight (8) percent. The fibre consumption proportion per species is presented in Figure 5.2.

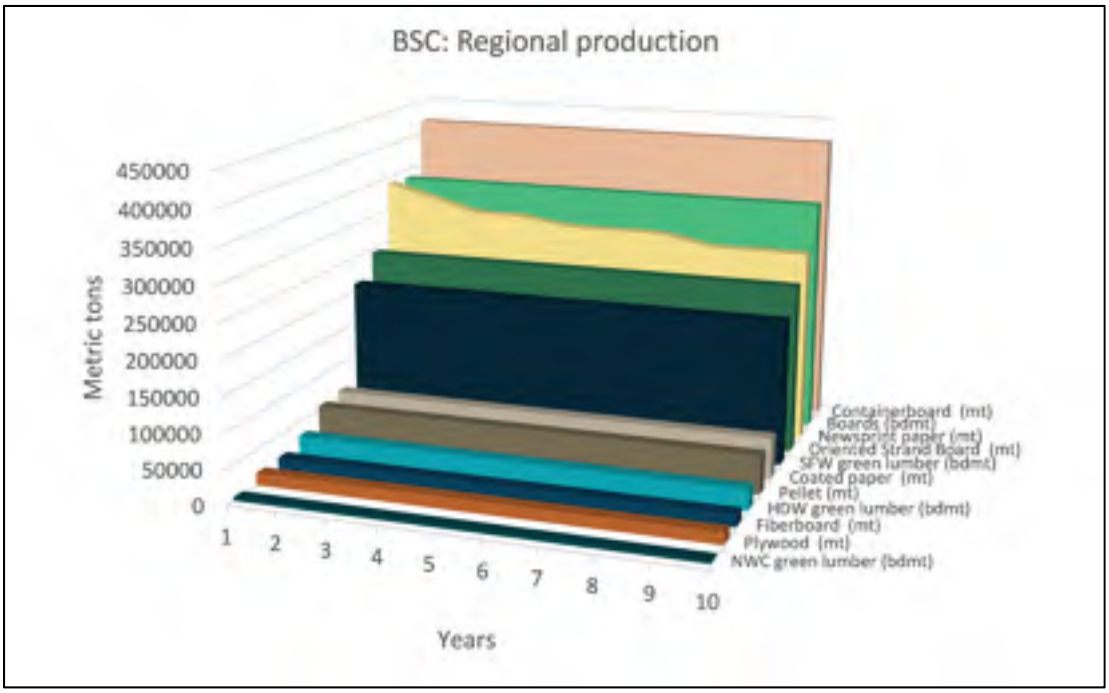

Figure 5.1 BCS: Regional production

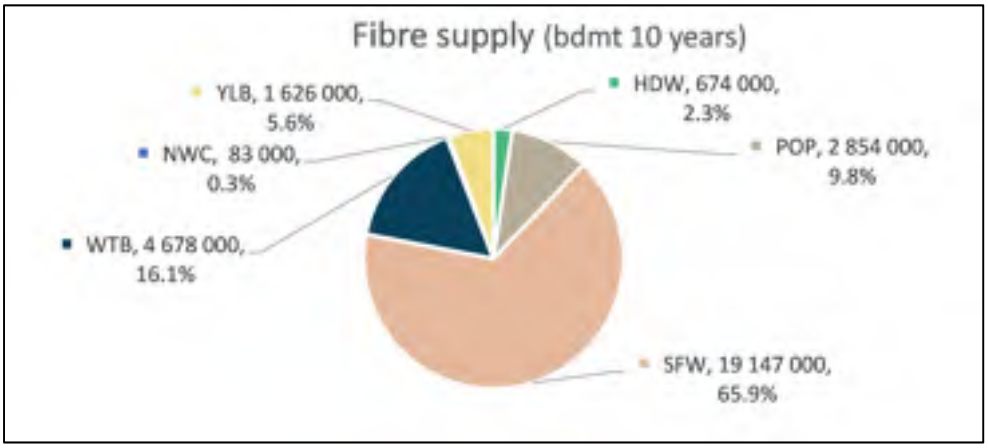

Figure 5.2 BCS: fibre consumption proportion per type

The total GHG emissions for the 10 years period is 16 589 kilotons (kt) CO_2 eq. as presented in Figure 5.3. These numbers are comparable to the one published by the Ministère du Développement Durable, de l'Environnement et de la Lutte contre les changements climatiques (MDDELCC) in their report *Émissions totales de gaz à effet de serre (GES) des établissements ayant déclaré au-dessus du seuil de 10 000 tonnes en équivalent CO2 (t éq. CO2) pour l'année 2015.*

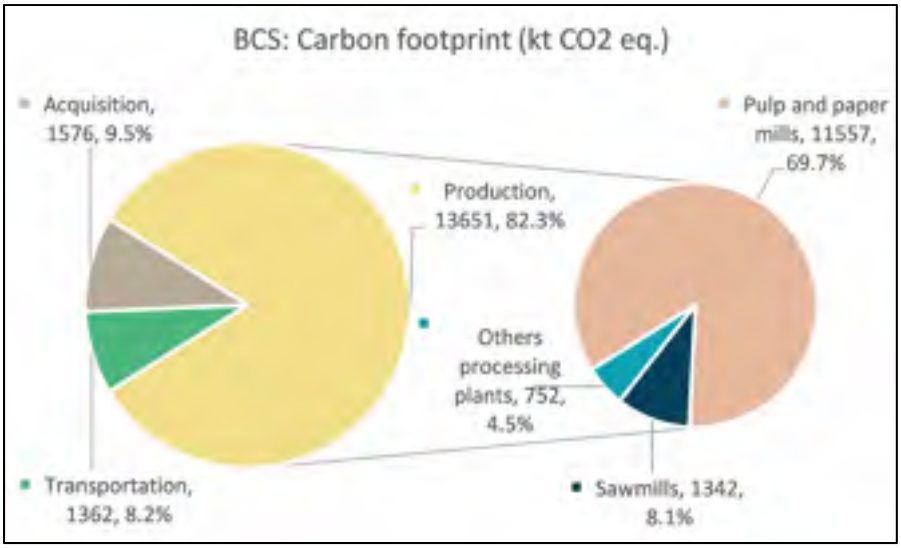

Figure 5.3 BCS: Regional carbon footprint

The carbon footprint analysis is composed of three segments: acquisition, transportation, and production. The acquisition segment takes in considerations the harvesting and forwarding of the fibre but does not include thinning and silvicultural operations. The transportation segment takes into considerations all of the products movements from the raw material procurement to the final products transfer point considering the various transportation modes as presented in Figure 5.4. Representing more than 80 percent of the emissions, the production segment is the main source of emissions and where the pulp and paper industry is accountable for 70 percent of the total carbon footprint. Additionally, 564 megatons of effluent and 493 kt of solid waste are produced.

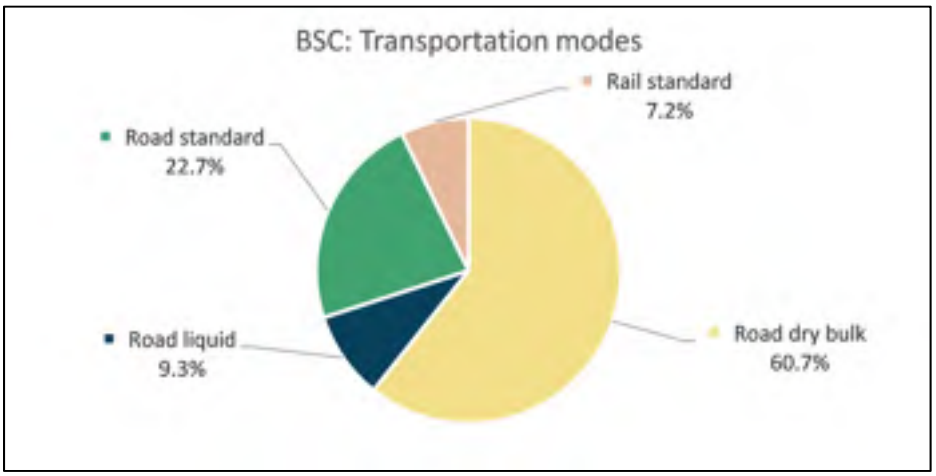

Figure 5.4 BCS: Apportionment of the transport modes.

Finally, due to the decreasing newsprint paper demand, it is estimated that at least 91 direct jobs will be lost throughout the period (see Figure 5.5). A correlation between direct and indirect jobs can be supposed but due to our limited knowledge of the phenomenon, the calculation of the latter is not covered in this work.

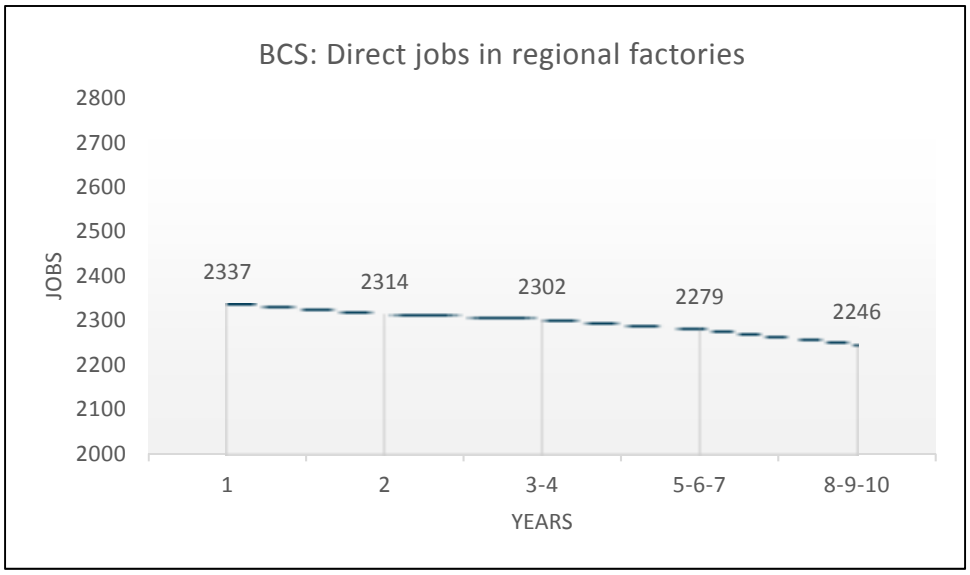

Figure 5.5 BCS: Direct jobs in regional factories

5.3 Scenario 1: All bioproducts enabled

The base case scenario defined, the evaluation of the integration of new bioproducts can now be conducted. In this first scenario (SC1), all production technologies are enabled to be opened (i.e. pressurized hot water extraction, lignin recovery platform, fast pyrolysis, and organosolv fractionation). The details of the proposed technologies and bioproducts are presented in section 4.3. The scenario is constrained by the following conditions: a down payment of twenty (20) percent of the capital expenditure, annuities based on a 20 years loan with a six (6) percent interest rate, and a cost of capital of eight (8) percent. The solution of the SC1 indicates that two (2) technologies are potentially good implementations in the existing system: the fast pyrolysis and the lignin recovery platform. By starting the production of two (2) new productions, the region shows a new NPV of 3 316 M $, an increase of 0.53% compared to the BCS. In the following sections, both productions are analyzed and a general discussion of the scenario is elaborated.

5.3.1 Crude bio-oil production

From the market size analysis, the crude bio-oil is an interesting commodity with a CAGR of 17.7 percent. The potential regional production starts in the first year at 25 000 metric tons and reaches near 100 000 metric tons in the last year of the analysis. The price of the unstabilized crude bio-oil has been set at 39.90$ per barrel (287$ mt^{-1}) at the mill gate, there is a price increment of five (5) percent yearly, and 35 percent of the capital expenditure is covered by governmental subsidies. Lastly, one assumption is that the pyrolysis technology is almost energetically self-sufficient by using the syngas and chars produced by the process. With these prerequisites, a first biorefinery opens in the second year with an input capacity of 200 bdmt per day (see Figure 5.6). In the third year, a same sized mill open in another location. A limitation occasioned by the model is the disability to open a technology past the third year. This situation explains why the production capacity is consequently higher than the demand in the third period, and from year 3 to 10, the production capacity stays unchanged. In the last period (i.e. year 8 to 10), the demand shows that there might be a potential to expand the production but the margin of error is too significant to take a decision

after the third year. One particularity common to these two plants is that they opened next to a large softwood sawmill with a connection to the rail network. Here, the fast pyrolysis technology has been considered as a standalone biorefinery, which has an incidence on the capex. Yet, with these small capacities, integrating the technology to a sawmill might enhance the profitability of the project.

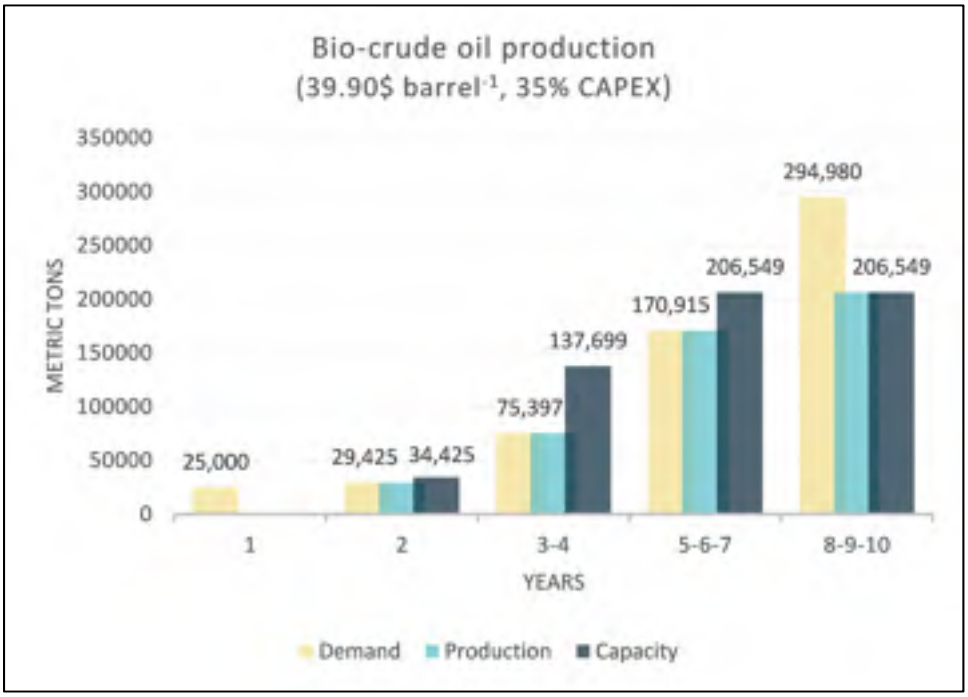

Figure 5.6 SC1: Crude bio-oil production

When investigating the reason behind the mills positioning, the ascertainment is that both biorefineries predominantly use hog fuel produced by the two sawmills as feedstock. This trend indicates that the acquisition cost is a factor to consider when positioning the biorefineries and that it might be valuable to further process the hog fuel. This situation might explain why two mills opened rather than an increase of the production capacity of the first mill. Surprisingly, the use of forest residues is limited and only one of the mill process it as feedstock toward the last years with a coverage radius of 15 kilometers (see Figure 5.7). Here, the coverage radius indicates the maximal distance in a straight line within which all harvest areas exploited by the mill are. On the other hand, the physical distance considering the road network may be longer than the radius distance. Overall, the technology has a

limited impact on the network, matches well with large sawmills and has a potential to increase the fibre value transforming low-quality feedstock to a commodity product. However, the opening of the fast pyrolysis technology set is precarious and has underperforming economics indicators to support its viability. The technology has a return on capital employed (ROCE) of (9.4) percent and an internal rate of return (IRR) of 9.7 percent. While the NPV of the solution is positive, insufficient capital is engendered to cover the technology's depreciation, here considered as linear on a 20 years basis and without residual value. The reason why the ROCE is negative while the IRR is positive is that the depreciation taken on the asset in future periods is not a cash flow, therefore not included in the NPV and IRR calculations. Also, the cost of capital considered (i.e. 8 percent) is lower than the IRR explaining the opening of the set.

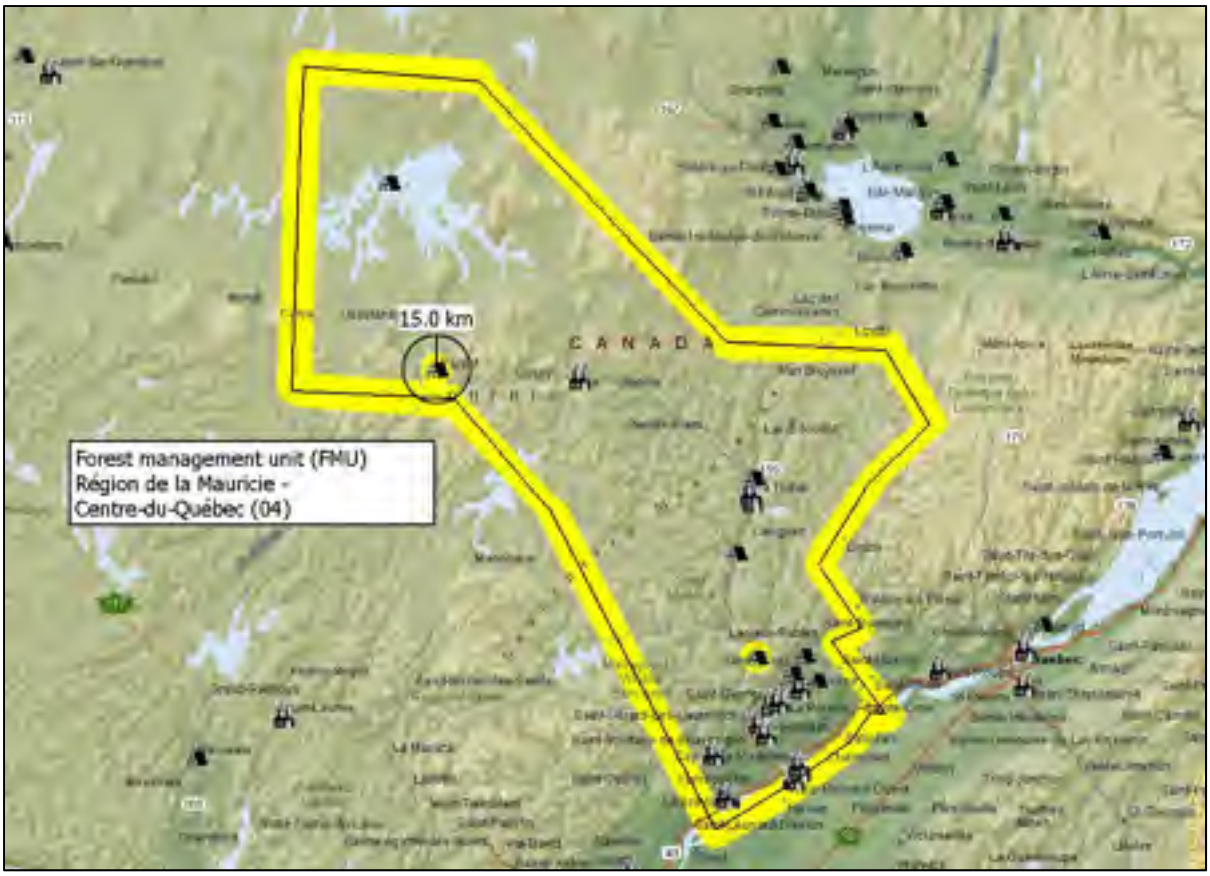

Figure 5.7 SC1: Crude bio-oil plants positioning

5.3.2 Kraft lignin production

The kraft lignin is a highly versatile specialty product and has the potential to become a commodity with its emerging applications. However, the market size specific to the kraft lignin has still to be developed resulting in regional production potential of 6 500 metric tons following a CAGR of 3.2 percent. With a mill gate price of 675$ mt^{-1} and an annual price increment of five (5) percent, a lignin recovery platform opens in the third year (see Figure 5.8). The size of the platform is equivalent to half of a median North American kraft lignin biorefinery and no constraint on the type of feedstock has been enforced, meaning that the quality of the lignin is not differentiated whether it comes from softwood or hardwood black liquor. Furthermore, by partially precipitating the lignin contained in the black liquor, kraft pulp mills are able to offload their recovery boiler that is often used at their design limits (Benali et al., 2016). When the pulp production is constrained by this bottleneck, there is a potential to increase the mill pulp production capacity. However, no increase has been considered in SC1 since the percentage of increase capacity may differ greatly from one design to another. Instead, a series of experiments shown in Figure 5.9 point to the potential improvements in the technology's internal rate of return (IRR).

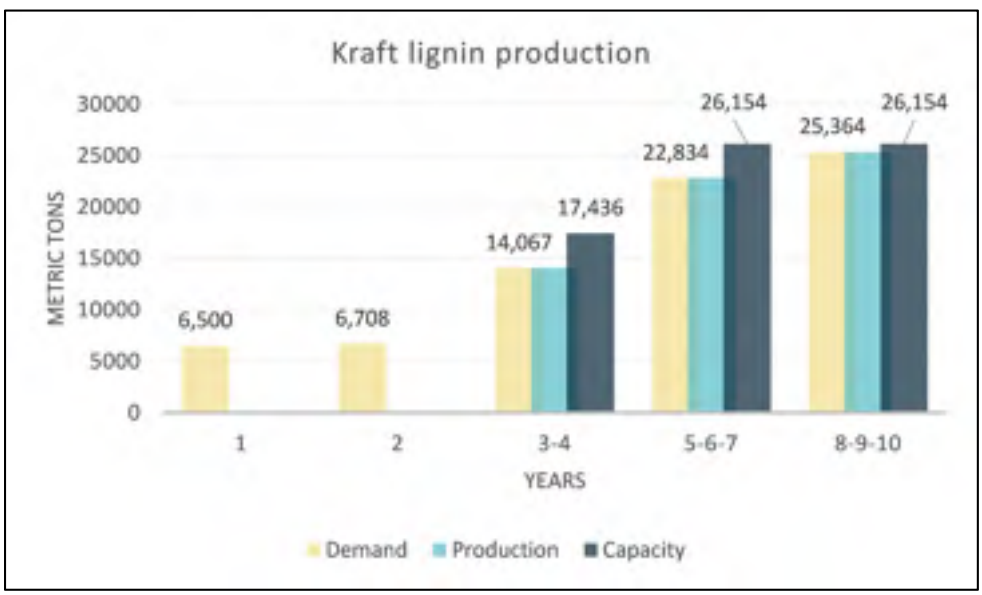

Figure 5.8 SC1: Kraft lignin production

With a ROCE of 15.4 percent and an IRR of 14.2 percent, the economic metrics specific to the lignin recovery platform show an interesting potential considering that no increase in pulp production has been considered. In the following chart, the input (i.e. fibre) and the output (i.e. pulp) of a kraft pulp mill are illustrated considering a steady production of lignin. With a ten (10) percent increase in the pulp production, the platform's IRR increase by 20 percent compared to the referential scenario, inferring that a pulp production increase may be the key parameter to trigger the decision to open such a platform. Thereby, further investigation of potential kraft pulp mills has to be conducted to assess the desirability of the technology. Moreover, an important aspect to take in consideration is the potential increase of the feedstock consumption which may have a consequential impact on the regional fibre supply distribution.

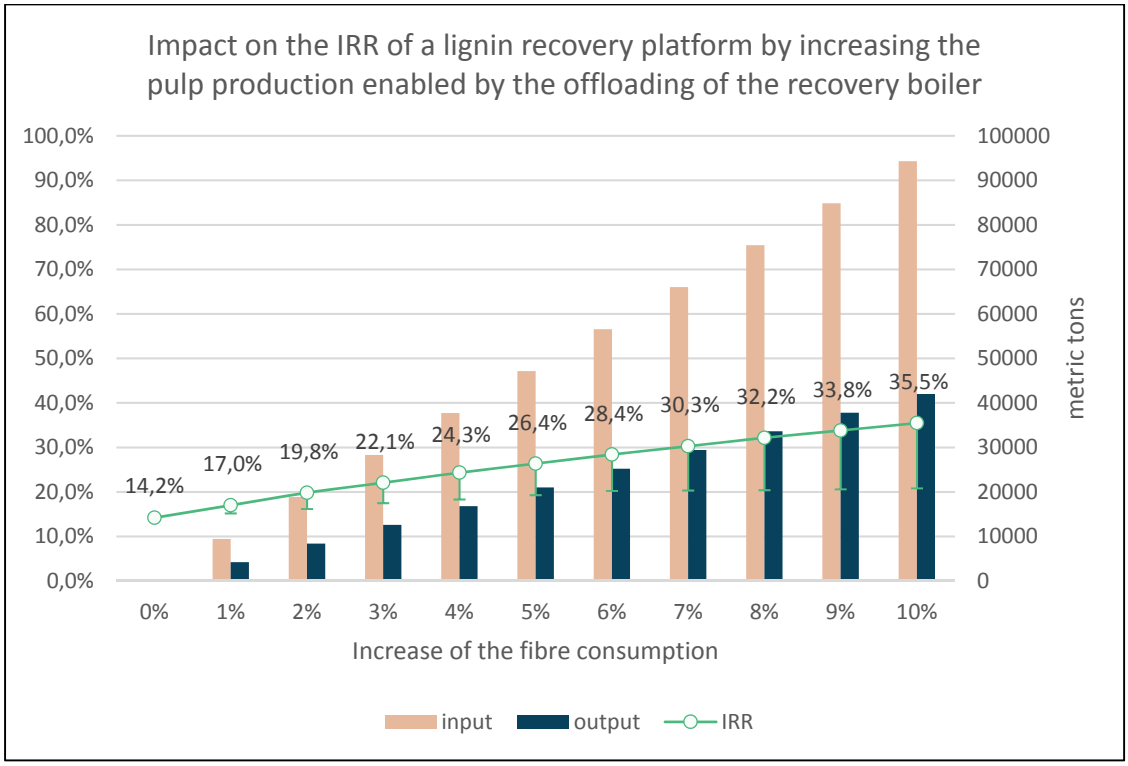

Figure 5.9 Impact on the IRR of a lignin recovery platform by increasing the pulp production

5.3.3 Discussion

The introduction of a standalone fast pyrolysis technology and an integrated lignin recovery platform have interestingly a limited effect on the existing network, leaving the initial productions and stakeholders unaffected as presented in Figure 5.10. Although no connection between the two productions has been considered in SC1, synergies between the two technologies could be further assessed where the lignin could be converted by the pyrolysis set to produce biochemicals, biomaterials, and biofuels. Together, the technologies have a ROCE of (6.6) percent and an IRR of 11.49%. Both numbers indicate that the SC1 has a low economic profitability and might be insufficient to cover the incurred risk and the technologies depreciation. Nevertheless, advanced research on the integration of these two technologies might reveal a more interesting opportunity than presented in this study since both technologies create value from residues and waste, and adding value to the existing network.

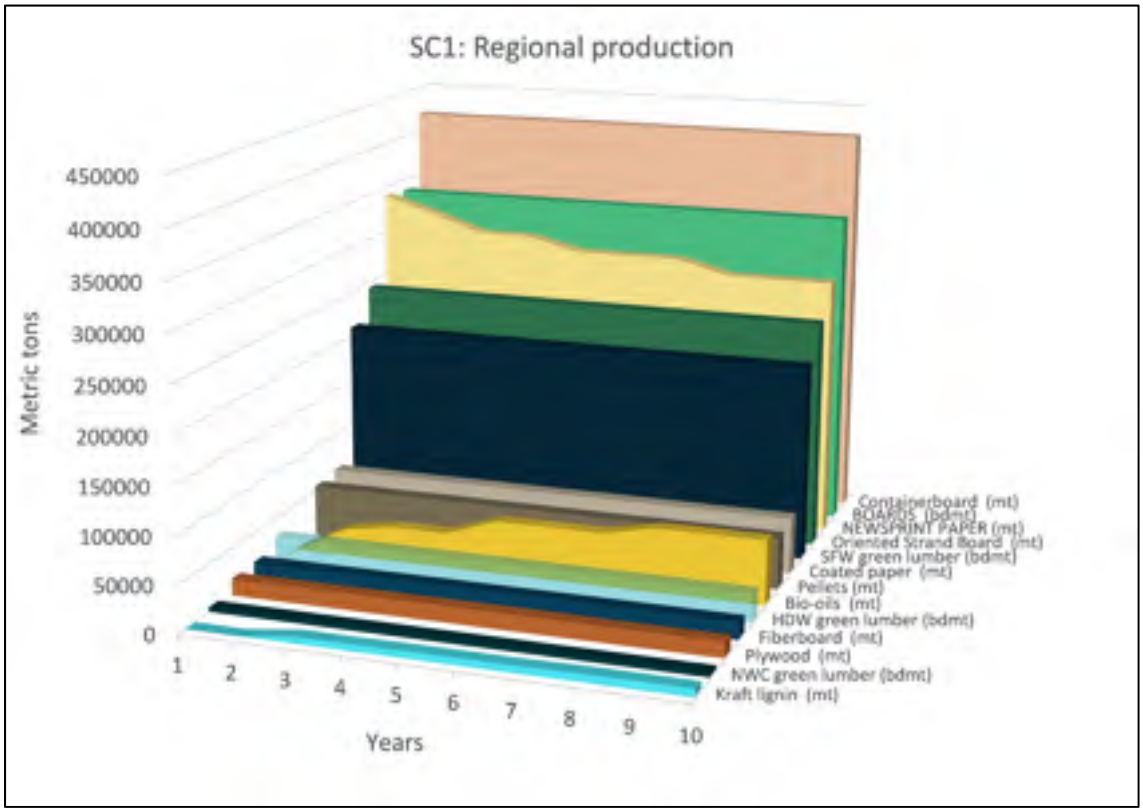

Figure 5.10 SC1: Regional production

The fibre supply, as presented in Figure 5.11, remains similar to the BCS where only a small amount of forest residues is introduced toward the end of the scenario. The GHG emissions for the 10 years period increase by 23.8 percent, from 16 589 to 20 539 kt CO_2 eq., and mainly from the new processes as illustrated in Figure 5.12. On the other hand, solid waste and effluents are not altered.

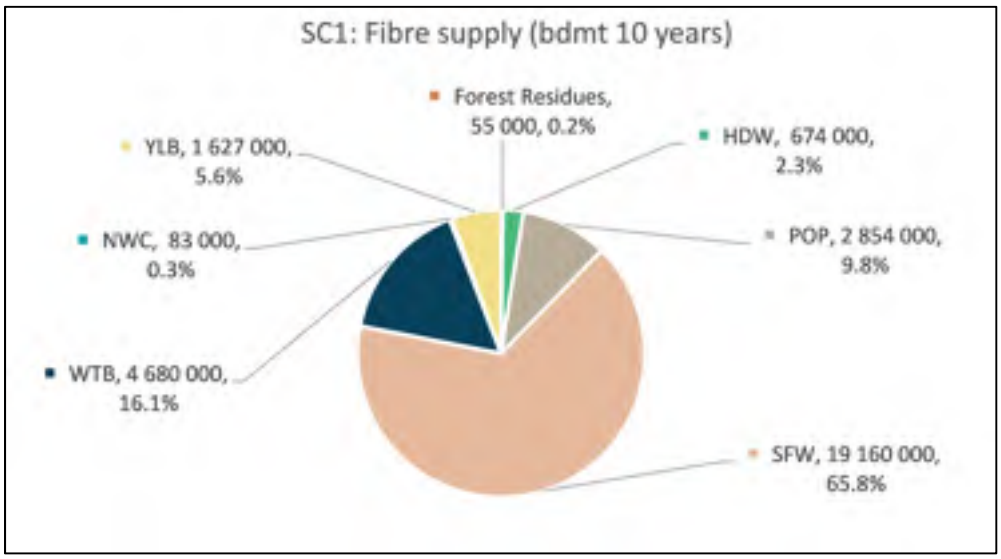

Figure 5.11 SC1: Fibre consumption proportion per type

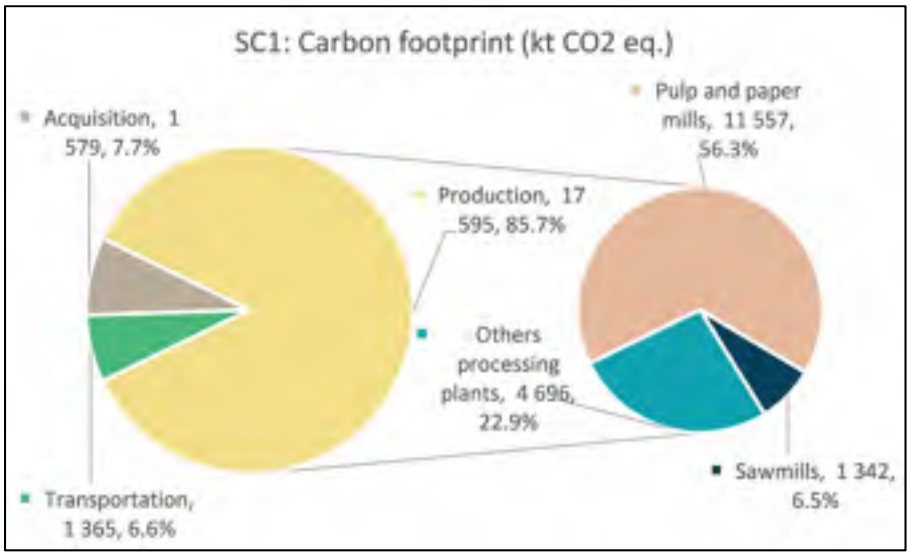

Figure 5.12 SC1: Regional carbon footprint

The apportionment of the transport modes is unchanged with the exception of the use of liquid rail, mainly for the transport of the crude bio-oil to the customers (see Figure 5.13). In Figure 5.14, an interesting addition to the regional direct labor force can be noted with a final variation of 9.5 percent from the BCS.

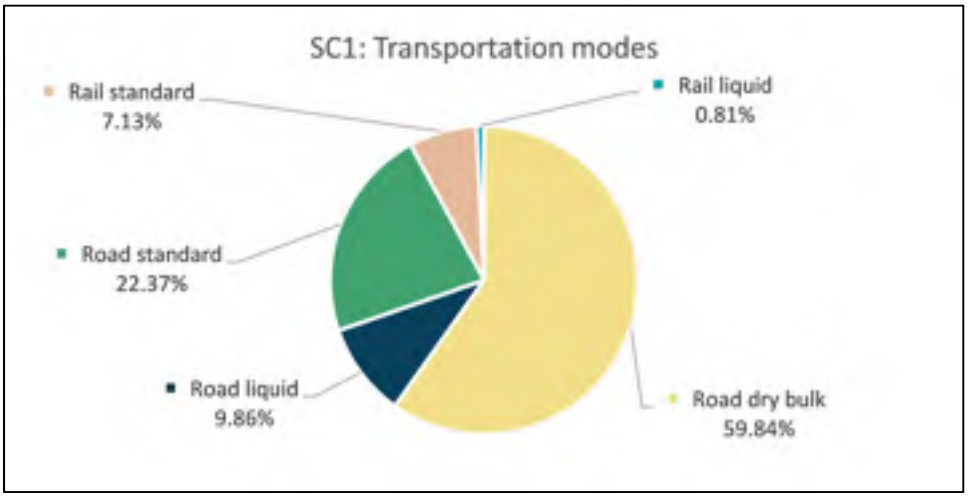

Figure 5.13 SC1: Apportionment of the transport modes

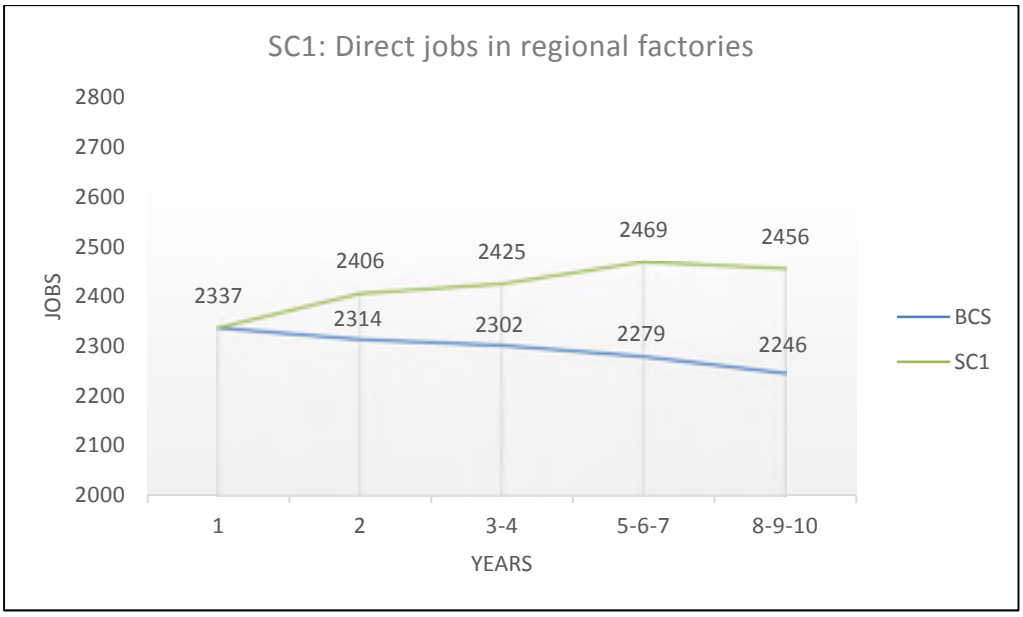

Figure 5.14 SC1: Direct jobs in regional factories

5.4 Scenario 2: Government enacts laws to support renewable diesel

The second scenario (SC2) is a study of the impact of enforcing the production of a specified quantity of crude bio-oil to satisfy a fixed renewable diesel (RD) demand. In Table 5.1, four (4) sub-scenarios with varying parameters are proposed to further assess the potential of integrating the fast pyrolysis technology. The scenario is constrained by the following conditions: a down payment of twenty (20) percent of the capital expenditure, annuities based on a 20 years loan with a six (6) percent interest rate, and a cost of capital of eight (8) percent. Even though the objective is to satisfy a renewable diesel demand, the final product for all of the sub-scenarios is the unstabilized crude bio-oil where one (1) kiloton of oil can be converted into 341.9 metric tons of diesel and 330.0 metric tons of gas. The demand for renewable diesel has been set to two (2) percent of the province's consumption (i.e. 64 M litres of diesel).

Table 5.1 SC2: Sub-scenarios parameters

SC2	Crude bio-oil ($ barrel^{-1})	Price increment	Government subsidies	Renewable Fuels Regulations
SC2.1	31.90$	None	None	Quebec: 2% RD blend to diesel
SC2.2	31.90$	5% yearly	35% CAPEX	Quebec: 2% RD blend to diesel
SC2.3	39.88$	25% per barrel 5% yearly	35% CAPEX	Quebec: 2% RD blend to diesel
SC2.4	39.88$	25% per barrel 5% yearly	35% CAPEX	Quebec: 2% RD blend to diesel (years 1-2), 5% (years 3 to 10)

The first sub-scenario follows a strict setup where the price is based on the energy content using the petroleum oil price per barrel as referential (i.e. $50 USD, HHV = 20 GJ/t). Neither price increment nor financial help have been included in the latter. The second sub-scenario is similar to the first but includes a five (5) percent annual price increment and 35 percent of the capital expenditure is covered by governmental subsidies. The third scenario takes the same parameters but considers a direct price increment of 25 percent. Finally, the last sub-scenario is subject to an increase of the renewable diesel demand in the third year from two (2) percent to five (5) percent.

5.4.1 Two percent RD blend to Quebec diesel

The solution structure of the three first sub-scenario is alike with the opening of four (4) mills located next to the three largest softwood sawmills in the region, and one next to the veneer mill in Shawinigan (see Figure 5.15). Only one (1) mill has an increase in production capacity, indicating the importance of the cost of acquisition when combined with a low economy of scale ratio (i.e. ratio of 0.8 from 200 bdmt to 400 bdmt). All biorefineries use primarily hog fuel as feedstock and occurrence of its transport between mills help to explain the positioning of the Shawinigan biorefinery. The total consumption of hog fuel is equivalent to 65 percent of the regional production, indicating a strong potential to use the wood waste produced by the mills. Moreover, an interesting balance between the usage of hog fuel and forest residues exist, and three out of the four mills use it as feedstock. The farthest distance to collect forest residues is within a 25 kilometers radius, an increase of 10 kilometers from SC1, and hog fuel transfers are within a range of 20 kilometers.

Figure 5.15 SC2.1-3: Crude bio-oil plants positioning

Considering a total production of 169 000 metric tons year^{-1}, the net present values of the three first sub-scenarios are presented in Table 5.2. With a mill gate selling price based on its energetic value (i.e. SC2.1-2), a notable reduction of the regional NPV can be observed. This situation indicates a non-profitability of the production without a complex financial engineering structure. Feedstock acquisition costs, operating costs, and capital expenditure highly influence the profitability of the scenarios and can change significantly the final outcome. One major limiting factor that might bias the scenarios is the cost related to the scalability of the biorefineries. At the present time, the largest fast pyrolysis biorefinery under construction (i.e. Ensyn Côte-Nord Project [17]) has a capacity of less than 35 thousand metric tons of crude bio-oil year^{-1}. Therefore, evaluating a production of 169 thousand metric tons year^{-1} without available economy of scales information may be a cause of the non-profitability. The product price is also a very important parameter to consider where the different applications of the oil may results in more profitability (e.g. the heating oil market versus the diesel market). In the first sub-scenario, the production cost is estimated at 46.36 Cad dollars barrel^{-1}, accounting for a net loss of 14.46 Cad dollars per barrel. By adding a price increment of five (5) percent yearly (or its equivalence in cost reduction), and by including a governmental subsidy of 35 percent of the capex, the cost per barrel is then 36.67 Cad dollars in the second sub-scenario. The result indicates a less significant loss but is still unable to reimburse the initial cash down. With the same parameters and by adding a price increment of 25 percent, the third sub-scenario has a positive cash flow with a variation of the NPV of 18 M Cad dollars. This price increment can be considered as a green product premium or from the carbon exchange market. To be noted that this price increment is not founded on existing data and is only used to showcase the potential.

Table 5.2 SC2: Sub-scenarios NPV

SC2	**NPV**	**Variation (Δ)**
SC2.1	3 121 M $	(5.40) %
SC2.2	3 246 M $	(1.59) %
SC2.3	3 317 M $	0.55 %

As in SC1, the introduction of this large production does not affect the existing stakeholders in the region since no concurrence is created on the feedstock acquisition (see Figure 5.16). Nonetheless, the use and transfer of hog fuel by the regional mills is an interesting opportunity to develop, and further research on the extent of the impact of this new application has to be conducted. In Figure 5.17, the fibre supply apportionment specific to the forest residues accounts for more than one (1) percent, indicating a potential breakthrough in the development of this unused fibre. Nevertheless, the consumed quantities remain low compared to its available volume (i.e. 3.6 percent of the branches residues) and represent 12 percent of the required feedstock to produce the crude bio-oil.

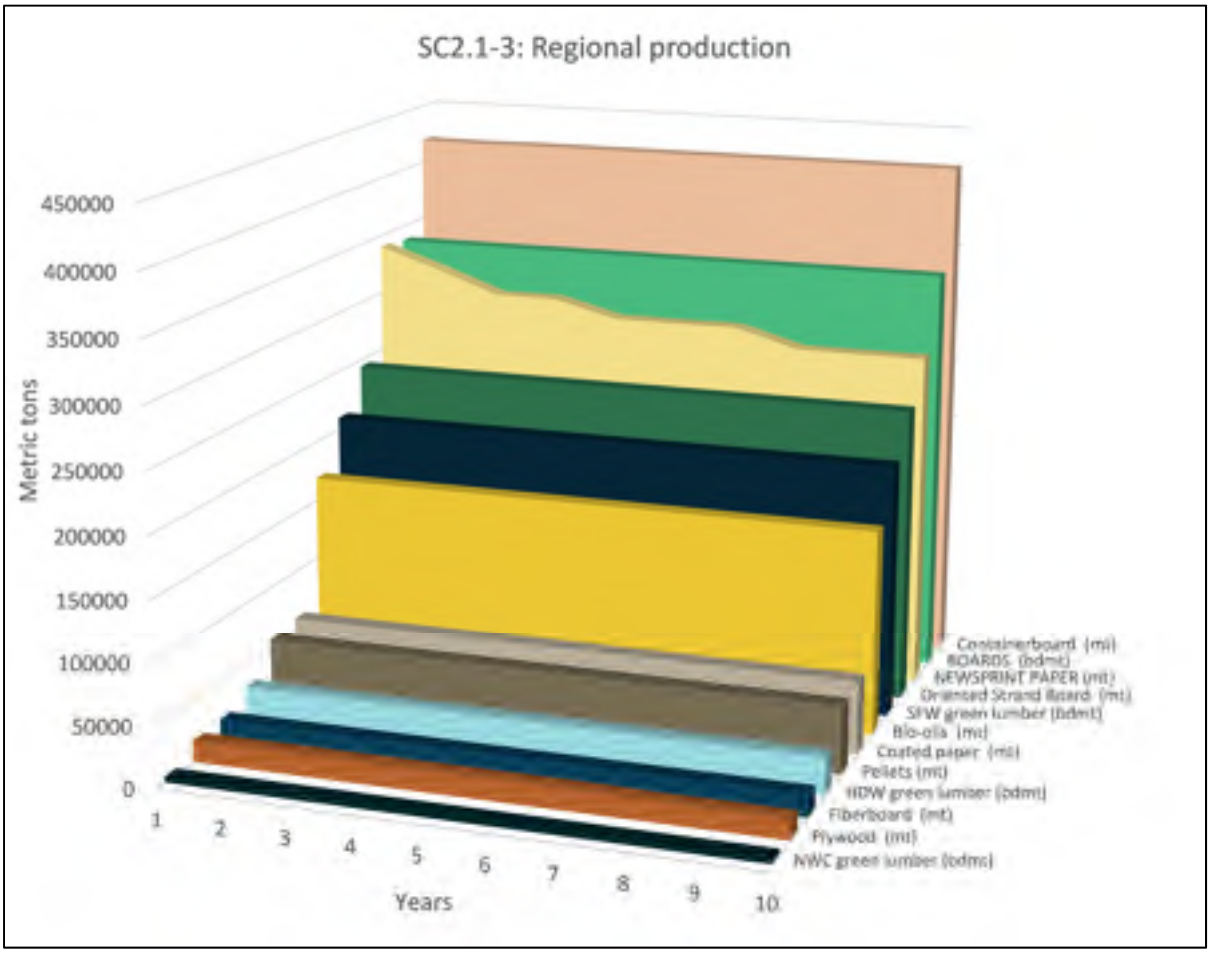

Figure 5.16 SC2.1-3: Regional production

A significant upsurge of the GHG emissions occurred, from 16 589 kilotons to 22 579 kt CO_2 eq., a 36.1 percent increase compared to the BCS (see Figure 5.18). The effluents and solid waste remain however the same as in the BCS.

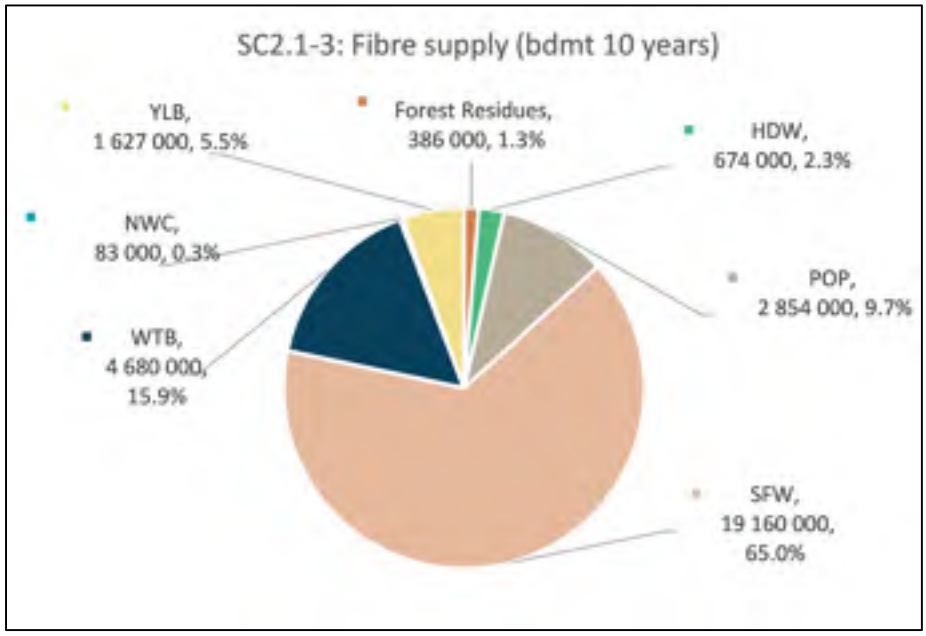

Figure 5.17 SC2.1-3: Fibre consumption proportion per type

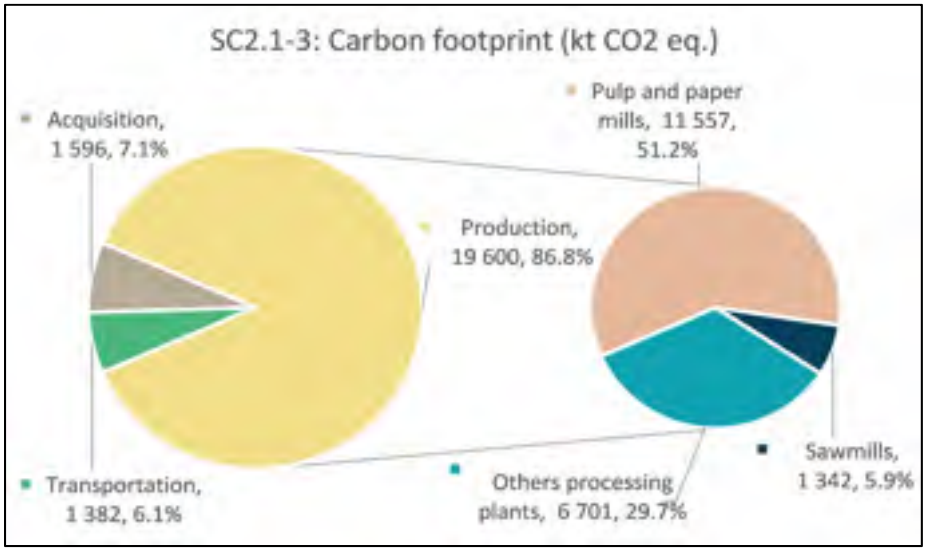

Figure 5.18 SC2.1-3: Regional carbon footprint

Overall, the apportionment of the transport modes is comparable to the BCS, and a small increment of the rail liquid is observed, reaching up to 2.4 percent of the tonnage movement (see Figure 5.19). The most interesting impact of this technology integration is the increase of direct jobs in regional factories, accounting for 500 new jobs created and distributed throughout the Mauricie region (see Figure 5.20). This occurrence has a significant potential to disrupt the socioeconomic context by stimulating the regional economy and promote the development of more industries.

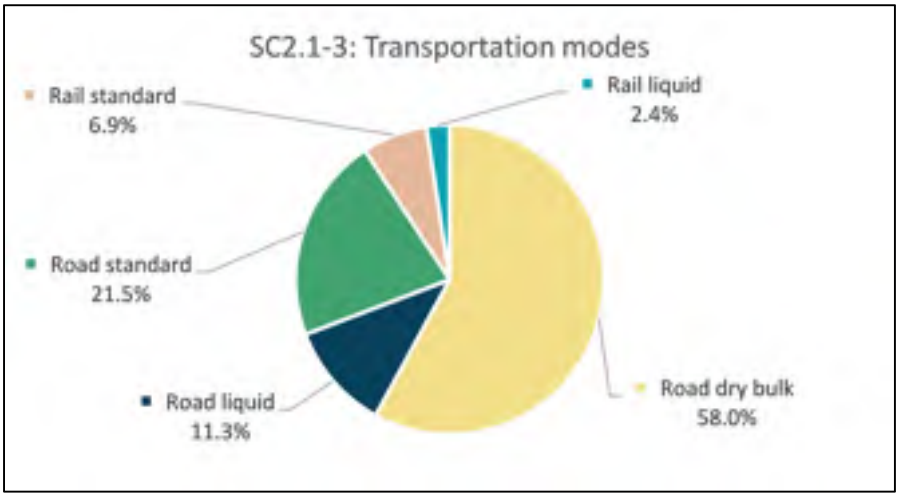

Figure 5.19 SC2.1-3: Apportionment of the transport modes

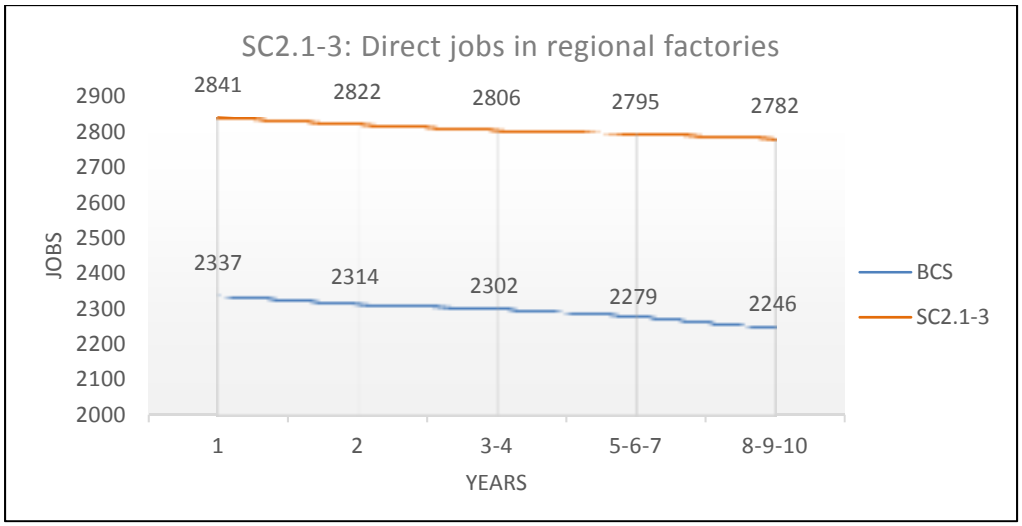

Figure 5.20 SC2.1-3: Direct jobs in regional factories

5.4.2 Up to five percent RD blend to Quebec diesel

Following the same parameters as the third sub-scenario, the fourth sub-scenario has a renewable diesel demand increment in the third year (i.e. from two (2) percent to five (5) percent of the Quebec diesel consumption). The solution structure of the two first years is comparable to the previous sub-scenarios in regard to the mills' positioning and capacities. In the third year, the small capacity biorefineries increase their production and three (3) new biorefineries are opened. Interestingly, the two available locations (i.e. Saint-Tite and Shawinigan) are opened in the third year with an extended production capacity, and a standard biorefinery is opened next to the newsprint paper mill. Limited by the model at a maximal input capacity of 400 bdmt day^{-1}, a total of seven (7) biorefineries are opened in the region as shown in Figure 5.21. By increasing the market size in the third year, the region shows a new NPV of 3 347 M $, an increase of 1.46% compared to the BCS and 0.90% from the SC2.3.

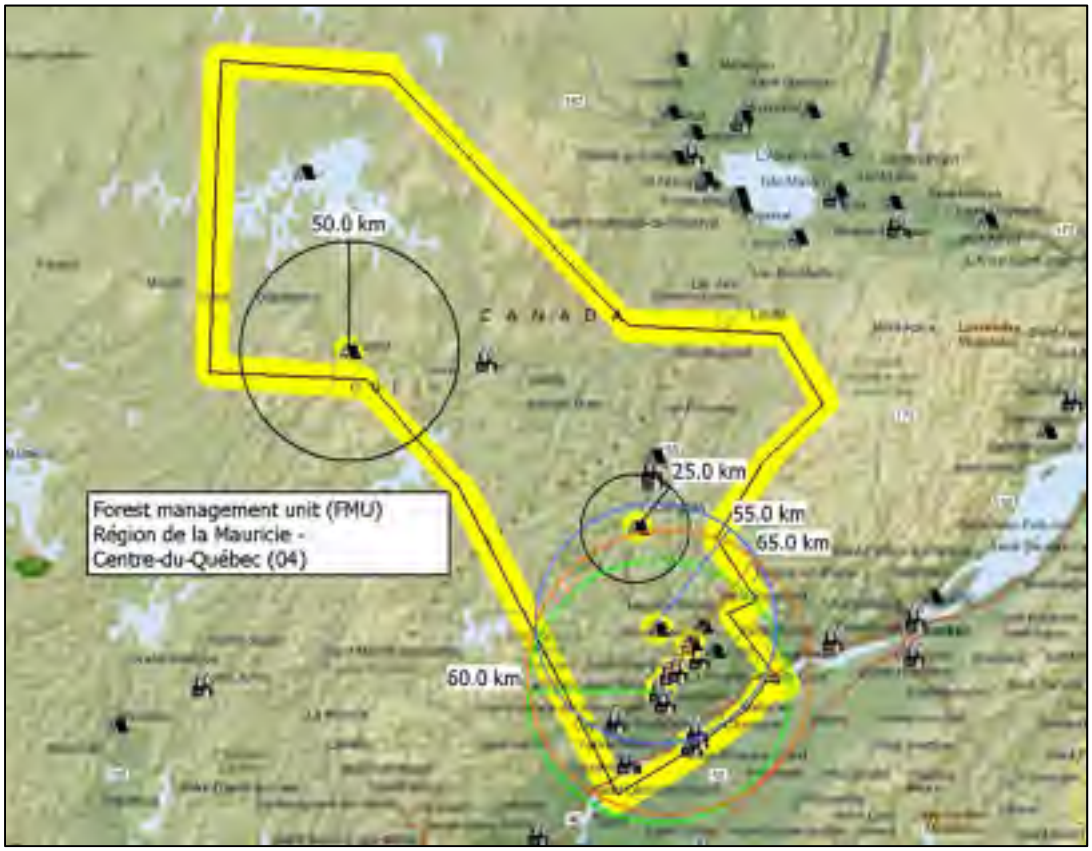

Figure 5.21 SC2.4: Crude bio-oil plants positioning

Yet, this solution appears to be biased by the capacity constraint enforced by the model. When observing the map, five (5) biorefineries open in the south of the region within a radius of 30 kilometers. This situation leads to the assumption that one (1) very large biorefinery would open in this area. As discussed previously, costs related to the economy of scale of such technology are not available as for now. Thereby, this solution is over constrained and might be more profitable than demonstrated in this fourth sub-scenario. The introduction of such production in the region has a potential to profoundly change the economic development of the region despite a negative ROCE (i.e. -5.9%). The IRR of the solution is, however, one of the highest of all the scenarios at 15.9 percent. From a regional production perspective, the crude bio-oil becomes one of the largest commodities, and no impact on the current productions is observed (see Figure 5.22).

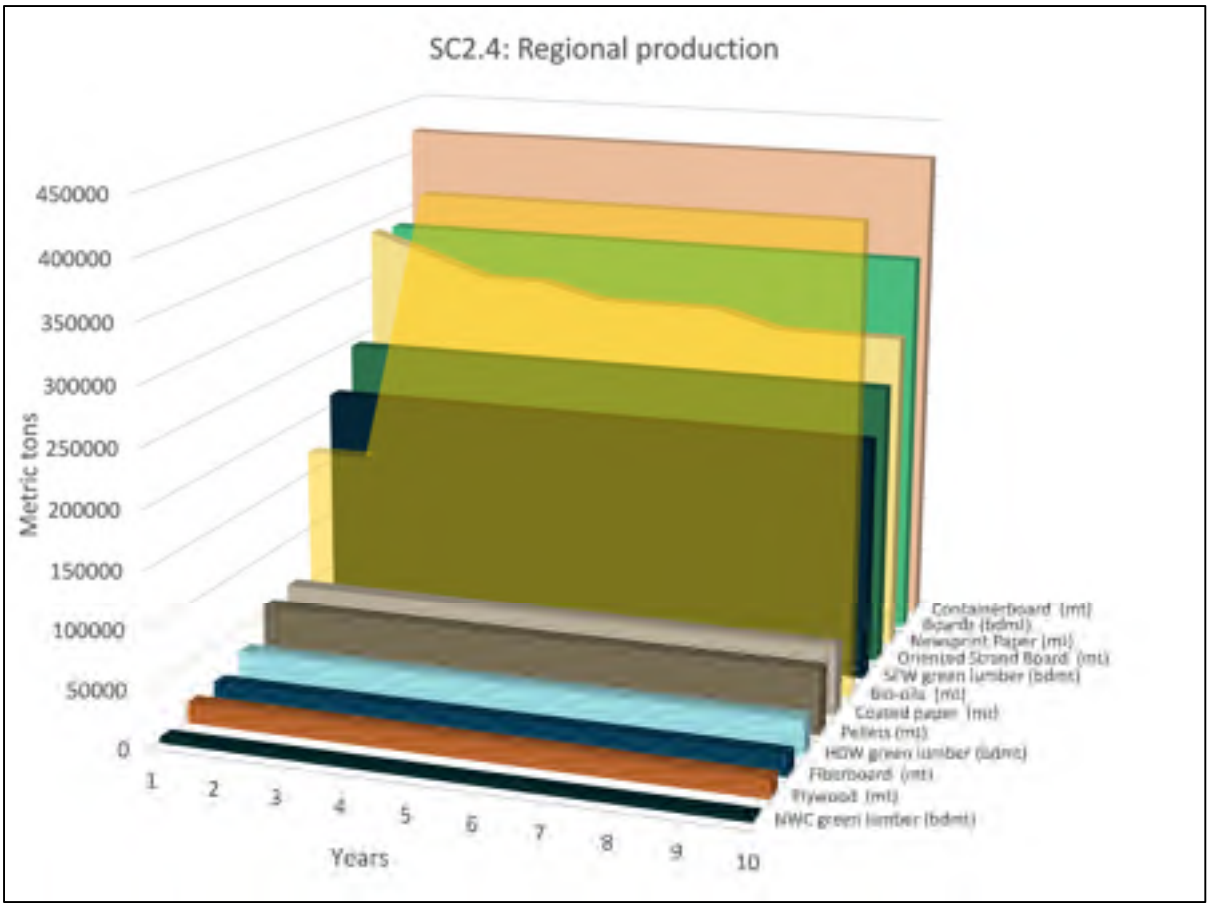

Figure 5.22 SC2.4: Regional production

Biorefineries coverage radius to access the forest residues is considerably larger than in the previous sub-scenarios and now intersects each other. This condition may create competition to access the fibre in the south of the region and demonstrate a potential value of the forest residues with a total consumption of 25 percent of the total available branches residues. As shown in Figure 5.23, forest residues represent a consequential portion of the fibre supply. Nonetheless, its contribution the feedstock requirement to produce crude bio-oil is only 38 percent, and where 62 percent of the feedstock comes from the hog fuel. Here, a factor that may influence the consumption of forest residues is the availability of the hog fuel. Indeed, 93 percent of the hog fuel produced in the region is transformed into crude bio-oil, raising questions on the effect of this supply reorientation. Currently, the hog fuel is used as fuel in boilers in combination to natural gas. While some sawmills are energy self-sufficient by burning the hog fuel, some other mills simply burn the feedstock to dispose of it. While small quantities would not affect the system, using more than 90 percent of it might create competition or detrimental effects that have not been considered in this scenario.

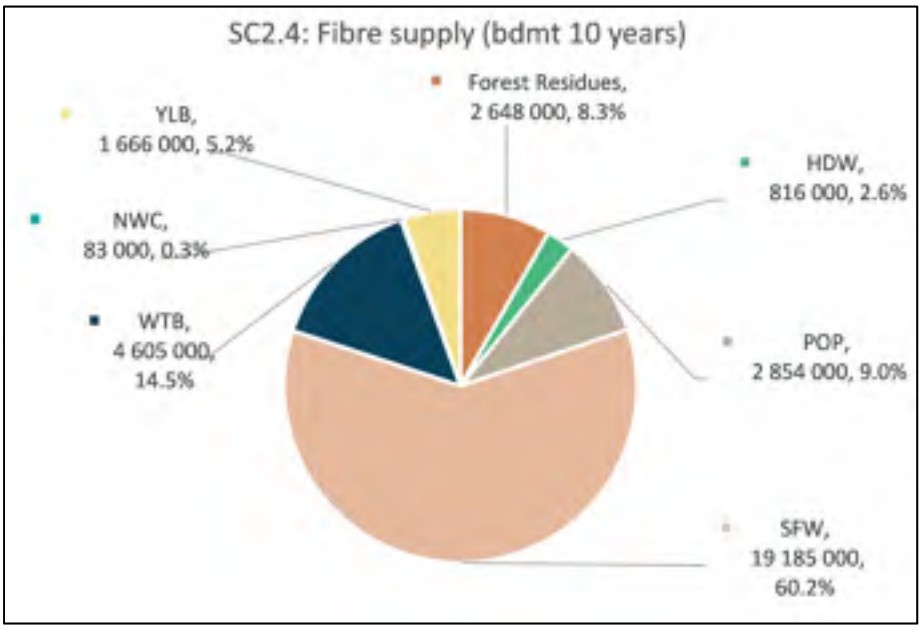

Figure 5.23 SC2.4: Fibre consumption proportion per type

A shown in Figure 5.24, the new biorefineries become one of the largest emitters of the region, increasing the total emission to 26 393 kt CO_2 eq., a 59.0 percent increase compared to the BCS, and a 16.9 percent increase from the previous sub-scenarios. In Figure 5.25, transportation modes proportion are not significantly transformed where only small adjustments are brought to the BCS, and with a more important use of the liquid transportation by rail.

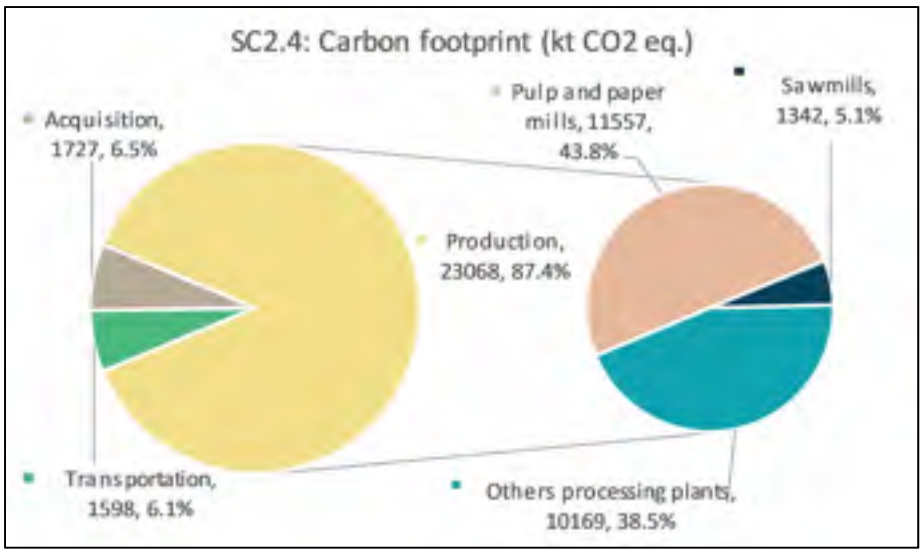

Figure 5.24 SC2.4: Regional carbon footprint

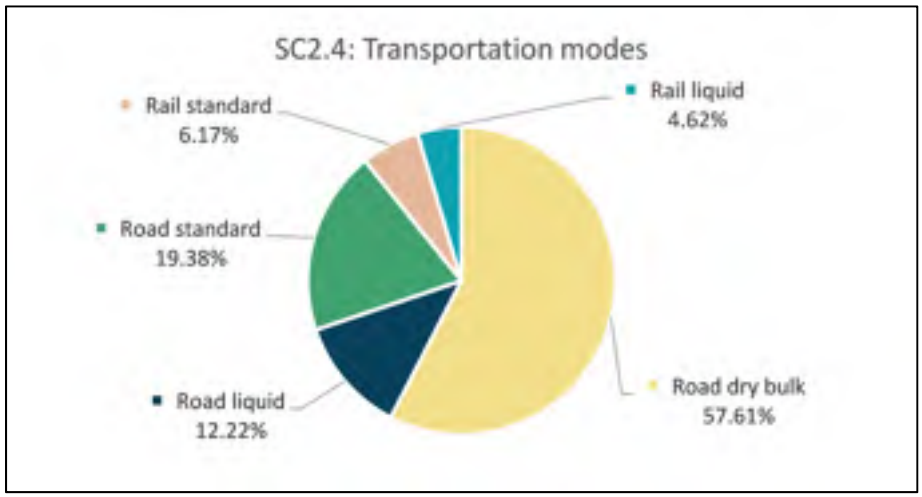

Figure 5.25 SC2.4: Apportionment of the transport modes

Finally and as the preceding sub-scenarios, incorporating the production of crude bio-oil to the system has a strong potential to generate jobs in the region. With a demand of two (2) percent of the Quebec diesel, 500 new employments are created, and at five (5) percent, an addition of 700 direct jobs is added to the system (see Figure 5.26). This situation alone may help to justify the governmental subsidies. However, these numbers are based on small to medium production capacity mills. In the occurrence of the opening of a large biorefinery, these numbers may be considerably lower.

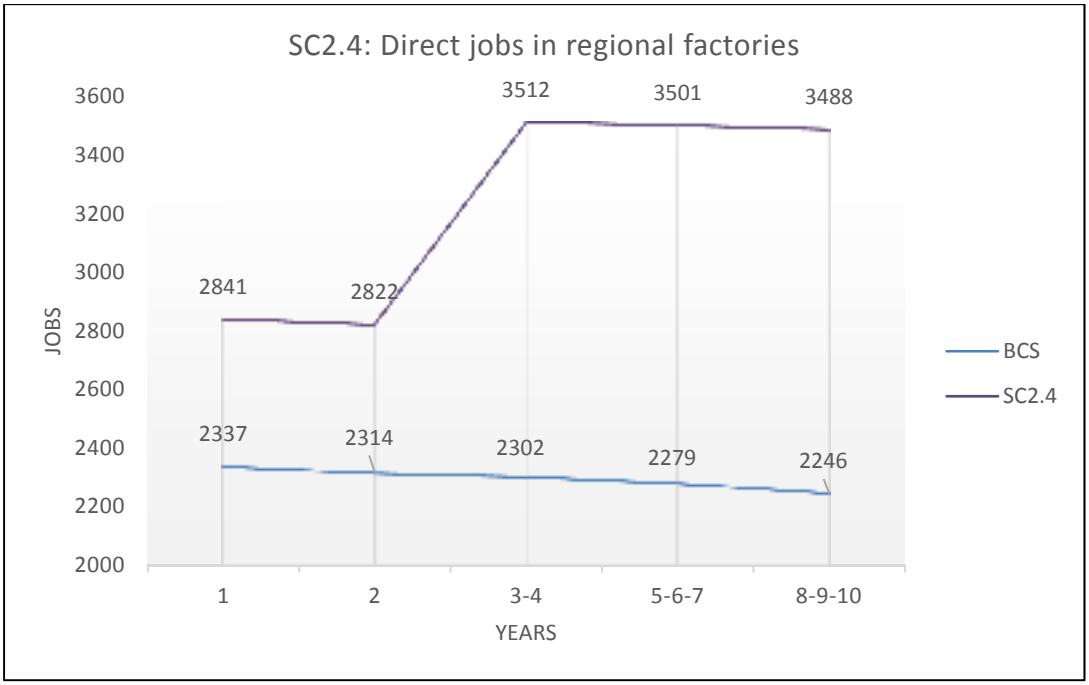

Figure 5.26 SC2.4: Direct jobs in regional factories

5.5 Scenario 3: Imposing pressurized hot water extraction

The pressurized hot water extraction is an interesting technology to consider due to its capacity to extract some components of the wood, keeping the potential to further process the production by-product (i.e. the extracted wood). In fact, this by-product has a strong potential to be used in pulp and paper plants, OSB mills, or even in pellet mills as feedstock, where benefits of its use have been observed. However, the profitability of the technology is limited by the production outcomes where two (2) specialty products are considered: the hemicellulosic crude sugars (C5 sugars) and the acetic acid (see Figure 5.27). While the cost of the feedstock acquisition is offset by the resale of the extracted wood, the price and volume of the specialty products considered do not cover the operating and expenditure costs. This situation results in a ROCE of -56.1 percent and an IRR of -16.8 percent. The regional NPV decreases to 3 285 M dollars, a negative variation of 0.42 percent compared to the BCS.

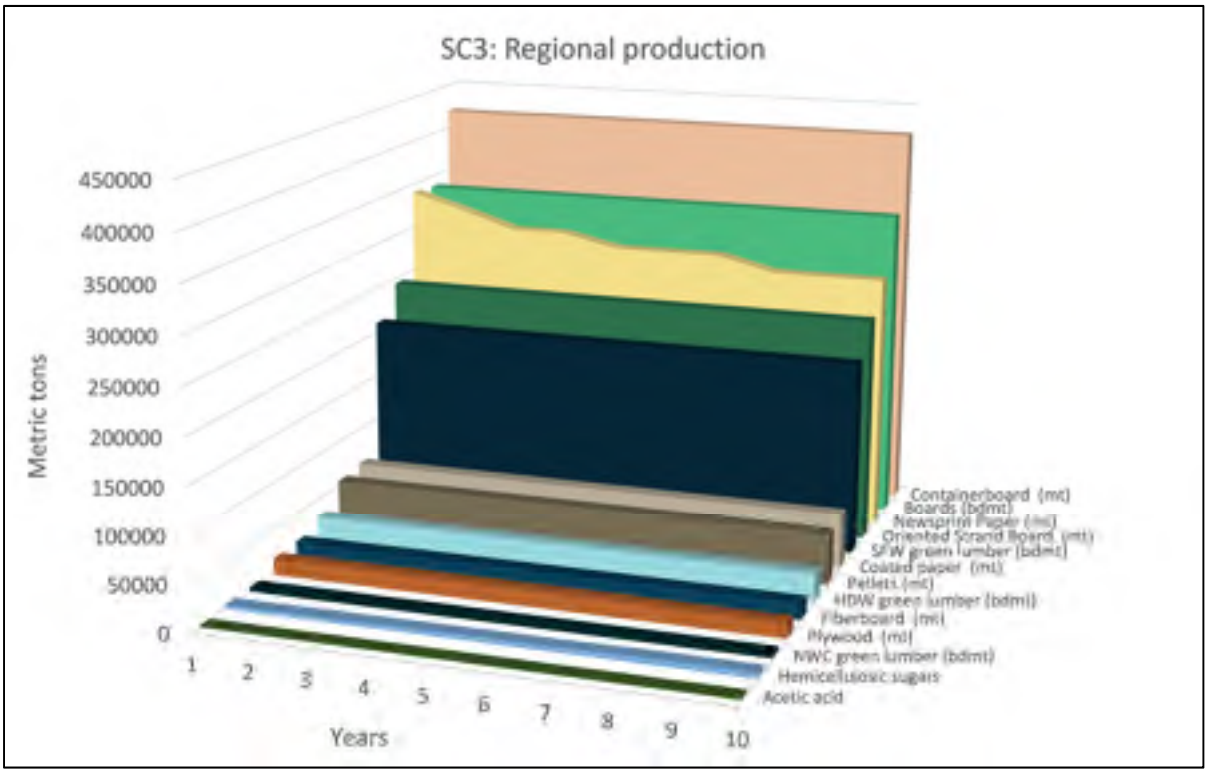

Figure 5.27 SC3: Regional production

To evaluate the impact of integrating this technology set to the Mauricie region, a constraint on the hemicellulose production was enforced. As presented in Figure 5.28, the production of the C5 sugars follows its associated demand with an over production capacity from years 3 to 10. In contrast, the production of acetic acid is far from its potential demand which starts at 13 000 metric tons in the first year and follows a CAGR of 6 percent. Instead, the acetic acid production is constrained by the C5 sugars production, resulting in a production lower than the technology's capacity. In the scenario, one (1) biorefinery open next to the oriented strand board mill located in Shawinigan. One limitation to be noted is that the cost of drying the extracted strands has not been considered in this scenario. The OSB mill has an input capacity three (3) times higher than the considered PHWE technology, indicating a secured access to the required feedstock and a potential to increase the production capacity. By the characteristics of the technology and its positioning, negligible impact on the fibre supply or on the transportation apportionment is observed. The technology is considered as a standalone biorefinery, and integrating it to the OSB mill could possibly improve the profitability of the project.

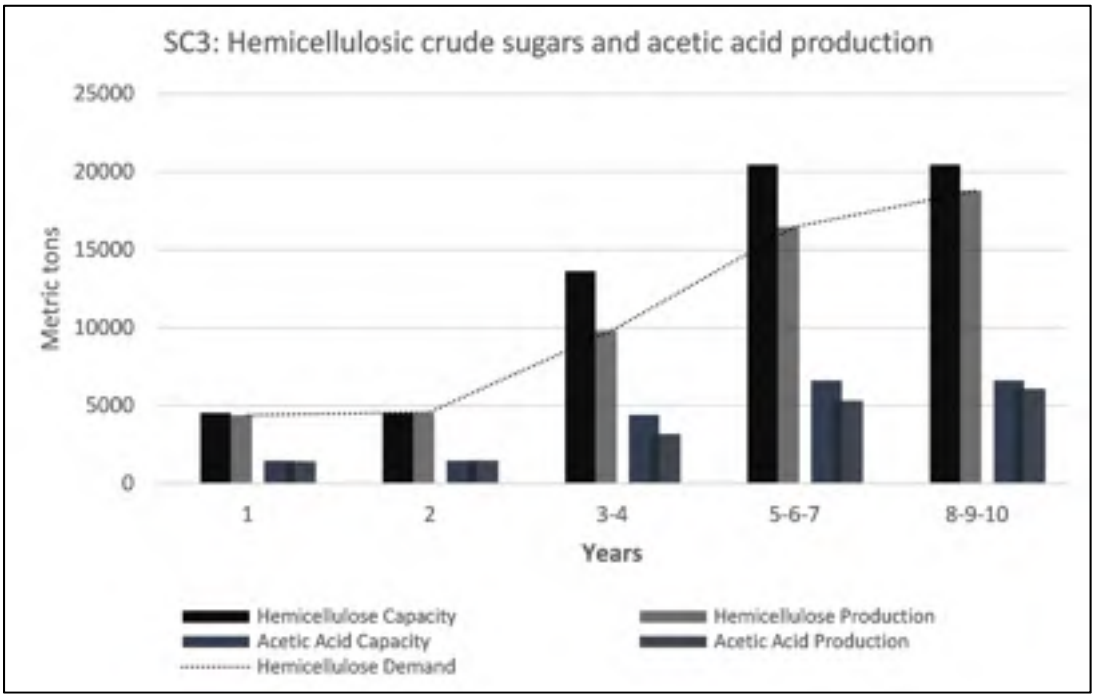

Figure 5.28 SC3: Hemicellulosic crude sugar and acetic acid production

A small increase of the GHG emissions of 1.9 percent is observed compared to the BCS and only from the production segment (see Figure 5.29). Moreover, a variation of the effluents and solid wastes are recorded, an increase of 2.5 percent and 19 percent, respectively. Finally, the technology has low employment creation potential with a negligible increase of one (1) percent throughout the years as shown in Figure 5.30.

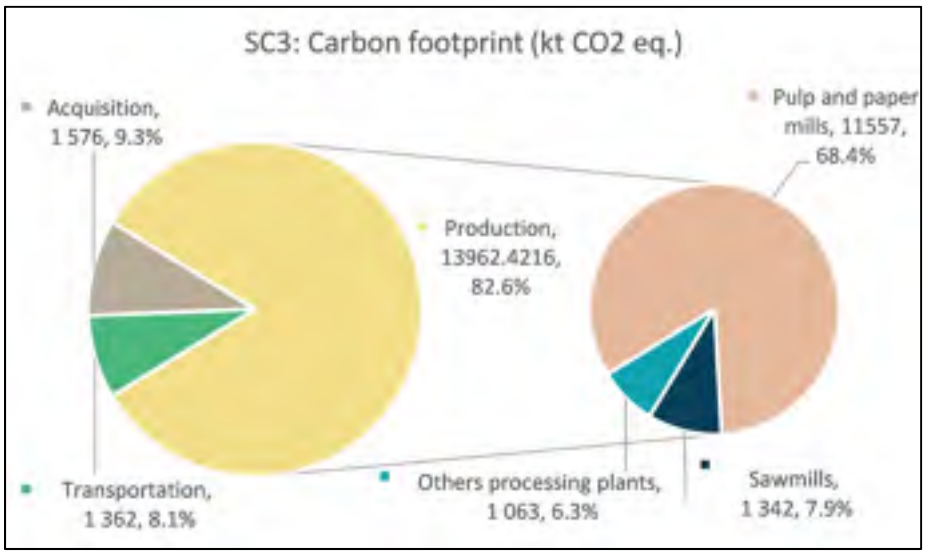

Figure 5.29 SC3: Regional carbon footprint

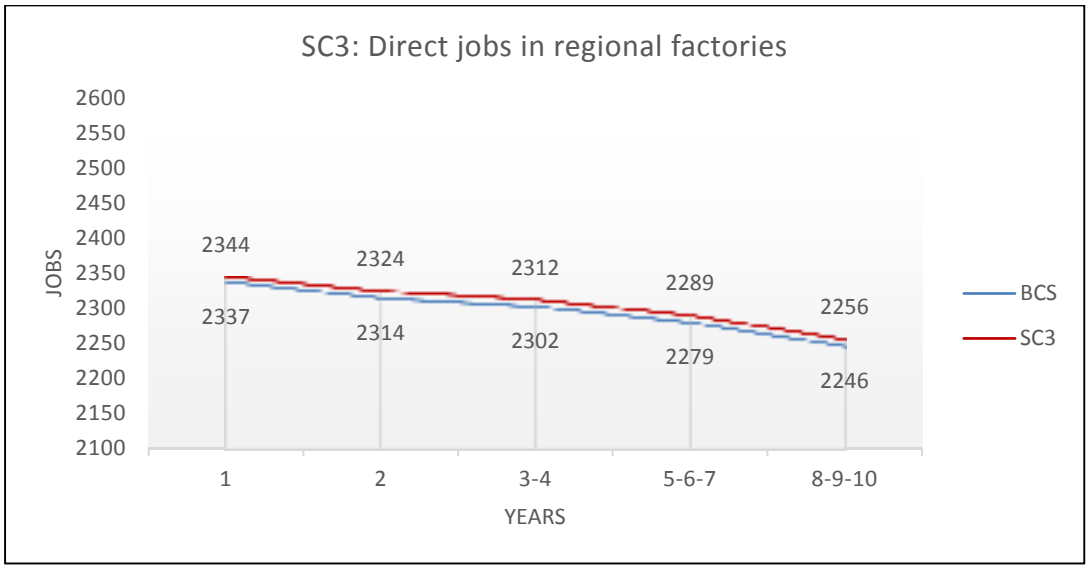

Figure 5.30 SC3: Direct jobs in regional factories

5.6 Scenario 4: Imposing organosolv fractionation

The organosolv process has a disruptive potential to change the forest bioeconomy by enhancing the fibre value through the fractionation of its various components. Six (6) bioproducts are considered as outputs of the process (i.e. cellulosic pulp, hemicellulosic crude sugars, lignin, furfural, formic acid, and levulinic acid). One constraint faced by the technology towards its integration is the demand and market size for most of these products. While the technology offers interesting yield and capacities, the demand limits considerably the solution (see Figure 5.31). To open the technology set, a constraint on the cellulosic pulp production is enforced where at least 85 percent of the demand has to be fulfilled. Furthermore, the lignin demand is increased to match the kraft lignin market and the prices are adjusted accordingly. With these settings, a small plant opens in the south of the region with an input capacity of 500 bdmt day^{-1}.

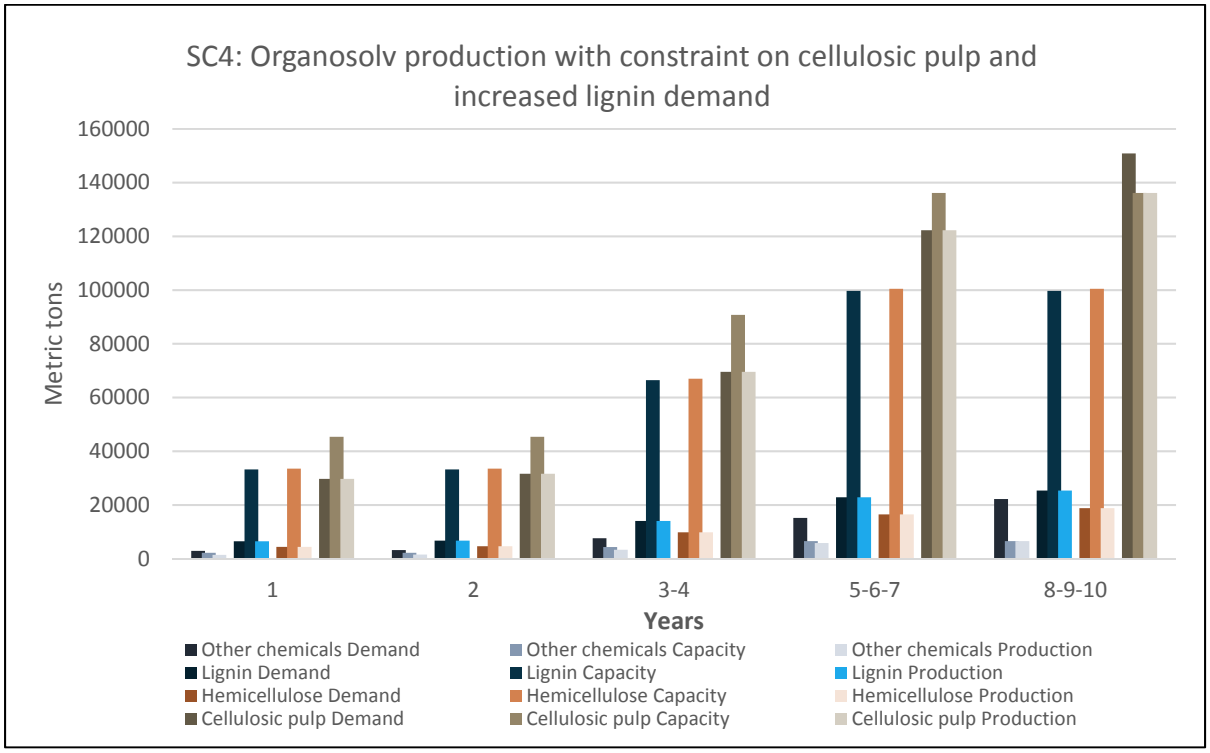

Figure 5.31 SC4: Production from Organosolv fractionation

The solution shows a significant loss of 4.15 percent compared to the BCS with a NPV of 3 162 M dollars. Interestingly, the loss is not directly caused by the technology, but rather from a reorientation of the fibre flows. One constraint set by the model is on the fibre availability where an artificial limit is created. By forcing the opening of the organosolv fractionation process, the artificial limit is reached and a reorganization of the fibre flow occurs. Here, the majority of the value lost is from the twelve (12) percent reduction of the newsprint paper production and from the failure to create value by the organosolv process (see Figure 5.32). It is important to note here that the solution is not realistic and is more an indication that a strong competition to access the fibre would be created. This situation might rather prompt a price increase, whether due to higher transportation distances or from an outbid to access nearby resources. On the other hand, the economic metrics show an interesting potential with a ROCE of -16.4 percent and an IRR of 7.7 percent. Therefore, with a good market penetration strategy on the specialty products, the technology might become an interesting choice to consider in the near future.

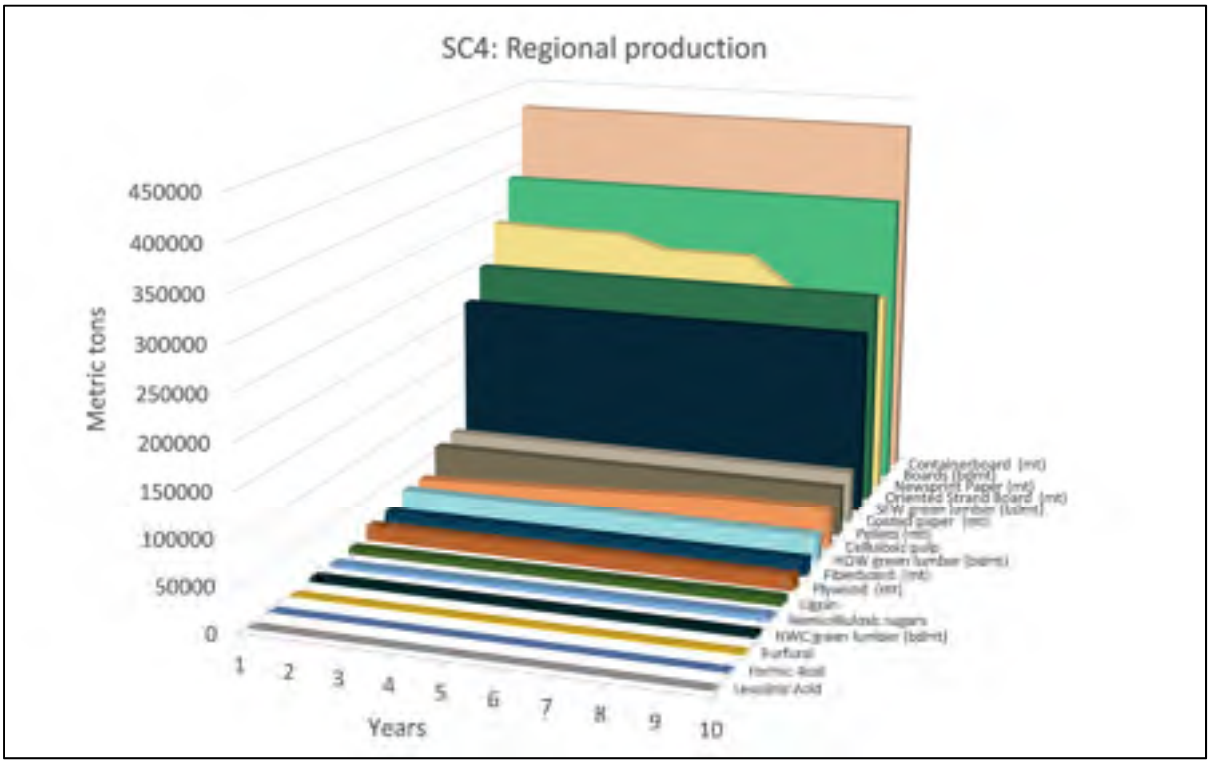

Figure 5.32 SC4: Regional production

The environmental impact of the organosolv fractionation process is far less than similar product oriented technologies and is able to recycle chemical used in the process instead of burning it. By introducing the technology set into the Mauricie region, an increase of 18.1 percent of the total carbon footprint is recorded. However, due to the decrease of the newsprint paper production, the final variation is of 15.7 percent, from 16 589 to 19 193 kt CO_2 eq. (see Figure 5.33). Furthermore, a 1.5 percent increase of the effluents and 1.0 percent of the solid wastes are recorded, demonstrating the low environmental impact of the technology.

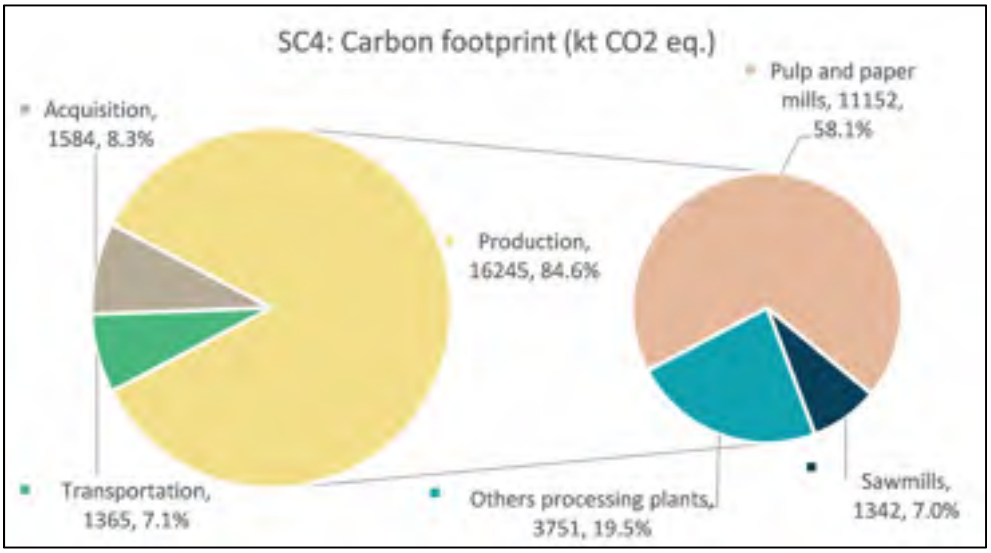

Figure 5.33 SC4: Regional carbon footprint

Despite the integration of six (6) new products to the regional value chain, the apportionment of the transport modes remain similar to the one of the BCS. This evaluation, however, does not reconsider the loss of volume engendered by the fibre allocation. Therefore, a potential increase of the road dry bulk and the road standard transportations can be expected from the twelve (12) percent decrease recorded at the TMP. Also, while the fibre allocation has been altered, the proportion of the fibre supply remains similar to the BCS. In contrast to the other scenarios, the organosolv technology requires a high-quality fibre and does not promote the value from the waste and by-product existing in the region. Thereby, its integration to an

existing network has fewer benefits to the other stakeholders and alternatively, might create competition on the fibre acquisition. Nevertheless, further considerations in regard to the manufactured products have to be conducted, and synergies could then be identified with the existing processes. Finally, the impact on the direct jobs in regional factories is minor, as shown in Figure 5.34 where two trends are compared to the BCS. The first one (i.e. SC4) is the numbers extracted from the solution considering the reduction of newsprint paper production. The second (i.e. SC4 adjusted) is a later calculation where no jobs losses are engendered from the artificial constraint.

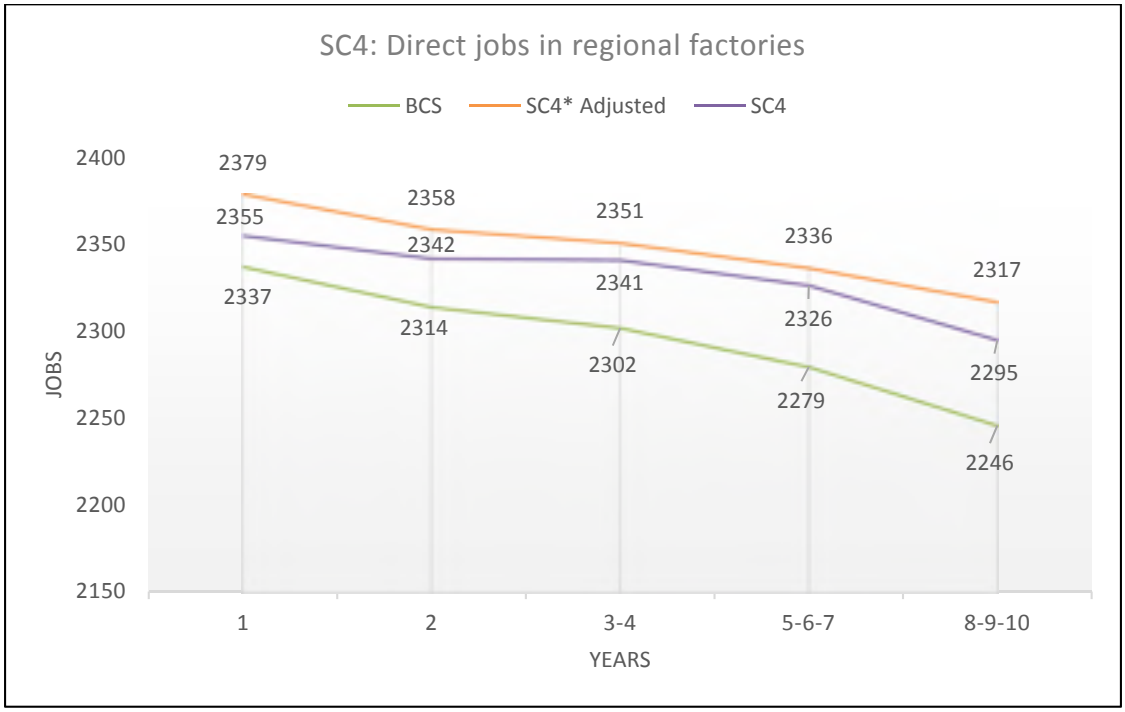

Figure 5.34 SC4: Direct jobs in regional factories

5.7 Discussion

In the previous sections, four scenarios were elaborated to guide the assessment of potential bioproducts. While some scenarios showed a positive IRR, all scenarios had a negative ROCE, indicating that many challenges are still to be overcome. In this section, scenarios are first compared to offer a comprehensive view of their impact, and secondly, a discussion on the limitations is developed to identify potential gaps incurred by the model and the scenarios in the evaluation of the biorefineries integration to the network.

5.7.1 Scenarios comparison

In the development of the green economy, profitability has to be the foundation that drives the transformation. While sustainable values can be promoted from the integration of bioproducts, economic metrics have to show strong potential, where the intrinsic risks can be mitigated. In the scenarios development, variables and assumptions are defined to the best of our knowledge to represent the Mauricie forest value chain and the proposed technologies. The first scenario enable the integration of all bioproducts based on their market access potential and offers one of the best solutions with the opening of two technologies (i.e. fast pyrolysis and lignin recovery platform). Nevertheless, the profitability of the solution remains imprecise with a NPV variation of 0.54 percent, an IRR of 11.49 percent and a ROCE of (0.60) percent. Furthermore, increased price and governmental subsidies are added to the crude bio-oil taking away most of the robustness of the solution. On the counter part, the lignin recovery platform has a good integration potential and can be more profitable than evaluated due to its capacity to offload the recovery boiler of kraft pulping mills. Also, high purity lignin has an interesting potential to replace petroleum based products in the near future, leading to the supposition that the CAGR applied to the scenario might be too pessimistic (see ANNEX III: Figure A - III - 2 and Figure A - III - 3). Therefore, the integration of the lignin recovery platform to existing kraft pulp mills has to be further studied in a more specific model than the one proposed. On the other hand, more analysis of the crude bio-oil production is conducted because of its potential to create value from unused waste and residues. Thereby, the second scenario is dedicated to the integration of the fast

pyrolysis process under various conditions and is divided into four sub-scenarios where optimistic financial engineering is applied. Indeed, the sub-scenarios are constrained by a renewable diesel demand varying from 2 percent of the total Quebec diesel demand in the three first sub-scenarios, and up to 5 percent in the last sub-scenario. While this constraint is realistic to prospective governmental policies, prices increases and governmental subsidies are also applied to enable the profitability of the sub-scenarios. Considering the best solution (i.e. SC2.4), a variation of the NPV of 1.46 percent, an IRR of 15.9 percent, and a ROCE of (5.9) percent are calculated. While the solution offers the most promising numbers among other scenarios, its structure may be biased by the optimistic considerations. Conversely, a severe economy of scale is considered which may affect the profitability but does not drastically change the solution. The fast pyrolysis is an interesting process to study and further improvement on the feedstock acquisition, the supply chain structure, and the process may lead to the project desirability. In the third scenario, the integration of the pressurized hot water extraction process offers a great potential to increase the fibre value. However, the technology is still economically unviable with a NPV variation of (0.42) percent, an IRR of (16.8) percent, and a ROCE of (56.1) percent. While the extracted biomass can be further transformed in standard processes making the acquisition cost almost inexistent, the revenues generated by the PHWE does not compensate for the capital and operating expenditures. This situation is fashioned by the considered demands and prices for the hemicellulosic crude sugars and the acetic acid. The technology set is highly correlated to the hemicellulose market and development in that segment will trigger the viability of the process. Finally, the fourth scenario considers the integration of the organosolv fractionation process, a technology first developed as an ecologically less harmful alternative to kraft pulping. Its integration is now of great interest due to its capacity to extract the wood components in a high purity form. The process has a positive IRR of 7.7 percent and a ROCE of (16.4) percent, which leads to the belief that the technology might be of interest considering a better market share of the bioproducts produced. One inconvenient of the technology is its disruptive potential when introduced into an existing network. This observation can be explained by looking at the variation of the NPV of (4.15) percent compared to the BCS. While this number is artificial, the probable impact would be an increased competition to

access the wood fibre. All in all, no clear answer on which process offers the best profitability potential considering the Mauricie forest value chain can be determined. The results show that the proposed technologies would require complex integration where the NPV variation is more often negative than positive (see Figure 5.35). One main constraint common to all the processes is the market potential of the bioproducts. Consequently, market penetration strategies are required to help the integration of these biorefineries. In addition, to be competitive on the market and to replace existing products, prices have to be comparable. Otherwise, the integration will require governmental assistance and intense financial engineering structure.

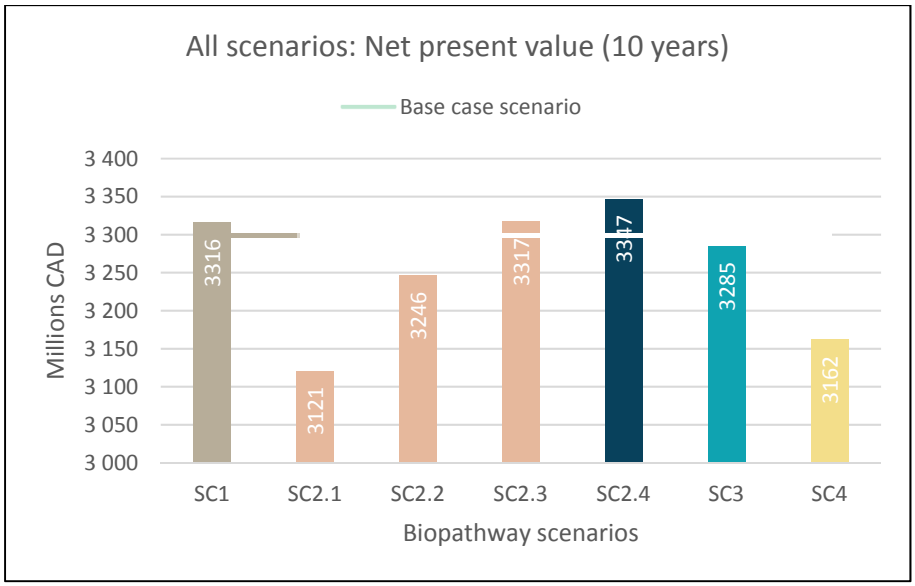

Figure 5.35 All scenarios: Net present values (10 years)

From another perspective, sustainable aspects may help in the realization of such projects, where the employment creation may help to motivate governmental assistance, and where reduction of the GHG emissions may have a potential value on a forthcoming carbon exchange market. Accordingly, two criteria are considered in the scenarios evaluation, the carbon footprint presented in Figure 5.36, and the increase of regional employment presented in Figure 5.37. One scenario that distinguishes itself from the others is the integration of the fast pyrolysis technology that has the greatest potential to create direct jobs in the region, but

is in the counterpart the largest emitter of the scenarios, as shown in the first and second scenarios. The third scenario is the less impactful in terms of emissions and has the weakest potential to increase regional employment. Moreover, it has the highest waste and effluent production, even with input capacity as low as 200 bdmt day^{-1}. Finally, the fourth scenario has a limited impact compared to pulping technologies and offers a modest increase in regional jobs. To be noted that the production volumes of each scenario are different, inducing that variation in the parameters may yield different results.

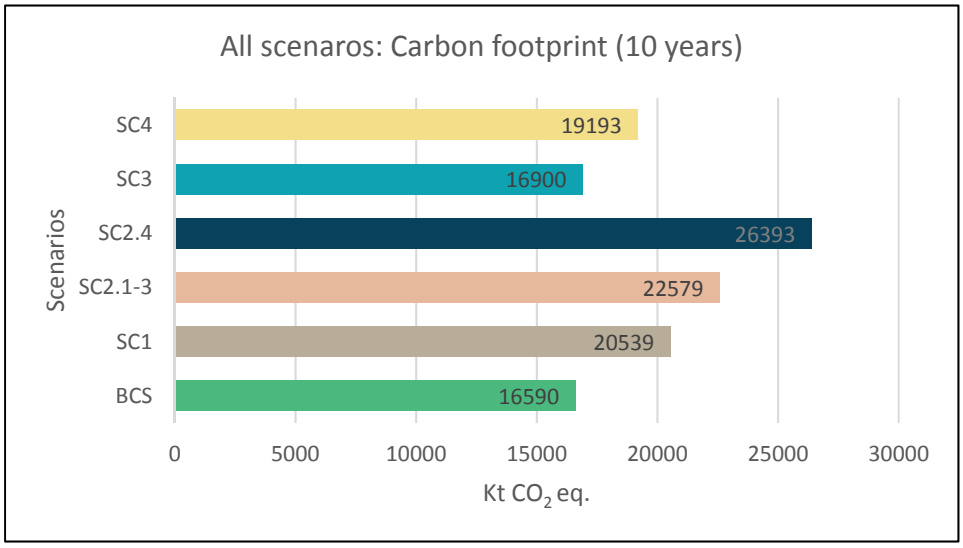

Figure 5.36 All scenarios: Carbon footprint

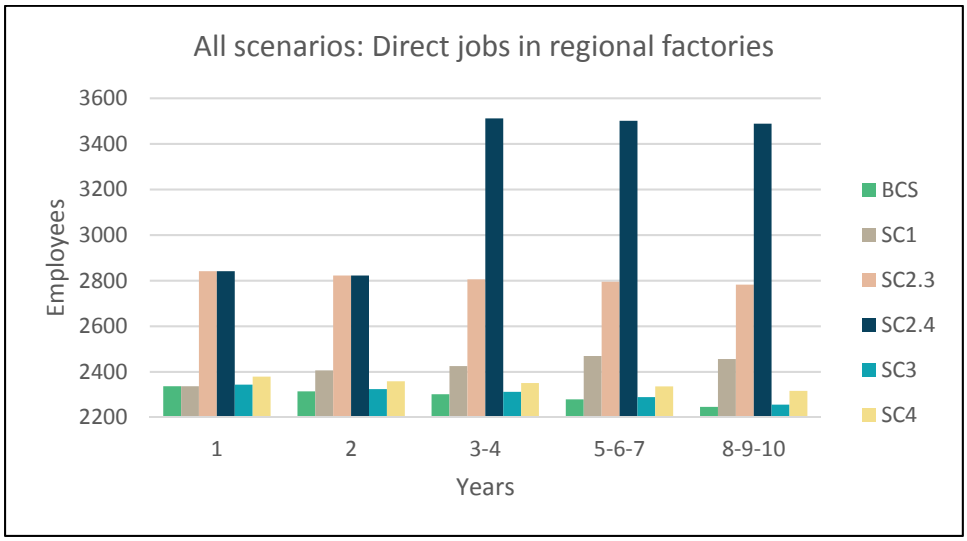

Figure 5.37 All scenarios: Direct jobs in regional factories

5.7.2 Limitations

From the scenarios formulation and the generic approach of the model, limiting factors are sometimes formed knowingly and unconsciously. While some of them can be moderated in data screening, others have the potential to shape the results creating gaps between the model and reality. In view of that, the identification of the possible limits is an interesting practice to help apprehend the value of the results and to guide further research. One main limitation that strongly shapes the scenarios is the cost of capital considered (or discount rate) of eight (8) percent. One problem incurred by this low rate is the opening of technology sets that have insufficient revenues to cover the technology depreciation, resulting in negative ROCE. Consequently, a higher cost of capital would be required to cover the risk and the depreciation, but in the process, would change drastically the solutions. Additionally, the solutions NPV variations compared to the BCS are too small to be significant, indicating that none of the scenarios are economically viable. However, the results might have been over constrained by some the parameters considered in the scenarios formation.

The first one is the two steps scalability where the biorefineries start with a fixed capacity and have the possibility to upgrade it once with a predetermined size increase. This approach causes inflexibility between the production and the demand, where the misadjustment may cause profit loss. Also, poor economies of scale are engendered by this approach due to the fact that when a demand exceeds the upgraded capacity of a mill, a new mill has then to be opened, restarting at the initial opening cost. Moreover, another limiting parameter is the market sizes considered. The introduction of bioproducts to the market is a challenge within itself, and precautious market opportunities have been considered in most of the scenarios. Accordingly, one consideration that might become of great interest in the selection of bioproducts is the carbon exchange market. By replacing petroleum based products by bioproducts, an offset of the GHG emissions can be calculated and new cash flow could be generated from the carbon credit trade. At the moment, the model does not consider such structure and may limit the specific advantages of the bioproducts.

As a final point, some omissions in the development of the scenarios may have a considerable effect on the solutions. The first one is that there is no construction time considered, meaning that if the model chooses to open a technology set, the capacity is then immediately available. Moreover, no ramp up production has been considered on the opening of the biorefinery even though a learning curve could have been added. Furthermore, no intermediary between the harvesting areas and the mills have been considered (e.g. log yards), resulting in a potential impact on the supply of wood and wood chips.

5.8 Conclusion

The introduction of bio-processing platforms to the forest industry is a complex challenge. Technology readiness level, market penetration strategies, and financial engineering are some of the key factors to help in the successful transformation of the bioeconomy. In this chapter, four potential technologies are evaluated to produce eight bioproducts. The prospective diversification of the forest product portfolio is evaluated where potential impacts are evaluated under sustainable considerations. In regard to the proposed scenarios, conclusions indicate that no low-hanging fruit is available and underline the need for more research and development. Accordingly, more scenarios can be assessed by the model proposed in this work, for instance, the comparison of the gasification technology compared to the fast pyrolysis for the production of renewable diesel. Moreover, the integration of other industries could be investigated to seek new synergies on feedstock acquisition, transportation, distribution, and energies.

CONCLUSION

Strategies employed to introduce new products to an existing network become of critical importance. While the inaction of an organization towards the reiteration of the product portfolio is a guaranteed ticket to an economic failure, the uncalculated integration of new products may, in counterpart, threaten the organization's competitive edge. Therefore, the assessment of potential products considering the economic vectors of a region may help to identify their degree of compatibility to the latter. By integrating the network concept to the product portfolio diversification assessment, the holistic impact of the introduction can be evaluated, where synergies and competition are considered. This approach allows notions such as business-to-business circular economy, sustainable development, and industry cluster to be included in the decision process, offering organizations potential competitive advantages. Thereby, the use of a decision support tool to screen prospective products may facilitate the strategic integration of new products and to gain competitive advantages.

Research contribution

Technologies and prospective products are developed and promoted increasingly. Industries are facing difficult choices as for the selection and integration of those products to their strategy. Potential market, technology readiness level, existing product portfolio, raw material availability, competition, network restriction – critical aspects have to be considered in the product integration evaluation. In regard to this problem, a generic mathematical model using mixed integer linear programming is proposed. By taking the concept of value chain, the optimization model helps to create scenarios where the impact of integrating proposed or specified products can be assessed considering a network approach. From the raw material supplies to the final deliveries, the model optimizes the value of the raw material by using divergent processes and bill of materials. Moreover, location, allocation, technology selection, production, distribution, and sustainability aspects are integrated into the strategic model to first replicate an existing network, and secondly, to apprehend the extent of the influence of integrating prospective product to the network. In so doing, the best suited products can be identified and detrimental products removed from the selection.

To test, validate and promote the generic decision support model, an extensive case study is applied to the Mauricie forest value chain. From the fibre availability to the identification of the market gaps, the Mauricie forest value chain is emulated in all its complexity. The harvesting operations and inbound logistics are developed and structured with the help of FPInnovations and with the use of their software FPInterface™. The bio-processing platforms are developed in collaboration with CanmetEnergy, a division of Natural Resource Canada, and with the use of their software I-BIOREF. From the base case scenario, eight (8) bioproducts are proposed as potential new productions through the mean of four (4) production technologies. The results indicate that two (2) bioproducts should be further investigated. The first one is the recovery of lignin from the kraft pulp mills black liquor by the use of an integrated technology. The second is the production of crude bio-oil via fast pyrolysis where the primary feedstock chosen by the model is the hog fuel. Subsequently, variations in the parameters to evaluate large production are applied. One principal trend developed in the crude bio-oil production is the proportion of hog fuel used in comparison to forest residues. Indeed, the fast pyrolysis technology, as presented in the scenarios, tend to be positioned next to large softwood sawmill to use the hog fuel directly. However, the impact of rerouting this fuel to other purposes is not evaluated while the forest residues are currently unused. Therefore, more scenarios on the strict use of forest residues should be conducted.

Overall, the integration of bioproducts to the traditional forest product portfolio is complex and nonetheless essential. While some scenarios have positive net present value, none are able to cover the technology depreciation resulting in negative ROCE. This general result may be caused by an over constrained demand or from a pessimistic approach in regard to the cost and potential economy of scale of the bioprocessing platform. Therefore, the technologies readiness level development through pilot plants integration to reduce capital and operational expenditures is required, as well as market penetration strategies development to expand and secure the demand. As a final point, the forest value chain has intrinsic potential to contribute to the forthcoming green economy and many opportunities are still to be evaluated. The substitution of polluting products will inevitably be replaced by

more eco-friendly alternatives, and as the time goes by, the forest industry potential is progressively attracting interest.

Intended users

The decision support tool is designed for network sizes ranging from a manufacturing plant to a regional network. All in all, the larger is the network, the more a user would gain from the synergies. The first intended sector aimed by the model is the primary materials processing industries (e.g. petroleum, forest, sugar, mining, etc.). Users that could benefit from the tool are governmental institutions, vertically integrated companies, collaborative stakeholders, and consulting firms.

Research perspectives

Limitations engendered by the mathematical model and the scenarios development give the opportunity to enhance the decision support tool.

- The first consideration goes to the sustainability, more specifically to the environmental and social aspects. The consideration of these two aspects is minimal and their impact only reported as an economic value in the utility function. Accordingly, three propositions can be advanced. The first one is in regard to the environmental aspect. The generic integration of a carbon exchange market would be interesting and could affect the selection of specific product in contrast of other because of its low emissions, or even from its sequestration potential. The second proposition goes to the social aspect. While the scenarios consider direct job creation, no concern on which type of employment is given nor to the salaries specific to the various jobs created. Therefore, scenarios could be more detailed on that matter. On the other hand, the model does not consider indirect jobs created in the region, the exploration of this avenue could be further researched. The final proposition is the potential use of a multi-objective function where economic, environmental, and social aspects are optimized using Pareto frontier. The use of a multi-criteria approach could be of interest for the users where control over the importance of each aspect would lead to a better control over the assessment desired.

- A limit observed in the analysis of the bioproducts integration is the difficulty to assess intermediary products because of their low market value compared to the final products. To lessen the gap between prices and enable a better evaluation of the intermediary products, the model could adopt a strategy to consider the potential of the intermediary products in function of the final products. At the moment, the user has to do this analysis prior to the optimization by considering the multiple potential final products.

- It would be interesting to include multiple value chains in the assessment of a region where non-competitive actors could benefits from collaboration on transport, energy, equipment, etc. The consideration of multiple sectors could improve the efficiency of a region and help to reduce the environmental impact.

- There is a growing interest in the Mauricie region for the production of renewable diesel from biomass (e.g. forest residues, hog fuel, etc.). The second scenario proposed evaluated the fast pyrolysis technology to this end. However, the yield of diesel from the crude bio-oil is small. Another alternative would be the production of diesel via gasification of the biomass and further processed using Fischer–Tropsch process where diesel yield are considerably higher. Therefore, scenarios assessing and comparing both technologies should be conducted.

- The final consideration is on the reduction of computational time. Decomposition methods could be used to reduce the resolution time. Currently, resolution times range from 0.5 hour to 8.5 hours.

ANNEX I

THE MANUFACTURING COMPAGNIES

Table A - I - 1 WestRock mill's information

ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_01	WEST ROCK	La Tuque Mill	1000 Chemin de l'Usine, La Tuque, QC G9X 3P5	47.44696	-72.78998	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
486	Container-board, White top linerboard	KRAFT	352,750	WTB, YLB, POP	Sawdust, shavings, round wood, and trimmings	Road Rail

Table A - I - 2 Resolute Forest Products mills' information

ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_02	RESOLUTE FOREST PRODUCTS	Laurentides Division	100 Rang 1, Shawinigan, QC	46.617597	-72.682216	CLOSED
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
277	Super-calendered paper	TMP	N/A	N/A	Round wood and wood chips	Road Rail
ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_03	RESOLUTE FOREST PRODUCTS	Produits forestiers Mauricie SEC	2419 QC-155, La Tuque, QC G9X 3N8	47.211756	-72.8892767	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
150	Softwood sawmill	SAWMILL	396,650	SFW	Round wood	Road Rail

Table A - I - 3 Commonwealth plywood mills' information

ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_04	COMMON WEALTH PLYWOOD	Shawinigan	1155 Av de la Fonderie, Shawinigan, QC G9N 1W9	46.5462927	-72.7508543	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
90	Plywood	VENEER	8750	WTB, YLB	Round wood	Road Rail
ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_05	COMMON WEALTH PLYWOOD	La Croche	101 Rang Beaumont, La Croche, Québec G0X 1R0	47.5073741	-72.7767983	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
37	Hardwood sawmill	SAWMILL	34,750	WTB, YLB	Round wood	Road Rail

Table A - I - 4 Groupe Remabec mills' information

ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_06	GROUPE REMABEC	Arbec inc. (Shawinigan)	775 Chemin de Turcotte, Shawinigan, QC G9T 5K4	46.6296522	-72.6400646	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
135	Oriented Strand Board	OSB	283,850	10% WTB, 90% POP	Round wood	Road Rail
ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_07	GROUPE REMABEC	Industries John Lewis ltée	1101 Bd Ducharme, La Tuque, QC G9X 3C3	47.4184233	-72.7854991	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
115	Pop sticks	Pop sticks set	61,900	WTB	Round wood	Road Rail
ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_08	GROUPE REMABEC	St-Rock de Mékinac	88 159 route, Saint-Roch-de-Mékinac, québec G0X 2E0	46.798893	-72.766249	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
115	Softwood sawmill	SAWMILL	418,750	SFW	Round wood	Road

Table A - I - 4 Groupe Remabec mills' information (continued)

ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_09	GROUPE REMABEC	St-Sévérin de Proulxville	380 159 Rte, Proulxville, Québec G0X 2B0	46.6809119	-72.5146558	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
48	Dried and planed sawn products	DRYING AND PLANING	N/A	N/A	Lumber	Road
ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_10	GROUPE REMABEC	Industries Parent inc.	201, rue de la Scierie, Parent QC G0X 3P0	47.9280758	-74.6294403	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
129	Softwood sawmill	SAWMILL	384,000	SFW	Round wood	Road Rail
ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_11	GROUPE REMABEC	Industries Parent inc.	525, rue de l'Aviation, Trois-Rivières QC G8T 5M4	46.3806577	-72.5290512	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
45	Dried and planed sawn products	DRYING AND PLANING	N/A	N/A	Round wood	Road Rail
ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_12	GROUPE REMABEC	RBF Scierie St-Tite inc.	830 Rte 153 Saint-Tite, QC G0X 3H0	46.735862	-72.5643794	CLOSED
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
35	Hardwood sawmill	SAWMILL	N/A	HDW, WTB, YLB	Round wood	Road Rail
ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_13	GROUPE REMABEC	Boiserie SAVCO inc.	690 rte 352, Sainte-Thècle, QC G0X 3G0	46.7081988	-72.4240314	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
33	Pallet wood	SAWMILL	49,700	HDW	Round wood	Road

Table A - I - 5 Kruger mills' information

ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_15	KRUGER	Wayagamack inc.	Ile De La Potherie, Trois-Rivières, Québec G9A 5E9	46.3576364	-72.5252024	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
343	coated paper	KRAFT	N/A	N/A	Round wood and chips	Road Rail
ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_16	KRUGER	Kruger Trois-Rivières	3735 Boul Gene-H.-Kruger, Trois-Rivières, QC G9A 6B1	46.3272361	-72.5574952	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
322	Newprint paper	TMP	N/A	N/A	Wood chips	Road Rail

Table A - I - 6 Independent mills' information

ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_14	Optitchiwan	-	km 164, route d'Obedjiwan, C.P. 270 Obedjiwan (Québec), G0W 3B0	48.670402	-74.933627	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
65	Softwood sawmill	SAWMILL	107,150	SFW	Round wood	Road
ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_17	Transfobec mauricie	-	752 rue St-Antoine, La Tuque, Québec, Canada, G9X 2Z4	47.4328045	-72.7838283	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
3	Wood litter	GRINDER	5,250	HDW, NWC	Round wood	Road Rail
ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_18	Cédart-tech inc.	-	631 Rue Notre-Dame, Sainte-Thècle QC G0X 3G0	46.8074611	-72.4973178	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
15	Clapboard	SAWMILL	5,250	NWC	Round wood	Road Rail

Table A - I - 6 Independent mills' information (continued)

ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_19	Atikamekw Aski	-	57, Rue Kenosi, Wemotaci (Québec) G0X 3R0	47.904145	-73.7889639	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
60	Softwood sawmill	SAWMILL	84,000	SFW	Round wood	Road
ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_20	Matériaux spécialisés louiseville inc	-	161, rue St-Paul,Louiseville (Québec) Canada J5V 2L6	46.2579837	-72.9500666	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
15	Sound-proofing Panel	FIBERBOARD SET	N/A	N/A	Production Waste	Road Rail
ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_21	Scierie Maski inc.	-	50, 10e avenue, Louiseville (Québec) Canada J5V 0A5	46.2554812	-72.9239908	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
15	Hardwood sawmill	SAWMILL	N/A	HDW	Round wood	Road Rail
ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_22	Lauzon Bois Énergétique recyclé inc.	-	3201, rue Lucille-Bastien, Saint-Paulin (Québec) J0K 3G0	46.426514	-73.01619	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
15	Hardwood pellet	PELLETIZATION SET	N/A	HDW	Production Waste	Road
ID	COMPANY	DIVISION	ADDRESS	LATITUDE	LONGITUDE	STATUS
PU_23	Granule de la mauricie inc.	-	4435, avenue Georges-Bornais, Shawinigan (Québec) G9N 6T5	46.5052168	-72.7155402	IN PRODUCTION
NB. EMPLOYEES	PRODUCTS	TECHNOLOGY SET	GUATANTEE OF SUPPLY (m3)	SPECIES	TYPES	TRANSPORT CONNECTION
15	Hardwood pellet	PELLETIZATION SET	N/A	HDW	Production Waste	Road

ANNEX II

MAURICIE'S AGGREGATED PROCESSES NETWORK

POTENTIAL AND EXISTING PROCESSES

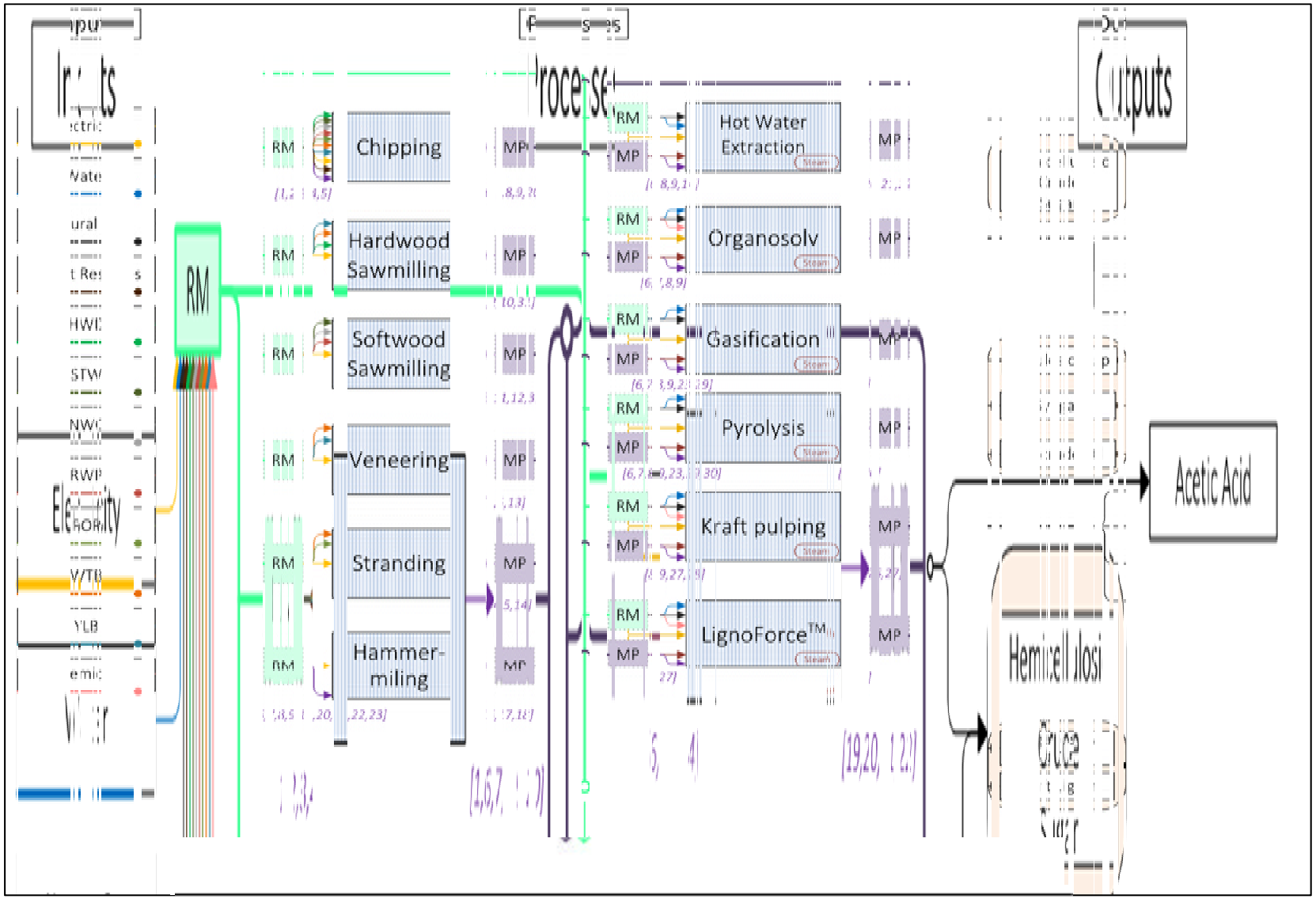

Figure A - II - 1 Mauricie's aggregated processes network (part 1 of 2)

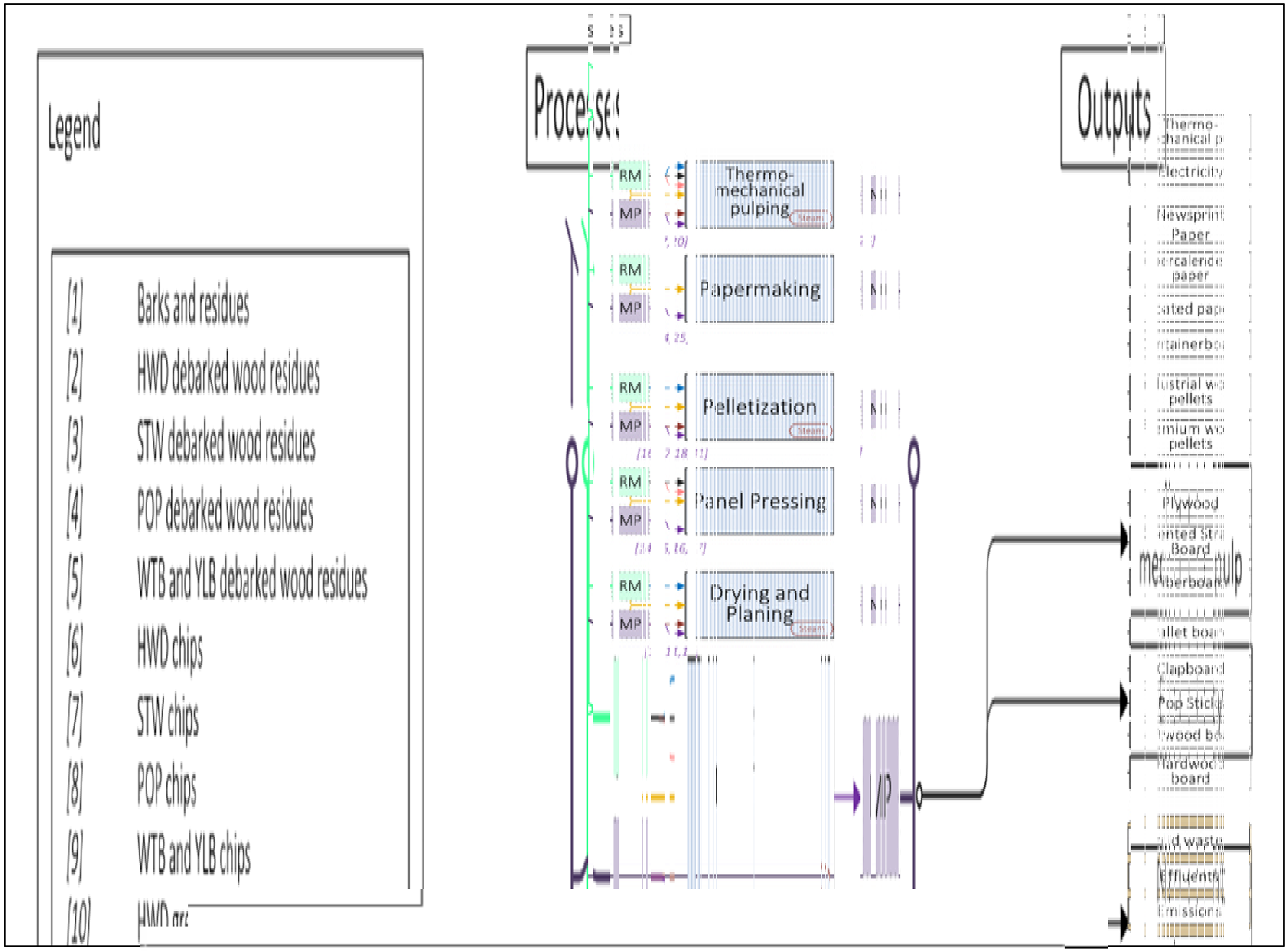

Figure A - II - 1 Mauricie's aggregated processes network (part 2 of 2)

ANNEX III

MAURICIE'S POTENTIAL AND EXISTING PRODUCTION

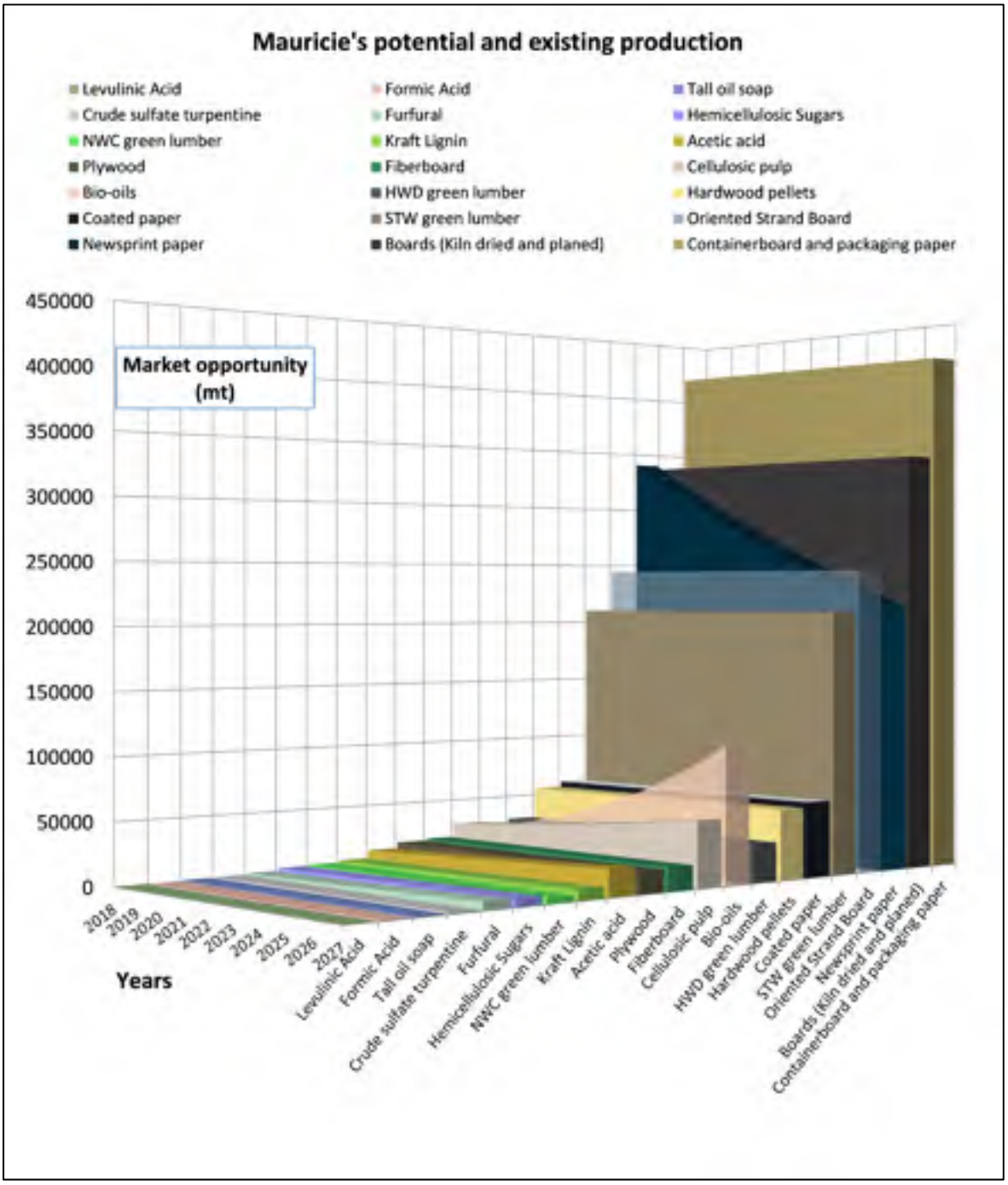

Figure A - III - 1 Mauricie's potential and existing production

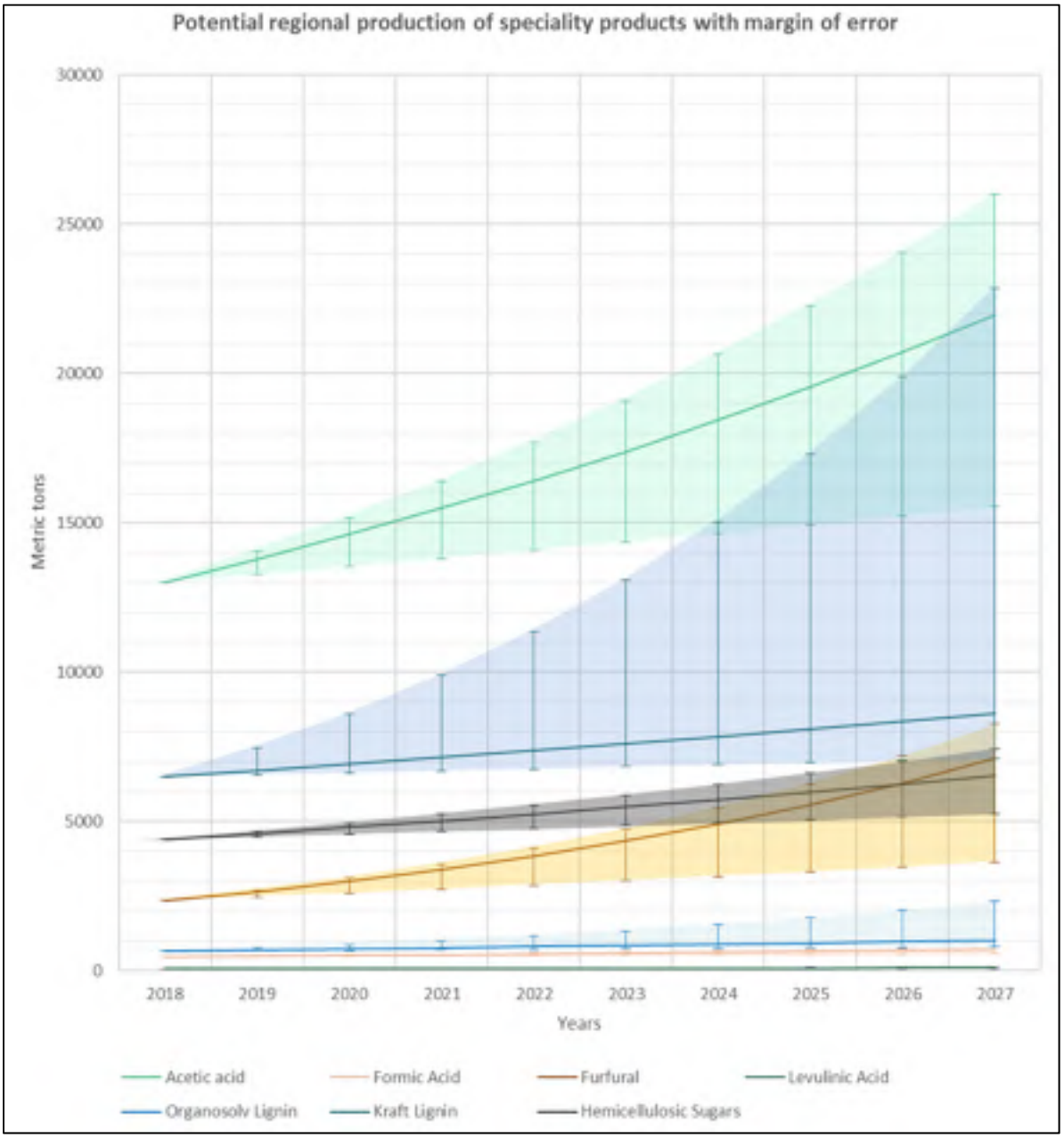

Figure A - III - 2 Specialty products potential production with margin of error

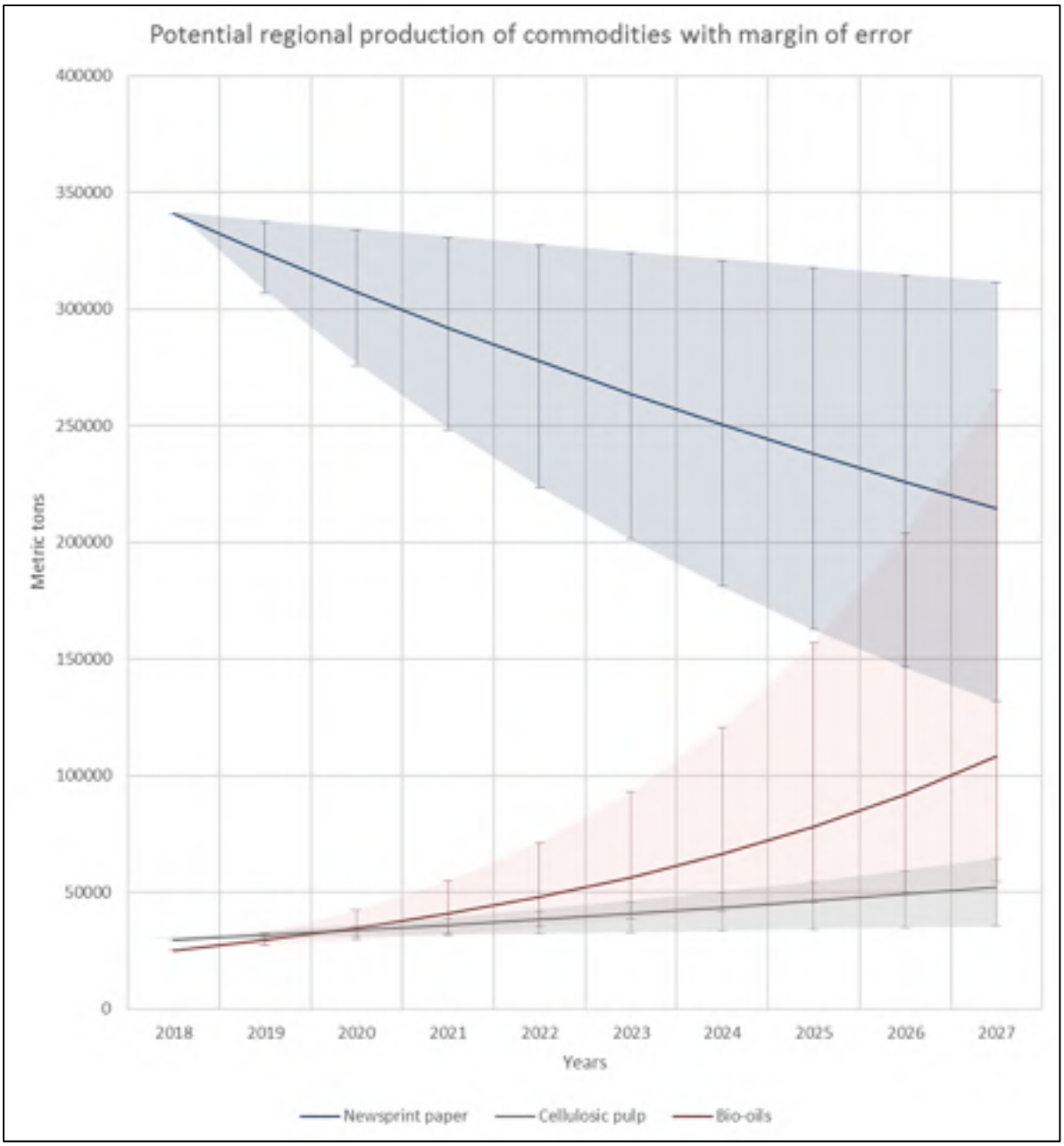

Figure A - III - 3 Commodities potential production with margin of error

ANNEX IV

RECIPES

Table A - IV - 1 Recipes

RECIPE	TECHNOLOGY SET	INPUTS	QTY IN (metric ton)	OUTPUTS	QTY OUT (metric ton)
1	Chipping set	HDW	1000	HWD chips	854
		Electricity (MW)	22	Bark and residues	146
		Man-hour	32.4	GHG	10
2	Chipping set	SFW	1000	SFW chips	833
		Electricity (MW)	22	Bark and residues	167
		Man-hour	32.4	GHG	10
3	Chipping set	POP	1000	POP chips	854
		Electricity (MW)	22	Bark and residues	146
		Man-hour	32.4	GHG	10
4	Chipping set	WTB	700	WTB and YLB chips	854
		YLB	300	Bark and residues	146
		Electricity (MW)	22	GHG	10
		Man-hour	32.4		
5	Chipping set	HWD debarked wood residues	1000	HWD chips	980
		Electricity (MW)	22	GHG	10
		Man-hour	32.4		
6	Chipping set	SFW debarked wood residues	1000	SFW chips	980
		Electricity (MW)	22	GHG	10
		Man-hour	32.4		
7	Chipping set	POP debarked wood residues	1000	POP chips	980
		Electricity (MW)	22	GHG	10
		Man-hour	32.4		
8	Chipping set	WTB and YLB debarked wood residues	1000	WTB and YLB chips	980
		Electricity (MW)	22	GHG	10
		Man-hour	32.4		
9	Chipping set	Forest Residues	1000	Chipped residues	980
		Electricity (MW)	22	GHG	10
		Man-hour	32.4		
10	Chipping set	Bark and residues	1000	Chipped residues	980
		Electricity (MW)	22	GHG	10
		Man-hour	32.4		
11	Hardwood sawmilling set	HWD	155	HWD green lumber	500
		WTB	690	HWD debarked wood residues	284
		YLB	155	Bark and residues	146
		Electricity (MW)	33.7	GHG	125
		Man-hour	394		
12	Softwood sawmilling set	SFW	992	SFW green lumber	496
		NWC	8	NWC green lumber	4
		RWP	0	SFW debarked wood residues	283
		Electricity (MW)	33.7	Bark and residues	167
		Man-hour	394	GHG	125
13	Veneering set	WTB	810	WTB and YLB debarked wood residues	146
		YLB	190	Veneers	470
		Electricity (MW)	33.7	Bark and residues	304
		Man-hour	1608.5	GHG	490
14	Stranding set	WTB	100	Strands	811
		POP	900	WTB and YLB debarked wood residues	0
		Electricity (MW)	33.7	POP debarked wood residues	0
		Man-hour	627.5	Bark and residues	146
				GHG	206

Table A - IV - 1 Recipes (continued)

15	Hammermilling set	HWD chips	1000	Pulverized fibre	998
		Electricity (MW)	5.5	GHG	15
		Man-hour	198.8		
16	Hammermilling set	SFW chips	1000	Pulverized fibre	998
		Electricity (MW)	5.5	GHG	15
		Man-hour	198.8		
17	Hammermilling set	POP chips	1000	Pulverized fibre	998
		Electricity (MW)	5.5	GHG	15
		Man-hour	198.8		
18	Hammermilling set	WTB and YLB chips	1000	Pulverized fibre	998
		Electricity (MW)	5.5	GHG	15
		Man-hour	198.8		
19	Hammermilling set	HWE HWD chips	1000	Pulverized fibre	998
		Electricity (MW)	5.5	GHG	15
		Man-hour	198.8		
20	Hammermilling set	HWE SFW chips	1000	Pulverized fibre	998
		Electricity (MW)	5.5	GHG	15
		Man-hour	198.8		
21	Hammermilling set	HWE POP chips	1000	Pulverized fibre	998
		Electricity (MW)	5.5	GHG	15
		Man-hour	198.8		
22	Hammermilling set	HWE WTB and YLB chips	1000	Pulverized fibre	998
		Electricity (MW)	5.5	GHG	15
		Man-hour	198.8		
23	Kraft pulping set	SFW chips	630	Kraft pulp	424
		WTB and YLB chips	370	Black Liquor	53.2
		Water	12.614	Kraft (other) [Tall oil, Turpentine]	0.1
		Natural gas	390.43	GHG	974
		Kraft chemicals	232.5	Electricity (MW)	0
		Electricity (MW)	537.5	Effluent	52719
		Man-hour	1414	Solid waste	45.74
24	Thermo-mechanical pulping set	SFW chips	1000	Thermomechanical pulp	945
		Water	171944	Electricity (MW)	99
		Natural gas	1024.29	GHG	16.2
		TMP chemicals	15.5		
		Electricity (MW)	2845.3		
		Man-hour	1188		
25	Thermomechanical pulping set	HWE SFW chips	NA	Thermomechanical pulp	0
		Water	0	Electricity (MW)	0
		Natural gas	0	GHG	0
		TMP chemicals	0		
		Electricity (MW)	0		
		Man-hour	0		
26	Papermaking set	Thermomechanical pulp	1000	Newsprint Paper	990
		Electricity (MW)	14.3	GHG	222
		Man-hour	164.4		
27	Papermaking set	Thermomechanical pulp	500	Coated paper	990
		Kraft pulping	500	GHG	222
		Electricity (MW)	14.3		
		Man-hour	164.4		
28	Papermaking set	Kraft pulping	1000	Containerboard	990
		Electricity (MW)	14.3	GHG	222
		Man-hour	164.4		
29	Pelletization set	Pulverized fibre	1000	Wood pellets	980
		Electricity (MW)	480	GHG	40
		Man-hour	1071		

Table A - IV - 1 Recipes (continued)

30	Panel Pressing set	Pulverized fibre	1000	Fiberboard	980
		Panel chemicals	1250	GHG	6
		Electricity (MW)	340		
		Man-hour	2166.48		
31	Panel Pressing set	Veneer	1000	Plywood	950
		Panel chemicals	750	GHG	6
		Electricity (MW)	340		
		Man-hour	2166.48		
32	Panel Pressing set	Strand	1000	Oriented Strand Board	950
		Panel chemicals	100	GHG	6
		Electricity (MW)	340		
		Man-hour	2166.4		
33	Panel Pressing set	HWE Strand	1000	Oriented Strand Board	950
		Panel chemicals	1000	GHG	6
		Electricity (MW)	340		
		Man-hour	2166.48		
34	Drying and planing set	HWD green lumber	100	Board	1000
		SFW green lumber	896	GHG	21
		NWC green lumber	4		
		Water	0.001		
		Electricity (MW)	579.7		
		Man-hour	2000		
35		HWD chips	1000	HWE HWD chips	1000
		Natural gas	47.96	Acetic Acid	21.5
	Hot water	Water	1.6679	Hemicellulosic Crude Sugar	67.6
	extraction set	Electricity (MW)	71	Solid waste	251.2
		Man-hour	256	Effluent	1527
				GHG	12
36		SFW chips	NA	HWE SFW chips	0
		Natural gas	0	Acetic Acid	0
	Hot water	Water	0	Hemicellulosic Crude Sugar	0
	extraction set	Electricity (MW)	0	Solid waste	0
		Man-hour	0	Effluent	0
				GHG	0
37	Hot water	POP chips	1000	HWE POP chips*	1000
	extraction set	Natural gas	47.96	Acetic Acid	21.5
		Water	1.6679	Hemicellulosic Crude Sugar	67.6
		Electricity (MW)	71	Solid waste	251.2
		Man-hour	256	Effluent	1527
				GHG	12
38	Hot water	WTB and YLB chips	1000	HWE WTB and YLB chips	1000
	extraction set	Natural gas	47.96	Acetic Acid	21.5
		Water	1.6679	Hemicellulosic Crude Sugar	67.6
		Electricity (MW)	71	Solid waste	251.2
		Man-hour	256	Effluent	1527
				GHG	12
39	Hot water	Strands	1000	HWE strands	1000
	extraction set	Natural gas	47.96	Acetic Acid	21.5
		Water	1.6779	Hemicellulosic Crude Sugar	67.6
		Electricity (MW)	71	Solid waste	251.2
		Man-hour	256	Effluent	1527
				GHG	12
40		HWD chips	1000	Hemicellulosic Crude Sugar	200.57
		Natural gas	412.49	Cellulosic Pulp	271.78
		Water	4.7312	Solid waste	3.8
	Organosolv set	Electricity (MW)	457.7	Organosolv lignin	198.8
		Organosolv chemicals	17.5	Levulinic Acid, Furfural, Formic Acid	12.9
		Man-hour	1200	Effluent	69150
				GHG	688

Table A - IV - 1 Recipes (continued)

41		SFW chips	1000	Hemicellulosic Crude Sugar	200.57
		Natural gas	412.49	Cellulosic Pulp	271.78
		Water	4.7312	Solid waste	3.8
	Organosolv set	Electricity (MW)	457.7	Organosolv lignin	198.8
		Organosolv chemicals	17.5	Levulinic Acid, Furfural, Formic Acid	12.9
		Man-hour	1200	Effluent	69150
				GHG	688
42		POP chips	1000	Hemicellulosic Crude Sugar	200.57
		Natural gas	412.49	Cellulosic Pulp	271.78
		Water	4.7312	Solid waste	3.8
	Organosolv set	Electricity (MW)	457.7	Organosolv lignin	198.8
		Organosolv chemicals	17.5	Levulinic Acid, Furfural, Formic Acid	12.9
		Man-hour	1200	Effluent	69150
				GHG	688
43		WTB and YLB chips	1000	Hemicellulosic Crude Sugar	200.57
		Natural gas	412.49	Cellulosic Pulp	271.78
		Water	4.7312	Solid waste	3.8
	Organosolv set	Electricity (MW)	457.7	Organosolv lignin	198.8
		Organosolv chemicals	17.5	Levulinic Acid, Furfural, Formic Acid	12.9
		Man-hour	1200	Effluent	69150
				GHG	688
44	Pyrolysis set	HWD chips	1000	Bio-oils	583
		Natural gas	0.0483	GHG	76
		Electricity (MW)	28.7		
		Man-hour	4030.05		
45	Pyrolysis set	SFW chips	1000	Bio-oils	583
		Natural gas	0.0483	GHG	76
		Electricity (MW)	28.7		
		Man-hour	4030.05		
46	Pyrolysis set	POP chips	1000	Bio-oils	583
		Natural gas	0.0483	GHG	76
		Electricity (MW)	28.7		
		Man-hour	4030		
47	Pyrolysis set	WTB and YLB chips	1000	Bio-oils	583
		Natural gas	0.0483	GHG	76
		Electricity (MW)	28.7		
		Man-hour	4030		
48	Pyrolysis set	Chipped residues	1000	Bio-oils	506
		Natural gas	0.0483	GHG	76
		Electricity (MW)	28.7		
		Man-hour	4030.05		
49	Lignin recovery platform set	Black liquor	1000	Kraft Lignin	465.4
		Water	2.2107	Solid waste	1657
		Natural gas	63.59	Effluent	101000
		Lignin recovery platform chemicals	402.4	GHG	19
		Electricity (MW)	77.6		
		Man-hour	120		

BIBLIOGRAPHY

Amidon, T. E., Bujanovic, B., Liu, S., & Howard, J. R. (2011). "Commercializing biorefinery technology: A case for the multi-product pathway to a viable biorefinery." Forests, 2(4), Pp. 929-947.

Benali, M., Ajao, O., Jeaidi, J., Gilani, B., & Mansoornejad, B. (2016). "Integrated Lignin-Kraft Pulp Biorefinery for the Production of Lignin and Its Derivatives: Economic Assessment and LCA-Based Environmental Footprint." In Production of Biofuels and Chemicals from Lignin (pp. 379-418). Springer Singapore.

Bosch-Mauchand, M., A. Siadat, N. Perry and A. Bernard (2010). "Vcs: Value Chains Simulator, a Tool for Value Analysis of Manufacturing Enterprise Processes (A Value-Based Decision Support Tool)." Journal of Intelligent Manufacturing Vol. 23(No. 4): Pp. 1389-1402.

Bridgwater, A. V. (2012). Review of fast pyrolysis of biomass and product upgrading. Biomass and bioenergy, 38, Pp. 68-94.

Bruch, J., & Bellgran, M. (2014). Integrated portfolio planning of products and production systems. Journal of Manufacturing Technology Management, 25(2), Pp. 155-174.

Cambero, C., T. Sowlati, M. Marinescu and D. Röser (2014a). "Strategic Optimization of Forest Residues to Bioenergy and Biofuel Supply Chain". International Journal of Energy Research Vol. 39(No. 4): Pp. 439-452.

Cambero, C. and T. Sowlati (2014b). "Assessment and Optimization of Forest Biomass Supply Chains from Economic, Social and Environmental Perspectives – A Review of Literature". Renewable and sustainable energy reviews Vol. 36: Pp. 62-73.

Cambero, C., & Sowlati, T. (2016). "Incorporating social benefits in multi-objective optimization of forest-based bioenergy and biofuel supply chains." Applied Energy, 178, Pp. 721-735.

Chambost, V., J. Mcnutt and P. R. Stuart (2008). "Guided Tour: Implementing the Forest Biorefinery (FBR) At Existing Pulp and Paper Mills". Pulp and Paper Canada Vol. 109(No. 7-8): Pp. 19-27.

Chopra, S. and P. Meindl (2012). Supply Chain Management: Strategy, Planning, and Operation, 6 edition, Pearson.

Christopher, L. (2012). "Adding Value Prior to Pulping: Bioproducts from Hemicellulose." Global Perspectives on Sustainable Forest Management, Dr. Dr. Clement A. Okia (Ed.), InTech, DOI: 10.5772/36849.

Cozzi, M., Di Napoli, F., Viccaro, M., & Romano, S. (2013). Use of forest residues for building forest biomass supply chains: technical and economic analysis of the production process. Forests, 4(4), Pp. 1121-1140.

Kouisni, L., Holt-Hindle, P., Maki, K., & Paleologou, M. (2012). "The Lignoforce system: a new process for the production of high-quality lignin from black liquor." J. Sci. Technol. For. Prod. Processes, 2(4), 6-10.

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

D'Amours, S., R. Epstein, A. Weintraub, and M. Rönnqvist (2011). Operations Research in Forestry and Forest Products Industry. Wiley Encyclopedia of Operations Research and Management Science.

Dansereau, L. P., El-Halwagi, M. M., & Stuart, P. R. (2012). Value chain management considerations for the biorefinery. In Integrated biorefineries: Design, analysis, and optimization. CRC Press/Taylor & Francis.

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 vol. 8(No. 5): p. 716-727.

Dasmohapatra, S. (2009) "Future Marketing Drivers for the Forest Products Industry" BioResources, Vol. 4 Issue 4, Pp1263-1266.

Deloitte. (2014). "Opportunities for the Fermentation-based Chemical Industry. An Analysis of the Market Potential and Competitiveness of North-West Europe." Retrieved from https://www2.deloitte.com/content/dam/Deloitte/nl/Documents/manufacturing/deloitte-nl-manufacturing-opportunities-for-the-fermentation-based-chemical-industry-2014.pdf

De Meyer, A., D. Cattrysse, J. Rasinmäki and J. Van Orshoven (2014). "Methods to Optimise the Design and Management of Biomass-For-Bioenergy Supply Chains: A Review." Renewable And Sustainable Energy Reviews Vol. 31(March 2014): Pp. 657-670.

Delong, D. L., R. A. Kozak and D. H. Cohen (2007). "Overview of the Canadian Value-Added Wood Products Sector and the Competitive Factors That Contribute To Its Success." Revue Canadienne De Recherche Forestière Vol. 37 (No. 11): Pp 2211-2226.

Dhubháin, Á. N., Fléchard, M. C., Moloney, R., O'Connor, D., & Crowley, T. (2008). "Social impacts of forestry: A case study approach." CORFORD. 4p

Ekşioğlu, S. D., A. Acharya, L. E. Leightley and Arora, S. (2009). “Analyzing the Design and Management of Biomass-to-Biorefinery Supply Chain.” Computers & Industrial Engineering Vol. 57(No. 4): Pp. 1342-1252.

Feng, Y., S. D'amours, L. Lebel and M. Nourelfath (2012). “Integrated Bio-Refinery and Forest Products Supply Chain Network Design Using Mathematical Programming Approach.” Integrated Biorefineries: Design, Analysis, And Optimization M. M. El-Halwagi Etp. Stuart, Eds.: Crc Press/Taylor & Francis.

Garrote, G., Dominguez, H., Parajo, J. (1999). “Hydrothermal processing of lignocellulosic materials.” Holz al Roh- und Wekstoff, 57, 191–292.

Holweg, M. and P. Helo (2014). “Defining Value Chain Architectures: Linking Strategic Value Creation to Operational Supply Chain Design.” Int. J. Production Economics Vol. 147.

Jeaidi, J., & Stuart, P. (2011). “Techno-economic analysis of biorefinery process options for mechanical pulp mills.” J-FOR-Journal of Science and Technology for Forest Products and Processes, 1(3), Pp. 62-70.

Jugend, D., & da Silva, S. L. (2014). Product-portfolio management: A framework based on Methods, Organization, and Strategy. Concurrent Engineering, 22(1), Pp. 17-28.

Kannegiesser, M. (2008). Value Chain Management, Springer Science & Business Media.

Kärna, J., E. Hansen and H. Juslin, (2003) “Social responsibility in environmental marketing planning”, European Journal of Marketing, Vol. 37 Issue: 5/6, Pp.848-871

Lehoux, N., P. Marier, S. D'amour, D. Ouellet and J. Beaulieu (2012). “The Value Creation Network of Canadian Wood Fibre”, Interuniversity Research Center on Enterprise Networks, Logistics and Transportation. Scientific Report Cirrelt-2012-33.: Pp. 210

Lepage, D. and S. Haddad (2015). Fibre Supply Study for Newfoundland, FPInnovations: 51p.

Mansoornejad, B., E. N. Pistikopoulos and P. Stuart (2011). “Incorporating Flexibility Design into Supply Chain Design for Forest Biorefinery.” Journal of Science & Technology for Forest Products and Processes Vol.1 (No°2): P. 54-66.

Martel, A. (2005). “The Design of Production-Distribution Networks: A Mathematical Programming Approach”. In: Joseph Geunes, Panos M. Pardalos (Eds.). Supply Chain Optimization - Volume 98 De Applied Optimization. S. S. B. Media, Kluwer Academic Publishers.

Melo, M. T., S. Nickel and Saldanha-Da-Gama (2009). "Facility Location and Supply Chain Management – A Review." European Journal of Operational Research Vol. 196(No. 2): Pp. 401-412.

Mendoza, G. A. and R. Prabhu (1999). "Multiple Criteria Decision Making Approaches to Assessing Forest Sustainability Using Criteria and Indicators: A Case Study." Forest Ecology and Management Vol. 131(No. 1): P. 107-126.

Oporto, G.S., R.H. Jara, D. DeVallance, T. Wang, and J. Armstrong. (2012). "Pre-treatment of Appalachian woody biomass for enhanced biofuel properties – Part I. Hot water extraction and pelletizing." Submitted to Biomass and Bioenergy. Manuscript Reference Number: JBB-D-12-01038.

Paquet, M., A. Martel and G. Desaulniers (2004). "Including Technology Selection Decisions in Manufacturing Network Design Models", International Journal of Computer Integrated Manufacturing Vol. 17(No. 2): Pp. 117-125.

Paredes H. and J. Jacobo. (2009) "The Influence of Hot Water Extraction on Physical and Mechanical Properties of OSB" (2009. Electronic Theses and Dissertations. 413.

Plaza, M. and C. Turner (2015). "Pressurized Hot Water Extraction of Bioactives". Trends in Analytical Chemistry Vol. 71: Pp. 39-54.

Porter, M. E. (1985). Competitive Advantage: Creating and Sustaining Superior Performance, Ny: Free Press.

Santibañez-Aguilar, J. E., González-Campos, J. B., Ponce-Ortega, J. M., Serna-González, M., & El-Halwagi, M. M. (2011). "Optimal planning of a biomass conversion system considering economic and environmental aspects." Industrial & Engineering Chemistry Research, 50(14), Pp. 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 Vol. 23: Pp. 299-311.

Shapiro, J. F. (2007). Modeling the Supply Chain, 2e Ed., Pacific Grove, Ca: Thomson-Brooks/Cole.

Sharma, P., B. R. Sarker and J. A. Romagnoli (2011). "A Decision Support Tool for Strategic Planning of Sustainable Biorefineries." Computers and Chemical Engineering Vol. 35(No. 9): Pp. 1767-1781.

Sima, Q., & Wang, Y. B. (2012). Research on remanufacturing industrial cluster promoting sustainable development of regional economy. In Advanced Materials Research (Vol. 347, pp. 621-626). Trans Tech Publications.

Talluri, S., Baker, R. C., & Sarkis, J. (1999). A framework for designing efficient value chain networks. International Journal of Production Economics, 62(1), 133-144.

Téguia, C. D., Chambost, V., Sanaei, S., D'Amours, S., & Stuart, P. (2016). 3 Strategic Transformation of the Forest Industry Value Chain. Forest Value Chain Optimization and Sustainability, 33 p.

Vidal, C. J. And M. Goetschalckx (1997). "Strategic Production-Distribution Models: A Critical Review with Emphasis on Global Supply Chain Models". European Journal of Operational Research Vol. 98(No. 1): Pp. 1-18.

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 Vol. 102(No. 2): Pp. 358-378.

Walters, D. And M. Rainbird (2007). "Cooperative Innovation: A Value Chain Approach." Journal of Enterprise Information Management Vol. 20(No. 5): Pp. 595-607.

Weigel, G., S. D'Amours and A. Martel (2009). "A Modeling Framework for Maximizing Value Creation in Pulp and Paper Mills." INFOR: Information Systems and Operational Research Vol. 47(No. 3): pp. 247-260.

Yamamiya, T., Ota, M., Mozammel, H. M., & Murakami, K. (2003, January). "Pyrolysis characteristics of biomass resources." In ASME 2003 International Mechanical Engineering Congress and Exposition (pp. 149-156). American Society of Mechanical Engineers.

CONSULTED WEBSITES

[1] Statistics Canada (2017) [online] http://www.statcan.gc.ca [Accessed Oct. 21st, 2016].

[2] Natural Resources Canada (2017) [online] https://www.nrcan.gc.ca/forests/resources/13507 [Accessed April 26th, 2017].

[3] National Geographic (2017) [online] http://www.nationalgeographic.com/environment/global-warming/deforestation/ [Accessed June 26th, 2017]

[4] Berkeley University of California (2017) [online] The S.J. Hall Lecture in Industrial Forestry – Lecture and Archive 1999 – Patrick Moore "Getting it Right: Environmentalism for the 21st Century". https://nature.berkeley.edu/events/2017/06/getting-it-right-environmentalism-21st-century [Accessed June 27th, 2017]

[5] Food and Agriculture Organization of the United Nations (2017) [online] http://www.fao.org/forestry/environment/11787/en/ [Accessed June 28th, 2017]

[6] United States Environmental Protection Agency (2017) [online] https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions [Accessed June 28th, 2017]

[7] Ministère de l'Énergie et des Ressources Naturelles Québec (2017) [online] https://www.mern.gouv.qc.ca/english/mauricie/overview/index.html [Accessed April 14th, 2017]

[8] Institut de la Statistique Quebec (2017) [online] http://www.stat.gouv.qc.ca/statistiques/profils/region_04/region_04_00.htm [Accessed April 14th, 2017]

[9] Biofuel Digest (2017) [online] http://www.biofuelsdigest.com/bdigest/2016/07/10/whats-new-and-important-about-c5-and-c6-sugars/ [Accessed May 4th, 2017]

[10] Grand View Research (2017) [online] http://www.grandviewresearch.com/industry-analysis/lignin-market [Accessed May 9th, 2017]

[11] Frost & Sullivan (2012). [online] http://www.frost.com/sublib/display-market-insight-top.do?id=269017995 [Accessed May 9th, 2017]

[12] PR Newswire (2017). [online] http://www.prnewswire.com/news-releases/organic-acids-market-industrial-food--feed-growth-forecasts-of-6-cagr-led-by-acetic-acid-581729631.html [Accessed May 4th, 2017]

[13] Orbichem (2017). [online] http://www.orbichem.com/userfiles/CNF%20Samples/aac_13_11.pdf [Accessed May 4th, 2017]

[14] Transparency Market Research (2017). [online] http://www.transparencymarketresearch.com/pressrelease/global-furfural-market.htm [Accessed May 5th, 2017]

[15] Grand View research (2017). [online] http://www.grandviewresearch.com/press-release/global-levulinic-acid-market [Accessed May 5th, 2017]

[16] Frost & Sullivan (2012). [online] https://www.frost.com/prod/servlet/report-brochure.pag?id=N945-01-00-00-00 [Accessed May 9th, 2017]

[17] Ensyn (2017). [online] http://www.ensyn.com/quebec.html [Accessed Aug. 4th, 2017]