UNIVERSITÉ DE MONTRÉAL

BIOMASS PROCUREMENT COST MINIMIZATION FOR IMPLEMENTATION OF A RETROFIT BIOREFINERY IN A PULP AND PAPER MILL

JOSE ALFONSO MELENDEZ ESQUIVEL

DÉPARTEMENT DE GÉNIE CHIMIQUE

ÉCOLE POLYTECHNIQUE DE MONTRÉAL

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présentée par : MELENDEZ ESQUIVEL Jose Alfonso

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a été dûment acceptée par le jury d'examen constitué de :

M. FRAYRET Jean-Marc, Ph. D., président

M. STUART Paul, Ph. D., membre et directeur de recherche

M. LEBEL Luc, Ph. D., membre et codirecteur de recherche

M. PERRIER Michel, Ph. D., membre

M. PULKKI Reino, Dr.Sc.For., membre

DEDICATION

For my parents whose unconditional support has never wavered. I am who I am because of you…

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RÉSUMÉ

La récente récession économique a touché de plein fouet l'industrie des produits du bois, laquelle a dû s'ajuster à la chute de la demande pour ses produits phares, notamment la pâte et le papier. Pour les compagnies forestières, une des pistes de solution consiste à varier l'éventail de produits qu'elles proposent en implantant des procédés de bioraffinage en rétro-installation dans leurs usines. Cependant, la production de produits à valeur ajoutée en plus des produits existants requiert une utilisation plus complète des ressources, et entrainera certainement des changements le long de la chaîne d'approvisionnement.

Ainsi, la modernisation d'une usine en rétro-installation s'effectue sur le moyen-à-long terme, et l'évolution de la chaîne d'approvisionnement impacte non seulement l'usine concernée, mais la compagnie dans son ensemble. L'impact sur les coûts de l'usine influencera notamment le choix de la compagnie d'implanter ou non un procédé de bioraffinage donné. Par conséquent, il est dans l'intérêt d'une usine d'explorer au préalable les options d'approvisionnement de la biomasse pour comprendre les effets sur le coût global.

L'objectif du présent projet est de déterminer différentes stratégies d'approvisionnement de la biomasse pour une bioraffinerie qui soient économiquement viables, qui engendrent une réduction des coûts d'approvisionnement, tout en satisfaisant les besoins en termes de qualité et de quantité de matière première.

La réalisation de la recherche se base sur l'étude de cas d'une usine de papier journal et de son réseau de distribution de produits forestiers. Ce contexte a été utilisé pour le développement du cadre méthodologique et des outils de modélisation requis pour atteindre les objectifs. La structure de la simulation, de l'optimisation et des modèles de coûts associés vise à représenter au mieux les activités d'approvisionnement menées par la compagnie à l'étude.

L'approvisionnement en matières premières est destiné aux opérations courantes (papier journal et cogénération) et futures (bioraffinerie) de l'usine. La méthode de comptabilité par activité ou *activity-based cost (ABC)* a été utilisée par le modèle de simulation pour calculer les coûts de livraison aux usines par produit et bloc de coupe. Ces coûts sont ensuite intégrés au modèle d'optimisation qui vise à satisfaire les demandes de l'usine en matière première sur une base annuelle.

Les modèles peuvent être vus comme des plateformes d’évaluation de différentes stratégies d’approvisionnement suivant les processus entrepris par la bioraffinerie durant sa période d’activité. De l’analyse de ces processus découlent des informations relatives aux quantités de matière première et coûts qui guideront les décideurs dans leur sélection d’une stratégie de bioraffinage qui tienne compte de manière effective des ressources disponibles.

Le projet analyse les coûts d’approvisionnement en matière première et la faisabilité de onze scénarios impliquant deux technologies de bioraffinage : (1) la pyrolyse rapide et (2) le fractionnement de la biomasse utilisant un solvant organique, dit Organosolv. Les scénarios considèrent différentes variantes d’intégration au procédé de production de papier journal de l’usine, sur un horizon de vingt ans. Dans cet horizon de temps, l’usine peut (ou non) décider de stopper, partiellement ou complètement, la production de papier journal.

En plus des lignes de production de pâte et papier et des procédés de bioraffinage implantés, l’usine possède aussi une chaudière à biomasse et une unité de cogénération qui desservent les besoins en vapeur et en électricité de l’usine. Les variations des prix et de la demande en énergie des procédés implantés sont considérées sur la durée du projet, de même que les variations de la demande en biomasse pour le fonctionnement de la chaudière.

Les nouvelles contraintes s’appliquant à la chaine d’approvisionnement en biomasse suite à l’implantation de nouveaux procédés ont été intégrées au modèle d’optimisation. Afin de réduire les coûts d’approvisionnement, les systèmes de récolte en forêt ont été changés du bois court au bois long, sur une période de 10 ans. Le changement de système devrait améliorer la récolte pour plusieurs produits (bois de sciage, bois à pâte, bois de chauffage et résidus) et réduire les coûts de récolte. Aussi, des contrats d’échange ont été mis en place pour assurer l’acheminement des copeaux produits par les scieries à l’usine de pâte et à la biorafinnerie.

Les scenarios testés se concentrent sur la satisfaction de la demande en matière première selon les ressources disponibles dans la région pour les différents processus initiés ou stoppés à l’usine au cours des phases de transition de l’usine de pâte vers une usine de bioraffinage, tout en minimisant les coûts d’approvisionnement au cours de l’horizon de temps du projet.

Les analyses et comparaisons de scénarios de bioraffinage couplées à l’optimisation de l’approvisionnement en biomasse permettent de déterminer quelle implantation de bioraffinage est techniquement et économiquement la plus réalisable pour l’usine et ses partenaires.

Les résultats de l'analyse des scénarios indiquent que des coûts d'approvisionnement moindres sont obtenus quand le procédé de pyrolyse rapide est implanté comparativement au fractionnement par solvant organique. Ce résultat s'explique notament par le coût d'approvisionnement de copeaux de feuillus depuis une forêt en contenant peu.

Des compromis pour chaque scénario ont été trouvés, permettent qui peuvent leur implantation à l'usine. Par exemple, le scénario créant le plus faible coût d'approvisionnement, induit un approvisionnement en copeaux de résineux pour le procédé de pyrolyse rapide, et une fermeture complète des lignes de production de papier journal lors de la sixième année. Cependant, en analysant le ratio du coût de la biomasse par rapport au revenu, le scénario se révèle avoir une valeur inacceptablement élevée à cause du compromis entre un produit (le papier journal) et un autre de moindre valeur (huile bio, vendue comme carburant de substitution).

Pour d'autres scénarios de bioraffinage qui requièrent de plus grandes quantités de ressources forestières pour les procédés actuels et futurs de l'usine (par exemple utilisation de copeaux de bois de sciage pour la ligne de production de papier journal et utilisation de déchets de bois pour la pyrolyse rapide), la matière issue de la récolte est mieux exploitée. Il ressort cependant que ces scénarios tendent aussi à avoir des coûts annuels de biomasse plus élevés, à cause de la plus grande quantité de matière à acquérir.

En ce qui est du fractionnement de la biomasse utilisant un solvant organique, le rapport du coût de la biomasse sur le revenu est acceptable seulement pour les scénarios où la production de papier journal est continue; ce qui sous-entend l'existence d'un flux continu de revenus issu de la vente du papier journal. Idéalement dans cette situation, l'usine augmenterait la capacité du procédé Organosolv. Cependant, l'étudié ne permet pas l'approvisionnement de telles quantités de matière (plus de 1000 tonnes/jour de copeaux pour le procédé de bioraffinage).

Ainsi, le choix de la stratégie d'approvisionnement à utiliser dépendra grandement de la décision de l'usine de maintenir ou non sa ligne de production de papier journal. Dans l'ensemble le meilleur scénario pour l'usine serait celui de l'implantation d'une unité de pyrolyse rapide utilisant les déchets de bois, dont la bio-huile serait vendue comme substitut de combustible lourd, tout en maintenant la ligne de production du papier journal. D'autre part, si le procédé Organosolv était implanté, sa capacité ne devrait pas dépasser les 750 tonnes/jour, pour que le

réseau d’approvisionnement de la biomasse puisse fournir assez de copeaux aux deux procédés (production de pâte, et bioraffinerie).

Avec le développement et l’application de modèles de simulation et d’optimisation pour évaluer les scénarios de bioraffinage, tous les objectifs de ce projet de doctorat sont atteints et les hypothèses vérifiées, tout en contribuant à l’ensemble des connaissances.

ABSTRACT

As the forest industry emerges from the last economic recession, it finds itself evolving, to adjust to changes happening in their product markets (wood products, pulp and paper, etc.). In order to flourish in these new markets, many changes will come about in forestry firms, including expanding product portfolios by incorporating more biorefinery processes into current facilities. However, the added production of multiple value-added products along with current production will imply a more complete utilization of current feedstocks, and will most likely put a strain on the feedstock procurement supply chain.

Thus, as the transformation of mills into retrofit forest biorefineries occurs over a medium-to-long period of time, additional changes will have to occur throughout the mill (and company) supply-chains. These changes in procurement supply chains will have an impact on the bottom-line costs of the mill, and may ultimately determine whether or not a process is implemented. Therefore, it is in the best interest of the mills to explore biomass material procurement options beforehand, in order to better understand their effects on overall costs.

The objective of the project was to determine the conditions where different biomass procurement strategies for a biorefinery, result in reduced feedstock procurement costs, such that, they satisfy the facility's feedstock quantity and quality requirements, and are economically viable for a forestry firm in a competitive market.

A case study newsprint mill along with its forest material supply network was used to develop the necessary methodological framework and required modeling tools to prove the objectives.

The simulation, optimization, and their associated cost models aim to imitate realistic procurement activities to source forest material for all of their current (i.e. newsprint and cogeneration) and future (i.e. biorefinery) operations. Activity-based cost (ABC) accounting methods, were used within the simulation model, to calculate delivered product costs for each product extracted from each harvesting cutblock in the network, which was then used in the optimization model to fulfill the customers’ feedstock demands on an annual basis.

The models can thus be used as a platform for evaluating various optimized procurement strategies for a company according to the process activities (which will determine the feedstock requirements) undertaken during the biorefinery’s lifespan. This creates valuable feedstock quantity and cost information which will assist decision-makers in developing the correct biorefinery implementation strategy that considers existing feedstock resources within the area.

The project analyzed the feedstock procurement costs and feasibility of 11 biorefinery scenarios involving two biorefinery technologies (fast pyrolysis, and organic solvent pulping) retrofitted in a newsprint production mill, over a 20 year biorefinery project lifespan. During this time, the newsprint mill may (or may not) choose to partially (or completely) shut down newsprint production.

Along with the main pulp and paper production lines, and the implemented biorefinery processes, the mill also has a biomass boiler and cogeneration plant to produce steam and power consumed at the mill. Over the lifespan of the project, steam and power demands will change depending on the processes implemented, and so will the biomass demands of the boiler.

Along with process changes, other modifications are done to the biomass procurement supply chain and included within the optimization model as constraints. To reduce biomass procurement costs, forest harvesting systems are changed from cut-to-length to full-tree equipment over a 10 year period of time. This harvesting system change is expected to improve the integrated harvesting of multiple forest products (sawlogs, pulp logs, fuel logs and residues) as well as reduce harvesting costs due to the lower harvesting cost of using a full-tree system. Also, fibre exchange contracts are in place with local sawmills to exchange sawlogs harvested for chip materials used by the pulp and paper mill and biorefinery.

The tested scenarios focused on fulfilling feedstock demand according to available resources in the area, for the different processes being initiated or shutdown at the mill during the transition phases from P&P mill to biorefinery, while minimizing procurement costs over the lifespan of the project.

Biorefinery scenario analyses coupled with optimized biomass procurement costs for the simulated forest network determined which biorefinery implementation has the best technical and economic feasibility for the mill, and surrounding forest industry.

Results from the scenario analyses indicate that lower procurement costs are obtained when a pyrolysis process is implemented instead of an organic solvent due to the higher cost of providing hardwood chips from a forest with low amounts of hardwoods.

Certain trade-offs were found to be present in each scenario, that may affect their application in the newsprint mill used. The lowest cost procurement scenario for example involves the procurement of softwood chips for the pyrolysis process, as well as a complete exit from newsprint operations by year six. However, when analyzed with a biomass cost to revenue ratio, this scenario was found to have a value above 0.5 which makes it economically un-attractive. This is due in part to the trade-off of one commodity product (newsprint) for another (bio-oil) with lesser value (sold as a fuel oil substitute).

In other biorefinery scenarios that utilize higher quantities of products from the forest for both the current and future biorefinery processes (e.g running newsprint while running pyrolysis biorefinery using hogfuel as a feedstock) tend to better utilize all the materials coming from harvesting operations (i.e. chips, residues, barks, hogfuels); nevertheless, they also tend to have higher total biomass costs per year due to the procurement of larger quantities of materials.

In the organic solvent pulping biorefinery, the biomass cost to revenue ratio was found to be acceptable only in scenarios where newsprint production was continued, due to the continued revenues from newsprint. Ideally in this situation the mill would increase the capacity of the organosolv process, however it was found that the biomass network cannot provide such large quantities of materials (above 1000 dry tonnes per day of woodchips for the biorefinery process).

Thus, the decision on which procurement strategy to use will depend on whether the mill decides or not to maintain its newsprint production.

If newsprint production is continued, and a pyrolysis technology is selected, than the use of hogfuel as a feedstock for the pyrolysis process is better suited as it will reduce feedstock costs, since there is an abundance of unused hogfuel in the supply chain. On the other hand, if organic solvent production is used, newsprint production must be maintained and the scale of the organosolv process needs to be reduced to 750tpd for the biomass procurement network to be able to produce enough woodchips to supply both processes.

With the development and application of both simulation and optimization models to evaluate biorefinery scenarios, all the objectives of the PhD study were accomplished, and the hypotheses proven, while contributing to the body of knowledge.

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LIST OF SYMBOLS AND ABBREVIATIONS

ABC	Activity-Based Cost
Chipper-CTL	Cut-to-Length harvesting system with forwarder-mounted chipper
CTBI	Canadian Triticale Biorefinery Initiative
CTL	Cut-to-Length harvesting system
DSS	Decision-Support Systems
FB-CTL	Feller Buncher with Cut-to-Length harvesting system
FT	Full Tree harvesting system
GIBRF	Green Integrated Biorefinery
GIS	Geographic Information Systems
LP	Linear Programming
MILP	Mixed-Integer Linear Programming
MINLP	Mixed-Integer Non-Linear Programming
MSW	Municipal Solid Waste
NLP	Non-Linear Programming
NLDP	Non-Linear Dynamic Programming
OR	Operations Research
PMH	Productive Machine Hour
P&P	Pulp and Paper
SC	Supply Chain
SCM	Supply Chain Management
SMH	Scheduled Machine Hour
TMP	Thermo-Mechanical Pulping
tpd	tonnes (dry) per day

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CHAPTER 1 INTRODUCTION

1.1 Problem Statement

The transformation of the pulp and paper industry has been motivated in the last decades by many factors. Amongst the most important, are increasing fuel and energy costs, shrinking markets for paper products such as newsprint, and strong competition in production from emerging economies (Brazil, Russia, India and China) [1]. However, within the last year, some of these factors have seen radical changes due to dropping oil prices [2], which have decreased fuel costs and depreciated the Canadian dollar (a favourable condition for P&P exporters). But other factors such as newsprint markets, and increased competition from emerging economies, have been unaffected, and mark irreversible changes in these traditional paper markets due to advancements in technologies that have come to replace these traditional products [3].

Newsprint mills in Canada, especially those that use thermo-mechanical pulping processes (TMP) have especially had a hard time accommodating the ever changing market place, and many have decreased production, been idled or shut down in order to stabilize supply and demand. But as the newsprint market continues to be downsized, many newsprint mills need to find suitable replacements and value-added products to produce if they wish to survive.

With the intent of adapting to changing market conditions, which seem to require less of some mainstay forest products (e.g. newsprint, copy paper, etc.), Canadian newsprint mills have sought out opportunities for introducing value-added products (e.g. bioenergy, combined heat and power generation, pellets, biofuels and biochemicals) into their current operations. Market demand for these new value-added products has seen expansion over the last few years [4] due to new policies which favour carbon neutrality, and sustainable use of renewable residual materials.

In addition to the introduction of new products, forestry companies are continually looking to improve the performance of their supply chains (SC), in order to lower operation and logistics costs, and increase their competitiveness. Canadian pulp and paper companies are always seeking ways of restructuring their up- and down-stream operations, and investment and financing strategies, in order to improve the economic performance of the entire supply chain (SC) [5, 6].

But more than just the addition of new products, and improvements in supply chain costs that will benefit Canadian forestry companies, long-term action plans and policies must be developed and put in place to achieve the long-term goals of the organization. In other words a business strategy. Corporate business strategies must be developed which optimize production for both the core business and additional products at the same time that they achieve short- and long-term competitive advantages. It is here that decision support systems (DSS) play a vital role, as they provide decision makers with tactical and operational level information from each stage of the supply chain necessary to develop and implement the most appropriate business strategy to aid in the improvement of their financial performance.

Thus, as the transformation of P&P mills into retrofit forest biorefineries comes about over a medium-to-long term period of time (5 to 10 years), redesigns due to process integration will have to take place throughout the mill supply chain as well as the company's business strategy. During said timeframe, day-to-day operations will be affected, and must be altered to minimize costs and maximize productivity [7]. Simultaneously, lower-level operational and tactical information concerning alterations and redesigns in processes and supply chains, as well as their impacts from the costs accounting systems used, needs to be communicated to higher level decision makers which will make sure that the mill's strategic goals are being satisfied (i.e. bottom-up decision making[8]).

Amidst the many changes that must take place, the biomass[1] procurement strategy and supply chain must be adjusted to properly accommodate the material requirements of each phase of the transformation process. The efficient procurement of biomass feedstocks in each phase, is critical for the long-term economic viability of the retrofit forest biorefinery. Having access to a reliable and low-cost fibre source, evaluating the entire fibre procurement logistics network of the biorefinery, and implementing changes to maintain competitiveness over the long-term will represent an enormous competitive advantage to any business organization [9, 10].

Feedstock quantities and quality for both the core business (e.g. newsprint), as well as biorefinery processes, and the supply systems used to procure them will determine the overall feedstock costs for the facility during each phase of the biorefinery implementation. Ultimately, the feedstock costs will impact overall product profit, and therefore, maintaining or reducing feedstock

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[1] The term "biomass" in this document refers to all materials required by a mill or biorefinery for all their processes, including sawlogs, pulp logs, clean whitewood chips, fuel logs, forestry residues, bark, hogfuels, etc. A more detailed description is given later-on in this document.

procurement costs for all processes in the facility will be an essential part of the transformation process. In addition, improving current cost accounting systems with newer, more accurate methods that take into account the production of multiple products that may or may not all use the same supply chain activities, will provide more accurate accounting of where costs are coming from (i.e. Activity-based cost accounting).

Nevertheless the procurement of biomass fibre (whitewood fibre as well as residuals) for a pulp mill, is a complex task, that involves a number of different activities and types of equipment for each task. The way biomass is harvested as well as its costs will be affected by a multitude of factors and decisions at both tactical and operational levels that must be taken into account.

In order for P&P companies to analyze the important trade-offs between business strategies for feedstock procurement in a timely manner, systems-based[2] decision support systems must be created that produce a simulated re-creation of current biomass procurement operations while estimating overall feedstock costs, taking into account all harvesting-related activities for each product. At the same time, these tools must allow companies to re-design and improve their supply chains to provide cost reductions in delivered feedstock products while including operational level data that affects tactical and strategic level planning for the entire biomass supply chain (SC). These decision support systems will be a critical element for the successful design, coordination and management of the P&P supply chains.

Both simulation and optimization have been found to be effective tools to use in the development of DSSs. Each methodology has its own specific application: Optimization tries to find the most cost-effective way of carrying out a network-wide activity (or set of activities) under a set of known and stable constraints, by maximizing desirable factors, and minimizing undesirable ones. On the other hand, simulation identifies the impact of different variables which may change over time, on the activity (or set of activities) and can also be used to visualize the real world behavior of a supply chain, plus identify and react to problematic areas within the system. [11]

Thus for the study of biomass procurement systems in a biorefinery implementation, simulation tools are used to explore the impact on costs of harvesting, using different harvesting systems

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[2] A systems-based approach refers the study of the interdependency and interactive nature of elements within and external to a organization/supply chain, etc.

amongst different harvesting conditions (e.g. harvesting sites, feedstock quantities available, etc.). Activity-based cost (ABC) accounting methods are then introduced into the simulation model, to improve product cost distribution and traceability to the source activities that generate them. Then, optimization uses the data provided by simulation to explore the consequences for the larger network, by seeking to maintain minimum procurement costs, while satisfying a changing feedstock demand over the lifespan of the biorefinery. These two methods, allow the analysis of low-level operations, while examining their impact on higher level strategies. This gives decision makers information/data from the procurement cycle of the supply chain, needed to make decisions that will maintain the economic viability of a biorefinery. Furthermore, by changing the original biorefinery conditions (technology, scale, etc.) we create a different outcome which can be compared to the previous set of biorefinery conditions. This is what is known as a scenario analysis. The systematic development of these tools, along with their validation and application towards a realistic case study mill is the main motivation for the research presented in this thesis.

1.2 Hypotheses and Objectives

The ultimate goal of this thesis is to present a systematic approach by which to evaluate biorefinery biomass procurement strategies, within an existing P&P mill operation (i.e. in retrofit), taking into account tactical and operational level conditions (e.g. equipment selected to harvest, cutblock selection, products extracted, intermediate locations used, preprocessing carried out, etc.) that ultimately affect biomass procurement costs. Based on this, the main hypothesis of this work is as follows:

Main Hypothesis: Optimizing the biomass procurement strategies of biorefinery implementation scenarios, will allow to compare the scenarios and determine which biorefinery implementation strategy creates the best conditions for the economic viability of the project (i.e. biorefinery implementation) over an extended period of time.

This overall hypothesis has been divided into four sub-hypotheses:

Sub-Hypothesis 1: The simulation of biomass procurement activities and harvesting systems for different forest characteristics at the cutblock level, will allow to supply biomass demands from the biorefinery, and compare the procurement costs of each forest site harvested.

Sub-Hypothesis 2: The combination of a forest harvesting simulation model and activity-based cost accounting method to improve the traceability of forest product costs, will allow to compare alternative harvesting systems in order to reduce harvesting costs for different biomass demands.

Sub-Hypothesis 3: By optimizing a simulated forest harvesting network taking into account strategic scenario decisions and tactical/operational planning and decision-making horizons, will allow to satisfy a P&P mill's quantity and quality requirements over an extended period of time.

Sub-Hypothesis 4: Adapted harvesting solutions can be implemented for different biorefinery scenarios, depending on the quality and quantity of required biomass. Their cost-optimized biomass procurement supply chains will impact the economic viability of the biorefinery.

The problem statement and hypotheses call for the systematic development of two modeling tools which when used to examine different biorefinery scenarios, will assist strategic decision-makers in identifying promising biorefinery strategies from a biomass procurement point-of-view. To that end, the methodology used was guided by the following **main objective**:

- To design a systematic methodology for the comparison of biorefinery implementation scenarios with optimized biomass procurement strategies which result in reduced feedstock procurement costs, such that, they satisfy the facility's feedstock quantity and quality requirements and are economically viable for a forestry company in a competitive market.

Furthermore, the accomplishment of the main objective is tied to the completion of the following **sub-objectives:**

- To design a forest/harvesting simulation model to evaluate a traditional forest biomass procurement supply chain used in a case study P&P case mill, for the procurement of both clean whitewood chips, and hogfuel in and integrated harvesting process
- To demonstrate how an alternative cost accounting method implemented in a forest harvesting supply chain simulation model, will allow for a more detailed view of the cost structure, which will better evaluate new procurement strategies using alternative

harvesting systems and sources of each product that will ultimately help decision-makers reduce procurement costs.

- To optimize a biomass procurement network in order to minimize procurement costs while satisfying mill feedstock demands, by implementing quantity and quality feedstock changes over time which are part of the strategic goals of the mill, while the tactical and operational level decisions are aligned with the overall strategic decisions.
- To assess the competitiveness of different biomass procurement strategies for several biorefinery implementation scenarios in order to determine the most economically viable solutions for the P&P mill being retrofitted with biorefinery technologies.

1.3 Thesis Organization

This thesis is organized as follows: In Chapter 2 the relevant literature is reviewed in order to identify the gaps in the body of knowledge. Chapter 3 gives a description of the case study mill and supply chain used to develop the simulation and optimization models as well as evaluate the biorefinery scenarios. Chapter 4 outlines the methodology followed in this study to create the simulation and optimization modeling tools, along with the mathematical model formulations (for the optimization model), constraints, and descriptions of their functions. Each modeling tool will help prove each one of the objectives presented beforehand that will ultimately help support the described hypotheses. Chapter 5 is a general discussion and synthesis of all work carried out, as well as implications of results obtained in each step. Chapter 6 presents overall conclusions, contributions to the body of knowledge and future work. In the Appendix you will find a published article detailing work carried out in agriculture

CHAPTER 2 LITERATURE REVIEW

2.1 Strategic Design of Retrofit Biorefineries

Biorefining and biorefineries refer to the process and facilities that integrate biomass conversion processes and equipment to produce fuels, power and chemicals from biomass. As stated by Ragauskas [12], biorefineries are analogous to today's petroleum refineries which produce multiple fuels from petroleum; industrial biorefineries would create products from renewable feedstocks [12, 13]. However, unlike petroleum refineries which use only one type of raw material (petroleum), a biorefinery will most likely have multiple types of renewable feedstocks entering the process at any given time.

The "forest biorefinery", as described by Chambost et al. [14], describes a retrofitted (i.e. continued production of core business products) or repurposed mill which creates multiple value-added products using integrated processes. The main focus of the integrated forest biorefinery is to take advantage of the existing facilities and supply chain networks already established in the forest-paper industry, and convert them into biorefineries. Part of the added benefit of biorefineries, is the fact that they can better utilize more feedstock types, in an integrated way, which reduces the amount of waste of the valuable resources.

Axegard [15] uses similar concepts to describe the "pulp mill biorefinery", where value added products are extracted from Kraft pulp mill residuals. Examples they present are the separation and purification of lignin and xylan from black liquor, glucomannan and xylan from wood chips-forest residuals, and extractives from bark. Van Heiningan [16] also identifies his "integrated forest biorefinery" as the transformation of chemical pulp mills into biorefineries, although for the most part, focuses on process integration and the extraction of hemicelluloses for production of value added chemicals prior to pulping; an approach also taken by Amidon [17] and his research team.

Other authors [18-21] have also placed the biorefinery in the context of retrofit or repurposing of P&P mills. Thorp et al. [22] considered the transition of pulp mills to biorefineries, the next logical step to create new revenue streams; but the biggest challenge they identified was to move away from their commodity business model which has come to be less profitable than before. This is where biorefinery integration and implementation strategies become useful.

2.1.1 Biorefinery Integration strategies

Strategic integration of biorefinery processes is an important element in the process of improving a forest company's performance because it facilitates the continuous alignment of business strategies within the ever changing business environment.

Dansereau [23] identified two strategies for integrating biorefinery processes in a retrofit P&P mill: a strongly integrated strategy, and a parallel-integrated strategy. The strongly integrated strategy implies a better utilization of current feedstocks used in the P&P mill core processes by extracting biomass components (i.e. lignin and hemicellulose) that through additional biorefining processes and upgrading, will have a higher product value than before. This leaves cellulose for the core P&P process and increases value of the other co-products. Because of its strong dependency on core business processes, the strongly integrated biorefinery processes such as lignin and hemicellulose extraction [24-26], work best with companies that aim to strengthen their competitive position in the P&P business, while achieving increased revenues.

On the other hand, the parallel-integrated strategy, builds biorefining processes adjacent to existing pulping lines in order to share services to the main processes: wood procurement and preparation, energy and water treatment integration, as well as the use of existing supply chains and sharing of manufacturing overheads [27]. Examples of parallel-integrated biorefinery technologies include pyrolysis [28, 29] and other thermochemical treatments [30]. Although the strongly-integrated processes would also have the benefits of sharing services, the main advantage of the parallel-integrated strategies is that they are less dependent on the core business, which at any point in time could be shut-down, or production decreased, without adversely affecting biorefining processes. This may fit in best with companies seeking to exit the P&P business.

Hytönen et al. [31, 32] analyzed the integration of biorefinery technologies into a kraft pulp mill from different aspects including techno-economic analysis [33], capital cost savings, operating costs synergies and revenue diversification for bioethanol production. Sammons Jr. [34] then proposed a general approach as a combination of several tools (process integration, mathematical optimization, and economic and environmental analyses) in order to determine the optimal biorefinery process and product design combination.

The number of potential biorefinery combinations (product/process/feedstocks) that can be integrated into a P&P mill is quite large as represented in Figure 2-1. The best integration strategy of a potential biorefinery alternative will depend on a number of factors such as the feedstocks (biomass) available in the local areas (both quantities and qualities), the P&P mill type (Kraft, TMP, etc.) and configuration, the biorefinery technology selected, the products and by-products produced, as well as financial (capital investment and production costs), environmental and social factors.

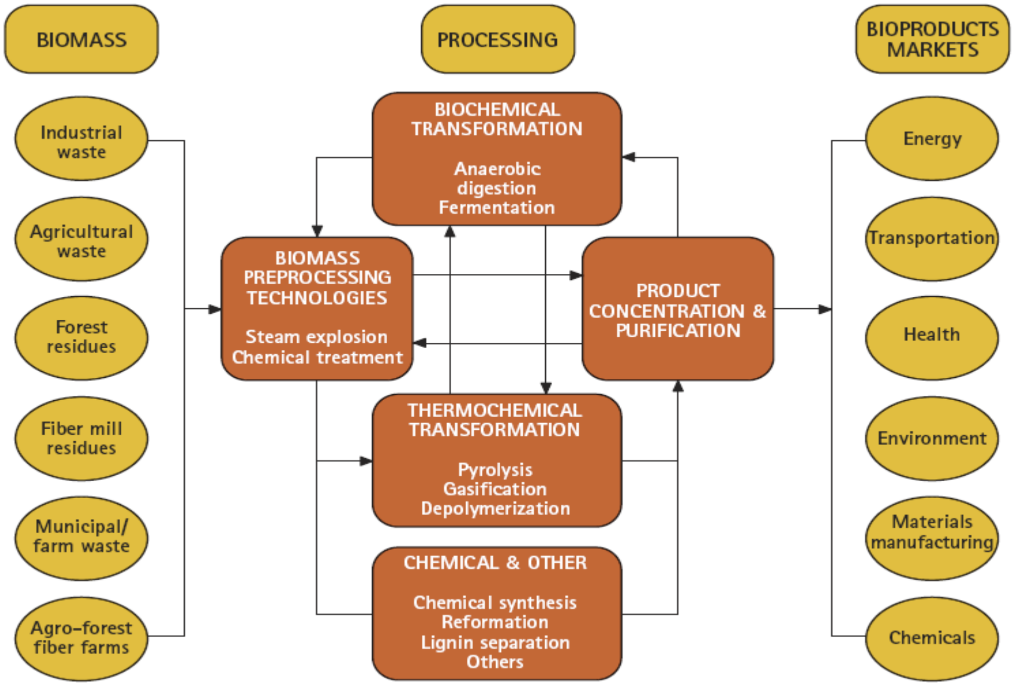

Figure 2-1: Potential forest biorefinery biomass, processing and product combinations [35]

With the integration of biorefinery processes into P&P mills, new challenges will come about in the procurement of raw materials for the facility. The added production of multiple biorefinery products along with current core business production will imply a more complete utilization of currently procured raw materials, and the need for more biomass materials, that will most likely put a strain on the feedstock procurement supply chain (SC). Furthermore, the added need for raw materials, will cause procurement costs to increase. Thus companies will have to seek out ways to maintain, or reduce their feedstock procurement costs if they want to remain competitive, as well as secure supplies to fulfill all feedstock demands of the mill over the lifespan of the facility [36].

The up- and down- stream operations carried out to supply materials to the P&P mill (and future biorefinery), and deliver produced products to final customers will play a significant role in the design of a biorefinery. Because changes in the P&P mill will no doubt affect supply chain operations, the study and analysis of both supply chain and supply chain management are of importance for the biorefinery design process as was shown by Mansoornejad et al. [37] who integrated the concepts of product/process design with those of supply chain design within the biorefinery in order to develop a methodology framework for decision-making.

2.1.2 Biorefinery Implementation strategies

One of the biggest challenges faced by decision makers regarding biorefineries is the implementation strategy to follow. In order to achieve the full potential of a forest biorefinery, there must be an implementation strategy to assure that both current and future processes in the retrofit facility maintain economic viability during the transition period, and beyond.

Strategy implementation is a term used to describe the activities within an organization to manage the execution of a strategic plan. In this case the strategic plan refers to the integration of biorefining processes within a P&P mill, along with all the changes that it will produce in both the biomass feedstock and product supply chains.

Chambost et al. [38] considered that diversification to a new business model as an essential part of the biorefinery implementation strategy which would include the addition of new products to the core business products (i.e. P&P products) in order to form the company's new product portfolio.

Wising and Stuart [39] expanded on the concepts of product portfolios in biorefineries by combining product design with process design using process systems engineering and process integration tools. Fernando et al. [40] also used the concepts of product portfolios to describe their 3 phase biorefinery process, where a great deal of focus was placed on the capacity of the processes to adapt to changing market demand using process flexibility. The goal as they described it, was to reach phase 3 where a biorefinery has multiple products, which can be of either high-volume low-value or low-volume high-value, and the flexibility to switch production between them.

Janssen et al. [41] further developed the concepts of a biorefinery product portfolio by proposing a phased approach for biorefinery implementation, taking into account the strengths and constraints of forest biorefinery industry.

Moshkelani et al. [42] presented a methodology by which to assess and implement a green integrated biorefinery (GIBRF) within a Kraft P&P mill. Their study suggested that a progressive implementation would be advantageous as it allows the mill to continue producing revenues throughout the process. However, the authors do conclude that the implementation strategy raises a number of unusual challenges such as selecting the appropriate process/product combinations to fit each mill, managing production flexibility of products so as to not oversaturate the market, and integrating the new processes with existing supply chains for products and raw materials. All of which are concepts that must be resolved before embarking in the implementation of a biorefinery retrofit. Rafione et al. [43] later expanded the GIBRF implementation strategy to a 5 phase strategy which takes into account the need to select the appropriate biorefinery technology and products for each mill, but does not resolve challenges external to the mill (i.e. production flexibility, supply chain integration, etc.).

Ultimately, it will be crucial to carry out a selection process to screen out the non-promising biorefinery integration and implementation strategies from the list of possible solutions at the early stage strategic design. This will ensure that the most promising combination of process technology and product portfolio are selected for the specific P&P mill under study [41].

Many P&P companies are eager to define long-term strategies and investments that will lead them to successfully transform their current operations towards integrated biorefineries which can fulfill future emerging markets. However, they face many challenging decisions to find the best investment strategy that will minimize their procurement and production costs and allow to maximize net profits. Decision support systems, such as simulation and optimization models, will play a vital role in the implementation strategies followed by P&P mills seeking to retrofit their facilities with biorefinery processes. These tools, plus, scenario analysis (the analysis of potential future events by considering possible future outcomes [44]) to compare different biorefinery alternatives which may include different technologies, feedstocks, production scale for both current and future processes, and other variables will provide decision makers with valuable information to determine the best course of action for the retrofitting of a current P&P mill with biorefinery technologies.

2.1.3 Critical Analysis 1

Retrofitting P&P mills with biorefining technologies incorporates product and process design into its implementation strategies so that the selected product will fulfill market demand as explained by Chambost et al. [38] as well as Wising & Stuart [39]. However, going back to one of the main differences between petrochemical refineries and biorefineries, is the fact that biorefineries will use a wide variety of feedstock materials in their processes as opposed to the single material used in petrochemical refineries. This brings to light the importance that needs to be placed on the study of raw material procurement for the biorefinery, as it will differ considerably from what has been done in the past (for petroleum refineries).

As is depicted in Figure 2-1, different types of feedstock materials can be used by a biorefinery, and finding the correct combination of feedstock/process/product (along with other important factors such as scale of production, technologies used, process configurations, etc.) should be an integral part of the pre-design phase of a biorefinery implementation strategy. To add to the complexity, biomass materials will also have a significant impact on the economics of the biorefinery depending on quality and quantities available in the region, and required by the mill. In order to determine the optimum biorefinery implementation strategy there should be a comparison of several different alternatives by which we eliminate out the ones that are considered non-feasible, or do not provide the best outcome for the mill.

In addition, because feedstock materials differ from one pulp mill to another, and from one region to another, incorporating the study of biomass procurement during a biorefinery implementation is needed. Likewise, how biomass procurement strategies will adjust (or be adjusted by decision makers) in order to a) comply with the mill’s feedstock demands for all core business and new processes; and b) maintain the lowest procurement costs possible so as to contribute to the viability of the biorefinery during all stages of the transition, must also be considered.

2.2 Supply Chain Management

Several authors [45-51] have reviewed and studied the concepts of supply chain (SC) and supply chain management (SCM). Christopher [50] defined supply chains (SC) as a “representation of a network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer”. Put into simpler words by Beamon [52] a supply chain consists of multiple business entities (i.e., suppliers, manufacturers, distributors, and retailers) working together to: (1) acquire raw materials, (2) convert them into specified final products, and (3) deliver these final products to retailers.

Furthermore, supply chain management (SCM) refers to the set of activities, resources, and information needed to plan, source, manufacture, store, sell and deliver products to customers. SC is traditionally characterized by a forward flow of materials, a backward flow of financial resources and ideally, information that flows both forwards and backwards as visualized in Figure 2-2.

An example of a typical biorefinery supply chain (as described in Figure 2-2) for a diverse product portfolio which includes traditional forestry products (e.g. lumber, paper), value added chemicals, as well as energy and fuel products. Supply chains are typically large, complex, very dynamic and involve a constant flow of information, products and funds between different stages with the overall objective of delivering the right product at the right time to the right place at the lowest cost for the greatest value. By accomplishing this overall objective, biorefinery supply chains manage to achieve many goals which benefit all parties involved [46-48, 53]:

- Maximize overall profitability (value preservation)
- Achieve high customer satisfaction levels (value growth)
- Improve product quality
- Reduce total delivered cost (procurement, manufacturing, distribution, inventory levels and holdings costs), and
- Create a sustainable competitive advantage

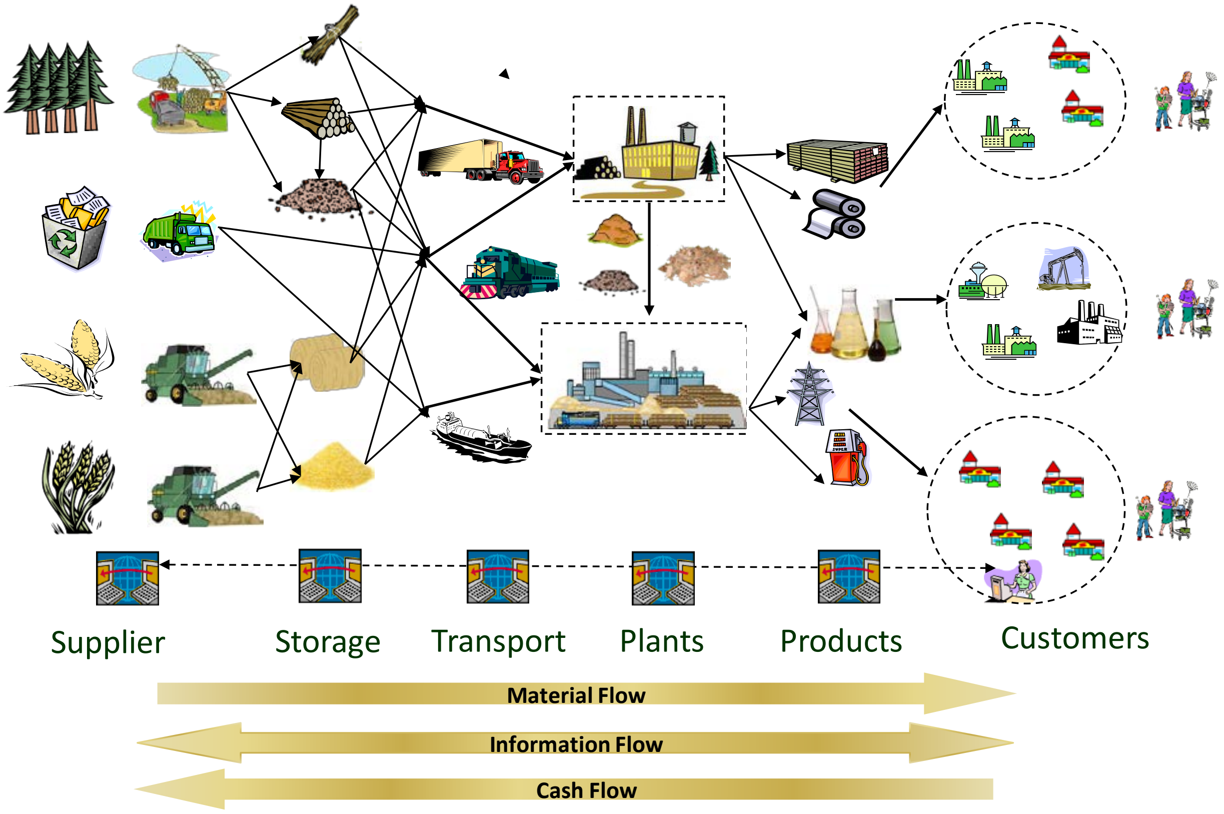

Figure 2-2: Example of a typical biorefinery supply chain

By analyzing industry data trends, Grossmann [45] was able to determine two distinct directions in which most industries were headed. On one hand a large portion of the commodity product industry (e.g. chemicals, petroleum) is seeking to “preserve value”; while on the other hand there are a number of industries (e.g. speciality chemicals, biotechnology and pharmaceuticals) that have great potential for “value growth”. The conclusion reached by the author (Grossmann) is that in order for companies to remain competitive and economically viable, industries seeking to preserve value must carry out enterprise-wide optimizations of their supply chains to reduce costs and inventories, improve operating efficiently and continuously improving their product quality.

Comparing the SCM goals previously mentioned with the example examined by Grossmann, shows why supply chain strategies have become an essential approach in process industries as both seek to maximize profitability by both preserving and increasing value. For most commercial supply chains, value will be strongly correlated to supply chain profitability; and the supply chain’s profitability is considered to be the difference between the revenue generated from the customer and the overall cost of production across the entire supply chain [46]. Thus, the success of a SC should not be measured by the success of the individual business units, but by the success of the SC as a whole.

In addition to the strategic overall SCM objective of maximizing profitability, Stadtler [49] also sees the overall objective of a supply chain as the need to increase competitiveness. This is because in recent years, no single company is solely responsible for the competitiveness of its products and services, it now depends on the supply chain as a whole. Thus competition is no longer between companies, but between supply chains. In order to improve supply chain competitiveness, there are two broad approaches:

- A closer integration and cooperation of the organizations involved seeking long-term benefits for all parties by aligning strategies,
- A better coordination of material, information, and financial flows in order to improve the efficiency of the SC and customer satisfaction.

2.2.1 Supply Chain Design

An initial stage in SCM, supply chain design, (i.e. strategic supply chain network planning) is an exercise where organizations set up long-term strategies and directions in order to make the right investment decisions for resource acquisitions and allocations in order to satisfy market demand. The objectives are usually financially oriented, being either profit maximization or cost minimization, subject to customer service and budget constraints [53]. Decisions taken to meet these objectives will typically fall into one of three decision-making/planning horizons according to the frequency and the time horizon in which they are made [46]. Conducting integrated planning becomes very important because every decision taken in one planning level can have significant impact on other decision levels [47, 54]:

- *Strategic planning* involves high level decision-making that focuses on the design and structure for the development of the organization or SC over the next 5 to 10 years. Decisions made include defining how resources will be allocated, what processes will be continued (core business) or introduced (e.g. biorefining processes) into the business model, location and capacity of production and warehouses, products contained in the product portfolio, transportation and distribution networks, etc. The strategic objectives (or goals) of the organization and the SC must be aligned to improve overall profitability.

Decisions made at this point are done so on a long term basis (typically years), and are not easily changed as they would incur in harsh financial penalties. Consequently organizations need to take into account uncertainty in anticipated market conditions over an extended planning horizon.

- *Tactical Planning* has a planning horizon that ranges anywhere from 6 to 24 months. Following the strategic planning's long term objectives and constraints, the goal is to determine an outline of regular operations, roughly estimating quantities and time frames for the flows and resources. Forecasts for the coming year are made for different markets in order to determine (with acceptable uncertainty) market demand. Organizations will try to incorporate production flexibility[3] into their respective supply chains, and exploit it to optimize performance [55]. This will lead to the definition of operating policies that will govern short-term planning and operations.
- *Operational Planning*: With a planning horizon going from a few days, up to 24 weeks, SC operations focus on handling incoming customer orders in the best possible manner. Inventory and production is allocated to individual orders, completion dates are set, allocation of orders to a particular shipping mode and shipment are made, etc. Because of the very short time frame, there is much less uncertainty of demand information. Given the constraints established by the supply chain configuration and planning policies, the goal during operations planning is to exploit the reduced uncertainty and optimize the actual performance of the supply chain.

All three SC decision/planning levels have an important impact over the profitability, competitiveness and (therefore) success of the organizational SC. There is a strong descending inter-dependency between levels: Strategic defines the supply chain, tactical constrains it, and operational defines the policies which will govern day-to-day operations. However, the inverse inter-dependency is also of importance, as typically the operational level will provide information regarding actual capacity and performance for an established supply chain. Integration of all levels will provide increased benefits which will create a more efficient supply chain.

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[3] Production or manufacturing flexibility is used as a tool to reduce production risk in the face of uncertainty in product market demands. By having a diverse product portfolio that can be produced within an organization's SC, production can be adjusted to meet changing markets.

As previously stated, the design of a supply chain network is a complex task that involves multiple planning and decision levels that all must be aligned with the goals of the company. It also requires comprehensive evaluations covering engineering and financial aspects that usually are specific and differ from one company to another. This is where developed decision support models allow for resolution of supply chain design problems. These models usually involve the use of mathematical programs and dominantly the mixed integer linear programs.

2.2.2 Supply Chain Modeling

The design of biorefinery supply chain networks involves a degree of complexity which is not easily evaluated without the use of decision-support systems (DSS) that can solve these large models involving both engineering and financial aspects specific to each company. With advances in information technology, the application of DSS, such as optimization modeling and simulation, that allow solving very large complex problems with the goal of maximizing overall revenues or minimal costs and risks, has become common in both industry and academia.

In the technical sense, simulation involves using a model to produce results rather than experiment with the real system (that may not exist yet) [56]. Simulation identifies the impact of different variables on the activity (or set of activities) and can also be used to visualize a system process, real-world facility or network [11]. Typically simulation models can be classified into two distinct categories: deterministic and stochastic. Deterministic simulation models usually contain a set of known inputs with no randomness involved. This causes the results to be exactly the same no matter how many times the model is run (assuming no changes in inputs). Stochastic simulation models on the other hand contain a degree of randomness and probability distributions are used to estimate the uncertainty of events [57]. Although simulation models cannot find optimal solutions in complex systems (such as supply chain networks), they can be integrated into optimization models to provide it with the information required to find the optimal solution.

Optimization modeling seeks to find the most cost effective solution (e.g. maximize or minimize a desired output) to carry out an activity (or a set of activities) subject to a set of constraints, by maximizing desirable criteria, and minimizing undesirable ones [11, 58].

Planning, scheduling and control are some of the more common areas in which optimization is used within a supply chain, but their use has become more generic and its common to find optimization of different types in many areas [47, 59].

Kallrath [58] explains that with the exception of very simple cases, optimization problems cannot be solved using simulation as it normally will provide reasonable results, but does not guarantee the solution found will be optimal. Deterministic modeling using heuristic programming can improve upon solutions, however because they may be based on “rules of thumb” they may reach incorrect, or non-optimal solutions. In contrast to this, mathematical optimization methods search directly for an optimal solution and guarantee that the solution satisfies all restrictions of the real world problem. Mathematical representation of a real world problem for optimization will typically consist of four key objects:

- Data or parameters of the model (costs, fixed operating conditions, capacities, etc.)
- Variables representing degrees of freedom (continuous, semi-continuous, binary, integer)
- Constraints or restrictions (mass balances, equality relations, capacity limits, etc.)
- Objective Function (mathematical representation of the goal)

Apart from building the model, a solver is needed. A solver is a set of algorithms implemented capable of solving the model. The mathematical models for optimization can usually be classified in several categories:

- Linear programming (LP)
- Mixed integer linear programming (MILP)
- Nonlinear programming (NLP), and
- Mixed integer nonlinear programming (MINLP)

A typical optimization formulation has the following form [60]:

$$\min_{x,y} f(x,y) \qquad \text{Objective function}$$

$$s.t\begin{cases} h(x,y)=0 & \text{Equality constraint}\\ g(x,y)\leq 0 & \text{Inequality constraint}\\ x\in X \subseteq R^{n} & \text{Continuous variables}\\ y\in Y & \text{Integer or Binary variables}\end{cases}$$

Depending on the level of the SC, i.e. strategic, tactical or operational, the optimization decision variables will provide information to make decisions on a number of different areas [61]:

- Number, size and location of manufacturing sites, warehouses and distribution centres, and the resources inside them
- Production decisions related to plant production planning and scheduling
- Network connectivity (e.g. allocation of suppliers to plants, warehouses to markets, etc.)
- Management of inventory levels and replenishment policies
- Transportation decisions concerning mode of transportation (e.g. road, rail, etc.) and also sizes of material shipments

SC optimization problems are often categorized as mixed integer optimization problems, because they may involve integer variables, and can be in the form of linear or nonlinear mixed integer problems. Most of the real world problems in process industries face with different types of mixed integer optimization.

Computer software programs used to solve optimization models use a set of developed mathematical algorithms to solve optimization problems. These algorithms are continuously being improved upon to increase efficiencies, and allow for resolution of larger problems. A very complete description and explanation of the algorithms used, including the simplex method and the branch and bound method, which is commonly used to solve LP, and MILP models, may be found in Shaprio [47].

2.2.3 Critical Analysis 2

The implementation of biorefinery processes and technologies in a P&P facility is a complex task, associated with risk and uncertainty which will not only affect internal processes, but will also have an effect on the up-stream (as well as the down-stream) supply chain activities that provide biomass materials to the facility. Therefore, different tools must be used to analyze the performance of specific process design changes in the future while at the same time, allow for the evaluation of multiple scenarios.

Advanced mathematical programming techniques such as optimization enable the addressing of SCM aspects of a project. This will allow decision makers to take into consideration several aspects of all three planning/decision horizons (i.e. strategic, tactical and operational) that can have a significant impact over the profitability, competitiveness and (therefore) success of the organizational SC in the current as well as in the future.

2.3 Supply Chain modeling and Biomass Procurement Optimization

Within project management in the forest industry, planning, scheduling and control are some of the more common areas in which optimization is used as shown by Karlsson et al. [62, 63]. Nevertheless, optimization modelling can be found in other decision making levels and application in business supply chains [23, 47]. The general applications of SC optimization and SCM in forestry (and potential for improvement of the forest SC) have been reviewed by Pulkki [64], where he outlined the use of SCM for reviewing the overall procurement supply chain on multiple decision levels and how optimization of operations and processes can improve operational level decisions, without negatively affecting the overall goal [57]. Weintraub & Epstein [65] reviewed more practical applications of optimization in the Chilean forest industry and its supply chain. Several optimization models were applied and to different operations within the SC (from logging operations in the forest to the end of the process at the sawmill, P&P mill or other), and their solutions were then reviewed by the authors.

Frombo et al. [66] used SCM tools in an effort to establish planning and management strategies for procurement of woody biomass for bioenergy. They created an optimization model which was divided into three sub-models to address different kinds of decision problems on all three SCM decision levels: strategic, tactical, and operational. The results they presented focused on the strategic planning level. Decision variables were plant capacity and biomass harvested from a specific site, while the objective function sought to minimize the costs of plant installation, maintenance costs, and biomass procurement costs. A similar study was done by Gan & Smith [67, 68], who sought to minimize the total costs of both the feedstock procurement of logging residues and electricity production in the United States. The method used involved determining the optimal power-plant size and the derivation of supply curves for biomass.

In recent years, supply chain modelling and optimization for biomass procurement systems has received considerable attention from both academia and industry [53, 65, 69, 70]. Results from these studies, such as models and practical case studies, can be used as decision support systems at strategic, tactical and operational levels of supply chain management [46].

Carlsson and Ronnqvist [69] presented the study of the optimization decision methodology in the forestry and P&P industries. The main purpose of this study was to exemplify the practical use of supply chain management (SCM), optimization models and methodologies in the forest industry. It was concluded that in the supply chain context, integrated supply chain planning is needed. This requires advanced planning tools and new technologies to support planning in the complex business supply chain environment.

Beaudoin et al. [44] used a tactical planning model for a multi-facility forestry company to maximize profits (increasing revenues and decreasing operating and transportation costs) by the centralized annual planning of wood allocation for all mills. To carry this out, the model determined which cutblocks were to be harvested each period over a 5 year term taking into account the mill's demand plans and the volume constraints of each forest block. Prices were set as a function of supply volume and freshness. In addition, they also presented the planning process for the development of alternative scenarios using Monte-Carlo analysis and a market demand anticipation system. Their results show how it is possible to manage a fibre flow from stump to end market, however they also show that changes in the input parameters will change the decision on the best implementation scenario. Therefore, the use of tactical models, which can be re-utilized to adapt to changing conditions in order to evaluate alternative scenarios, may be of great benefit for forestry companies. A similar study using a two-stage tactical planning model was carried by Shabani et al. [71] to determine the cost of uncertainty in biomass supply for a bioenergy plant.

D'Amours et al. [72] presented a non-exhaustive literature review paper on the forest industry and applications of operations research. They described the wood fiber flow from forest to customer, examining several areas within the forest industry (e.g. forestry, pulp and paper, lumber, panel and engineered wood and energy supply chains). In addition, they also reviewed studies involving applications of optimization and SC in a wide range of problems, ranging from long-term strategic problems related to forest management or company development to very short-term operational problems, such as planning for real-time log/chip transportation or cutting. The review showed that very little work has been done to link the forest supply chain to the other forest products supply chains (e.g. forestry with P&P or forest residue harvesting), and that integration of the various supply chains is still a major challenge for the industry, which should be the focus of future research work in developing areas within forestry, such as bio-energy and biorefinery research.

2.3.1 Biomass procurement for bioenergy

One of the research areas within forestry that has emerged over the last decades, is the production of renewable energy (bio-energy) made available from materials derived from biological sources (i.e. biomass); with one of the more known applications of this being the co-generation of heat and power (CHP). One of the benefits of CHP production in forestry, is that the production of bio-energy can be integrated into existing facilities or produced in a stand-alone facility; biomass is burned in a boiler to create high-pressure steam, which is then circulated through one or several steam turbines to generate electricity. Afterwards, low pressure steam extracted from the turbines can be used for drying and other heating (or heat exchange) needs of the mill [59, 73, 74]. If the heat or steam needs of the facility are low, the steam may be re-circulated through additional condensing turbines to produce more power. One of the major benefits of cogeneration, is that biomass boilers can use a wide gamut of biomass feedstocks, ranging from forestry and agriculture residues, to municipal solid waste and sludges. Of the properties that must be carefully monitored, moisture content within the incoming biomass is of particular care. A higher moisture content, will reduce the recovered energy and efficiency from said feedstock [74-76]. Drying forest biomass at roadside, or at storage or mill site, enhances the degree of efficiency of combustion, as well as provide significant savings in transportations costs [77].

Another important factor with biomass feedstocks for bioenergy production, is delivered material cost. This is where SCM and OR have been used to improve both quantities, and costs of delivered materials. For example, Hamelinck et al. [77] as well as Uslu et al. [78] evaluated several technologies to densify and reduce moisture content in feedstocks in order to reduce transportation costs.

Transportation costs are one of the major contributors to the cost of delivered biomass feedstocks. Gunnarsson et al. [79] studied supply chain modeling and developed a mixed integer linear programing (MILP) model for the procurement of chipped forest fuel biomass to satisfy the demand from heating plants. In accordance with other forest biomass procurement studies, the authors confirmed that transportation constitutes one of the higher cost activities in the procurement supply chain. In addition, their results showed that contrary to the practice, the optimal solution often suggested the use of mobile chippers and direct transportation of biomass to the heating plants, instead of sending it to an intermediate storage location first.

Flisberg et al. [80] presented a decision support system (DSS) based on a mixed integer programing (MIP) model to address the procurement logistics decision problems of chipped forest biomass, in particular the selection of harvest areas and harvesting systems for the production of forest biomass fuel.

Alam et al. [81] also carried out a study of biomass procurement for a bioenergy plant with the objective of minimizing total biomass procurement costs. Unlike other authors though, their decision support model was based on a combination of a geographic information system (GIS) with a non-linear dynamic programming model which allowed them to minimize procurement costs, while determining wood material flows and costs based on the required energy output of the plant. Similar studies using GIS-based systems and economic models, and transportation system optimization models have been developed by Sultana & Kumar [82], Tittmann et al. [83], and Freppaz et al. [84].

Rauch and Gronalt [85] developed a model for designing a forest fuel CHP plant supply chain in Austria by making decisions about transportation modes and spatial arrangement of terminals. The model was a MILP model with the objective function of minimizing the total procurement cost. Eight scenarios were constructed and compared, where the effect of changes forest fuel supply (domestic resources vs imports), transport modes (truck only, truck and ship, or truck, ship and rail), energy price (increases by 0%, 20% and 40%), and truckload capacity (50%, 40% and 30%) on the overall cost were examined.

Several literature review studies on feedstock procurement supply chains have been carried out over the last decade. Gold and Seuring [86] presented one of the first which reviewed bioenergy studies carried from the year 2000 to 2009, with a broad area of research, including any type of study related to bioenergy, biofuel and biorefinery procurement of biomass and supply chain logistics including both forestry and agricultural sources. Their review focused more on analyzing the amount and types of studies conducted, but also showed that (among other conclusions) most studies focused on two main goals: having a secure, constant supply of material; and reducing procurement costs. Key operational level issues pointed by many authors through the entire biomass procurement supply chain were also examined.

Mafakheri & Nasiri [87] presented a bioenergy literature review in which they evaluated the models created for different operational areas of biomass procurement supply chains: harvesting and collection, pretreatment, storage, transport and energy conversion. In addition, they considered six categories of challenges that could impact the planning and design of biomass procurement supply chains: technical, financial, social, environmental, policy/regulatory and institutional/organizational. They also present recommendations on future work considering challenges they summarized in each category, such as the need for decision models that support biomass technology selection (i.e. harvesting and preprocessing) under changing technological environment, and the need for developing generic frameworks for estimating biomass resource availability and costs. Discrepancies between theoretical models and the existing practices within the biomass industry were another challenge they encountered, recommending the development of models that better represent reality and validation of results with practical case studies instead of just focusing on illustrative numerical examples.

2.3.2 Biomass procurement for Biorefineries

Within the field of study of biorefineries, biofuels and bioproducts, biomass procurement operations are typically included in one of two ways: maximizing the usage of materials at a pre-determined fixed cost within the facility/process to minimize waste, or improve biomass procurement costs by examining the biomass procurement supply chain.

The first method (i.e. maximizing biomass usage within the facility/process) has been used by Laflamme-Mayer [88], and Dansereau [23], among others [55, 89-91]. Typically the facility or process' biomass demands are set up variable in a manufacturing process optimization model that seeks to maximize the total profit by minimizing operational costs. This will lead to maximizing the material usage within the facility/process (efficiency improvement) so as to reduce wasted material and maintain the quantities of biomass demand as low as possible. This method is effective when the model's focus is to optimize operations within the manufacturing process. Biomass analysis becomes of secondary importance, and quantities available and costs set as parameters (i.e. fixed values), and their values can typically be obtained from suppliers. However, because the values supplied are used as fixed parameters within the facility/process model, a reduced overall cost (by optimization methods) of biomass materials supplied has not been carried out. This is where the second method is better suited.

An example of this first method of examining biomass procurement within the context of a biorefinery facility optimization model was done by Ekşioğlu et al. [90] who developed a biorefinery model based on agriculture residues (along with some forest residues) used in Mississippi. The study analyzed the logistical challenges in supplying biomass to a biorefinery and centered on the integration of decision levels (strategic, tactical, and operational). The authors then created a model which focused on determining the number, size, and location of biorefineries according to the resources available within a predetermined area.

The second method of evaluation of biomass operations within biorefining activities, is to improve biomass procurement costs by evaluating the upstream supply chain operations. This includes all activities carried out to harvest, process (e.g. drying, comminution, etc.), and transport biomass materials required by the facility/process. The forest biomass procurement supply chain can then be modeled and optimized, seeking to minimize material procurement costs by analyzing and improving the whole supply network of facilities, equipment, and methods used to gather, process and transport materials to the mill.

This method of reducing biomass procurement costs has been used in the study of biorefineries by Feng et al. [53], who examined the potential opportunities of integrating biorefinery with forest product manufacturing systems to reduce biomass transportation cost and increase biomass utilizations for value-added products. A MIP model was developed for the integrated forest biorefining supply chain design. The optimal decisions on the supply chain configurations, locations, technologies, and capacity options were determined taking into account the various flows of forest products, by-products, energies, fuels, as well as forest and process residues. Due to the size of the problem, practical realistic data collection became an issue. The model was validated using an experimental case. By using an integrated forest biorefining supply chain design approach, the results demonstrated that the existing forest product mills should not be closed, and that the supply chain network should be expanded with the integrated CHP and pellet facilities.

Another example of a biomass procurement supply chain optimization study was carried out by Faulkner [92]. He proposed a MILP model to address both strategic and tactical decisions for the value chain design and management of a biorefinery. The author used a simulation model to generate baskets of products using all available sources of biomass in the case study. The output of the simulation was then used as the input for the MILP model. However, despite biomass abundance (including forest residues) and existence of a robust chemical industry (i.e. potential market), testing the model for three different sizes of integrated biorefinery reported no profitable instance. In order to improve performance of the value chain two options were proposed: using a less expensive mode of transportation (i.e. via pipeline) for delivery of the most profitable product; or shutting down the mill in the non-profitable months to negate the truck transportation cost.

Kim et al. [93] also presented a study on the optimization of a biomass procurement system for the production of biofuels using a MILP model that would determine the number, location and capacity of fuel conversion sites (first to bio-oil, then in a different location to bio-diesel or gasoline), as well as the material flows from field to final customer.

Literature review papers that focus on biofuels and biorefineries exist such as the one carried out by Yue et al. [94] which summarized the findings of many papers in this field that also include optimization modeling at strategic, tactical and operational decision-making horizons, showing that strategic biorefinery design focusing on location and transportations network decisions were the first type of modeling problems to be explored. Afterwards, as more information became available regarding new technologies, additional studies (included in the review paper) began the process of exploring the applications and integration of all these planning levels. The authors then expand on the need for multi-scale modeling and optimization frameworks that would allow to envision from bottom to top (e.g. molecule, process, supply chain, eco-system) all areas of interest for a biorefinery/biofuel supply chain. They also expand on issues (economic, social, environmental) related to modeling of biofuel supply chains.

Sharma et al. [95] also carried out a literature review paper where they analyzed the distinct models that have been used to study the biomass supply chain. They found that of the 32 papers reviewed, a majority of models focused on strategic decisions related to number, location, and capacity of sites, and supply chain network design. Tactical and operational decisions were related to material flow and fleet management (i.e. planning & scheduling). Another important result from this review, is the fact that only three of the review papers studied the delivery of biomass to a single conversion site, and of those systems, none were within the realm of forestry (most dealt with the procurement of energy crops).

Hybrid modeling approaches (between stochastic and deterministic models) can handle uncertainty as well as large-size network problems. The main conclusions drawn from this study affirm that mathematical modeling has been gaining momentum during the last decade, as more and more studies are carried out in this field, focusing firstly on strategic decisions and network planning using MILP with the objective of minimizing costs or maximizing revenues. Almost all the working models are applied to real case situations to show their practicality, and Sharma el al. concluded by determining that future work should focus on developing models for large-scale problems that include uncertainty and sustainability issues.

Another literature review carried out in the field of biomass optimization for bioenergy and bioproducts was done by Cambero et al. [96] to study the body of work done to link the optimization of economic, environmental and social aspects. They found that only a few recent attempts have been made at linking economic (or techno-economic) with environmental issues in an optimization model, and no attempts at measuring or including social aspects. They concluded that aside from the need to create multi-objective optimization models to optimize economic and environmental aspects, additional decision support systems are needed to include social aspects. The development of these tools, was later addressed by the same authors in a subsequent study paper expanding on the development of multi-objective optimization combined with multi-criteria decision support systems [97].

2.3.3 Critical Analysis 3

The use of SCM, and optimization tools for the study of biomass procurement activities has developed considerably over the last few decades, spanning all three decision/planning levels. Initially developed for the improvement of main harvesting activities for current forest product mills (saw and pulp mills). Over time, as additional forest products have developed (e.g. bioenergy, biofuels, etc.) they have also made use of SCM to improve operations. Due to the use of residual biomass materials from forest harvesting, along with many other feedstocks from other industries (e.g. agriculture residues, MSW, etc.), for bioenergy, there has been a particular interest in improving biomass procurement operations; and with the rise in interest (and markets) of biofuels and bioproducts, biorefineries will also seek to use optimization and other modeling tools to improve biomass procurement activities.

In their review, Gold and Seuring [86], indicated the need to continue to improve biomass procurement costs. Modeling tools which support technology selection under a changing technological environment was brought up by Mafakheri & Nasiri [87] as a need to improve biomass procurement operation, and was later explored by Hamelinck et al. [77], Uslu et al. [78], and Gunnarson et al. [70], among others. Going forward, biorefineries will also need to examine ways to improve or reduce operational costs within their biomass supply chain systems as they will influence the economic viability of the overall biorefinery project. Ignoring these aspects may make a project un-feasible as was shown by Faulkner [92]. One aspect that will bring additional cost reductions to biomass procurement activities, which has not been covered by most authors, is the need to be able to model and optimize the integrated harvesting of materials for both the traditional forest industry (saw and P&P mills), as well as for the bioproducts forest industry (bioenergy, biofuels, and biorefining). It is expected that with the integrated harvesting of all forestry products and by-products new cost reductions and supply chain improvement may be found as cost allocations will better distribute the total cost of harvesting activities, over a larger gamut of products.

In addition, authors such as Sharma [95], and Yue et al. [94] have indicated that OR research within the realm of biomass procurement is headed toward the inclusion of more aspects of uncertainty, and risk. There is also development of more models that integrate operational/tactical information with strategic models (i.e. bottom-up) in order to get a complete overview of the entire supply chain, so as to make better decisions.

2.4 Simulation of Biomass Procurement Activities

In order for P&P companies to analyze the important trade-offs between business strategies for feedstock procurement in a timely manner, decision support systems based on systems engineering must be created that produce a simulated re-creation of current biomass procurement operations while estimating overall feedstock costs within a virtual environment. Simulation models identify the impact of different input variables which may change over time (e.g. tree dimensions, forest cutblock composition, harvesting systems, etc.) on the activity (or set of activities) and can also be used to visualize the real world behavior of a supply chain. They also identify and react to problematic areas within the system [11]. At the same time, these models allow companies to re-design supply chains to provide cost reductions in delivered feedstock products while taking into account operational level data that affects tactical and strategic level planning for the entire biomass supply chain (SC).

Optimization models have already been discussed as a successful way of improving biomass procurement operations on multiple planning/decision levels when an optimum solution among all solutions is sought. However, on multiple occasions several authors (e.g. Carlsson & Rönnqvist [69], Beaudoin et al. [44], Shabani et al. [98], Feng et al. [53], Alam et al. [99], and Dems et al. [100]) have expressed how challenging it is to obtain accurate operational and tactical level data from forestry companies to be used to evaluate more realistic problems.

This is where simulation models can be most useful assuming that the simulation models can be “tested” or validated previously. They can provide users with information based on empirical evidence that is not available anywhere else due to a variety of factors: supply chain partners not willing to share information, concerns by a company over the confidentiality and sensitivity of information, or it could be that the information has never been collected in the way the authors require it.

Another reason to use simulation models, is that optimization can often work as a “black box” operation, taking database inputs, “crunching the numbers”, and presenting a solution, without the user understanding the interplay of various factors and how the supply chain network works as a whole [11]. Simulation models walk/step through the details of a process in a controlled, often virtual, environment based on specific rules in order to replicate the way a system works so as to gain a better understanding of the system. Almost always, the simulation model will generate data about the SC system that can be post-processed into meaningful metrics for high-level business analysis or further modeling tools (i.e. optimization models) [101].

The procurement of forest biomass fibre (woodchip fibre as well as residuals) for a P&P mill, is a complex task, that involves a number of different activities and types of equipment for each stage of the process. When procuring biomass, several factors must be taken into account, such as the fact that the specific harvesting operations selected, depend on: the state of biomass on the field (type, size, age, quality, stand species mix, accessibility, etc.), required feedstock end-use properties (moisture content, particle size, contamination ratio, homogeneity) and other physical, biological and social factors (climate, environment, topography, soils, location remoteness or distance to deliver to customers, habitat, harvesting contracts, costs, overheads and other labour constraints). These will all affect the method (and cost) of harvested biomass. When all factors are combined they create a unique procurement route for each harvested area [102, 103].

This combination of multiple factors that affect biomass procurement costs, plus simulation's dynamic and detailed view of a procurement supply chain, make simulation an ideal companion to tactical/strategic optimization modeling. Simulation also makes use of bottom-up methodologies, and cost allocation systems to estimate biomass costs more effectively, as they can form part of the simulation model, without increasing the complexity of an optimization program. A bottom-up approach as defined by Shapiro et al. [47, 51], and LaFlamme-Mayer [88], focuses on creating IT systems able of taking large quantities of lower-level operational data and integrated processes; sorting, analyzing, and grouping them together so that it may be used in higher decision levels (tactical and strategic).

Simulation tools of all types are of common use within the forest industry at all levels of decision-making. Some of the more common activities for which simulation models are used in forestry, are to calculate the potential production of materials from the forest, as well as the flow of those materials to diverse, and typically multiple customers, and the possible interactions between each one of the activities involved in the procurement supply chain and their respective costs.

2.4.1 Modeling biomass procurement costs

Simulation models are often used to calculate the cost of delivering materials from the forest to a particular customer (or set of customers) in order to decide if the total procurement cost for that area/feedstock material is cost-effective. These calculations usually involve looking at both the large supply chain activities (e.g. harvesting, processing, and transportation costs), as well as the individual activity components (harvesting and processing systems used, and transportation vehicles and routes, etc.).

In equipment costing, simulation allows for the economic evaluation of each piece of equipment used within a forest harvesting system. Taking into account capital, operational, labour, and overhead costs, and using standard economic methods[4] [104-106], the cost of using each piece of equipment to extract material from a specific forest cutblock is calculated. Once these equipment costs are known, quantities of materials extracted from the site (i.e. productivity) are used to determine the cost per unit for each material.

The calculation of harvested and delivered biomass costs, is one of the main outputs of many simulation models in the forest industry. This economic information is used by decision makers to compare between alternatives, or to determine if a project is viable or not. Rummer [105] described four basic methods by which forest operations costs are assigned: 1) expert opinion, 2) transaction evidence, 3) accounting and 4) engineering cost analysis. These four methods can also be combined to create better cost estimates according to availability of data, or required output for a decision making process. So, while a basic engineering cost analysis of harvesting equipment or expert opinion might be enough for operational level decisions (e.g. harvest a stand using a particular set of equipment or not), a combination of all the methods described by Rummer [105] might be needed in order to make strategic level decisions that will affect the overall customer's operations (e.g. run an economic cost analysis, that also includes any accounting costs such as administrative costs, where data may be based on previous transactions, and results are revised by experts).

2.4.1.1 Activity-based cost (ABC) accounting

Typically the accounting methods to calculate costs such as the ones described above, use a unit production cost analysis method to allocate all costs to materials produced, including capital, operational, labour and overhead costs. They do this, by assigning costs based on units or volumes of materials produced. However, this method does not differentiate between materials (or products) created using the same equipment (e.g. assuming same quantities produced, a sawlog, would have the same harvesting cost as a fuel log).

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[4] Operational and overhead cost estimates change from one model to another, and according to the specific piece of equipment. This is where having an industrial partner (expert opinion) assisting in the development is of great value, as they have a better understanding of which factors should or should not be included. The better developed these calculations are, the more realistic the final values will be to company estimates.

When dealing with integrated harvesting of conventional (sawlogs, and pulp logs) and non-conventional (fuel logs and forestry residues) materials from the forest, there is a need to differentiate costs on products jointly produced using the same equipment. Therefore, material costs should be made on accurate information about the performance and activities carried out to produce those materials [107]. A more detailed view of the whole process (i.e. harvesting system) and the activities that are generating the costs can be addressed with an activity-based costing (ABC) approach.

The main difference between a traditional cost-accounting systems and ABC, is that the traditional system assumes that products create cost, and therefore all costs (direct and indirect) from the manufacturing process should be allocated evenly according to the measure of units produced. ABC takes a more realistic approach by assuming that activities create cost by consuming resources (e.g. machinery, personnel, facilities and utilities), and cost objects (i.e. materials extracted from the forest and delivered to the customers) create demand for activities. Thus the cost of a final product (i.e. cost object) is dependent on the activities that created it, and not the resources. This allows to show differences in costs when creating multiple products using the same resources (e.g. sawlogs and pulplogs from the same tree, using the same equipment). By taking this approach to the assignment of cost, the accuracy of product cost data is improved, by tracing costs back to the activities from where they originated, for each individual product [107-111]. This new cost information should reveal problems to tackle and opportunities to exploit.

The general ABC methodology as described by Turney [109] is shown in Figure 2-3. It assigns costs to activities via two stages: in the first, resource (e.g. machinery, personnel, etc.) costs are assigned to activities (e.g. movement of materials, felling, forwarding, bucking, etc.) using a cost driver (e.g. number of materials extracted from the forest, number of final products, etc.). In the second stage activity costs are assigned to cost objects (e.g. sawlogs, pulp logs, hogfuel, etc.) by means of an activity driver (labour hours, machine hours, number of cycles).

However there have been some adaptations of the methods in the literature, which all maintain the general stages of ABC, but specify alternative, or additional stages to include in the ABC approach used for a specific case. Tsai [108, 111] applied ABC to the joint manufacturing of multiple products within an illustrative case study, and added an additional intermediate step in the ABC methodology where he assigns activity costs to processes before assigning them to cost objects. This additional step shows how direct costs (fixed machinery costs, labour, etc.) are typically unaffected by ABC as the focus of the method is to assign the indirect costs (overheads, profits, utilities, etc.) to activities, and then these activities to cost objects. The study carried out by Tsai shows that ABC can be used to differentiate products create from joint processing by specifying individual cost drivers for each product, more than just focusing on the quantities of products created. This has the importance that it is directly applicable to forest harvesting activities, with each piece of equipment being a process, that carries out multiple activities to produce the cost objects (e.g. products).

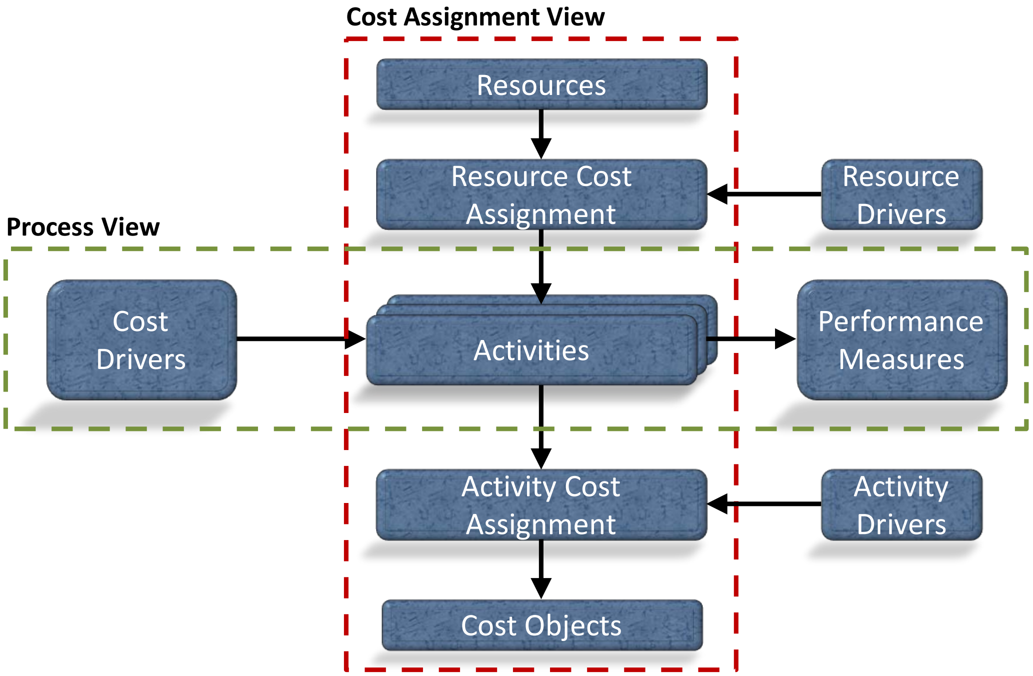

Figure 2-3: The 2 stage ABC methodology viewed from a process or cost perspective[109]

Nurminen et al. [107] included additional steps in the ABC methodology when they applied it to cut-to-length (CTL) harvesting activities. The additional steps included in their analysis have to do with the definition of the scope of the project, required output data, and definition and analysis of resources and activities. Using the ABC methodology, they were able to trace costs back to timber assortments and cutblocks. They showed how applying the method could be used to calculate the efficiency of both an individual activity or the whole logistic system.

Within the forest industry, additional studies that apply ABC methods exist such as Korpunen et al. [112, 113], Laflamme-Mayer et al. [88, 114], and Korbel [115] who have developed ABC models and operations-driven costing methods for various types of facilities in the forest products sector. Results from their works show that the ABC method is applicable for cost predicting and controlling of sawmills, and P&P mills.

Additionally, Hytönen & Stuart [116] used the principals of ABC for product costing in the development of a methodology for enhancing the decision-making process related to strategic investment for retrofit forest biorefinery implementation. Dansereau et al. [117] applied ABC principles to the development of an integrated supply-chain planning framework for decision-making, and then applied it in the integration of biorefinery processes within a newsprint mill.

2.4.2 Application of simulation and optimization models in forestry

Forestry supply chain simulation models have various applications in forestry such as: equipment and harvesting systems[5] comparisons, were done by Wang et al. [119], who used simulation to study operational variables and different types of harvesters in a cut-to-length (CTL) harvesting system, and then compared their harvesting costs and productivities. Their results showed that the harvesting cost and productivity of each machine, is also affected by external conditions such as harvesting site conditions (e.g. tree size). This type of result coincides with findings from other authors [120-122] who also found that harvesting costs vary according to site conditions, and therefore should be taken into account when calculating biomass costs. Dempster et al. [122] as well as Arnosti et al. [121], also used simulation to compare various types of harvesting systems for extraction of biomass (thinnings and residuals) from fire-prone areas. These types of simulation models are of greater use, since, they allow to compare the whole harvesting system for biomass extraction, and allow calculating the overall cost of removing material from each specific site.

Once the material is removed from the site, and loaded onto a truck, simulation models can also be used to calculate the cost of transportation to a specific destination (e.g. the report published by Berwick M and M. Farooq [123]). The same type of cost calculations used for harvesting equipment can also be applied to truck transport [124]: a calculation of capital and operational

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[5] A harvesting system refers to the tools, equipment and machines used to harvest an area. The individual components of the system can be changed without changing the harvesting method. A harvesting method on the other hand, refers to the form in which wood is delivered to the logging access road, and depends on the amount of processing (e.g. delimbing, bucking, barking, chipping) which occurs in the cut-over [118].

costs is carried out, followed by the addition of labour and overheads. Knowing the distance to travel, and assuming a fixed carrying capacity for the trucks (be it by mass or volume), these models can calculate the cost of transport for each material. Changes in distances due to new harvesting areas, or customers, then become dynamic variables which only need to be adjusted to determine the new results.

Another application of simulation models occurs at higher levels of decision-making, where the entire supply chain is evaluated to determine the cost of procuring feedstocks for an identified customer. One simulation model of this nature was developed by Sokhansanj [125], which was originally designed for procurement of agricultural feedstocks, but since then, has been adapted to function and evaluate forestry feedstocks [126]. This study simulated the procurement of biomass for an energy plant from beetle-killed trees. However, its focus was only on the procurement of fuelwood and residues, and therefore only calculated the cost of moving, chipping and transporting these materials to the energy plant without evaluating harvesting costs.

Commercially available simulation/optimization tools in the forest industry vary according to their defined purpose. Some such as Woodstock-Stanley [127, 128], are used for planning and determining quantities of available material for harvest, and are used by provincial governments in Canada for the definition of their sustainable annual allowable cuts (AAC) which predefine the amounts that can be harvested in any particular region by any particular company. Arabi [129] mentions several of these governmental and commercial simulation tools developed in Canada: SYLVA II used by the Quebec Ministry of Natural Resources and Wildlife, HSG Wood Supply, FOREXPERT, Woodstock-Stanley, GISFORMAN, GIS-Complan, Strategic Forest Management Model (SFMM), Patchworks and WPPT .

Other models such as FPInterface^{TM} [130] developed by FPInnovations [131], started with the basics of harvest supply chain, productivity and cost simulation (originally developed as BiOS for biomass harvesting simulation), but since then have been expanded into a suite of integrated products which allow for complete simulation of all aspects of the forest industry. Morneau-Pereira et al. [57] as well as Arabi [129, 132] used two of the models developed by FPInnovations (FPInterface^{TM} and Optitek) as part of a bigger tactical planning optimization (LogiOpt) for lumber production. Simulation was used to carry out as much of the “elementary operations" as possible, and these results were fed to an optimization model which maximized the sawmill's income.

A positive aspect of commercially available models is that the software updates are fairly regular, and increase the model's functionality. However, one challenge many of these commercially available software packages present, is that they are designed to be initially very generic, and must be adapted to each individual supply chain case or harvesting scenario (G. Rix, personal communication, April, 2015). Additionally, in cases such as in the P&P industry and, or when trying to design the integration of new technologies and processes (e.g. biorefineries), due to the specific characteristics in the commercial simulators, it is difficult to use standard planning systems. Hence, there is a need for more tailor-made simulation models, and decision support systems (DSS) [133].

2.4.3 Critical Analysis 4

Previous sections in this study have drawn attention to the uses and applications within the forest industry of optimization modeling to solve problems and obtain optimum solutions, whether they be to maximize profits, or to minimize costs. But optimization, is not without its limits, as has been discussed. Working in many instances as a "black box" without the user understanding how interactions between variables are actually happening. This becomes an issue when results are analyzed, as many times authors do not provide detailed descriptions of all areas of a biomass procurement supply chain, since the optimization models do not provide that level of detail.

Because simulations walkthrough processes and activities, they can present a clear picture to the user of what is actually happening and where interactions are occurring. Simulations can be considered as replicating the "what is" of a biomass procurement supply chain. After "what is" is well understood the next logical step is to ask "what if", both in terms of alternative configurations, as well as for alternative cost allocation systems (ABC modeling), and their impacts on delivered costs. Thus, the true value of simulation modeling as a companion for optimization is in providing a virtual sandbox for doing what-if analyses, which help decision makers identify the impact of different variables within an organization's supply chain when constraints change. After the "what is" and the "what if" have been understood, then it is possible to study the "what's best" question answered by optimization using all the information provided by simulation.

Also a recurring problem found in the literature review, is the fact that researchers have trouble obtaining realistic information from industry due to a number of reasons. This is where simulation models used as companion tools to optimization models tend to provide the best benefits. Because it is possible to simulate all activities with detailed information previous to an optimization, simulation can provide the missing data with reasonable validity, as well as serve as a platform to include uncertainty factors, system dynamics, and alternative scenarios. Studies of this nature have been carried out by Marques et al. [134] who used a combination of optimization and discrete-event simulation modeling to study the inclusion of uncertainty in a P&P mill's feedstock delivery problem.

Looking towards the modeling of integrated harvesting of traditional and non-traditional products that come from the forest, it is evident that there needs to be a clearer understanding of the actual cost structure of each material extracted from a harvested cutblock. Cost allocation, especially indirect costs (i.e. overheads) is not properly addressed by traditional cost allocation systems. Previous studies of ABC applied in the forest industry have shown how it can facilitate a more detailed understanding of activities and processes carried out both in a facility or within the supply chains. In addition, the ability to accurately assign indirect costs to products, as well as trace those costs back to the activities responsible for them allows identification of individual activities which may require change or improvement in order to reduce costs.

Only Nurminen et al. [107] has looked at the application of ABC to harvesting activities, but does not include the study of integrated harvesting of forestry residues, nor do they compare the results of the CTL harvesting system to any others harvesting system (e.g. full-tree harvesting). Therefore including the study of an ABC accounting methodology in a forest harvesting simulation model will not only benefit the study, but will also help expand the knowledge of its applicability to the industry.

2.5 Gaps in the Body of Knowledge

Based on the critical analyses carried out on the literature review, the following gaps in the body of knowledge where identified:

Simulation modeling and Activity-based cost accounting methods

Calculating the costs of procuring biomass for a biorefinery requires a complete understanding of all activities carried throughout the supply chain. It also requires an understanding of how machine costing for each piece of equipment is carried out, which variables most affect these values, and how those costs are then allocated to individual products. This information adds valuable knowledge to a biorefinery transformation strategy. Yet, because biomass procurement is very dependent on lower level operational information regarding the local area conditions (forest), and the existing supply chain network, the best way to calculate their costs, is to design a simulation model based on the existing biomass procurement supply chain.

No study on biomass procurement for a biorefinery has developed a simulation model for biomass costing, capable of determining both quantities and costs of materials extracted from a cutblock and delivered to a biorefinery. Also no current simulation models in forestry have examined the benefits of using ABC accounting methods for calculating material costs, plus the cost traceability that ABC can achieve in order to better account for the source of costs. Commercially available simulations could be used in some instances, however they require detailed data from the case study (which may or may not exist), plus they are not designed to be easily modified or show detailed descriptions of how outputs are calculated (due to their commercial nature); therefore not considered in this study as a viable option.

Due to these aspects, **there is a need for a systematic development of a forest/harvesting simulation model capable of using ABC methods, as well as operational and tactical level information to address the simultaneous (or integrated) harvesting of traditional and non-traditional forestry materials for a biorefinery, that can be modified to reflect changes in decision variables from the supply chain.** The unique decision variables for biorefinery transformation include for example harvesting techniques for different quantities and qualities of biomass demand.

Simulation and Optimization techniques for Biorefinery biomass procurement activities

In the implementation of a biorefinery within and existing pulp and paper mill, it will be critical to improve all areas of the mill including up- and down-stream supply chains as they will influence the economic viability of the overall biorefinery project. Decision makers will be seeking to implement a biorefinery strategy in their mill, and will expect tactical and operational level decisions to be aligned with the strategic goals of the company.

Other industries as well as many areas of the forest industry have already proven the effectiveness of simulation and optimization tools to help improve processes and assist decision-makers by providing scenario-based analyses of alternatives that will reduce costs. Thus the use of these tools in the implementation of a biorefinery is a logical choice, especially in the case of their biomass procurement supply chain networks, which will undoubtedly be changed by the introduction of new processes which will require additional quantities of materials at the lowest costs possible. **Thus there is a need to design tools (i.e. optimization of a simulated biomass procurement network) that can integrate operational and tactical level information (cost data, productivity, harvesting systems, etc.), to evaluate current industry biomass needs and costs, in order to better align all decision levels with the business strategy.**

It is expected that with the integrated harvesting of traditional (e.g. saw and pulp logs) and non-traditional (e.g. fuel logs, forest residues) new cost reductions and supply chain improvements may be found as cost allocations will better distribute the total cost of harvesting activities, over a larger gamut of products. However, few studies in the literature have reviewed integrated harvesting, and even fewer still have applied this to biorefinery feedstock procurement activities.

Thus, **there is a need to study how the changes during a biorefinery implementation strategy will affect the upstream biomass procurement strategy, and how it will adjust (or be adjusted by decision makers) in order to a) comply with the mill's feedstock demands for all core business and new processes; and b) maintain the lowest procurement costs possible so as to contribute to the viability of the biorefinery during all stages of the transition.**

The identified gaps in the body of knowledge may be studied by developing the proper simulation and optimization modeling programs that will work in conjunction to create a virtual supply chain network representative of reality with which to evaluate and compare alternative biorefinery production scenarios. The idea is to use simulation modeling to create a large scale database that contains harvesting cost and productivity data of harvesting forest cutblocks using multiple types of harvesting systems. Having all this information, then the biorefinery will decide how much material of what types it will require in each time period, and the optimization model will supply the necessary amounts according to the optimized selection of harvesting locations.

CHAPTER 3 THEORETICAL AND FIELD CASE STUDIES

3.1 Theoretical research

A comprehensive study of biomass materials, sources, and supply chains was required to develop the necessary decision support systems. Thus before embarking on field research, theoretical studies were carried out in order to develop a basic understanding of biomass procurement supply chains, and the characterization of each component. Understanding the biochemical and chemical make-up of biomass, the differences and similarities between feedstocks of different sources (agriculture, forestry, MSW, etc.), and the variability of these components in each material will improve the pairing of materials to biorefinery processes when designing the biorefinery's biomass procurement supply chain.

Along with the proper knowledge of biomass characteristics, there is also a need to understand the process by which different biomass feedstocks are harvested and converted into what we will call "intermediate materials", transported, and then preprocessed into delivered products[6]. This requires a comprehensive evaluation of the different harvesting systems that are used to procure biomass; the individual pieces of equipment that are used, the combinations of equipment used (i.e. harvesting systems) and the interactions between these systems that affect both the productivity of the harvesting systems and the operating costs which in turn affect the cost of the delivered biomass. An economic analysis of harvesting equipment is also carried out, to determine how costs (e.g. capital, operational, overheads) for harvesting equipment are calculated, and how to allocate those costs to the harvested materials.

With the knowledge of feedstock characteristics and harvesting systems, two case studies were evaluated during the course of this project. The first one, involved the evaluation of an agriculture crop and residues (triticale to be precise), and was in part motivated by interest from the Canadian Triticale Biorefinery Initiative (CTBI). Based mostly on theoretical knowledge along

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[6] It is worth clarifying that the conversion of biomass feedstocks into material products used in the biorefinery or P&P mill main processes are referred to as "preprocessed" since "processed" would refer to the conversion that occurs in the facilities main processes, where materials are converted to: energy, pulp, paper, biofuels, biochemicals, etc. Products is another term used throughout this document to refer to the products of the biomass procurement supply chain, and not the products that would be produced at the biorefinery or P&P mill.

with interviews conducted on members from the CTBI network and farmers, a theoretical agriculture feedstock procurement model was developed with the objective of fulfilling the feedstock demands of a theoretical "greenfield"[7] biorefinery that uses triticale from the local area. The model includes both a feedstock characterization module (tells us how much material is available from the farm), as well as a harvesting and transportation module that indicates the costs of delivering the material to the end customer. Further details regarding the development of this agriculture simulation model, can be found in appendix B along with results and the corresponding published publication. The development of the previously mentioned agriculture simulation model served as a testing platform to determine what the best approach would be to develop a more complex forest/harvesting simulation model.

Along with the literature review already carried out for forestry operations, several months were spent at a case study pulp and paper mill in order to conduct field research into planning and decision-making being carried out within the P&P mill's biomass procurement supply chain and network. Interviews with key personnel from the P&P mill were conducted, as well as from contractors carrying out harvesting operations, thirds parties involved in the supply chain (sawmills and local government), to obtain the best overview of the case study mills operations. Information was also collected from the mill, mostly related to costs and quantities (volumes) of materials extracted from the forest, calculation methods used to determine final delivered biomass prices, and information related to the mill's 2010 biomass demands and costs to use it as the basis year for any validation required once the simulation model was created. However, the focus of the internship was more on understanding the logistics and calculation methods involved in the supply chain, than obtaining data to use in a model. This allows to develop a simulation model to determine any information that could be required in future analyses.

Co-currently to the literature review and field study activities, some commercial simulation models were also evaluated, specifically FPInnovation's FPInterface, to determine whether they could be used to calculate the necessary data and information required by the optimization model and biorefinery scenarios. Several factors influenced the decision not to use these commercial simulation models:

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[7] Greenfield refers to a newly built facility. The alternative is a "brownfield" facility which would be either the refitting or repurposing of an existing facility to produce new products.

1. At the time, this software package was not used for the development of biorefinery simulations, thus it could not be easily adjusted to function for our purposes since information pertaining to biorefinery feedstocks and alternatives was not available.
2. In addition to the previously mentioned, this software package requires a large amount of data pertaining to the forest (i.e. volumes, locations, routes, etc.) to be provided by the case study mill, which was found to be difficult to obtain, and with no assurances that it was in the proper format for the simulation program to read.
3. Commercial software simulation model is "locked": because the simulation model is commercially available to anyone, the program has been secured so that modifications to the system cannot be made easily. This makes the introduction of previously untested harvesting systems, or unused cost allocation methods very difficult to introduce into the program since it involves contacting programmers to determine whether it can be introduced or not. This also makes the viewing of internal calculation methods impossible, since equations, and other heuristics used by the program are not visible to the user.

3.2 Case Study Mill and Forestry Supply Chain

Before continuing with the development of the simulation model, it is important to better understand the case study mill, their biomass procurement supply chain, and the materials and products involved in the supply of materials from the forest to the P&P mill and future biorefinery. Several terms will be used throughout this thesis, which are defined in this section.

3.2.1 The Pulp & Paper Mill

The final destination of the biomass procurement supply chain, is based on an existing pulp and paper (P&P) mill located in eastern Canada. The mill uses two main streams of feedstocks: softwood chips (with a species distribution of 49% spruce and 51% fir) in their thermo-mechanical pulping (TMP) process for the production of pulp and subsequent production of newsprint, with a production capacity of 250,000 metric tonnes of TMP newsprint per year. In addition to their main TMP process lines, the mill uses around 50,000 dry tonnes[8] of hogfuel in a high-moisture biomass boiler, where they burn several different types of biomass feedstocks to offset fuel-oil consumption, and generate the steam required by the mill's process lines. The biomass boiler has a high tolerance for moisture content (up to 70% on dry mass basis) in incoming feedstocks, which allows for very wet materials to be used (e.g. sludge from their waste water treatment tanks, wet bark from legacy piles, etc.). They also have a small co-generation turbine which generates electricity either to use internally, or to sell back to the grid. Any future implementation of biorefinery processes, would be installed here in the P&P mill, alongside with existing pulp and papermaking process lines.

3.2.2 The Forest

The P&P mill leases a large area of boreal forest from the Crown, to supply required feedstocks to its P&P mill. The forest area leased by the P&P mill is divided into several Forest Management Areas (FMA), which are further divided into harvest cutblocks. Each cutblock is unique with different sizes, species, and tree ages, which affect the harvested volumes and assortments. Although the forest areas consists of a mix of softwood and hardwood species, the predominant species are firs and spruces accounting for 90% to 95%. The rest are a mix of hardwood species (beech, birch, aspen, poplar, maple, etc.). Among the softwood species, more fir than spruce are found at the forest cutblocks closer to the mill, with a fir-to-spruce ratio

Figure 3-1: Typical forest cutblock

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[8] Dry tonnes or bone-dry metric tonnes (bdmt) are used throughout the thesis to refer to units of weight of materials and products. However moisture content is taken into consideration. It just varies so much, that it is easier to refer to dry tonnes of materials instead of indicating the moisture content of each source material.

of 65% to 30%. Forest areas farther away from the P&P mill (beyond 300km), tend to have more spruce than fir. The harvesting age for forest cutblocks is approximately 60-80 years. Due to conditions of the forest in and around the P&P mill (e.g. poor soils, colder climate, etc.), harvested trees tend to have smaller height and diameters than in other parts of the country. The diameters-at-breast height (DBH) are usually between 12 cm to 16 cm, and at the time of harvest, the average tree density per hectare can range between 2500 and 5000 trees, varying from tree to tree and cutblock to cutblock.

3.2.3 Biomass Products and Intermediate Materials from the Forest

The two main products from the biomass procurement supply chain delivered to the P&P mill, and the intermediate products from which they are derived, are represented in Figure 3-2. Final products are considered those materials that have been mechanically pre-processed and are ready to be fed into the mill's TMP, biomass boiler, or other biorefinery processes. Intermediate products, are those that have been extracted from the forest, but not yet been preprocessed; thus they include all types of logs which are cut from the trees; as well as forestry residues (branches, bark, and foliage) that have not been comminuted.

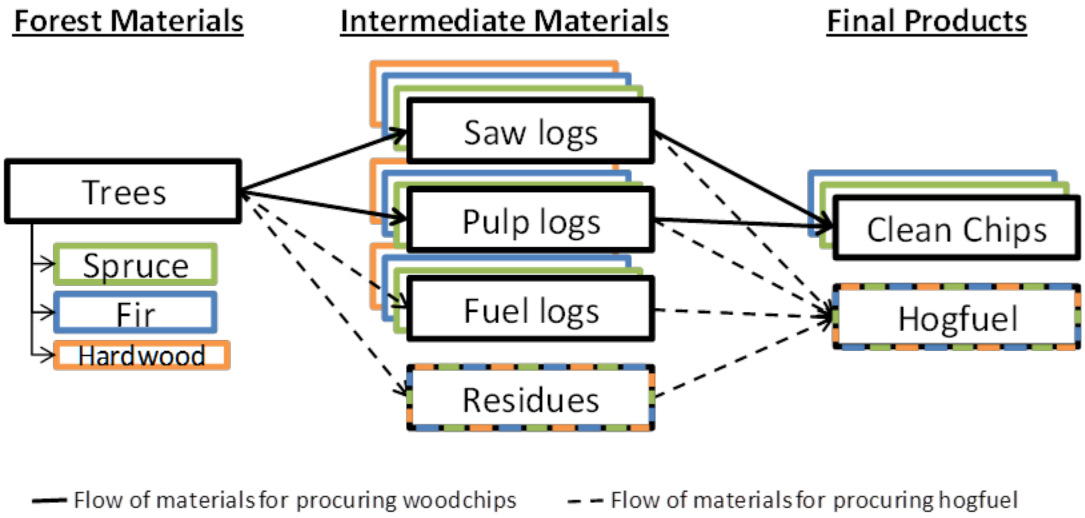

Figure 3-2: Breakdown of materials from whole harvested trees to final products for all species

Figure 3-2 shows that there are two distinct final products delivered to the P&P mill: Clean woodchips for use in the TMP process, and hogfuel for the biomass boiler. Clean woodchips (Figure 3-3), can be further distinguished by wood species, since they are delivered as separate products. Clean hardwood chips are also considered a final product, although currently, there is no need for clean hardwood chips at the mill.

Figure 3-3: Clean softwood chips

Hogfuel material delivered to the mill, is a combination of all the residual feedstocks from all species, that are not used to produce woodchips, as well as residues from the woodchip debarking process and any materials the mill can procure for the purpose of burning in the biomass boiler, some of which are depicted in Figure 3-4:

- bark ("fresh" from dry drum de-barker, wet or dry from sawmills)
- fuel logs: hardwoods, off-spec or damaged logs recovered from the forest,
- sawmill residues that can be purchased or traded
- green forestry residues (branches mixed with foliage).

a) Barks b) Fuel logs c) Sawmill residues d) Mixed sources

Figure 3-4: Hogfuel produced from various forestry sources

a) Saw logs b) Pulp logs c) Fuel logs d) Forestry residues

Figure 3-5: Intermediate materials extracted from the forest

In Figure 3-2, we can see how trees are first converted into intermediate products, and then these are converted into final products. These intermediate products, serve the purpose of facilitating handling and transportation[9]. from the forest, to an intermediate location or final customer, where they can be further processed into chips or hogfuel. Figure 3-5 show examples of each one of the intermediate products extracted from the forest. Saw logs and pulp logs (as their names indicate) are used by different processing facilities (i.e. sawmill and pulp mill). They are the two main (and highest value) products extracted from the forest, with sawlogs typically having more value than pulp logs. Fuel logs on the other hand, are all left over logs that do not meet the requirements to be used as saw or pulp logs (hardwoods, damaged or off-spec logs, etc.). Branches, tops, and any other residual materials are classified as forest residues (figure 3-5d).

Each log type (i.e. saw, pulp or fuel) is determined by the minimum top diameter of each log: sawlogs (minimum diameter of 9 cm); pulp logs (minimum diameter of 5 cm), or any log produced with a minimum diameter below 5 cm is a fuel log (logs that will be used as fuelwood in a boiler). In addition, all logs have an established length for each type of log: 5 m for sawlogs, 2.5 m for pulp logs, and 2.5 m or lower for fuel logs. All the branches, barks and foliage that comes off them are classified as forestry residues. Examples of all intermediate materials are shown in Figure 3-5.

3.2.4 Harvesting Activities

The harvesting operations within the forest, and transfer of materials to customers is carried out by independent contractors/crews which are hired by the P&P mill. Cutblocks, made up of a certain amount of hectares of forest land (between 5 ha and 200 ha), are assigned to each contractor to be harvested. They are in charge of felling, bucking[10], sorting and loading the materials onto the transport trucks. Transportation is usually handled by separate contractors.

Depending on the harvesting system used by the contractor, additional processing activities (i.e. grinding of materials into hogfuel) can be carried out at cutblock roadside, where logs and

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[9] Logs (round wood) have a high bulk density, are easily handled and stacked on trucks which maximizes payload quantities when compared to other forms of the materials: bundles, chips, residues, slash, etc. [135]

[10] Felling is the process of cutting down an individual tree either by hand, or with a piece of equipment. Bucking is the process of cutting felled, de-branched trees into logs of different sizes according to product specifications.

hogfuel are stored until a truck arrives and can be loaded with material. These additional processing activities are usually carried out by contractors as well.

The most commonly used harvesting system by contractors in the area, is the cut-to-length (CTL) method depicted in Figure 3-6. In this method, a harvester goes out into the forest, cuts down the trees (fells), de-branches, buck, and sorts the produced logs at the stump. Afterwards, a forwarder picks up the sorted logs and takes them to roadside, where they can be stored at roadside, placed on trucks or (if damaged) further processed into hogfuel by a mobile grinder. The collection of residues is sometimes carried out by an additional forwarder which collects all dropped residues out in the forest, brings them to roadside, where they are then processed by a mobile grinder into hogfuel that is then placed into a hogfuel truck and sent to the pulp mill for use in the biomass boiler.

Figure 3-6: Cut-to-Length harvesting system with hogfuel grinder at cutblock roadside *(modified image, original courtesy of Forest Energy Portal [136])*

Contractors are free to use whichever harvesting system they feel provides them the best harvesting efficiency. There are many systems to choose from, but in the local area, aside from the CTL system mentioned previously, there are two more systems used: the full-tree (FT) harvesting with roadside processing, and a hybrid system (FB-CTL) that combines elements of the two previously described systems. Selection by each contractor of the harvesting system to use, is mostly based on experience and practical knowledge obtained from running previous generations of equipment, however, they are always willing to try new systems, as long as they can clearly see the benefit it will provide them (both in productivity and profit).

The full-tree (FT) harvesting system depicted in Figure 3-7, uses different harvesting equipment out in the forest than does the CTL system (i.e. CTL uses a harvester and forwarder, whereas the

FT system uses a feller-buncher and skidder), and differentiates itself from the CTL system because it carries out all processing operations at roadside. Initially, a feller-buncher cuts down (fells) the trees, and sets the full trees down in bunches, where a skidder will drag the bunches of trees to cutblock roadside. There, a processor takes care of the de-branching, bucking and sorting activities. Since all processing is taken care of at roadside, logs can be immediately placed on trucks, or stored. In addition, any unwanted trees for chips, branches, and residues are piled at roadside where they can be processed into hogfuel. Because residues are produced at roadside, there is no need for an additional forwarder to collect them as was in the case of the CTL systems. This reduces the overall harvesting cost of these residues, which is advantageous for the mill.

Figure 3-7: Full-tree harvesting system with hogfuel grinder at cutblock roadside *(modified image, original courtesy of Forest Energy Portal [136])*

Figure 3-8: Hybrid harvesting system with hogfuel grinding at cutblock roadside *(modified image, original courtesy of Forest Energy Portal [136])*

The harvesting system depicted in Figure 3-8, combines equipment from both previously mentioned CTL and FT harvesting systems. This hybrid system (FB-CTL) uses a feller-buncher to fell trees, followed by processors to de-branch, buck and sort the trees in the forest.

The combination of feller-buncher with two processors de-bottlenecks the typical CTL harvesting system (the harvester tends to have the lowest productivity of all the equipment used and is the bottleneck in that system), usually allowing for the overall productivity of the harvesting system to increase. Once the processors have created log piles, a forwarder takes the logs to roadside so that they can be loaded on to trucks, or storage. As well as in the original CTL harvesting system, and forwarder may also be used to go to the forest, collect the residues, and bring them to roadside where they can be converted to hogfuel using a mobile grinder.

A fourth harvesting system modeled in this study involves the use of a forwarder with a mobile chipper and collection bin. The harvesting system (Chipper-CTL) that is depicted in Figure 3-9, shows how this equipment reduces the amount of activities carried out to collect residues, and convert them to hogfuel. This system, initially reviewed by Zamora-Cristales [137], is seen as a method of improving the collection of residues from the forest; however, little information is available regarding the economics of the system. Thus, part of what is sought to be accomplished by modeling and evaluating the system, is to determine if its implementation in economically viable or not within and existing harvesting supply chain.

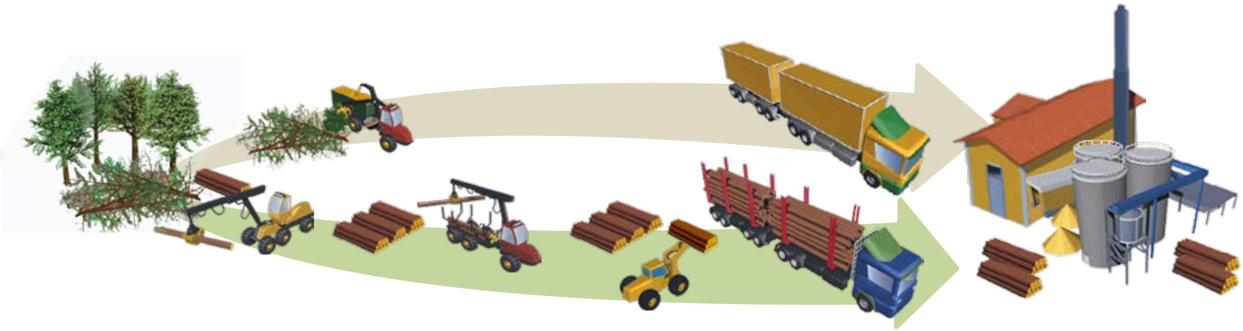


Figure 3-9: CTL harvesting system with forwarder-mounted chipper for hogfuel production in the forest *(modified image, original courtesy of Forest Energy Portal [136])*

3.2.5 Intermediate locations

Within the biomass procurement supply chain, there are a series of locations where forest materials are delivered and converted from intermediate materials (saw, pulp, fuel logs, and residues) to final products (chips and hogfuel). These intermediate locations are shown in Figure 3-10, and can be of four different types:

1. Sawmills: sawmills produce softwood chips and various materials that can be used as hogfuel (e.g. bark, sawdust, shavings, etc.) as a by-products of their sawmilling operations. A mutually beneficial exchange program has been adopted between the P&P mill and these local non-company owned sawmills. There are three sawmills in the local region with which the P&P mill can exchange sawlogs for softwood chips and hogfuel. In this exchange program, the forest harvesting cost and transportation cost of woodchips and hog fuels from sawmills to the P&P mill are incurred by the P&P mill, while the transportation cost of logs from forest to sawmills, as well as preprocessing cost of woodchips and hogfuel are incurred by the sawmills. As is, the cost agreement is beneficial for both parties, as the sawmill receives sawlogs for its process, while removing unwanted by-products from their site, and the P&P mill receives ready-to-use materials at a lower cost due to no preprocessing costs, and a fixed transportation cost (i.e. from sawmill to pulp mill).

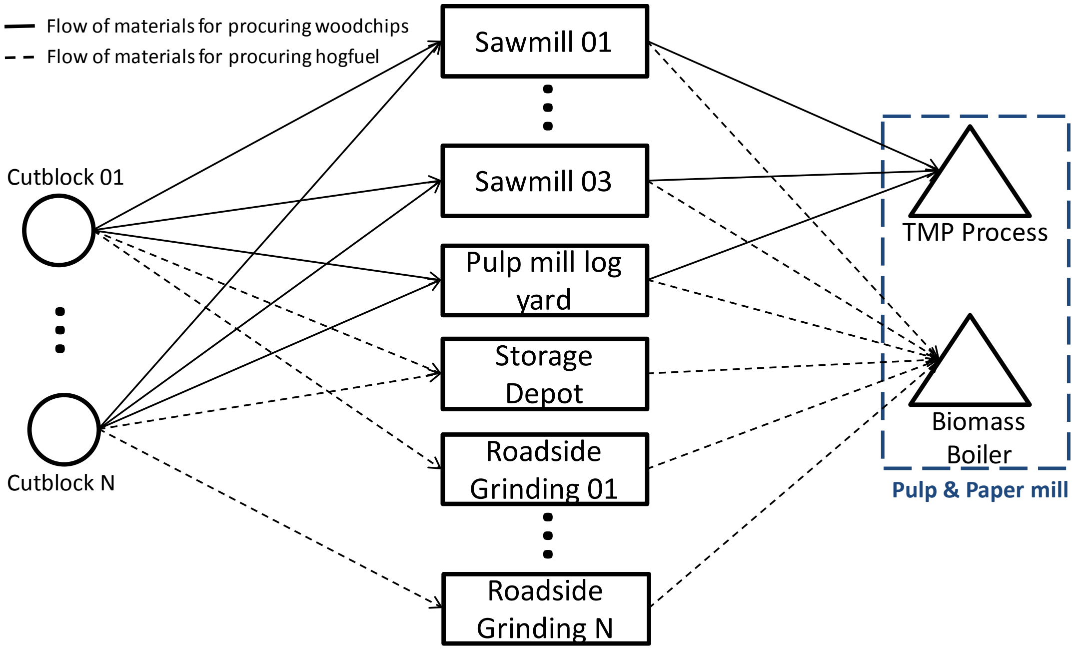


Figure 3-10: Case study mill’s feedstock supply chain with intermediate locations

2. Pulp mill log yard: The P&P mill’s log yard is another intermediate location where pulp logs and sawlogs can be processed into softwood chips and hogfuel. Located right next to the pulp mill, logs are sorted and stored, then when needed by the P&P mill’s TMP process, they are debarked, chipped and sent to the TMP process. Given that the bark produced is considered a by-product of the wood chip production and is consumed internally in the P&P mill biomass

boiler, the preprocessing costs are assigned only to the woodchips, while the bark produced on site is considered “free hogfuel material”. Aside from the by-product bark, no other hogfuel material is produced at this intermediate site.

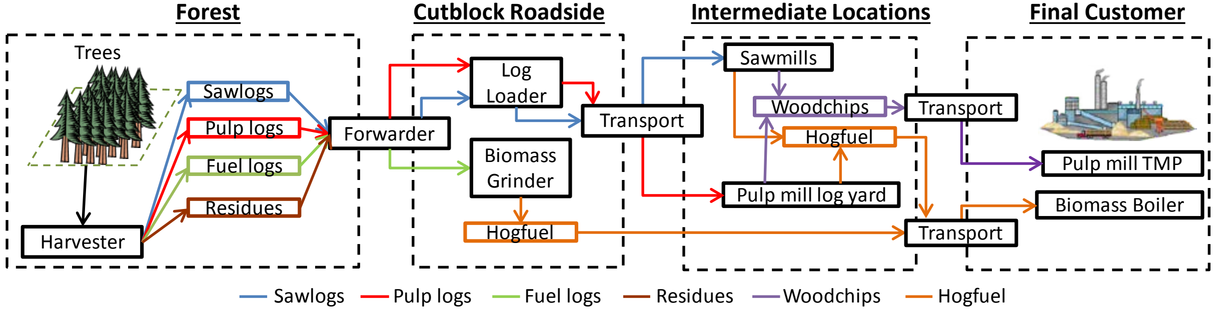
3. Storage depot: Log materials to be processed into hog fuel may be sent to a storage depot, located approximately 50 km away from the P&P mill. Materials delivered here are stored for as long as it is necessary. Upon required, the materials are processed by a large mobile grinder into hogfuels, which are then placed on a truck and delivered to the P&P mill’s biomass boiler. The storage depot is not owned by the P&P mill and the preprocessing costs are higher when this facility is used mainly due to storage and land rental costs, plus additional material handling, loading and unloading costs.
4. Cutblock Roadside: This type of intermediate location used in the supply chain, is also for the conversion of materials into hogfuel. The company owns a mobile grinder (operated by contractors) that can be moved to each cutblock, where forest residues or any log materials can be fed into it to produce hogfuel. Because the grinder can be moved around, in this category of intermediate location, there will be as many roadside locations, as there are cutblocks harvested. The P&P mill has used this method more frequently because they have found a significant cost savings compared to shipping the materials to the storage depot. The drawback of preprocessing materials at roadside is that there currently is only one mobile grinder for all their operations, therefore proper scheduling and planning is needed to optimize the use of the equipment in cutblocks.

With the inclusion of intermediate locations, all feedstocks, harvesting systems, and locations have been described, and are now summarized in Figure 3-11.

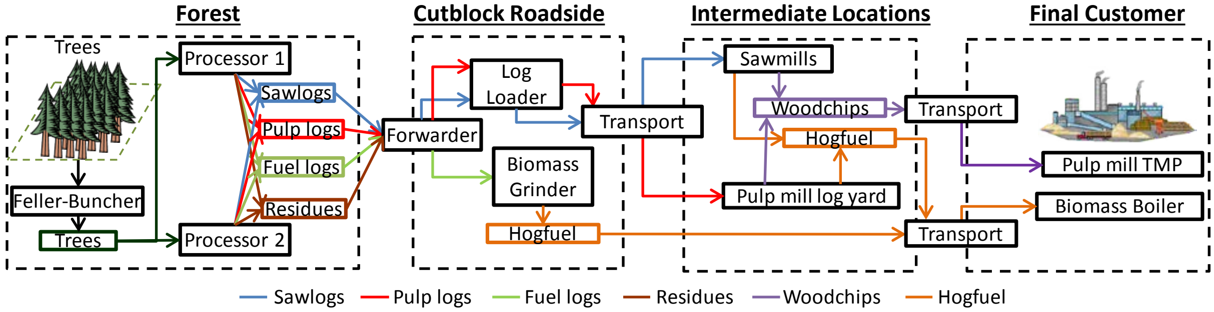
From a business standpoint, the company is seeking alternative processes to incorporate into the P&P mill that will allow it to diversify its product portfolio which up to now has been limited to the production of newsprint, and a small amount of electricity production. The inclusion of new products into their portfolio, may ultimately take over the entire facility, and newsprint production could be phased out. The mill has not explored the timeline of a shift in production like this, nor the implications this would bring to the business model or biomass procurement supply chain. In addition to the changes occurring within the mill, they must also apply changes to the biomass procurement supply chain since in the past, biomass costs in the area have been higher than biomass costs for other company-owned mills. Therefore, maintaining or reducing biomass procurement costs over the biorefinery’s lifespan for the integrated harvesting of both softwood chips and hogfuel products, is a necessary step for the P&P mill.

In current practices, harvesting of softwood chips materials (i.e. spruce and fir sawlogs and pulp logs) and harvesting of hogfuel for the biomass boiler, are carried out separately, and costs associated with the harvesting are always assigned to saw and pulp logs. But if the P&P mill wishes to procure more biomass materials for the production of other bioproducts in a future expansion, the biomass procurement supply chain must be adapted to the changing needs within the facility. This will require the re-evaluation of current harvesting practices in order to determine opportunities for improvement. By comparing harvesting systems to the alternatives listed beforehand, the integrated harvesting of residual materials for hogfuel, the review of cost allocation systems used and comparison to alternatives, as well as the optimization of the whole system to improve overall procurement costs.

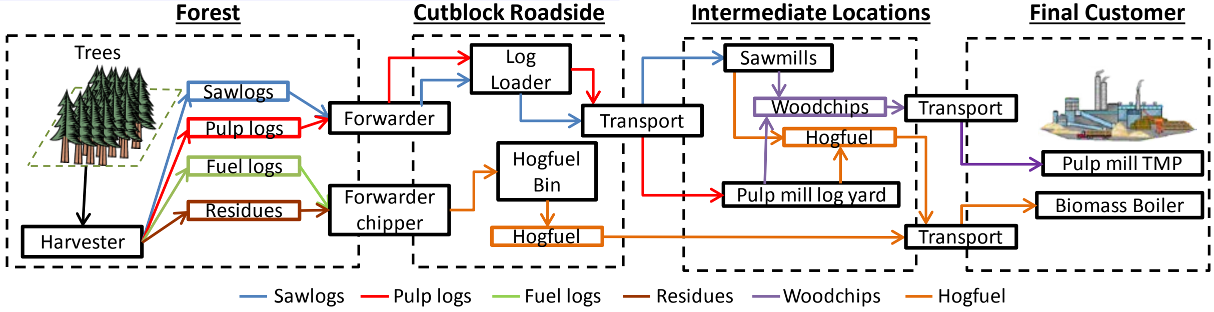
a) Cut-to-Length (CTL)



b) Cut-to-Length with Feller-buncher (FB-CTL)



c) Cut-to-Length with chipper-forwarder (Chipper-CTL)



d) Full-tree harvesting (FT)

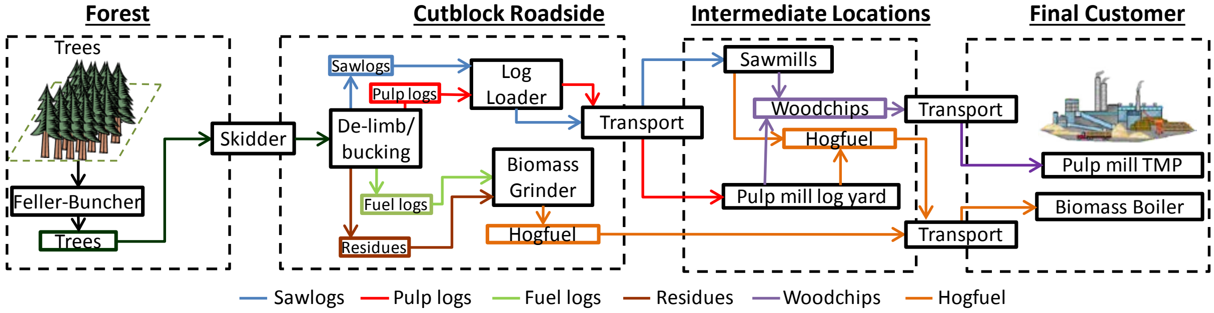


Figure 3-11: Description of forest harvesting systems, supply chain and materials extracted and delivered to the P&P mill

3.3 The Biorefinery Case Study

As Figure 2-1 showed, there are many potential combinations of biorefinery processes/technologies with feedstocks that will produce a wide variety of products. Two main categories of products can be produced: low value, high volume commodity products, and high value, low volume value-added speciality products. The commodity bio-products market typically refers to fuels and in their many chemical make-ups (i.e. ethanol, biodiesel, bio-butanol, etc.) and bioenergy production; whereas the value-added product market tends to remain open to a wide gamut of products that seek to establish their place within current markets either as replacement or substitute products (green chemicals such as bio-ethylene and or polylactic acid) or open new markets for new products (e.g. nanocrystalline cellulose) [59]. Product diversification strategies, can be used to reduce the risk of biorefinery products, as they allow to shift production from one product to another if markets should shift their demands. Thus a combination of both commodity and value-added products from traditional and future biorefinery products may provide the best alternative.

With the need for a diversified product portfolio in mind, there is also a need to make decisions regarding which biorefinery processes and technologies to be use. Three main categories of processes exist by which biomass is processed into usable products: biochemical and thermochemical processing, and chemical separation (also referred to as fractionation).

Biochemical conversion processes typically involve conversion of specific components of biomass (cellulose, hemicellulose, lignin, starch, sugars, oils, lipids, etc.), into usable products (ethanol, methane, hydrogen, carbon dioxide, etc.) by microorganisms. Three main pathways are the most commonly referred to as biochemical processes. These consist of fermentation, digestion (both aerobic and anaerobic) and transesterification.

Thermochemical processing of biomass involves the application of heat to biomass to produce a chemical change, and/or exploit the energy contained in the molecular bonds of the material. Different amounts of heat applied under different conditions (with or without oxygen, high or low pressure, short or long material residence time, etc.), produce different ratios of solid, liquid and gaseous products (i.e. bio-char, bio-oil and syngas). Generally, thermochemical conversion is carried out by 3 distinct processes: combustion, pyrolysis and gasification; however, other processes include liquefaction that applies heat and pressure to a mix of solids and liquids [138], and torrefaction which applied a steady low amount of heat to solid materials in order to convert them to bio-char.

Chemical separation or fractionation processes typically combine both physical and chemical treatments of biomass to separate them into their individual biochemical components. In many cases chemical and or physical separations are used before or after a biochemical or thermochemical process in order to generate additional products from the same biomass (e.g. value prior to pulping, organic or ionic solvent pulping or lignin precipitation).

Of the three main categories of biorefinery processes mentioned beforehand, the biochemical process has been the least used within the forest industry due to the recalcitrant nature of wood toward its separation by microorganisms. In addition, other agriculture feedstocks (i.e. corn, wheat, sugarcane, etc.) where found to be better suited for the production of 1st generation biofuels using biochemical processes. However, over the past 7-10 years, renewed interest has arisen for the use of biochemical processes with wood; research efforts have developed processes and enzymes to facilitate the conversion facilities are now starting to produce multiple products from wood materials.

The other two categories of biorefinery processes, have been more closely linked with the P&P and forest industry, as they have been widely used. The traditional thermochemical combustion process has been used since the very beginning for the production of steam, and chemical separation processes are abundant with the P&P industry (e.g. Kraft, soda, acid sulphite pulping processes, etc.).

Using the information on the subjects of biorefinery products and processes and knowing the biomass procurement supply chain they have in place, a series of discussions were carried out with both academics and mill personnel. Determining which biorefinery technologies would be of interest to research, both for academic purposes (e.g. new un-test technologies with potential marketable products), as well as their potential for implementation (i.e. economic viability). One thermochemical (Fast pyrolysis) and one chemical separation process (Organic solvent pulping) were selected to be further developed, and linked to the feedstock procurement supply chain in order to develop a series of biorefinery implementation scenarios linked to the feedstock procurement supply chain.

Fast pyrolysis involves the rapid heating of biomass with heating rates usually around 300°C/min [139]. At these heating rates, biomass decomposes to generate mostly vapours and aerosols which have very low residence time in the reactor, and are cooled within a few seconds of formation. The rapid heating, extraction and quenching of condensable gases halt thermal decomposition of predominantly liquid products. After cooling and condensation, a dark brown liquid is formed which has a heating value of around half that of conventional fuel oil [140, 141]. The bio-oil produced, in the initial biorefinery project, will be used as a fuel oil substitute, (low value, high volume product). However, it may be upgraded via several physical and chemical processes to produce fuels (e.g. hot gas filtration, hydro-treating, catalytic vapor cracking, etc. [142]) or several chemicals such as calcium salts, furfural, acetic or propionic acids [143]. Because fast pyrolysis involves the decomposition of biomass via thermal degradation, the process is less sensitive to changes in biomass feedstocks, and can be considered feedstock flexible. This will allow for the study of scenarios which can feed either woodchips, hogfuel or a combination of both materials to the process. The pyrolysis unit used in the study is assumed to be able to consume 400 tonnes-per-day (tpd) of dry input materials. Thus if a larger production rate is required, a secondary 400 tpd unit would be installed.

Organic solvent pulping (also known as organosolv), is a process by which lignin and hemicelluloses are separated from cellulose with the use of an organic solvent (or their aqueous solution) such as ethanol under high temperature and pressure (200°C and 2.7 MPa) [26, 144]. A schematic representation of the organosolv process is presented in Figure 3-12. The organic solvent can then be recycled back into the process, and all three components can be used to produce multiple value added products. Cellulose and C_6 sugars from hemicellulose can be used to produce bio-fuels, C_5 sugars from hemicellulose are used to produce chemicals such as furfural, acetic and formic acids, while lignin can be dried and sold as a solid fuel, or a value added chemical [23]. Although the process has significantly higher yields when used with hardwoods, the use with softwood feedstocks has been studied out by other researchers [26], and shown to be viable process. Chemical separation processes such as the organosolv process , tend to be less feedstock flexible than their thermochemical alternatives. Solvent concentrations, temperature and pressure conditions are set to function for specific types of feedstocks, and therefore are sensitive to changes in incoming materials and potential contaminants. Because of this, when designing the organosolv scenarios, woodchips (both hardwood and softwood) are used as feedstock for this process. Because the use of hardwoods is more common with the organosolv process, initially a smaller 100 tpd material infeed demonstration scale[11] plant would be installed at our case study mill. Using this demonstration scale plant, it is assumed that an adaptation of the process to softwoods at a commercial scale will be possible within a 5-year period, and at that time, a much larger 1000 tpd process plant would be installed.

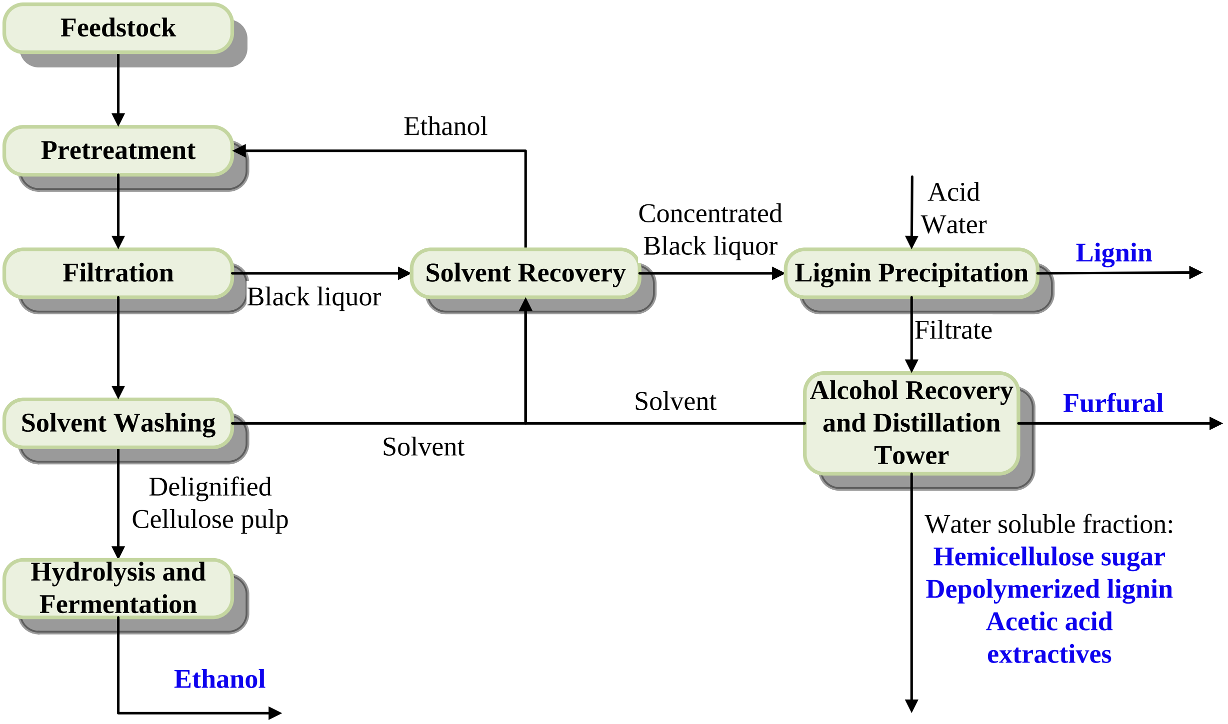


Figure 3-12: Schematic representation of the organosolv extraction process with co-product recovery (*based on Pan et al. [26] and Zhao et al.* [144])

This chapter, introduced the reader to the main case studies used in the PhD to develop the decision support systems (optimization and simulation models), as well as introduce specific terminology used in this project. In addition, it also reviewed the biorefinery technologies that would be used to create the biorefinery implementation scenarios along with their biomass procurement supply chain. The next chapter, will describe the methodology followed.

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[11] Demonstration scale plants typically are about one-tenth the size of a commercial scale plant. Their equipment and process flowsheets much more resemble the final commercial scale plant than a pilot plants does. Sizable amounts of products are produced, and these facilities are usually used to test and improve the process before making a final decision to go to full commercial scale [145].

CHAPTER 4 OVERALL METHODOLOGICAL APPROACH

A systematic methodology has been used in this study to pursue the overall objective of comparing biorefinery implementation scenarios with optimized biomass procurement strategies which result in reduced feedstock procurement costs, such that, they satisfy the facility's feedstock quantity and quality requirements and are economically viable for a forestry company in a competitive market.

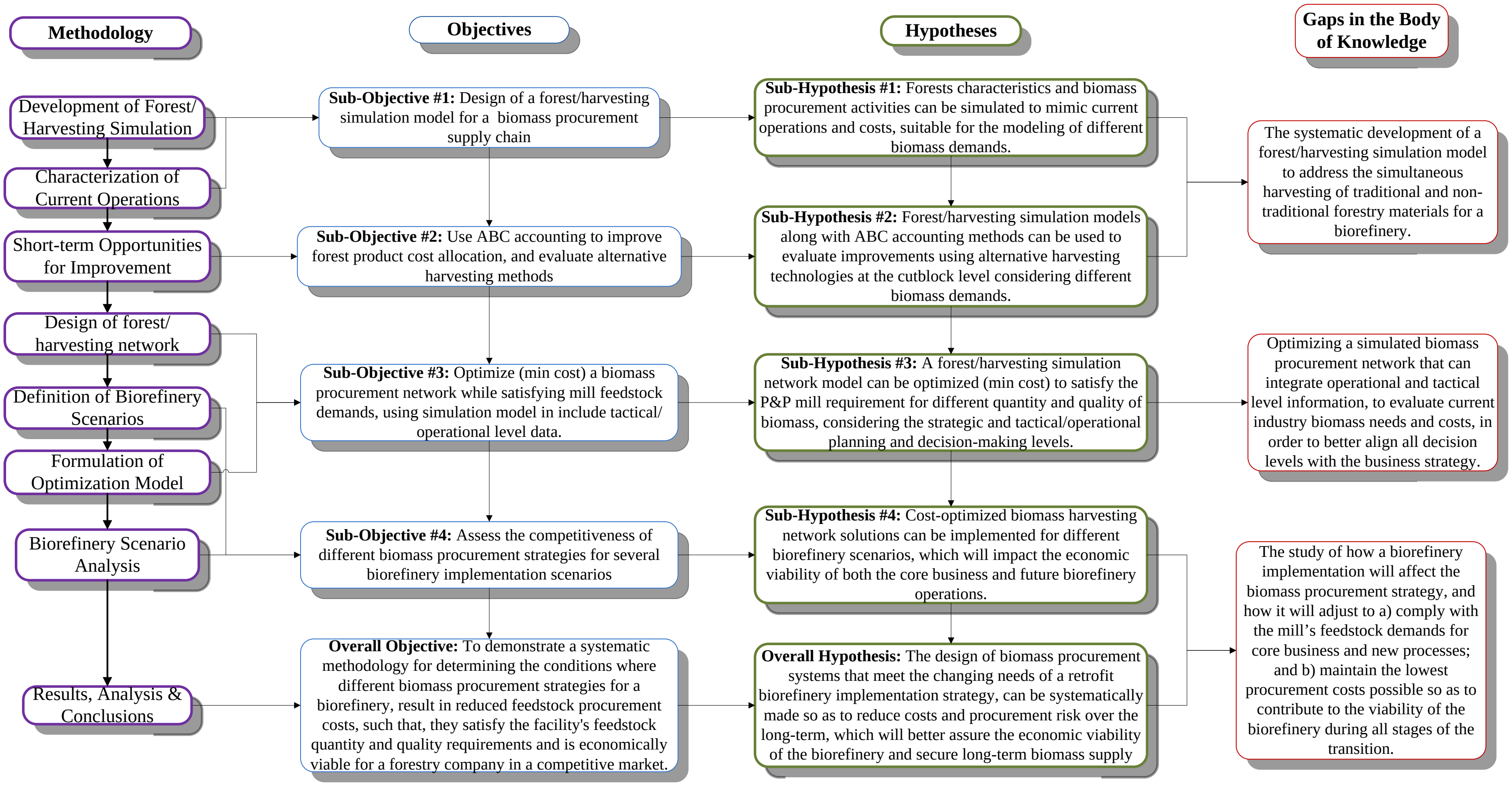
The project was carried out using the scientific method. Initial observations from an industrial problem explained in chapter 1 of the thesis helped develop the required research questions for the project, which in turn gave way to the main hypothesis of the project. After the main hypothesis was determined, the sub-hypotheses were developed which in turn gave way to both the objectives and the experiments required to support or reject them. These experiments, included the development of the decision-support tools needed and their application for the scenario analysis. Once the experiments were run, and the appropriate analyses were conducted. Quantitative analyses of results were used to make comparisons of multiple procurement strategies, under different biorefinery scenarios. Afterwards, conclusions were drawn to support or reject the stated sub-hypotheses, and main hypothesis of the project.

To analyze each biorefinery scenario, and the impact that biomass procurement strategies have on their overall economic viability, two main decision support systems were developed using a systematic methodology in quantitative research. These decision support systems (i.e. simulation and optimization models) were developed based on the describe case study pulp and paper (P&P) mill and its biomass procurement supply chain, as well as the biorefinery technologies explained in section 3.3. In addition, data provided by the case study mill regarding current operations and biomass costs were used to not only model, but also validate any calculations carried out during the process.

The first is a forest harvesting simulation model that will re-create individual forest cutblocks and the harvesting activities that extract materials and deliver them to the P&P mill or biorefinery (in the last stage of this methodology). The second is an optimization model that will use the information provided by the simulation model (for multiple cutblocks harvested with multiple harvesting systems), to optimize (minimize costs) a simulated forest supply chain network (including forest cutblocks, sawmills, storage depot, roadside processing stations, and the pulp and paper mill) and determine the best procurement strategy to use for a set biorefinery process implemented in an existing P&P mill over the designed life-span of the mill (set at 20 years).

The links between each stage of the methodology and the sub-objectives, sub-hypotheses and gaps in the body of knowledge are described in Figure 4-1. Each stage in the methodology is developed to be part of a sub-objective which needs to be accomplished before proceeding to the next stage (e.g. the simulation model must be developed previous to the development of the optimization so that the multiple cutblocks of the biomass procurement network can be created and input into the database which will feed the optimization model). Thus in order to prove the overall objective, each sub-objective (and sub-hypothesis) must be proven in the determined order according to the systematic methodology used in the study.

The following sub-sections further describe each step of the overall methodology. Figure 4-2 shows the methodology along with the different components or activities of each stage.



Sub-Objective #1: Design of a forest/harvesting simulation model for a biomass procurement supply chain

Sub-Objective #2: Use ABC accounting to improve forest product cost allocation, and evaluate alternative harvesting methods

Sub-Objective #3: Optimize (min cost) a biomass procurement network while satisfying mill feedstock demands, using simulation model in include tactical/ operational level data.

Sub-Objective #4: Assess the competitiveness of different biomass procurement strategies for several biorefinery implementation scenarios

Overall Objective: To demonstrate a systematic methodology for determining the conditions where different biomass procurement strategies for a biorefinery, result in reduced feedstock procurement costs, such that, they satisfy the facility's feedstock quantity and quality requirements and is economically viable for a forestry company in a competitive market.

Sub-Hypothesis #1: Forests characteristics and biomass procurement activities can be simulated to mimic current operations and costs, suitable for the modeling of different biomass demands.

Sub-Hypothesis #2: Forest/harvesting simulation models along with ABC accounting methods can be used to evaluate improvements using alternative harvesting technologies at the cutblock level considering different biomass demands.

Sub-Hypothesis #3: A forest/harvesting simulation network model can be optimized (min cost) to satisfy the P&P mill requirement for different quantity and quality of biomass, considering the strategic and tactical/operational planning and decision-making levels.

Sub-Hypothesis #4: Cost-optimized biomass harvesting network solutions can be implemented for different biorefinery scenarios, which will impact the economic viability of both the core business and future biorefinery operations.

Overall Hypothesis: The design of biomass procurement systems that meet the changing needs of a retrofit biorefinery implementation strategy, can be systematically made so as to reduce costs and procurement risk over the long-term, which will better assure the economic viability of the biorefinery and secure long-term biomass supply

The systematic development of a forest/harvesting simulation model to address the simultaneous harvesting of traditional and non-traditional forestry materials for a biorefinery.

Optimizing a simulated biomass procurement network that can integrate operational and tactical level information, to evaluate current industry biomass needs and costs, in order to better align all decision levels with the business strategy.

The study of how a biorefinery implementation will affect the biomass procurement strategy, and how it will adjust to a) comply with the mill's feedstock demands for core business and new processes; and b) maintain the lowest procurement costs possible so as to contribute to the viability of the biorefinery during all stages of the transition.

Figure 4-1: General methodology with links to project objectives, hypotheses and gaps in the body of knowledge.

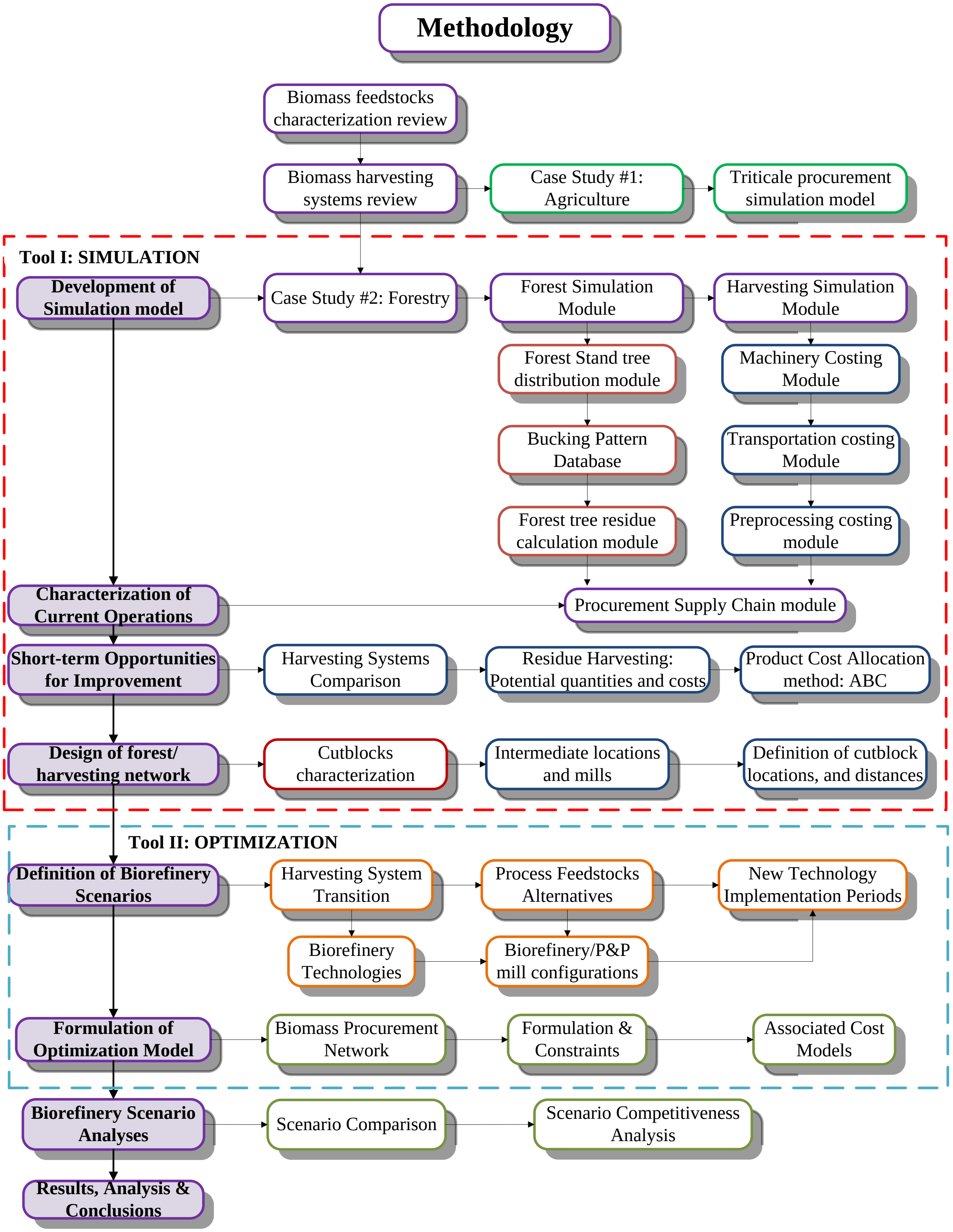


Figure 4-2: Descriptive methodology of all activities carried out throughout the study

4.1 Development of the Forest/Harvesting Simulation Model

The deterministic simulation model created is separated into two main components. One that handles the simulation of the forest for calculating quantities and types of materials and products extracted. The other component of the model calculates the costs of running each piece of equipment and the total costs of running each harvesting system analyzed. A general overview of each component is given in the following sections.

4.1.1 Component 1: The Forest simulation

The forest simulation model essentially creates a virtual forest within the program. The simulation model recreates one hectare of forest land so as to define the characteristics of that particular cutblock, and then can be up-scaled to whichever size the user needs. Each hectare of forest, is populated with a random set of trees of different heights, diameters[12], and species according to limits set by the user.

Once the forest has been created each tree is separated into different log products (i.e. intermediate materials) and recorded into a bucking database created by the simulation model. The simulation applies various bucking rules created to separate trees into the 3 log intermediate materials (i.e. saw, pulp and fuel logs[13]) and residues (branches and foliage) by measuring diameter every 2.5 meters from the bottom upwards, and then deciding at what length (every 2.5, or 5m) to cut the tree to produce an intermediate log material. The bucking simulator assumes that the optimum separation of products involves maximum production of sawlogs, followed by the production of pulp logs, and finally fuel logs. What this implies is that whenever a tree section meets the requirements to be converted into a sawlogs (length and diameter), it will be, by the model. Otherwise, the model will cut the section into pulp logs if it meets the length and diameter requirements; or into fuel logs as a last product.

The bucking database repeats this tree breakdown into intermediate materials for every height and tree diameter combination possible within the user specified limits for trees grown in the

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[12] Tree diameters are always specified as diameter at-breast height (DBH).

[13] Each limit of height and diameter for each intermediate log product is defined by the user.

local area (heights between 8 m and 17 m; and diameters between 8 cm and 16 cm[14]). With the breakdown of trees of different heights and diameters into intermediate materials (data stored in the bucking database), the model proceeds to calculate the breakdown of every tree on the hectare of land, then summarizes all the material quantities according to type of intermediate material and tree species (outputs of the simulation model). The model presents quantitative results in dry tonnes (bdmt), but can be converted to volumetric units if necessary.

Residues are also quantified for the entire cutblock separated into branches and foliage (leaves and needles), but mixed within the different species, since it is highly unlikely that the residues of a specific tree species will be collected and used individually. In order to keep residue collection sustainable and allow for the recycling of nutrients back into the soil, all foliage material is assumed to be left behind in the forest.

Considerations of site soil quality and nutrient recycling for sustainable residue removal, suggest that removal of foliage (leaves and needles) from the harvest site not be done [67], therefore the model assumes all the foliage material is left behind. In addition to the foliage left behind, other authors [68] have suggested that there is about a 30% of forestry residues that should not be recovered because they are economically non-viable (i.e. too expensive to pick up every single branch on a cutblock), or mechanically not recoverable (i.e. the equipment doing the collection cannot recover all the branches on the site). Therefore in our model, there is an additional 30% of branches that is also assumed to be left behind.

Outputs of this portion of the model include all the classified quantities of all intermediate materials extracted from the designed forest.

4.1.2 Component 2: Harvesting Simulation and Costing Model

The second component of the simulation model focuses on calculating the cost of operating the equipment and harvesting systems necessary to extract intermediate materials from the forest, bring them to roadside where they are preprocessed or mounted onto trucks. Then it calculates the cost of transporting those materials to the intermediate locations and subsequent transport to the final destination (i.e. P&P mill/biorefinery); and calculates the costs involved with

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[14] Heights and diameter limits based on average cutting heights and DBH for class 3 and 4 softwood trees in the local area specified by mill personnel.

preprocessing to obtain the final products (i.e. woodchips and hogfuel). Calculation of individual equipment costs include capital, operational and overhead costs for all equipment, as well as the overheads for the harvesting systems (e.g. the use of trailers to transport all equipment from one location to another; contractor administrative costs, etc.)

Data for capital, operational and overhead costs for all machinery as well as labour costs, and averaged yearly productivity values for currently used machinery was provided by the P&P mill. Data for equipment not currently used was obtained from distributer websites [146], and other academic or commercial sources [122, 147].

In the machinery costing component of the simulation, the individual costs for each piece of equipment (e.g. harvester, forwarder, log loader, feller-buncher, hogfuel grinder, etc.) are calculated as exemplified in Figure 4-3. Costs included are capital (cost of ownership of the equipment), operational (labour, repairs, etc.) and overhead costs. Individual machine costs, are then aggregated into harvesting systems to calculate the total cost of running all the equipment in unison[15], for a single cutblock.

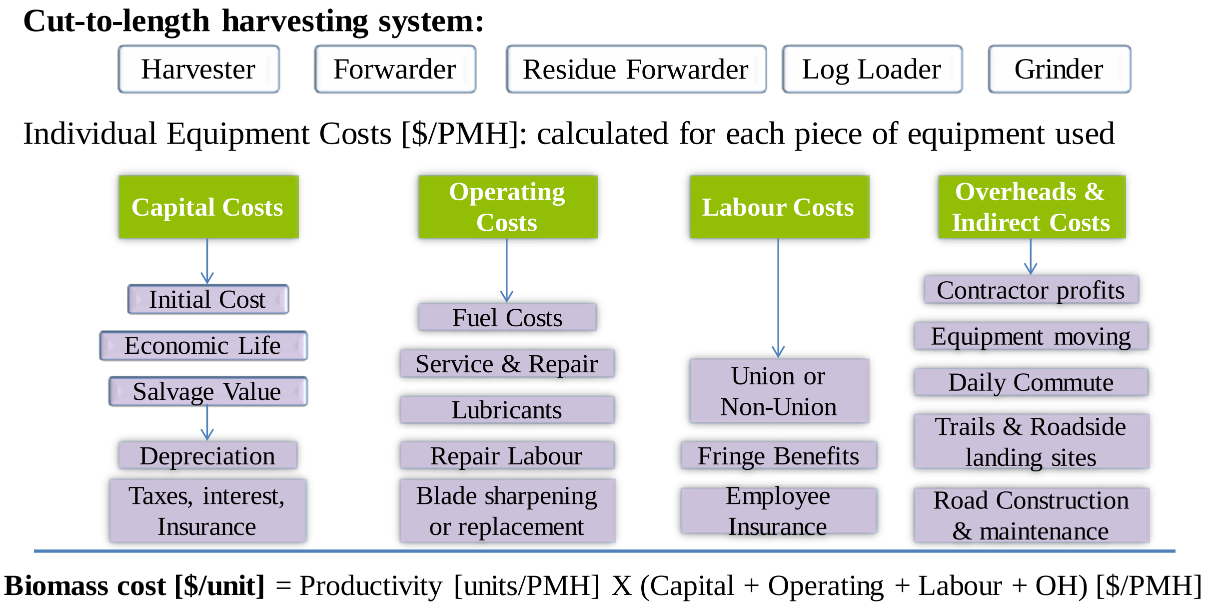

Figure 4-3: Biomass costing of machinery used to harvest using a CTL harvesting system

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[15] Costs at this point are expressed in units of $/bdmt of material extracted.

The transportation costing module, calculates the costs of transporting each type of intermediate material to the intermediate locations for further processing, or the transport of products to the final destination.

Figure 4-4 shows that a similar methodology as the one used to calculate machinery costs (i.e. using capital, operational, labour and overheads), was used in the transportation module. After calculating the truck and trailer fixed (capital) and variable (operational, labour, overheads) costs, and knowing the maximum carrying capacity for each type of truck and trailer (log, chip or hogfuel trailer), plus knowing the distance to travel from the forest to each intermediate location, and assuming that the truck will travel at the maximum speed of 80km/h on highways and 40km/h on rural roads, it is possible to calculate the cost of transportation for each unit (i.e. bdmt or m^3) of material delivered.

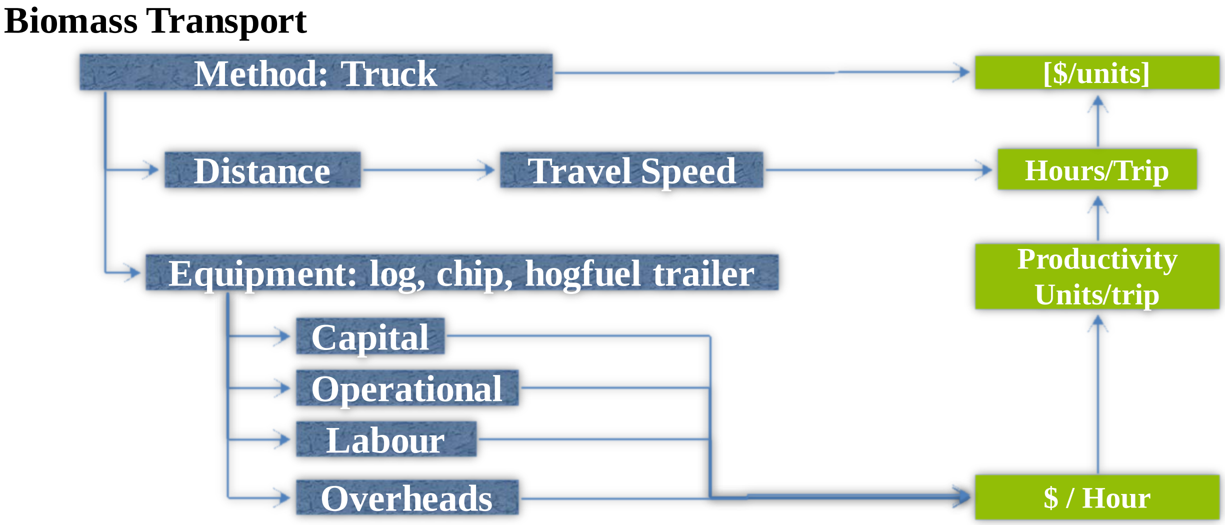

Figure 4-4: Biomass transport costing using trucks to deliver all materials to P&P mill.

Preprocessing costs of converting intermediate materials into woodchips and hogfuel are calculated according to the location where they are carried out. At the sawmills, woodchips are produced as a by-product of their sawmilling operations, and because the pulp mill is exchanging equal quantities of sawlogs to woodchips, there is no preprocessing cost for these chips. Hogfuel has no preprocessing cost either, however a $5/dry tonne surcharge was accorded by both parties (sawmill and pulp mill) to cover loading and unloading costs. At the pulp mill, preprocessing costs are calculated using the standard techno-economic analysis for equipment and activities (i.e. debarking, washing, chipping) used to prepare materials for the process. Hogfuel grinding at the storage depot and out at forest roadside using the mobile grinder are also calculated using a machine cost analysis as those done for other equipment in harvesting operations. The cost calculations for the hogfuel grinder, include the use of additional equipment i.e. a material handler to load material onto the grinder, and a bulldozer to load hogged material onto the truck. Information regarding the capital, operational and labor costs for both the mobile grinder and equipment at the P&P mill cannot be specified in this thesis due to a non-disclosure agreement signed with the case study mill.

4.2 Characterization of current forest harvesting operations

The next step in the process was to use the designed simulation to model the current biomass procurement supply chain for extraction of material from a single test cutblock, and calculate the cost and quantities of the intermediate materials and final products coming from different intermediate locations:

- Woodchips and hogfuel from sawlogs: Woodchips and hogfuel procured from the sawmill, exchanged for harvested sawlogs
- Materials from pulp logs: Woodchips and hogfuel produced at the P&P mill’s log yard
- Hogfuel procured from the storage depot from material delivered there
- Hogfuel produced at cutblock roadside and delivered straight to the P&P mill

The test cutblock and supply chain along with their respective distances from one another are shown in Figure 4-5 and details regarding the input information used to model the test case forest cutblock are given in Table 4.1.

Once the current biomass procurement supply chain has been simulated, it can be used to determine whether or not the simulation model is behaving properly with respect to the real case study mill. This is done by verifying output information (such as products costs), with values provided by the case study mill for their procurement operations. This data will then be used to validate the model. Furthermore, the validated simulation model of an actual procurement supply chain can then be used to extrapolate (simulate) the output of different procurement strategies from different forest areas (changes in heights, dbh, species mix, etc.). By accomplishing the task of simulating a forest/harvesting biomass procurement network for the P&P mill, the first sub-objective of our study will be completed.

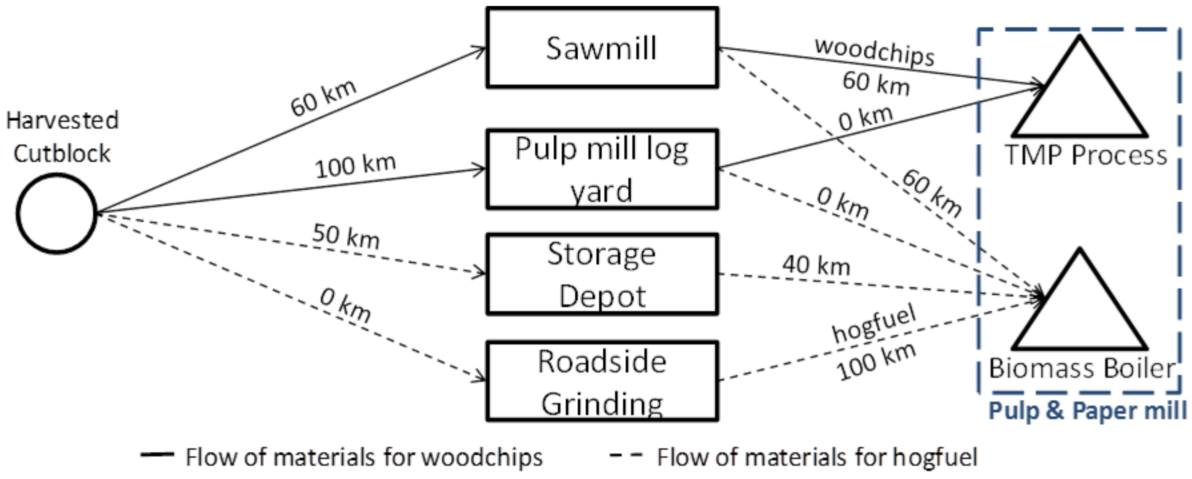

Figure 4-5: Test cutblock with case study supply chain and distances

Table 4.1: Test case cutblock information for simulation model

Cutblock	UNITS	VALUE
Cutblock tree density	[trees/ha]	2,500
Average tree height	[m]	14
Average tree diameter at breast height (dbh)	[m]	0.12
Average tree density	[GMT/bdmt]	0.85
Forest Cutblock Species composition		
Spruce	[%]	60
Fir	[%]	31
Hardwoods	[%]	9
Bucking Database inputs		
Minimum diameter/length for sawlog	[m]	0.09/5
Minimum diameter/length for pulp log	[m]	0.05/2.5
Minimum diameter/length for fuel log	[m]	0.01/1
Stump height	[m]	0.2
Case Study Mill 2010 annual chip demand	[bdmt/year]	240,000

4.3 Short-term opportunities for improvement

Having designed a tool that can effectively simulate the currently used biomass procurement supply chain, the new objective is to improve upon the current harvesting network by applying a new cost allocation system based on activities rather than material quantities produced, and then evaluate alternative harvesting systems in an effort to lower biomass harvesting costs as explained in section 3.2.4.

The implementation of activity-based cost accounting method within the simulation tool is done as a separate module within the simulation tool, which will allow for comparison of the original cost allocation system to the ABC method calculations.

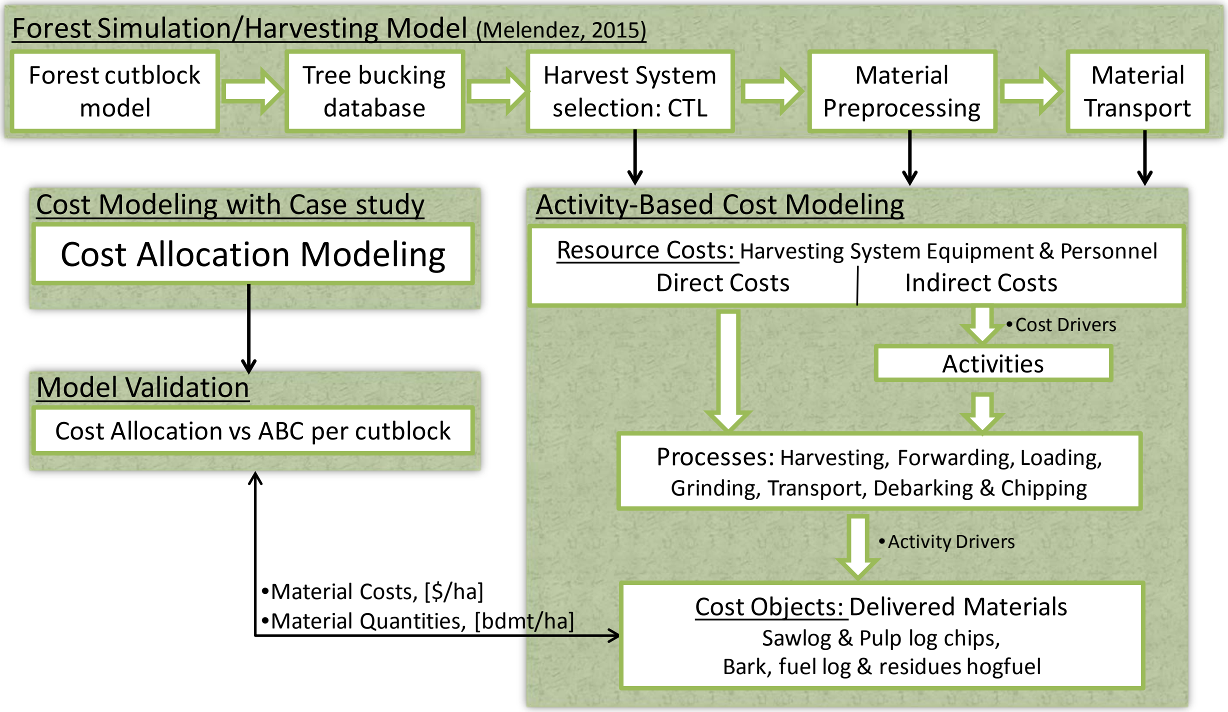

Figure 4-6: ABC framework implemented in forest simulation/harvesting model

Figure 4-6 shows the ABC accounting implementation methodology used within the simulation model. The original cost allocation model is substituted for an ABC method for each harvesting system evaluated. The ABC method starts by identifying the resources, activities and cost objects within the harvesting system. Each resource's direct (capital, labor, fixed operational) costs and indirect (variable operational, profits, and overheads) costs are then identified using information from the original cost allocation model. Following Figure 4-6, direct costs are assigned to processes, while indirect costs are assigned to activities using identified cost drivers for each activity. Activity costs, are then transferred to processes, and combined with the direct costs. Finally the process costs are assigned to the delivered materials (cost objects) by determining which activities are required to produce them (activity drivers).

To validate the ABC methodology used, results are compared to costs calculated using the original cost allocation model for the same cutblock, harvesting system (CTL) and materials extracted. Once the methodology has been validated, the process is repeated on the 3 additional harvesting systems described previously (FT, FB-CTL and chipper-CTL) so as to compare the selected harvesting systems amongst themselves.

With the inclusion of the ABC methods and the new harvesting system alternatives, the simulation model is now capable of simulating one cutblock (of any size) harvested using 4 different harvesting systems, and able to produce quantities and costs for every material extracted from said cutblock.

4.4 Design of forest/harvesting network for optimization

A P&P mill harvesting operation usually has to deal with several hundreds of cutblocks, of many different sizes, and compositions (some productive, some non-productive), located throughout an entire region surrounding the P&P mill and other intermediate locations. Therefore in order to evaluate a complete supply chain network for a biorefinery, we must create multiple cutblocks, with different material compositions, dispersed throughout the P&P leased forest land where they are allowed to harvest material for their operations.

To do this, the simulation modeling tool develop was used multiple times to create multiple cutblocks of different sizes, tree compositions, and locations (all information determined by the user before each cutblock is designed). Following the general characteristics known to us about the forest area surrounding the P&P mill and described in section 3.2.2., 3 sizes of cutblocks were defined (below 50 ha, 75 ha and 150 ha). Tree characteristics (average cutblock heights and DBH as well as species compositions) were individually created for each cutblock, in order to create a great deal of variability within the forest to make sure it mimicked reality as much as possible, while still following the constraints set by the forest characteristics detailed in section 3.2.2. The simulation model then creates each cutblock, harvests, and reports the costs for all harvesting systems previously included as well as the quantities of materials produced in each cutblock.

As for the locations of each cutblock, the map depicted in Figure 4-7 shows the area surrounding the P&P mill, as well as the location of the 3 sawmills and the storage depot included in the network. The outlined regions are the areas where the P&P mill has cutting rights, and the points within these areas marked in yellow are the locations selected to place cutblocks for our study. One cutblock of each size is located at each yellow mark of Figure 4-7, mainly to simplify the amount of distance calculations needed in the network.

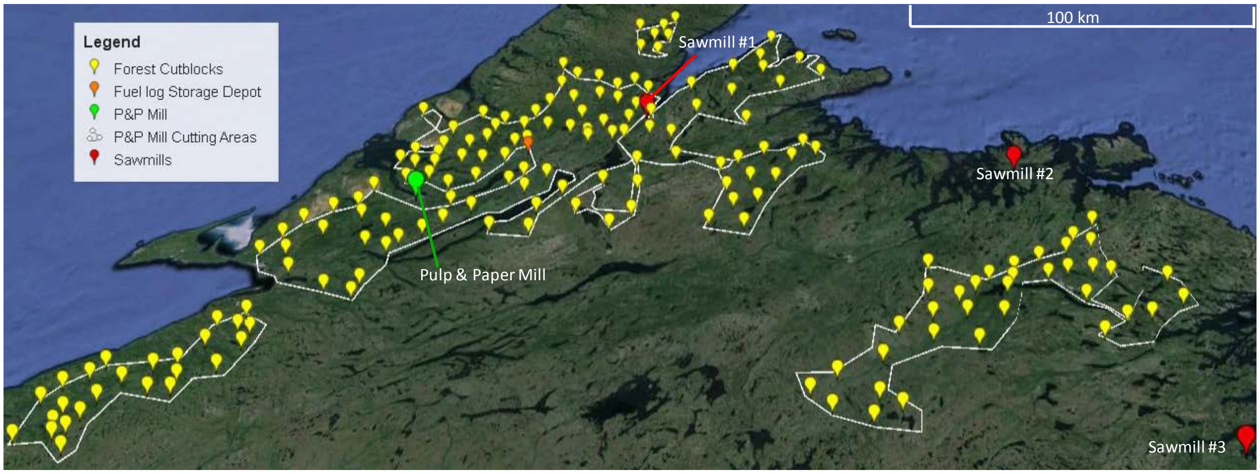

Figure 4-7: Forest Cutblock locations with P&P mill, sawmills and fuel depot (*map created using Goolge earth, 2014*)

All cutblocks are located within the leased land to the P&P mill, dispersed throughout to make sure the farthest and closest distances have been represented, and the total number of hectares (55,927 ha) used in the study was made sure to be lower than the actual number of hectares within the leased land (the mill manages over 1.3 million hectares, of which around 700,000 ha are productive and used for harvesting activities), but enough to supply material to the P&P mill for a set number of years.

Distances from each cutblock to each of the sawmills, fuel depot, and P&P mill were estimated using Google Maps and Google Earth [2014] which uses existing roads and highways to calculate the shortest distance from one location to another. With The information regarding distances for each cutblock, the information can be input into the transportation module of the simulation model, and costs for delivering all materials to all locations can be calculated.

Six-hundred forest cutblocks were created to represent the available resources in the area, which can supply enough material for the P&P mill’s current operations during multiple time periods. All the information create by the simulation model for all materials, costs, quantities, etc. from each cutblock were uploaded into a database which will feed this information into the optimization model described later on.

4.5 Definition of Biorefinery Scenarios

There are 5 main categories of decision parameters that must be defined for each biorefinery scenario evaluated in this study and presented in this section (section 4.5). The goal of defining these parameters is to be able to give answer to the following questions:

- How much of a cost reduction is it possible to achieve by using a lower cost harvesting system within the biomass procurement supply chain during the P&P mill-to-biorefinery transition?
- Which biorefinery technology best suites the P&P case mill according to the biomass types available in the region?
- Should the P&P mill continue to produce newsprint at current levels, or exit the core business?
- When is the best time to reduce or shutdown P&P operations if the plan is to exit the market while biorefinery processes start up?

4.5.1 Harvesting system transition

Because the biorefinery is interested in the collection of forestry residues, harvesting systems that can collect residues with a lower procurement costs are favoured by them. Melendez et al. [148] showed that the full tree (FT) harvesting system is capable of harvesting traditional forestry products as well as residues. Because it carries out de-branching and bucking activities at cutblock roadside, the forestry residues produced, have a much lower cost than those produced by the other harvesting systems (CTL, FB-CTL and Chipper-CTL).

Thus as part of the biorefinery implementation strategy being developed, the P&P has decided to request that all contractors gradually change their harvesting systems over to FT. The gradual change-over of equipment will give contractors time to purchase, train, and familiarize themselves with the new harvesting equipment, while at the same time, allow them to retire old harvesting systems. This change will occur in stages once every 5 years, from the beginning of the biorefinery implementation. During the first 5 year stage, every contractor is allowed to continue to use their harvesting system of choice. In the second 5 year period (years 6-10), half of the contractors used will have to transition to the FT method, and in the third 5 year period (years 11-15) the remaining contractors will transition to the FT harvesting system.

These changes in the harvesting systems used by contractors, will be part of the inputs to the optimization model. The optimization model will determine which contractors will harvest each cutblock, under the established strategic conditions that every 5 years half of the contractors will switch over to the FT harvesting system.

4.5.2 Biorefinery technology

As has been mentioned previously, (section 3.3) a series of discussions were carried out both with academics, and mill personnel to determine which biorefinery technologies would be of interest taking into consideration applicability of the technology, and potential for economic viability. From those discussions two technologies were selected: A fast pyrolysis and organic solvent pulping (also known as organosolv). Therefore in our scenario analysis, both technologies will be evaluated for their effectiveness in the case study mill. As will be explained in section 4.5.6, only two technologies were selected because of the large amount of biorefinery implementation scenarios that can be created with just these two options, therefore evaluating more technologies would create many more scenarios which have already been established are not of interest to the P&P mill.

4.5.3 Process feedstock alternatives

The feedstocks available to each process, are mainly divided into clean woodchip materials, and residual hogfuels. Process feedstock flexibility is sometimes a very important characteristic in many implementations, especially when there are other processes (such as TMP pulping, and a biomass boiler) that may already be requiring large amounts of materials. The introduction of new processes that require additional quantities of materials, may put an un-sustainable strain on the biomass procurement supply chain. However, if that process is capable of accepting other materials not currently used, it may actually improve the collection process, as more materials from the same sources can be collected simultaneously. Feedstock flexibility and the collection of multiple types of feedstocks in different quantities will be tested with the two technologies selected as pyrolysis is a feedstock flexible technology which may use either woodchips or hogfuel, whereas the organosolv process, will only accept woodchip materials.

4.5.4 New technology implementation period

The average lifespan of a biorefinery project (for conceptualization and design purposes) is 20 years. However, not all biorefinery processes can be started up at full scale from year 1. One of the main decisions that must be made in a biorefinery implementation strategy, is when to implement a new technology and at what scale. These decisions will directly affect the necessary biomass materials procurement operations, and must be planned accordingly so as to not negatively affect the supply chain.

For the each of the two biorefinery processes selected (i.e. pyrolysis and organosolv), a two-stage implementation strategy will be proposed for the new technology installation at the mill. For pyrolysis, it involves running at half the desired production capacity for the first 5 years using a single 400 tpd reactor, and then installing a second 400 tpd reactor to reach the desired production capacity in year 6.

For the organosolv process, the initial installation is of a 100 tpd demonstration scale plant that would be installed in year 1. The scenario then assumes that the process is successfully adapted to the use of softwoods, and the decision to go ahead with a 1000 tpd commercial scale plant is approved, which would be installed in year 6.

4.5.5 Biorefinery/P&P mill configurations

Along with the previous decision of when to install new biorefinery processes, the P&P mill must also decide whether or not to maintain pulp and paper production. Currently operating with two paper lines, the pulp mill has the option to close them down one at a time, or both at once at any time they see fit. Thus in this study, we explore the effects that staying in, reducing, or exiting newsprint production will have on the overall biomass procurement supply chain, and new biorefinery processes.

4.5.6 Summary of Biorefinery Scenarios

A series of biorefinery scenarios are constructed that will affect the demands placed on the P&P mill’s total feedstock demands over a 20-year time horizon. Each biorefinery scenario is a combination of biorefinery technology, feedstock used, P&P continuation or decrease in production, and the year of implementation of the biorefinery technologies. In addition to these factors, the biorefinery scenarios will also transition all contractors from the currently used CTL and feller-buncher with CTL harvesting systems, over to a full-tree harvesting system during the first 10 years.

Tables 4.2 and 4.3 show all the scenarios evaluated along with the details showing the differences between them. In addition to the created biorefinery scenarios, tables 4.2 and 4.3 also present the characteristics of the current operating conditions of the mill, along with the feedstock procurement rate, which will be used as the “base case” scenario to compare all changes carried out. The base case scenario, is divide into 3 separate scenarios to show the different changes which apply to all subsequent biorefinery scenarios:

1. Original Data (OD) scenario: This scenario presents the P&P mill procurement network “as-is”, with no changes what-so-ever. It reflects current procurement strategies and feedstock demands.
2. Base Case 1 (BC1): As with the previous scenario, it reflects current P&P mill demand, but with the difference that BC1 has been optimized using an optimization formulation discussed in the next section of this study
3. Base Case 2 (BC2): The last of the “base case” scenarios, this scenario reflects the current mill demand with no changes occurring within the facility, the biomass procurement supply chain optimization, and also a change in the harvesting system methods as described in section 4.5.1 where contractors transition from current methods over to a full tree harvesting system.

Table 4.2: Pyrolysis biorefinery alternative scenarios

	Average Clean Chip demand for all processes [bdmt/day]	Average Hogfuel demand for all processes [bdmt/day]	Feedstock used in 1st 400 tpd Pyrolysis unit (installed year 1)	Feedstock used in 2nd 400 tpd Pyrolysis unit (installed year 6)	Continued Newsprint Production	50% Reduction in Newsprint Production (year of reduction or shutdown)*	Total Shutdown of Newsprint Production
OD	686	143	-	-	yes	no	no
BC1	686	143	-	-	yes	no	no
BC2	686	143	-	-	yes	no	no
PY1a	1,366	250	chips	chips	yes	no	no
PY1b	686	930	hogfuel	hogfuel	yes	no	no
PY2a	1,109	250	chips	chips	no	yes (6)	no
PY2b	429	930	hogfuel	hogfuel	no	yes (6)	no
PY3a	851	143	chips	chips	no	no	yes (6)
PY3b	171	823	hogfuel	hogfuel	no	no	yes (6)
PY4a	1,023	179	chips	chips	no	no	yes (11)
PY4b	343	859	hogfuel	hogfuel	no	no	yes (11)
PY5a	1,194	214	chips	chips	no	no	yes (16)
PY5b	514	894	hogfuel	hogfuel	no	no	yes (16)
PY6	549	531	hogfuel	chips	no	yes (6)	yes (11)

*Numbers in parenthesis represent the year in which the reduction or shutdowns are carried out for each scenario

OD: the original data representing only 1 year's worth of data obtained from the P&P mill, un-optimized; BC1 is the original data scenario but optimized with no biorefinery processes, and BC2 is the original optimized scenario, but with the transition in harvesting methods from CTL to full-tree

The biorefinery scenarios presented in Table 4.2 and 4.3 identify the biorefinery technology that they use with the letters “PY” for pyrolysis, and “OS” for organosolv. The numbers of each scenario are used to indicate the decisions made regarding the year of implementation of the biorefinery technologies, and decisions regarding the newsprint production all described in the last three columns of both tables. The “a” or “b” indicators used in the scenario names of Table 4.2, indicate the type of feedstock used in the biorefinery process. The letter “a” for the use of clean woodchip materials, and the letter “b” for hogfuel materials. The only exception to this last indicator is the last scenario of Table 4.2 (scenario PY6) which has no indicator for the feedstock used, since one of the reactors uses woodchips, and the other one uses hogfuel.

The scenarios presented in Table 4.3 have no need for and “a” or “b” indicator, because the organic solvent pulping process is very sensitive to contaminants and changes in its feedstock. Thus only clean woodchip materials are used in this process. The forth column of Table 4.3 does change somewhat from the previous, as the last two rows (OS10 and OS11) present two numbers indicating that there is a two stage implementation of the softwood organosolv process; first installing a 500 tpd digester in year 6, and then installing a second unit of the same size in year 11.

Table 4.3: Organic solvent biorefinery alternative scenarios

	Average Clean Chip demand for all processes	Average Hogfuel demand for all processes	Initial OrganoSolv unit size using **hardwood** chips (installed year 1)	Final OrganoSolv unit size using **softwood** chips (installed year 6)	Continued Newsprint Production	50% Reduction in Newsprint Production	Total Shutdown of Newsprint Production
						(year of reduction or shutdown)	
	[bdmt/day]	[bdmt/day]	[bdmt/day]	[bdmt/day]			
OD	686	143	-	-	yes	no	no
BC1	686	143	-	-	yes	no	no
BC2	686	143	-	-	yes	no	no
OS7	1,439	364	100	1,000	yes	no	no
OS8	1,181	311	100	1,000	no	yes (6)	no
OS9	924	257	100	1,000	no	no	yes (6)
OS10	889	239	100	500 (6)-1000 (11)	no	yes (6)	yes (11)
OS11	853	221	100	500 (6)-1000 (11)	no	yes (6)	yes (16)

*Numbers in parenthesis represent the year in which the reduction or shutdowns are carried out for each scenario

OD: the original data representing only 1 year's worth of data obtained from the P&P mill, un-optimized; BC1 is the original data scenario but optimized with no biorefinery processes, and BC2 is the original optimized scenario, but with the transition in harvesting methods from CTL to full-tree

Finally, the second and third columns of Tables 4.2. and 4.3 (i.e. Average clean chip demand for all processes; and Average hogfuel demand for all processes) indicate the averaged amount of materials needed per day at the facility over the 20 year period. This is an averaged amount, only used to establish the differences between scenarios due to the fact that during the 20 year period, these quantities change depending on what processes are started and stopped.

4.6 Formulation of Optimization Model

4.6.1 Description of the optimization problem

The general biomass procurement supply chain problem addressed by the optimization model is shown in Figure 4-8. There are a large number of available forest cutblocks that can be harvested in any given time period using several contractors that have different harvesting systems. The harvesting of a cutblock, produces several intermediate materials that are transferred to one of several intermediate locations. Not all intermediate materials can go to all intermediate locations.

At the intermediate locations, the delivered materials are converted into final products, which are then delivered to the final processes inside a P&P mill/biorefinery to fulfill the process's feedstock demands in every time period evaluated. Along the supply chain, materials and products may be kept in storage (at a cost) at the various intermediate locations.

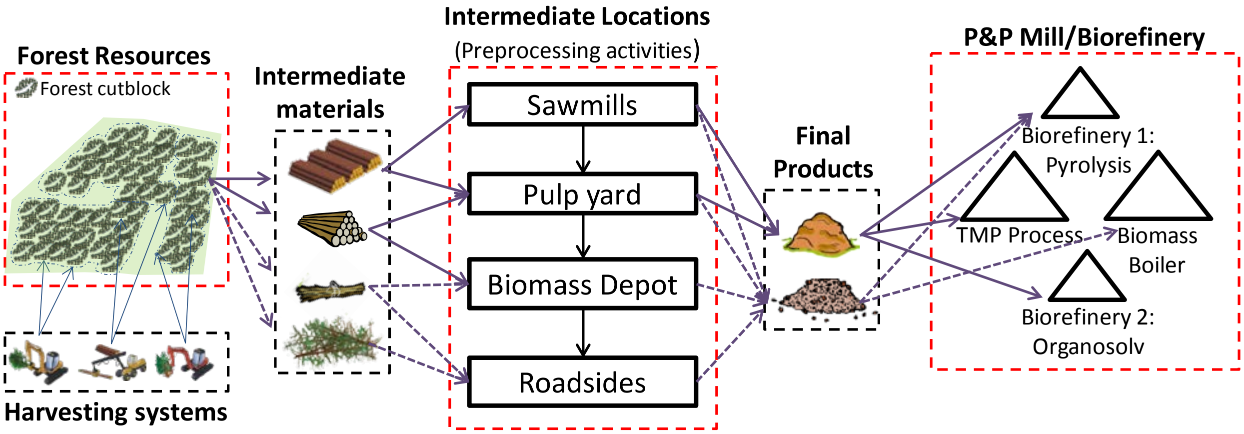

Figure 4-8: Biorefinery biomass procurement supply chain

The final customer of all biomass feedstock materials, the P&P mill, is going through a transformation that will see the introduction of new biorefinery processes, and the reduction, or shutdown of paper making lines, changes in the demand of materials will occur several times throughout the lifespan of the project. In addition to the changes happening inside the P&P mill, the P&P mill has also requested that all their contractors switch to a full-tree harvesting system over the course of the project to help reduce material costs.

The problem is therefore to optimize the different intermediate material workflows at each harvested cutblock, transportation and inventory with the aim of minimizing the procurement cost of all biomass materials of the biorefinery, taking into account the constraints related to demand, supply and mass balances.

4.6.2 Optimization model mathematical formulation

The mathematical model used for optimization of biomass procurement operations for the biorefinery, was formulated as a mixed-integer linear programming problem (MILP) used to evaluate the different procurement strategies of both wood chips and residual materials (hogfuel) from integrated forest harvesting operations to a biorefinery over a 20-year time horizon. The model seeks to satisfy the mill’s long-term feedstock requirements, while minimizing the procurement cost. It examines the impacts of changing harvesting systems taking into account the wide variability of materials obtained from the boreal forest.

4.6.2.1 Optimization model nomenclature

Sets

$t \in T$	Set of time periods
$i \in I$	Set of forest cutblocks
$f \in F$	Set of forest management areas (FMA)
$l \in L$	Set of intermediate locations
$k \in K$	Set of final customers destination
$h \in H$	Set of harvesting systems (aka contractor) used to harvest a specific cutblock
$r \in R$	Set of recipes at intermediate locations to convert intermediate materials into final products
$m \in M$	Set of intermediate materials extracted from forest cutblocks
$g \in G$	Set of final products delivered to the customers

Parameters

C_{mifh}	Unit cost of producing material *m* at forest cutblock *i*, in FMA *f*, using harvesting system *h*, [\$/bdmt]
C_{mifl}	Unit cost of transporting material *m* from forest cutblock *i*, in FMA *f*, to intermediate location *l*, [\$/bdmt]
D_{gkt}	Demand for product *g* from customer *k* during time period *t*, [bdmt/year]
p_{glr}	Quantity of product *g* produced at intermediate location *l* with unit usage of recipe *r*, [bdmt/year]
q_{mlr}	Quantity of material *m* consumed at intermediate location *l* with unit usage of recipe *r*, [bdmt/year]
C_{gl}	Unit cost of producing product *g* at intermediate location *l*, [\$/bdmt]
C_{glk}	Unit cost of transporting product *g* from intermediate location *l* to final customer *k*, [\$/bdmt]
SC_{ml}	Spot market unit price for material *m* purchased at intermediate location *l*, [\$/bdmt]
CI_{mif}	Unit inventory holding cost of material *m* at forest stand *i*, in FMA *f*, [\$/bdmt/year]
CI_{ml}	Unit inventory holding cost of material *m* at intermediate location *l*, [\$/bdmt/year]
CI_{gl}	Unit inventory holding cost of product *g* at intermediate location *l*, [\$/bdmt/year]

a_{ifh}	Operating time for completing clear-cut harvest at cutblock *i*, in FMA *f*, using harvesting system *h*, [years]
Q_h	Capacity of harvesting system *h* in each period, [bdmt]
Q_{mifh}	Highest amount material *m* produced using harvesting system *h* at forest cutblock *i* in FMD *f,* [bdmt]
Q_{gl}	Capacity of product *g* produced at intermediate location *l*, [bdmt/year]
Q_{ft}	FMA annual allowable harvesting quantity in FMA *f* in period *t*, [bdmt/year]

Decision Variables

X_{ift}	Binary decision variable: being 1 if stand *i* of FMA *f* is harvested during time period *t*; 0 otherwise.
X_{ifht}	Binary decision variable: being 1 if stand *i* of FMA *f* is harvested using harvesting system *h* in period *t*; 0 otherwise.
Y_{mifht}	The production quantity of material *m* at cutblock *i* in FMA *f* by harvesting system *h* in period *t*, [bdmt/year]
S_{mlt}	Quantity of material *m* purchased at intermediate location *l* from spot market in period *t,* [bdmt]
Y_{rt}	Number of times recipe *r* is used in period *t*
Y_{glt}	Quantity of product *g* produced at intermediate location *l* in period *t*, [bdmt/year]
I_{mift}	Inventory quantity of material *m* at forest cutblock *i* in FMA *f* at the end of period *t*, [bdmt/year]
I_{glt}	Inventory quantity of product *g* at intermediate location *l* at the end of time period *t,* [bdmt/year]
I_{mlt}	Inventory quantity of material *m* at intermediate location *l* at the end of time period *t*, [bdmt/year]
F_{miflt}	Transported quantity of material *m* from forest cutblock *i* in FMA *f* to intermediate location *l* in period *t,* [bdmt]
F_{glkt}	Transported quantity of product *g* from intermediate location *l* to customer location *k* in time period *t,* [bdmt]

4.6.2.2 Mathematical model

The objective function of this tactical/operational planning model seeks to minimize the total procurement cost of softwood chips and hogfuels delivered to the P&P mill's TMP and biomass boiler, as well as the pyrolysis and organosolv biorefinery processes put in place during the biorefinery implementation.

The objective function is:

$$\begin{aligned} Min\ Z\colon & \sum_{t\in T}\sum_{f\in F}\sum_{i\in I}\sum_{m\in M}\left(\sum_{h\in H} C_{mifh} * Y_{mifht} + \sum_{l\in L} C_{mifl} * F_{miflt} + CI_{mif} * I_{mift}\right) \\ & + \sum_{t\in T}\sum_{l\in L}\sum_{g\in G}\left(C_{gl} * Y_{glt} + CI_{gl} * I_{glt} + \sum_{k\in K} C_{glk} * F_{glkt}\right) \\ & + \sum_{t\in T}\sum_{l\in L}\sum_{m\in M}\left(CI_{ml} * I_{mlt} + SC_{ml} * S_{mlt}\right) \end{aligned} \qquad \text{(E.1)}$$

Each of the optimization model's segments is a total cost calculated by multiplying the unit cost and a quantity related to activities carried out throughout the biomass procurement supply chain. Table 4.4. gives a description of what each one of these components represents.

Table 4.4: Objective function components

Component Formula	Description
$\sum_{t\in T}\sum_{f\in F}\sum_{i\in I}\sum_{m\in M}\left(\sum_{h\in H} C_{mifh} * Y_{mifht}\right)$	The total cost of all materials produced and extracted from all harvested forest cutblocks using a particular harvesting system for each one.
$\sum_{t\in T}\sum_{f\in F}\sum_{i\in I}\sum_{m\in M}\left(\sum_{l\in L} C_{mifl} * F_{miflt}\right)$	The total cost per period of transporting all materials extracted from all forest cutblocks harvested to all intermediate locations.
$\sum_{t\in T}\sum_{f\in F}\sum_{i\in I}\sum_{m\in M}\left(CI_{mif} * I_{mift}\right)$	Total cost of maintaining material inventories in the forest after the cutblocks have been harvested.
$\sum_{t\in T}\sum_{l\in L}\sum_{g\in G}\left(C_{gl} * Y_{glt}\right)$	Total cost of producing all products at all intermediate locations
$\sum_{t\in T}\sum_{l\in L}\sum_{g\in G}\left(CI_{gl} * I_{glt}\right)$	Total cost of maintaining product inventories in intermediate locations after they have been produced.

$\sum_{t\in T}\sum_{l\in L}\sum_{g\in G}\left(\sum_{k\in K} C_{glk} * F_{glkt}\right)$	The total transportation cost of moving final products from intermediate locations to the final customers
$\sum_{t\in T}\sum_{l\in L}\sum_{m\in M}(CI_{ml} * I_{mlt})$	Total cost of maintaining material inventories in intermediate locations before they have been processed into final products.
$\sum_{t\in T}\sum_{l\in L}\sum_{m\in M}(SC_{ml} * S_{mlt})$	Total cost of all spot market purchases of materials made at all intermediate locations.

The main decision variables of the model include:

- Which forest cutblocks to harvest in what time period
- What harvesting system and contractor[16] to use to harvest each particular forest cutblock
- How much of each material to move from the forest to an intermediate location for processing.
- How much product to produce every period at every intermediate location.
- How much product to transport to the final customers.
- How much material and products to keep in inventories along the supply chain.

4.6.2.3 Constraints

Demand Constraints:

$$\sum_{l\in L} F_{glkt} = D_{gkt} \;\; \forall\, g,k,t \tag{E.2}$$

Constraint (E.2) is the demand constraint from all P&P mill and biorefinery processes who are the final customers of the biomass procurement supply chain. Feedstock demands from all processes are combined and a single number for every period (typically 1 year) for every feedstock required is set before running the optimization model (i.e. quantity of spruce chips, fir chips, hardwood chips, and hogfuel for all processes in each time period). The constraint then establishes that all the product demand must be satisfied by the delivered materials from intermediate locations.

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[16] Each type of harvesting system (CTL, FT, FB-CTL) reviewed earlier can be utilized by a number of contractors (in total 20) available in the local area. Every contractor will have a different productivity, equipment configuration, etc. to differentiate between them.

Flow Balance Constraints:

$$\sum_{r\in R} p_{glr}\, Y_{rt} + I_{glt-1} - I_{glt} - \sum_{k\in K} F_{glkt} = 0 \quad \forall\, g, l, t \tag{E.3}$$

$$\sum_{i\in I} \sum_{f\in F} F_{miflt} + S_{mlt} + \; I_{mlt-1} - I_{mlt} - \sum_{r\epsilon R} q_{mlr} * Y_{rt} = 0 \quad \forall\, m, l, t \tag{E.4}$$

$$\sum_{h\in H} Y_{mifht} + I_{mift-1} - I_{mift} - \sum_{l\in L} F_{miflt} = 0 \quad \forall\, m, i, f, t \tag{E.5}$$

Constraints (E.3), (E.4) and (E.5) are flow balance constraints at the forest, and intermediate locations for all materials and products. Constraint (E.3) refers to the final products produced at each intermediate location, indicating that the quantities of each product produced, plus the previous periods inventories must be equal to the inventory quantities at the end of the current period plus what is transferred to the final customers (IN + OUT = 0). Similarly, (E.4) keeps tally of the materials in all intermediate locations indicating that what comes in (delivered intermediate materials plus any quantities of materials purchased at spot markets plus the inventories of materials in the previous period) must equal the inventories of each material at the end of the current period plus the quantities of materials consumed using each type of recipe. Constraint (E.5) also keeps a tally on materials, but in the forest, indicating that all the materials produced from trees for every cutblock harvested, plus the previous period inventories from other harvested cutblocks must be equal to the quantities of materials transferred to intermediate locations, plus the quantities of materials left in inventories in the forest.

Intermediate location capacity constraints:

$$\sum_{r\in R} p_{glr}\, Y_{rt} \leq Q_{gl} \quad \forall\, g, l, t \tag{E.6}$$

Constraint (E.6) is the capacity constraint for the production of softwood/hardwood chips and hogfuels at each of the intermediate locations. Q_{gl} is established as the upper limit of the production capacity of each intermediate location, and therefore all conversions or exchanges of materials for chips or hogfuels must be kept below this value. This constraint is mostly used to limit the quantities of chips and hogfuel exchanged with each sawmill. In other intermediate locations, the upper limit is set high enough not to limit the model's operation, but for sawmills, this exchange limit is based on the size of the mill, and historical values for transactions carried out in the past between the P&P mill, and the sawmills.

Clear-cut operation constraints at forest cutblock *i*, FMA *f*, using harvesting system *h*:

$$Y_{mifht} = Q_{mifh} * X_{ifht} \quad \forall\, m, i, f, h, t \tag{E.7}$$

Constraint (E.7) is the clear-cut constraint stating that if a cutblock is selected to be harvested using a particular harvesting system, then all trees in the cutblock must be harvested and either sent to an intermediate location, or placed in a material inventory.

Harvesting system capacity constraint:

$$\sum_{i \in I} \sum_{f \in F} a_{ifh} X_{ifht} \leq Q_h \quad \forall\, h, t \tag{E.8}$$

Each harvesting system used by the optimization model to harvest a cutblock, has a maximum amount of cutblocks that they can harvest per time period. Considering that the time period is a year, then the maximum amount a time any contractor can dedicate to harvesting activities, has been set to 9 months. This assumption considers that every year there will be 3 months out of the year where due to environmental concerns, or equipment maintenance, or other reasons, the contractors will not be able to carry out harvesting activities.

Constraint (E.8) specifies the previous statement, by calculating the time (in fractions of a year) it takes for each harvesting system (contractor) to harvest each cutblock assigned. The sum of all the times of each contractor, must then stay below the described maximum allowable harvesting time of 9 months (Q_h).

FMA annual allowable harvesting amount constraint:

$$\sum_{m\in M}\sum_{i\in I}\sum_{h\in H} Y_{mifht} \leq Q_{ft} \quad \forall\, f,t \tag{E.9}$$

Constraint (E.9) is a harvesting sustainability constraint. All cutblocks are organized into forest management areas (FMA). These FMAs have a maximum annual allowable cut of softwoods and hardwoods, which has been established by the local government to insure that not all harvesting activities are carried out in a single FMA, but spread out over all areas.

Constraint (E.10) establishes that once a forest cutblock has been selected for harvest, only one harvesting system (aka contractor) may be used to harvest that cutblock in any given period:

$$\sum_{h\in H} X_{ifht} = 1 \quad \forall\, i,f,t \tag{E.10}$$

Constraint (E.11) says that if a harvesting activity occurs at a forest cutblock in a FMA, the cutblock must be chosen to be harvested:

$$X_{ifht} \leq X_{ift} \quad \forall\, i,f,h,t \tag{E.11}$$

Constraint (E.12) further indicates that if the cutblock is selected, it cannot be re-selected again within the planning horizon, which further reinforces the clear-cut constraint within a single period.

$$\sum_{t\in T} X_{ift} \leq 1 \quad \forall\, i,f \tag{E.12}$$

And finally, the non-negative constraints are provided by (E.13):

$$X_{ift}, X_{ifht} \in \{0,1\}, Y_{mifht}, S_{mlt}, Y_{rt}, Y_{glt}, I_{mift}, I_{glt}, I_{mlt}, F_{miflt}, F_{glkt} \geq 0 \tag{E.13}$$

4.6.2.4 Optimization model implementation and associated cost models

The mathematical model was solved using IBM ILOG CPLEX Optimization Studio v12.6®, on an Intel Core i7, 2.7 GHz processor with 8.0GB of RAM. The optimality gap was kept below 1%. A Microsoft Access Database was developed to allow aggregation of all input data from the simulation model (developed with Microsoft Excel 2010®), and automatic data input and output from the CPLEX server.

The case study network involves 2 to 4 customers (TMP, biomass boiler, pyrolysis and organosolv processes) for final products depending on whether the biorefinery processes are included, 10 intermediate products produced from each cutblock harvested, 3 sawmills, a pulp mill log yard, a storage depot, and as many roadside preprocessing sites as there are cutblocks (i.e. 600), all of which are evaluate over a planning horizon of 20 years. Computationally, the biomass procurement system creates over 4.5 million constraints, and 5.5 million variables (372,000 binary) which create a very large optimization problem, not easily (in a timely manner) solved with available equipment. Therefore, the procurement optimization problem was divided into four sub-problems with each consisting of a five-year planning horizon. This decomposition approach was necessary to significantly reduce the number of constraints and variables created, as well as reduce the solution time to a manageable timeframe (under 30 minutes per sub-problem) and mostly to avoid the need for excessively large database. In order to find the overall solutions for each biorefinery implementation scenario, the four sub-problems that compose a single biorefinery implementation scenario were optimized in succession with different planning horizon variables changed in-between each run (e.g. final customers product demands due to start-up or shutdown of biorefinery processes). Cutblock selections, harvesting and material flow decisions, as well as inventory results from one sub-model were imported into the next one to ensure the continuity of the overall scenario optimization problem.

The breakdown into four runs of the optimization model also allows changes to a contractors harvesting system technologies every 5 years, as would be the case in practice. As was mentioned before in section 4.5.1, the implementation strategy involves the transition of all harvesting crews from their current harvesting systems, over to a full-tree system. Once the optimal solution has been found for each sub-problem, results are aggregate to present the solution found for each biorefinery scenario.

Excel was used to prepare an associated cost and quantity spreadsheet that breaks down optimization results into individual time periods, materials and products, and then presents cost information in cost per dry tonne per year per product ($/bdmt/year/product) a format better suited for analysis and comparison. This way, we are able to visualize each products cost per year, and track its provenance back through the supply chain to determine how its calculated, and what materials are influencing these results. If further details as to where those products are coming from (e.g. sawmills or storage depot), or from what materials are they being produced (e.g. forestry residues, or hardwood fuel logs, etc.), it is possible to use the developed spreadsheet cost model to walk backwards through the supply chain and determine these details.

4.7 Biorefinery Scenario Analyses

With both the simulation and optimization models set-up in sequence to create, evaluate and optimize a biomass procurement supply chain network, it is now possible to evaluate the biorefinery scenarios that were described in section 4.5.

Using the same forest resources and the same biomass procurement supply chain, all the biorefinery scenarios were run through the optimization model. Their results were then formatted with the associated cost model described in the previous section (section 4.6.2.4.) to determine the costs of each biomass product per year.

Once the biorefinery scenario supply chains have been optimized results are analyzed to determine viability of scenarios, and then assess the competitiveness between them to try and determine which scenario will create a winning biorefinery strategy for the P&P mill. Comparative analyses of all the scenarios are based on biomass products costs per year, price stability over the project time horizon, average cost of all materials needed by the implementation strategies, potential benefits (profits) that may be created by each scenarios product portfolio, and cost savings that the scenarios create when compared to current biomass procurement costs.

A biomass cost to revenues ratio was also calculated for each scenario to determine how much is spent on biomass to produce each dollar of revenue from biorefinery products. To do this, the selling price of all biorefinery products were obtained from different sources (newsprint, bio-oil[17] [149], ethanol, acetic acid, lignin and furfural [23, 150, 151]) to prepare the ratio. Quantities and costs of biomass feedstocks over the 20-year time horizon were calculated using the optimization model and the total cost of all materials over that time frame was used to compare to the total revenues produced from all quantities of products produced.

Conversion rates for production of P&P mill and biorefinery products were made as follows:

- TMP production of newsprint holds a 98% conversion rate from woodchips to newsprint
- A 75% (w/w) conversion rate from woodchips to bio-oil was considered, and dropped to a 65% conversion when hogfuel was used as a feedstock [140].
- Conversions of woodchip materials to organosolv products were taken from Kautto et al. [152] for use in this study (see Figure 4.9).

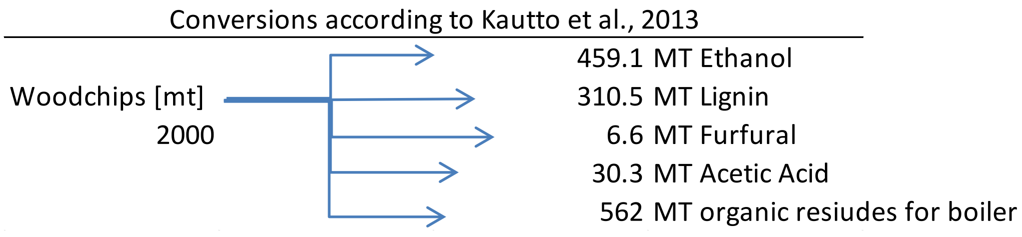

Figure 4-9: Organosolv biorefinery production rates for all products and residues from woodchips

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[17] Bio-oil was priced as the equivalent of heavy fuel oil (price for April, 2015) on an energy basis.

CHAPTER 5 SUMMARY AND SYNTHESIS

5.1 Presentation of Publication and Additional Reports

A complimentary publication to the research carried out is found as an Appendix:

- Article 1 (Appendix A): Melendez, J., Stuart, P. (2015). Systematic Assessment of Triticale-based Biorefinery Strategies: A Biomass Procurement Strategy for Economic Success. Accepted in *Biofuels, Bioproducts, and Biorefining*.

In addition, a list of book chapter, conference and other presentations related to the work carried out in this thesis, is also presented below:

- Book Chapter: Meléndez, J., LeBel, L., Stuart, P. (2012). A Literature Review of Biomass Feedstocks for a Biorefinery. In: El-Halwagi, M., Stuart, P. (Eds). *Integrated Bio-refineries: Design, Analysis, and Optimization*, CRC Press/Taylor & Francis. 433-461
- Webinar: Meléndez, J. (2014). Calculating biomass feedstock costs: From forest to mill gate. VCO **Webinar**, April 23rd, Montreal, Canada.
- Conference Presentation #6: Meléndez, J., LeBel, L., Stuart, P. (2013). Biomass supply chain optimization for commodity and value-added biorefinery products. **Presentation** at *1st FIBRE Conference*, May 13-16, Cornwall, Canada.
- Poster #2: Meléndez, J., LeBel, L., Stuart, P. (2013). Optimizing the biomass procurement supply chain for the biorefinery value chain. **Poster** at *1st FIBRE Conference*, May 13-16, Cornwall, Canada.
- Workshop presentation: Meléndez, J., LeBel, L., Stuart, P. (2013). Optimizing the biomass procurement supply chain for the biorefinery value chain. **Presentation** at the 2nd VCO Workshop on Biomass, April 9-10, Pointe-Claire, Canada.
- Poster #1: Meléndez, J. (2013). Biomass procurement optimization for the forest biorefinery. **Poster** at FIBRE Workshop, February 18-19, Québec, Canada.
- Conference Presentation #5: Meléndez, J., Stuart, P. (2013). A case study for biomass procurement optimization within the transforming pulp and paper sector. **Presentation** at *Paperweek*, February 4-8, Montreal, Canada.

- Conference Presentation #4: Meléndez, J., Stuart, P. (2012). Biomass procurement cost characterization in a transforming forest industry, **Presentation** at the 2012 International Bioenergy and Bioproducts Conference, October 17-19, Savannah, United States.
- Conference Presentation #3: Meléndez, J., et al. (2012). Transformation of a pulp and paper mill into a biorefinery: effects on the biomass procurement strategies. **Presentation** at BIOFOR 2012, May 14-15, Thunder Bay, Canada.
- Conference Presentation #2: Meléndez, J., et al. (2011). Modeling of Biomass Feedstock Procurement for the Biorefinery. **Presentation** at CORS 2011, May 30 - Jun 01, St. John's, Canada.
- Conference Presentation #1: Melendez J. & Stuart P., (2009). Out of the Box Carbon Feedstocks for the Forest Biorefinery. **Presentation** at the 2nd International Biorefinery Conference, Syracuse, New York, USA, 2009.

5.2 Links between publications

A linkage between the methodology and the articles to be published of the study has already been presented in Figure 4-1. Figure 5-1 serves to compliment this figure as it not only shows the linkage of the main articles with the objectives of the study, but also the linkage of all other activities carried out during the PhD and their linkage to the main articles, and methodology.

In Figure 4-1, the links between the methodology sections, and the sub-objectives of the PhD study were shown. Now Figure 5-1 compliments this information by showing the links between the methodology developed and all the activities carried out throughout the process, and their links with the main articles of the thesis. In addition it also shows how all the articles are linked together sequentially. The articles are linked in the same way. Without the tools developed and applications done in one, the others would not be possible.

There were several initial research activities that needed to be carried out before the project tool development phases of the project could be started. These steps involved the characterization of different types of feedstock materials, applications and products that may be created from them. Also the study of harvesting systems for both agriculture and forestry feedstocks were researched in order to get a better understanding of what would be needed in order to develop simulation models. Fortunately for us, the opportunities to produce two publications out of these initial research efforts was presented: The first was a conference paper, which was later presented at the 2009 International Biorefinery Conference in Syracuse, NY; and the second was a literature review chapter on biomass feedstocks for the biorefinery published in Integrated Bio-refineries: Design, Analysis, and Optimization.

Both of these publications served as introductions into the concepts of biorefinery feedstocks, supply chains, procurement activities, and cost calculations.

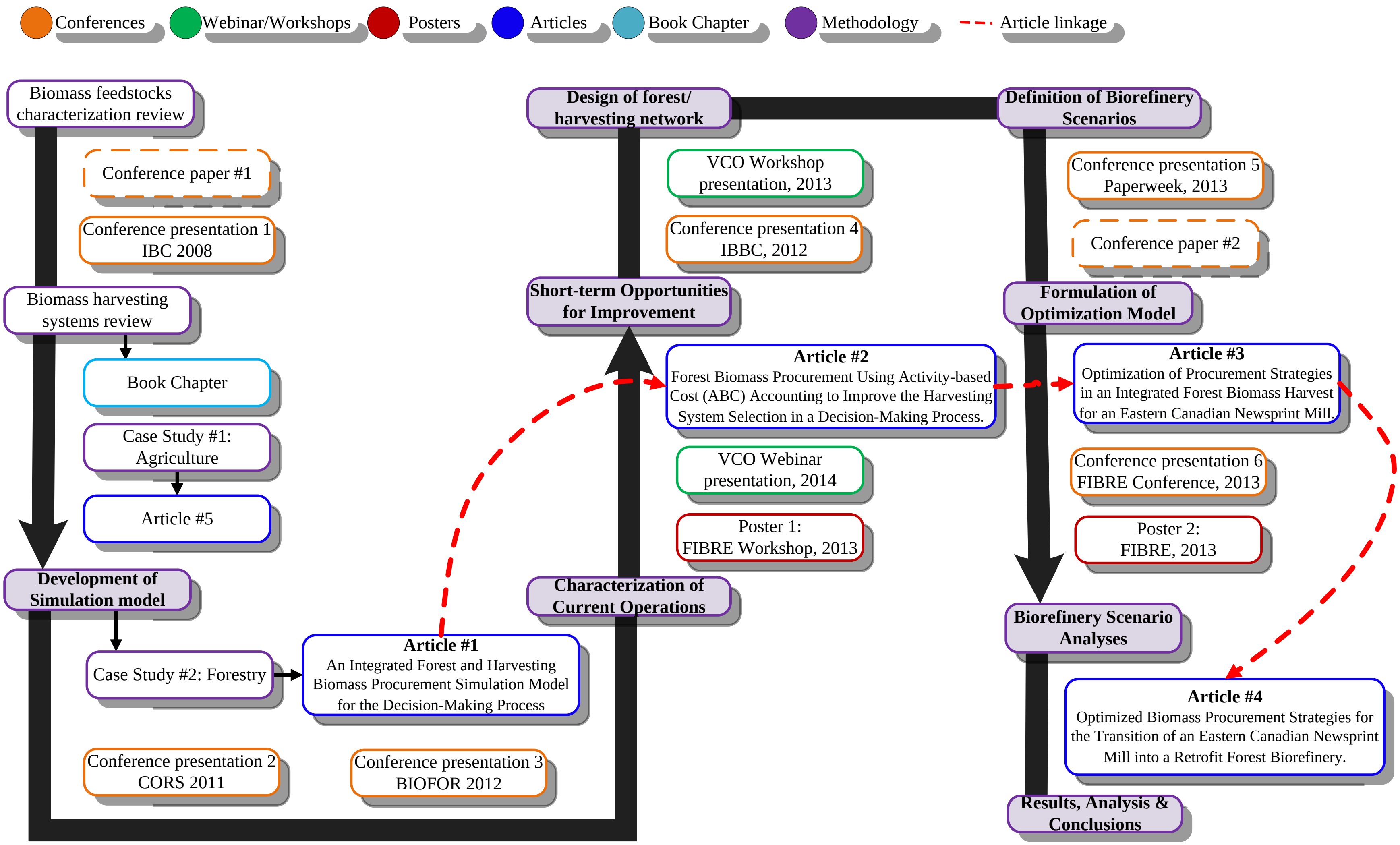


Figure 5-1: Linkage between publications, methodology and other academic activities carried out.

After the initial literature review research was carried out, theoretical case study was developed in the field of agriculture crops focusing on the study of triticale (*X Triticosecale Wittmack*). Similar to what had been done before, a feedstock characterization, harvesting systems and potential products were studied. Mass balance calculations for harvesting quantities were calculated, and a simple simulation model was developed to calculate the cost of harvesting materials and delivering them to a biorefinery. The project served as a first attempt at the development of a simulation model for production and harvesting of biomass for a biorefinery, and allowed us to explore the different areas that would need to be developed in a much larger forestry simulation model. Results from the agriculture study carried out were published as an additional article (article #5 in Figure 5-1) which can be found in the Appendix B.

Thus after a thorough literature review of biomass feedstocks and harvesting systems, and an internship spent at the case study pulp and paper mill, the development of a the simulation model was carried out, this time focusing on forestry feedstocks. Presentations on the development of the project and simulation (and optimization) modeling tools were presented at CORS 2011 and BIORFOR 2012 conferences, and results from both the development and characterization of current operations were summarized in “Article 1”. Techno-economic analyses of the CTL harvesting system was reviewed, and costs were calculated for the current harvesting systems used by the P&P mill.

Once the current biomass procurement supply chain had been successfully modeled and validated, then we proceeded to find alternatives ways that could improve upon both the simulation model, and harvesting activities. This is where “Article 2” comes in. It examines the application of activity-based cost (ABC) accounting methods to the simulation model to calculate individual product costs based on activities carried out. Then, it uses the simulation model created in Article 1 and modified in Article 2, to examine the use of alternative harvesting systems instead of the currently used methods. A general overview of the simulation model calculations was presented in a Value Chain Optimization (VCO) network webinar, as well as in a FIBRE conference poster session.

These two articles, examined the development of a simulation tool capable of creating and harvesting a forest for the purpose of calculating quantities of materials and costs of delivery. Using this tool, the next step in the methodology, was to develop a much larger system that would be representative of the types of forest areas that a P&P mill deals with to procure feedstocks for its year-round processes, as well as include other players that might interact within the case study mill's biomass supply chain (i.e. sawmills, contractors, etc.). Information regarding this section of the study were presented in a VCO sponsored workshop and at the 2012 International Bioenergy and Bioproducts Conference.

After decisions have been made regarding the biorefinery scenarios that will be evaluated using the case study biomass procurement network, a mathematical optimization problem was formulated. "Article 3" is the first one to tackle the problem of optimizing a biomass procurement supply chain network. It continues the flow of the methodology, by using the information created by the simulation model with all the harvesting system alternatives, product costs, and delivery points (intermediate locations and final customers); and examines the procurement of biomass (woodchips and hogfuel) for the current needs of the P&P mill. Results regarding the formulation and biorefinery scenarios were presented at multiple activities as is shown in Figure 5-1.

Finally "Article 4" wraps all the previously developed subjects into one by examining the biorefinery scenarios using the developed optimization model, and the simulated biomass procurement supply chain network, in order to determine which scenarios are best suited for the existing supply chain, and how will the implementation of these scenarios affect the biomass procurement costs. The idea behind this final article, was to examine and compare the cost results of each biorefinery scenario, and be able to develop a biorefinery implementation strategy for the existing P&P mill, based on the scenario chosen.

5.3 Synthesis

In this section of the thesis, an overview of the most pertinent results from the work done in this Ph.D. research project is presented in order to highlight the main values and deliverables from the proposed methodology. The focus was on four main themes developed throughout the project:

1) A systematic development of a forest and harvesting simulation model for integrated harvesting of traditional and non-traditional materials,

2) The use of ABC accounting to improve cost allocation methods and compare harvesting system alternatives in the simulation model

3) The optimization of a biomass procurement network that can be adjusted to fulfill current and future biorefinery needs; and

4) The study of biorefinery implementation scenarios and the impact that biomass procurement strategies have on the bottom line of the overall facilities.

Each one of the themes mentioned has been examined in the main articles used to prepare this thesis, and the main findings and results for each one of them are presented in the next sections.

Because the case study is based on an existing newsprint mill, any results that pertain to sensitive cost information are presented as normalized values due to the confidentiality requirements of this highly competitive commodity business environment.

5.3.1 The systematic development of a forest/harvesting simulation model

Developing a simulation/harvesting model, was done to allow for a comprehensive study of the biomass procurement supply chain. Due to the changing conditions that a biorefinery implementation will create on internal and up-stream activities (downstream activities as well), standard planning systems may lack the necessary freedom to properly allow for adjustment to be made to scenarios. Hence the need for a more tailor-made simulation model. Results presented in the following section, show the quantities and cost information obtained from the simulation of forest land. This information is an example of the information that is later used by the optimization model to fulfill the mill's demands.

5.3.1.1 Quantitative Results

The first type of results created by the forest/harvesting simulation model, are quantities of intermediate materials and final products produced from the materials on a hectare of simulated forest. Using the specified (see table 5.1) intermediate material minimum requirements (for each log type, the height and minimum diameter), the model determines the bucking pattern of each tree on a cutblock. At the same time, it determines the volume of each log produced, and the associated residual materials (bark, foliage and branches) produced for each tree on the cutblock. Quantitative results for the simulation of a typical cutblock are shown in Figure 5-2.

Figure 5-2 shows a detailed description of all the intermediate materials that can be extracted from the sample cutblock. This figure shows a combination of two types of graphs. The bars represent the quantities of each material extracted from the cutblock, while the pie graph shows the composition of that bar related to the individual species present on the cutblock. The comparison of information from the species composition for each intermediate material and the original species composition of the cutblock shows that in all materials, the percentages stay the same as the original (original tree species composition was 60/31/9::spruce/fir/hardwoods).

Table 5.1: Sample cutblock input information for simulation model

	UNITS	VALUE
Cutblock		
Cutblock tree density	[trees/ha]	2,500
Average tree height	[m]	14
Average tree diameter at breast height (dbh)	[m]	0.12
Average tree density	[GMT/bdmt]	0.85
Forest Cutblock Species composition		
Spruce	[%]	60
Fir	[%]	31
Hardwoods	[%]	9
Bucking Database inputs		
Minimum diameter/length for sawlog	[m]	0.09/5
Minimum diameter/length for pulp log	[m]	0.05/2.5
Minimum diameter/length for fuel log	[m]	0.01/1
Stump height	[m]	0.2
Case Study Mill 2010 annual chip demand	[bdmt/year]	240,000
Case Study Mill 2010 annual hogfuel demand	[bdmt/year]	50,000

Quantities of all materials produced from a single hectare of land using the simulation model were presented to experienced mill personnel, and validated according to their experience with forest cutblocks in the local area.

Merchantable materials (i.e. sawlogs, pulp logs and fuel logs) that can be extracted from the sample cutblock show that pulp logs are the largest product quantities extracted. This of course changes according to the characteristics setup in the model for each cutblock (height and DBH of each tree), but results conform with data reported by the case study mill for the local forest area.

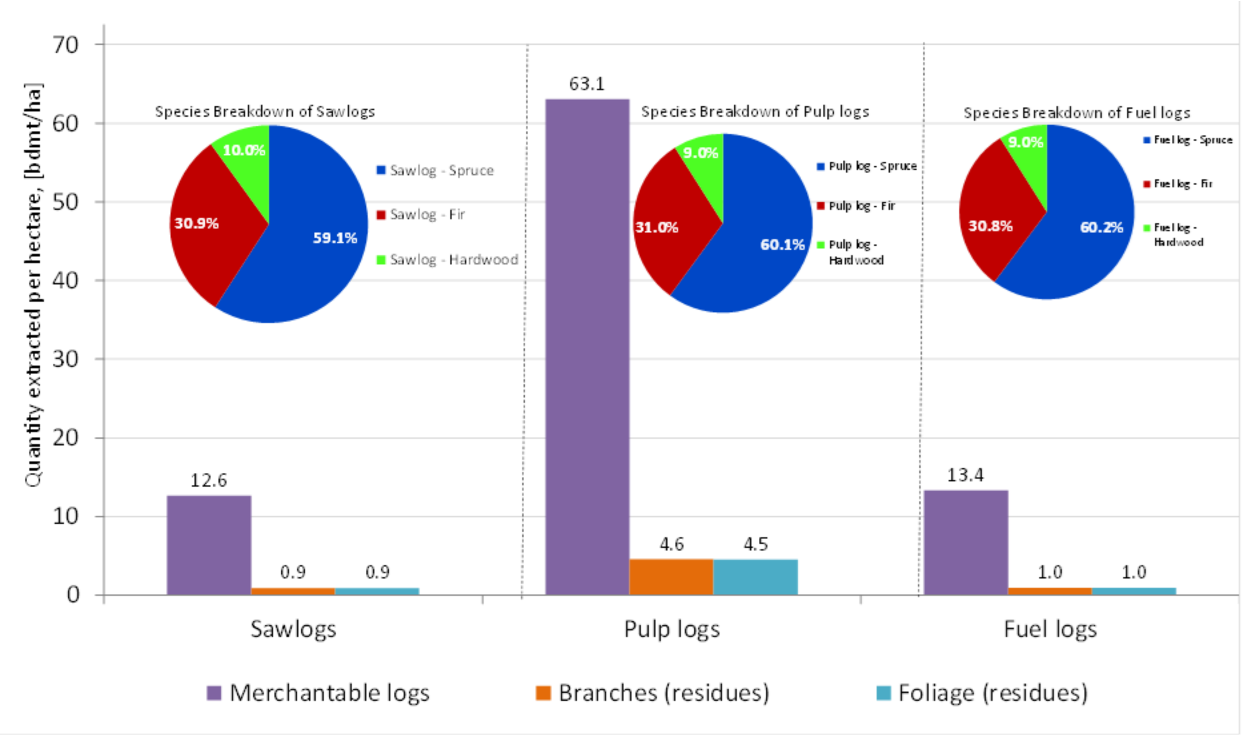


Figure 5-2: Quantitative results of intermediate materials from a sample cutblock modeled using the forest simulation model.

Hence the importance of combining the harvest for both sawmills and pulp mills, as each material harvested individually without taking into account the use of the other would not be feasible due to the low quantities of sawlogs and fuel logs produced.

The other bars in Figure 5-2 (orange and teal bars), represent residual materials that have the potential to be extracted from the simulated cutblock and used as hogfuel. These quantities are calculated by the simulation model, using allometric equations developed by Lambert et al. [153] and Honer et al. [154], and adapted and provided by FPInnovations personnel. The equations estimate the amount of biomass produced by a certain species of tree of a certain height and diameter (DBH) to determine how much biomass would be available per species on a larger scale. These types of estimates make it possible to determine with reasonable accuracy the amounts (and locations) of forest residues available for harvesting.

An estimated 14 bdmt of residual branches and foliage could be extracted from this sample cutblock. These and the quantities of hardwood materials that have no current market, and the other fuel log materials extracted, there are 34 metric tonnes of residues that could be extracted.

Considerations for site quality and nutrient regeneration have to be taken into account, thus leaving leaves and needles (foliage) on the harvest site, as well as an additional 30% of branches is a necessary assumption. Even so, there are still 19 bdmt of material that could be extracted for bioenergy use from the sample site; whether this is economically feasible will be determined by the simulation models cost calculations.

The simulation of intermediate material amounts extracted from the sample cutblock, are an example of the quantitative capabilities designed into the simulation model, the freedom the model presents to allow the user to create their own simulated forest will allow them to create forest conditions for a large number of forested regions. Thus the simulation model becomes highly adaptable for use in project with different forest resource conditions (natural growth forests, managed forests, forest plantations, etc. they can all be simulated using the model).

5.3.1.2 Simulation model’s biomass cost results

5.3.1.2.1 Cost modeling validation and normalization

In order to verify that the simulation model’s cost outputs are reasonable, they were compared to values reported by the case study mill, for all their harvesting operations in 2010.

Costs for harvested quantities of woodchips from different forest management areas (FMAs) were provided to us, and the simulation model was used to recreate the harvesting of similar forest cutblocks. The harvesting costs of the designed cutblocks along with averaged distances for each FMA to the final customers allowed to recreate the costs in the simulation model.

Comparing several managed cutblocks in different FMAs to the overall costs provided by the mill is a better validation method than comparing a single cutblock, because the case study mill’s data significantly changes from one cutblock to another, and not enough data was provided to be able to evaluate every type of cutblock they harvest. By comparing the overall price, and using averaged cost values on a FMA level lets us compare averaged costs for a large quantity of cutblocks with similar characteristics to the ones we produce with the simulation model. In addition, this validation method allows to “fine tune” the simulation model to the characteristics of each FMA. By using a weighted average cost (quantities harvested in each FMA and their cost) for each simulated FMA, it allows us to calculate the overall cost of all harvesting activities which was then compared to the overall cost of woodchip materials for the P&P mill for 2010; value that was also used to normalized all cost results presented. The original data and results from the simulation are presented in Figure 5-3. Notice that the original data total cost has a value of 1, since it is the value used to normalize.

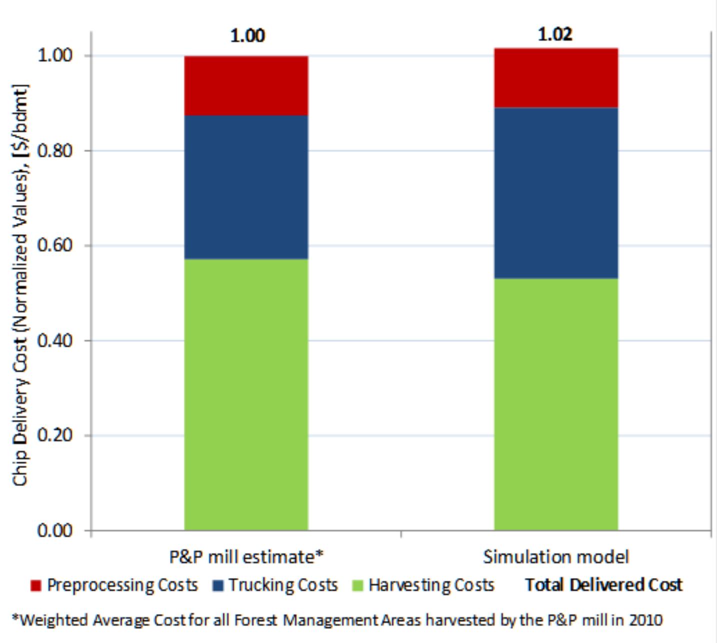


Figure 5-3: Comparison of weighted average chip material costs for all FMAs harvested to satisfy the P&P mill's demand and simulation estimates for the same demand (normalized values)

Differences in costs shown in Figure 5-3, are mostly due to transportation and harvesting. Transportation costs are larger in the simulation because an averaged distance was used to calculate the costs for each FMA, whereas in the original data, these values are specific to each cutblock contained within the FMA. In harvesting, the averaging of multiple cutblocks has the opposite effect when compared to the fewer cutblocks used in the simulation model. Because integrated harvesting is more effective and the simulated forest does not change in productivity, the simulation model underestimates the cost of harvesting activities when compared to the averaged-out cost of harvesting all the cutblocks within a FMA in the original data.

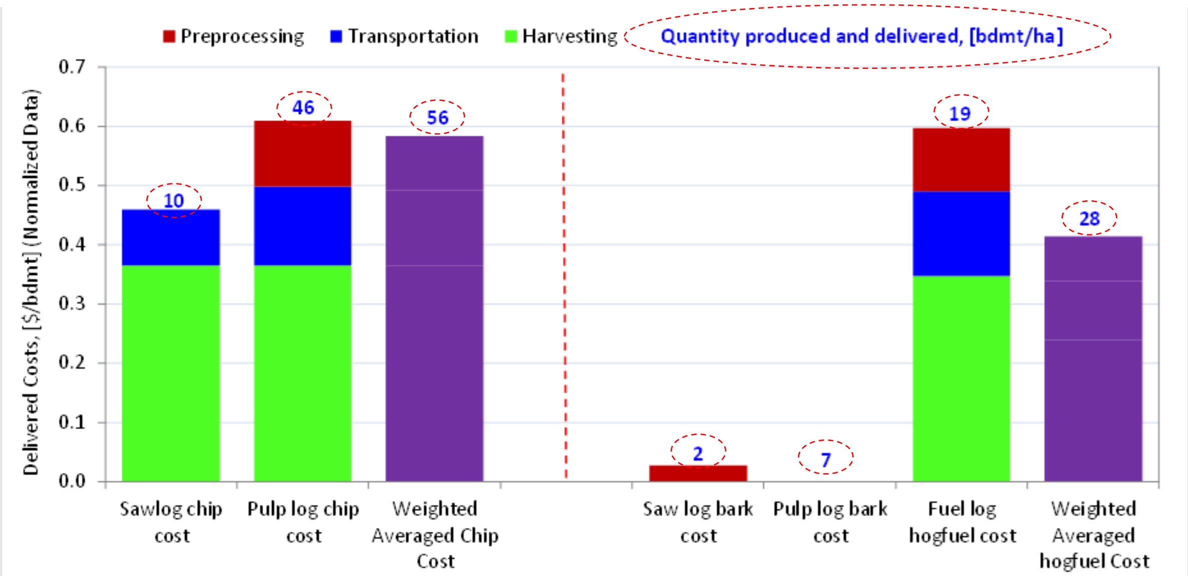
5.3.1.2.2 Characterization of current operations using a sample cutblock

The simulation model also allows for the evaluation (or not) of residual materials from the simulated forest. Many forestry companies lack this type of information because they do not use the residues, and have never sought to know how much is produced or could be produced if a certain cutblock is harvested. Thus when information is requested from students to carry out analyses for these materials, none can be provided. This is where the simulation model again has an advantage, as it not only calculates how much of these residues are produced, but allows to remove them, while leaving behind enough for sustainability purposes, and to calculate the cost of removal and preprocessing of these materials.

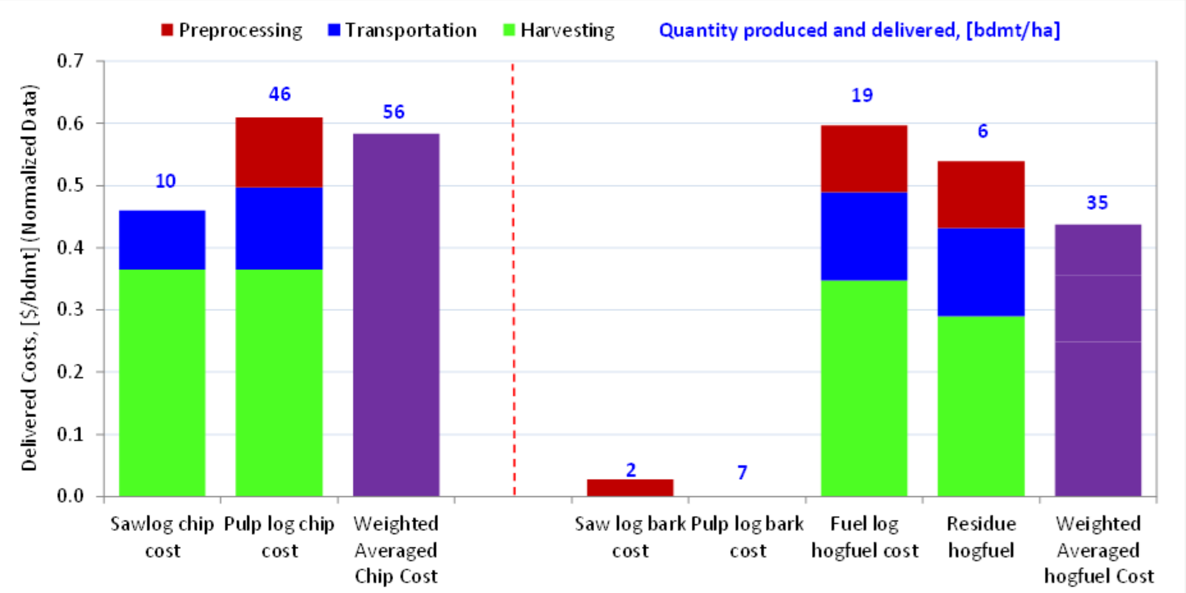
Figure 5-4 compares the harvesting (or not) of residues on the final weighted average cost of hogfuel, which is the final product that forest residues would be converted to if recovered from the cutblock. The two bar graphs show the difference on overall weighted average hogfuel costs per tonne and the quantities procured. The numbers on top of each bar are the quantities of material extracted of each type, while the normalized delivered cost of those quantities is shown in the Y-axis.

Each graph in figure 5-4 is divided into two parts. The left side shows the quantities and costs per tonne for materials procured from the cutblock that will produce woodchips, and the right side shows the materials procured from the cutblock or intermediate locations (from material procured from the cutblock) that will produce hogfuel. The purple bars, are the weighted average cost per tonne for final products (woodchips and hogfuel) derived from the materials.

Of the products converted from materials extracted from the simulated sample cutblock, chips produced from pulp logs are the most expensive, followed closely by hogfuel produced from fuel logs, then hogfuel from residues, and woodchips produced from sawlogs according to Figure 5-4. The current cost allocation method, does not differentiate between the products, and assigns shared costs (such as harvesting cost) equally to each unit produced. Thus the increase cost of some products compared to others comes from transportation and preprocessing since these costs are specific to each product and its destination. Because the pulp mill is farther away from the sawmill (see Figure 4.5) and pulp logs preprocessing cost is higher than the preprocessing cost of sawlogs, the pulp logs will have a higher overall cost compared to sawlogs (and the other products). Hogfuel produced at roadside, as well needs to travel all the way to the P&P mill, therefore it too has a high transportation cost, as well as the added cost of hogging at roadside.



a) Costs of materials extracted from simulated cutblock **without** residue harvesting



b) Costs of materials extracted from simulated cutblock **with** residue harvesting

Figure 5-4: Simulation model costs for products procured from a single cutblock, pre-processed and delivered to P&P mill

Exploring other cost allocation methods that may allow to differentiate between products, could potentially bring about significant savings to both woodchips and hogfuels by redistributing costs to materials that require more of the activities that produce them (costs). Activity-based cost accounting is one of such methods which is described in the next section, and applied to the simulation model to improve upon its cost allocation to materials.

The fibre exchange agreement with sawmills, provides the P&P mill with a lower cost source of woodchips as well as a small portion of low cost hogfuel. This arrangement works well for both parties (win-win), as the sawmills receive sawlogs in exchange for byproducts (chips and residues) produced in their own operations. The benefit for the pulp mill, is that they receive ready-for-process products (chips and hogfuel) without having to incur preprocessing costs (cleaning, debarking, chipping).

The main source of hogfuel according to figure 5-4 (both *a* and *b*) are fuel logs which includes all hardwood log materials produced. The second largest contributor of materials for hogfuel, is actually the bark produced in the P&P mill, followed in figure 5-4*b* by residues. The cost per tonne of byproduct barks from mills, is significantly lower than all the other materials as they have none of harvesting costs associated to them. In the case of sawlog bark, there is a small representative fee that is paid to the sawmill to cover transportation and some of the preprocessing costs. Barks produced at the P&P mill are free as described in section 3.2.5. The importance of these bark materials produced in mills, is that due to their low cost, they help lower the overall weighted average cost of hogfuel for the P&P mill. In addition it shows how the integrated procurement for both products (woodchips and hogfuel) produces cost reductions that would not be present if activities were carried out separately.

When the weighted average hogfuel costs of 5-4*a*. and 5-4*b*. are compared to one another, they show that residues are actually increasing the weighted average cost of hogfuel for the mill; therefore currently it would not be advisable to gather and process residues from harvesting activities due to the increased cost. The high cost of collecting residues from the forest is most likely to blame because the CTL system is not designed to gather these residues. It would be recommended that if the mill is interested in collecting residues, they change to another harvesting system that may allow for the collection of residues at a lower cost.

5.3.1.3 Sensitivity analyses to changes in input parameters

To test how the simulation model reacts to changes in several input parameters, a sensitivity analysis was carried out for 4 input parameters: harvesting system productivity, percentage of hardwoods in the cutblock, tree diameter (dbh) and tree height. For each of the 4 parameters studied, values were increased/decreased in order to observe the changes in the cost and quantity results. One parameter was done at a time, while everything else in the simulation remained the same. The impact of changes in input parameters was measure both in terms of quantities of products produced, as well as the cost of those products, produced from the materials extracted from the sample cutblock. Figures 5-5*a* and 5-5*b* show results for quantities extracted of woodchips and hogfuel respectively, while figures 5-5*c* and 5-5*d* present the costs for those products.

Tree height and tree diameter (dbh) (average values for the cutblock) are important parameters to analyze, as they always vary from one cutblock to another. Figures 5-5*a* and 5-5*b* indicate, that of the two parameters a change in the tree's dbh creates a much larger impact on the total materials extracted from the stand than does the tree's height. In fact, as figures 5-5*c* and 5-5*d* show, an increase in the tree's dbh also has a significant impact in decreasing the cost per unit of materials extracted, due to the larger quantities of higher value wood products (i.e. sawlogs) that are produced. This will ultimately lower the cost of woodchips and because of the added production of low costs barks produced from the mills, the cost of hogfuel is also reduced.

The percentage of hardwoods present in a cutblock have an inverse effect on the production of woodchips because neither the sawmills nor the pulp mill uses hardwoods for chip production. This means that all hardwoods are used for hogfuel and therefore as shown by figure 5-5*b* an increase in the percent of hardwoods present in the cutblock will increase the amount of hogfuel produced.

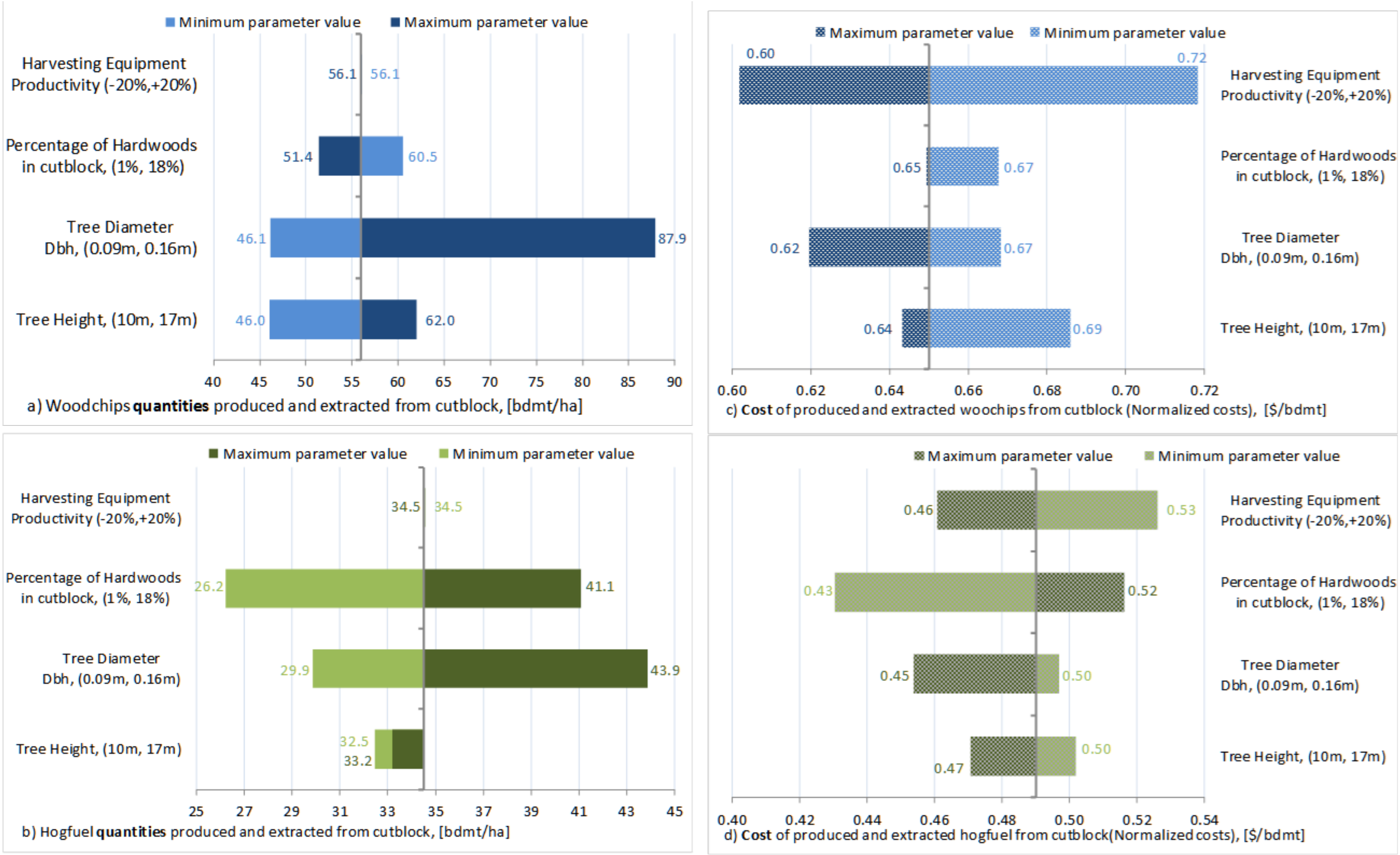


Figure 5-5: Sensitivity analyses for the developed simulation model, testing their effects on quantities of materials extracted, and costs for both hogfuel and woodchips

However, more importantly, a decrease in the percentage of hardwoods in a cutblock, will have a larger effect on the cost of hogfuel than an increase would have as shown in figure 5-5*d*. An increase from 9% to 18% hardwoods will increase the cost by 6%, whereas a decrease from 9% to 1% will decrease the cost of hogfuel by 12%. Two factors within the supply chain are causing this effect. The first, is the lower amount of hardwood logs that are being extracted from the cutblock. Remember from figure 5-4 that hogfuel produced from fuel logs is the highest cost hogfuel from the cutblock. At the same time, because a decrease in hardwoods means an increase in softwoods there will be an increase in the amount of woodchips materials produced (as shown in figure 5-5*a*) which in turn produces a larger quantity of lower cost barks that also decrease the overall cost of hogfuel.

Finally changes in harvesting system productivity as shown in figure 5-5*c* have the largest effect on woodchip costs due to the lower time it takes to harvest and extract the material. This of course lowers the cost per unit of machinery, labour, etc., which ultimately is reflected on woodchip costs. Productivity changes don’t change the quantities of materials being extracted, only the time it takes to harvest the cutblock. Seen from the harvest of a single cutblock, this does not seem to be an important parameter, but when a much larger network with multiple cutblocks is considered, a higher harvesting productivity means more cutblocks can be harvested per year by each contractor. This is good for the customers as well as the contractors doing the harvesting, therefore it is a parameter that should be considered in the analysis of a much larger system.

However, before examining a much larger system involving multiple cutblocks, it will be necessary to improve the simulation model’s cost allocation method by including activity-based costing, and then use this new method to analyze alternative harvesting systems which could potentially reduce the procurement costs of residues.

5.3.1.4 Conclusions

The proposed simulation model framework developed a forest model that takes into account all the operational level activities involved in the harvesting of a forest cutblock. By using a case study procurement supply chain, we were able to both mimic a forest harvesting activities as well as create a virtual forest cutblock that allows the user to introduce enough variability into the simulation model to create multiple types of forests. This will help in future studies analyze how different harvesting systems may react to different harvesting conditions.

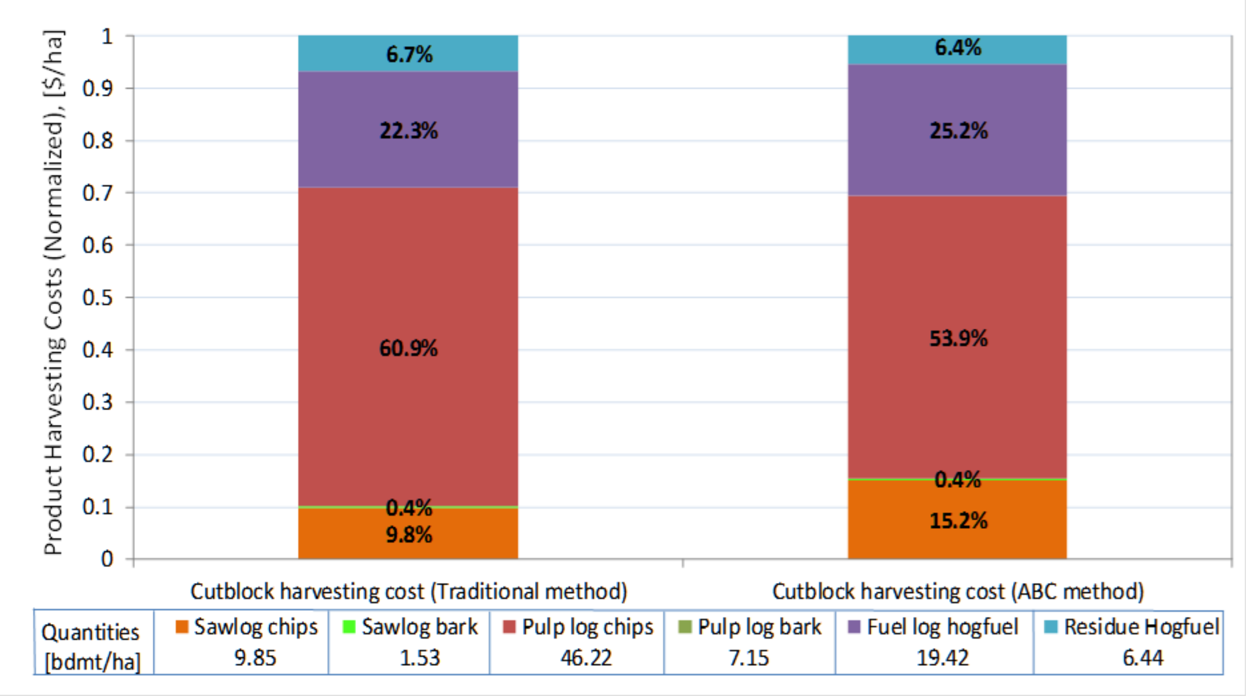
Using the developed model we were able to effectively evaluate traditional harvesting activities involving multiple types of mills in a supply chain, producing and exchanging different materials for the required products at the P&P mill. The simulation model results, showed how integrated harvesting of materials for the production of both woodchip and hogfuel is beneficial for both products, as the by-products created in the intermediate mills, allow for reductions in the overall cost of hogfuels, while the sharing of harvesting costs between more materials, helps bring down the cost for all. The sensitivity analysis carried out also helped reaffirm the interconnection that all the harvested materials have, and their effects on the quantities and costs of one another, when changes occur in the characteristics of the forest.

The result of this, is the completion of the first sub-objective of this thesis, as well as the confirmation of the first sub-hypothesis.

Forest residue collection however was found to be causing negative effects on the overall cost of hogfuel materials due to high costs of collection in the forest, and thus we must examine other harvesting systems that may aid in decreasing their costs.

5.3.2 ABC accounting to improve product costs

Activity-based costing (ABC) is a method commonly used to improve the accuracy and traceability of product cost data by identifying the activities that generate costs, and linking them to the products they produced by way of activity drivers. This in turn, redistributes many indirect costs into the products that actually produce them (by way of activities), increasing some product costs, and decreasing others. It is important to note that seen from an overall cutblock total cost standpoint, the total cost of extraction of all materials does not change (i.e. the cost per cutblock); what changes is the individual unit cost (cost per dry tonne of each material). The comparison made in Figure 5-6 exemplifies this by comparing results of the original cost allocation method for each product, to the new ABC accounting method for each product.



Quantities [bdmt/ha]	🟧 Sawlog chips	🟩 Sawlog bark	🟥 Pulp log chips	🟩 Pulp log bark	🟪 Fuel log hogfuel	🟦 Residue Hogfuel
	9.85	1.53	46.22	7.15	19.42	6.44

Figure 5-6: Comparison of stacked product costs extracted from the sample cutblock using a traditional cost allocation method and an ABC method

This comparison of both allocation methods is done of course before any changes are made to the procurement supply chains to decrease activities identified by ABC as non-productive, or activities with very high production costs. Figure 5-6 presents the results for the total product costs extracted from the cutblock using the traditional cost allocation method, and the ABC method. In addition to the cost information provided by the bar graphs in Figure 5-6, the quantities of materials extracted are also specified at the bottom of the figure. These quantities are for both cost accounting methods, as they do not change.

The differences lie in the individual product costs. The percentages shown in Figure 5-6 are the percentage of the total cutblock harvesting cost contributed by each product's total cost[18]. There are noticeable changes in the main material costs (sawlogs, pulp logs, and fuel logs), mainly, the proportion of cost increasing for sawlogs and fuel logs, while the pulp log costs decrease. In the ABC cost method bar, pulp logs are still shown to be the highest cost contributor due in part to

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[18] Product's total cost refers to the total tonnes of each intermediate material extracted from the cutblock, multiplied by the costs of harvesting, transport and preprocessing to convert them to the final product.

the large quantity of pulp log material extracted from the cutblock, nevertheless other materials now have a higher contribution due to the reassignment of indirect costs done by ABC.

What ABC also allows us to do, is trace all product costs back to the activities that originally produced them. A cost breakdown per product extracted from the cutblock is represented in Figure 5-7.

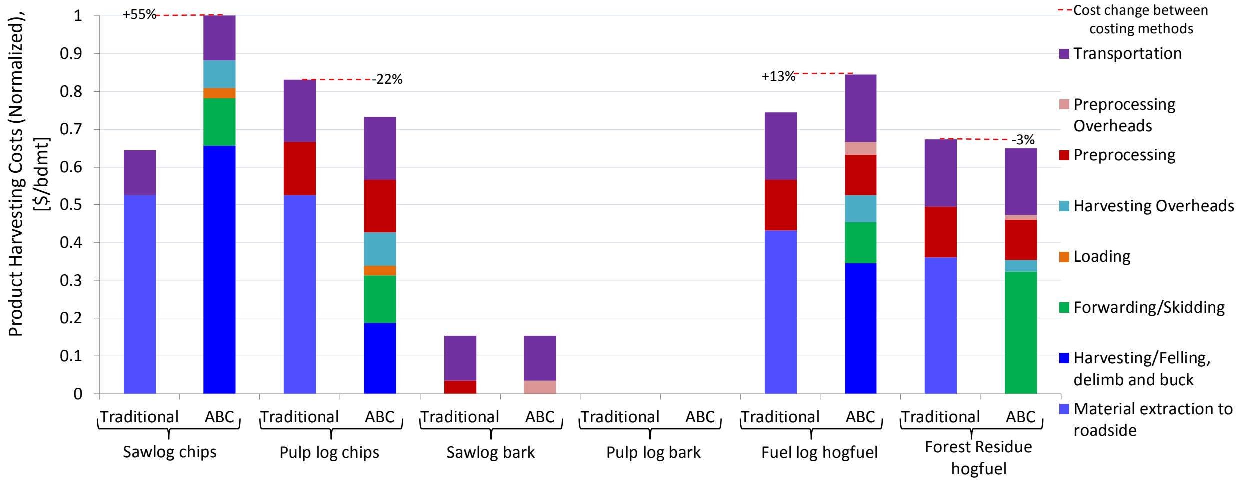

Figure 5-7: Costs breakdown for all products produced from materials extracted from the cutblock using the traditional and ABC methodology

Because the traditional cost accounting method does not breakdown individual costs for the processes being carried out in the forest, the combined harvesting, forwarding, loading and harvesting overhead costs are identified separately in the legend as “material extraction to roadside” for the traditional cost allocation method.

Identified in Figure 5-7 with a dashed line, is the cost change percentage between the traditional and ABC method for each product. This percentage indicates the degree by which the total product cost changed when ABC was applied to the model.

The sawlog chip cost was the most radically altered, which increased by 55% of the original cost, mostly due to a reallocation of indirect costs within harvesting costs. This occurs because ABC does not use the quantities produced to allocate cost, but rather uses the harvesting productivity for each material[19] produced (cost driver) to assign costs to activities and processes creating an

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[19] Harvesting productivity of each material: rate at which each material is produced individually considering each machines overall productivity. E.g. is the overall machine productivity is 10 bdmt/hour, then ABC determines which

inverse relationship between costs and productivity. Only when assigning activity costs to materials (cost objects) does it use the quantities produced as an activity driver. The overall effect in harvesting, is that the higher the material's harvested productivity (i.e. material produced per tree) the lower the materials harvesting cost. This of course greatly benefits pulp logs as they have a much higher production ratio than all other materials (sawlogs, fuel logs and residues) in this particular cutblock.

Sawlog and pulp log barks produced at the mills, have already been shown to have a very low production cost. With ABC, this low (or null) cost is maintained. Only for sawlog bark is there a cost shown to be associated to transport, since bark produced at the sawmill needs to be transferred to the pulp mill in a separate trailer, this cost is exclusive to the bark, and cannot be reassigned. Not so in the case of pulp log bark, since the pulp logs are transported to the pulp mill and afterwards separated into chips and bark, so all of the transport and processing costs can be assigned to the chips.

The cost of forest residue hogfuel has the lowest overall change in cost using ABC (only decreases by 3%), but it benefits from the methods added level of detail to activities being carried out. The ABC method shows that most of the cost for forest residue harvesting is coming from forwarding activities (i.e. picking up material from the forest floor, and taking it to roadside to be processed). This is due to a number of factors, such as the low bulk density of forest residues which means less material can be carried per trip in the forwarder; or the added time the equipment must spend picking up smaller branches and tops in the forest which increases the cost. Thus, if harvesting residues are required, than reducing forwarding costs is of importance.

5.3.2.1 Alternative Harvesting Systems Simulation

With the inclusion of ABC methodology into the simulation model, it has allowed us to breakdown individual costs for each material extracted from a cutblock, and redistribute indirect costs to better represent the actual usage of equipment and activities that produce our final products. This led to discover that forest residue recovery from the forest using CTL is not an

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materials use more activities to be produced, and then assigns the cost produced by the overall productivity according to those activities.

economically viable process due to the high costs associated with forwarding the bulky materials to roadside.

Therefore the evaluation of alternative harvesting systems that seek to reduce overall procurement costs for all materials extracted from the forest cutblock is needed. As described previously (section 3.2.4), 3 alternative harvesting systems were evaluated to determine whether they can improve procurement cost for all materials including forest residues: the full-tree (FT) system, a feller-buncher with the cut-to-length (FB-CTL) system and a cut-to-length with a forwarder-mounted chipper (Chipper-CTL). Results of the harvesting systems comparison using the ABC method are presented in Figures 5-8 and 5-9.

Figure 5-8 presents the comparison of all harvesting system alternatives for the total delivered costs of products produced from materials extracted from the sample cutblock, and the breakdown of their costs according to the ABC method. Examining the cost for saw and pulp log chips in Figure 5-8, will show that neither the FB-CTL and Chipper-CTL alternative harvesting systems improve on the final product cost.

FB-CTL may provide a higher rate of harvesting (i.e. increased productivity), however that comes at an increased cost per tonne, which limits its usefulness when compared to the standard CTL system. However, a trade-off between cost and harvest productivity might be of interest to contractors hired to harvest stands which have a limited time-frame in which to carry out the operations, or to those that are bottlenecked by the lower productivities of the CTL system. The chipper-CTL harvesting system apparently does not increase the cost of harvesting saw or pulp log for chips; but the increased cost of operating the forwarder-mounted mobile chipper make the collection of fuel logs for hogfuel 12% more expensive than the current CTL method (Figure 5-8, fuel log hogfuel bars). These results for the Chipper-CTL are a result of the increased capital costs of the mobile chipper and need for multiple chip bins for a single system. It makes the harvesting system too expensive to operate when compared to the other systems. It does however reduce the cost of residue collection by 15% (compared to the CTL system cost for harvesting residues).

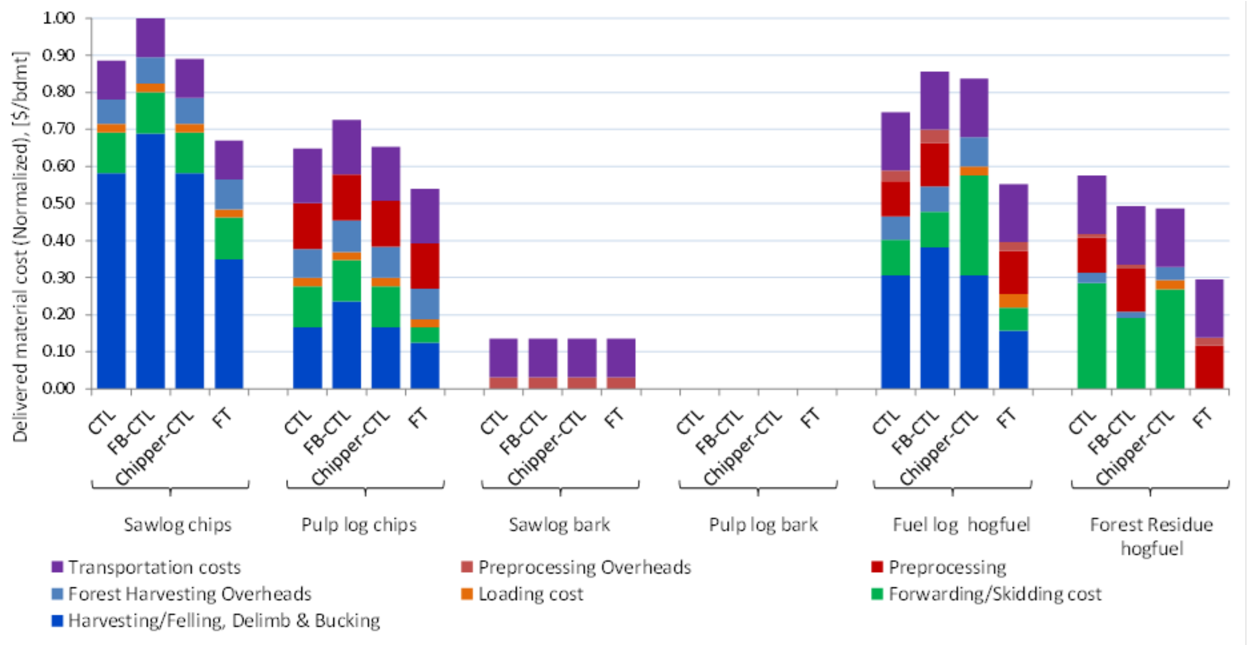
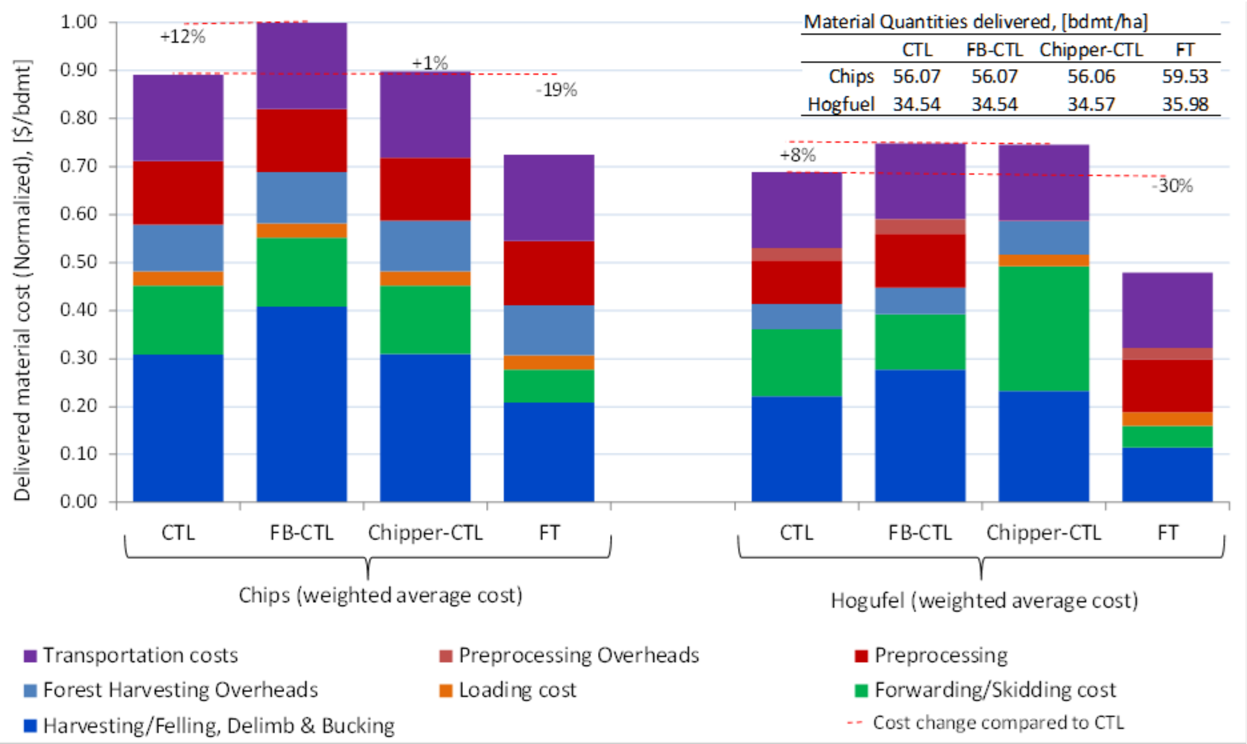


Figure 5-8: Alternative harvesting systems comparison of total costs per product using ABC

The full-tree harvesting system alternative is, as shown in figure 5-8, the lowest cost alternative for the integrated harvest of chips and hogfuel materials from the cutblock. In all materials shown in figure 5-8, it shows a significant reduction in both harvesting and forwarding/skidding costs. In residue collection, because the whole trees are skidded out of the forest before being processed, residues have no added cost of forwarding, which significantly reduces their cost as compared to the other alternatives. One of the main reductions made by the full-tree harvesting system, is in skidding, when compared to forwarding. In forwarding, every tree section must be loaded onto the forwarder and hauled to roadside, while in skidding, the complete tree is dragged to roadside, with less effort than what it takes to have all the material placed onto the equipment. This allows for heavier loads to be skidded rather than forwarded, and thus reduces the cost of this activity.

Once the individual costs for each material are estimated using the ABC method in Figure 5-8, they are then combined to produce a single cost (i.e. weighted average cost) for chips and a single cost for hogfuel in Figure 5-9 as would be done to determine the weighted average costs of the cutblock. The weighted average costs of chips is composed of both sawlog and pulp log chips, while the weighted average hogfuel cost is composed of both sawlog and pulp log bark, fuel logs and forest residues. The total quantities of each material extracted and delivered to the P&P mill by each harvesting system are also shown in Figure 5-9. The percentages next to the dotted lines represent the cost change of the harvesting system compared to the original CTL for each particular material.



Material Quantities delivered, [bdmt/ha]

	CTL	FB-CTL	Chipper-CTL	FT
Chips	56.07	56.07	56.06	59.53
Hogfuel	34.54	34.54	34.57	35.98

Figure 5-9: Comparison of alternative harvesting systems weighted average total costs for final delivered chip and hogfuel materials to P&P mill.

The FT harvesting system is the one with the lowest costs for both chips and hogfuel, showing a cost reduction of 19% for chips and a 30% reduction in cost for hogfuel. Particularly in hogfuel, the decrease in cost is not only due to the lower cost of the harvesting system, but as well as the quantities of sawlog and pulp log bark which help bring down the average cost of hogfuel.

In addition to the lower harvesting costs, Figure 5-9 also shows that there is a small increase in the quantities of materials extracted from the cutblock using the FT system. This is due to the fact that the entire tree is taken to roadside before any de-limbing or bucking is carried out, meaning that all the logs are extracted from the field. In the other 3 methods, the simulation model requires that the forwarders capacity be at least 80% full, otherwise the materials become too expensive to remove from the forest floor.

The costs for the Chipper-CTL system were supposed to reduce the cost of hogfuel while allowing for the economical removal of saw and pulp logs, however, due to the very high costs (both capital and operational) of the forwarder-mounted chipper, the system is not viable under the current conditions.

Finally the comparison of the FB-CTL appears to show that this method is unfeasible as well, due to high harvesting costs presented in figure 5-8. However, one would argue that the study cannot completely determine this system as unfeasible since the FB-CTL system provides an increase capacity for a contractor to harvest more cutblocks over a given timeframe. A larger analysis would need to be conducted which includes the harvesting of multiple cutblocks over a specific time horizon in order to determine if the higher costs of delivered materials are offset by the increased amount of cutblocks harvested.

5.3.2.2 Conclusions

The purpose of the implementation of activity-based cost (ABC) methods to the existing forest simulation model, was to enhance the understanding of the cost structure of products produced from materials extracted from a cutblock. This cost allocation method, improves on the current simulation model, giving a larger visibility and traceability to the biomass procurement supply chain.

With the developed simulation model, forest managers can check the profitability of a prospective operation under different working conditions and assess the competitiveness of alternative harvesting systems. Using this type of cost allocation systems combined with simulation models, it is possible to predict the costs of harvesting particular cutblocks using several harvesting systems (or contractors that use different harvesting systems), which can then be used to create harvesting schedules that assign the best system to a cutblock, thereby assisting in the reduction of overall harvesting costs for an entire procurement network. The ABC method, also allows for the re-allocation of costs to more accurately represent the costs involved in a joint-harvesting operation of multiple materials, which if products are delivered to different customers, may change the internal cost distribution.

With this new cost allocation method, and the application of the simulation model to include different types of harvesting systems, the second sub-objective of this thesis has been completed.

5.3.2.3 Implementing the simulation model to create a biomass procurement network

With the design and testing of the simulation model completed, the model can now be used to simulate the much larger biomass procurement network which will supply the P&P mill with feedstock resources over the lifespan of the biorefinery project. The network characteristics were explained in section 4.4, and a map of the region selected was illustrated in Figure 4.7. The simulation model created 600 different cutblocks, spread across the region. In each cutblock 10 intermediate materials were harvested:

- Spruce sawlogs, pulp logs, and fuel logs;
- Fir sawlogs, pulp logs, and fuel logs;
- Hardwood sawlogs, pulp logs, and fuel logs;
- and mixed forestry residues.

These products were harvested using one of 3 harvesting systems (CTL, FB-CTL or FT). The Chipper-CTL harvesting system evaluated in the previous section was not included in the optimization model because as shown previously, the capital cost of the system makes it uneconomic to run when compared to the others.

A total of 20 contractor crews were assumed to be available to harvest materials in the procurement network, each utilizing one of the 3 harvesting systems, and each having their own individual productivity and system configuration.

Transportation costs from each cutblock to each one of the 3 sawmills, the storage depot, and the pulp mill log yard were calculated as well to allow the optimization model to selected the where to send each material, or to keep it in storage.

5.3.3 Optimization of the current mill’s biomass procurement network

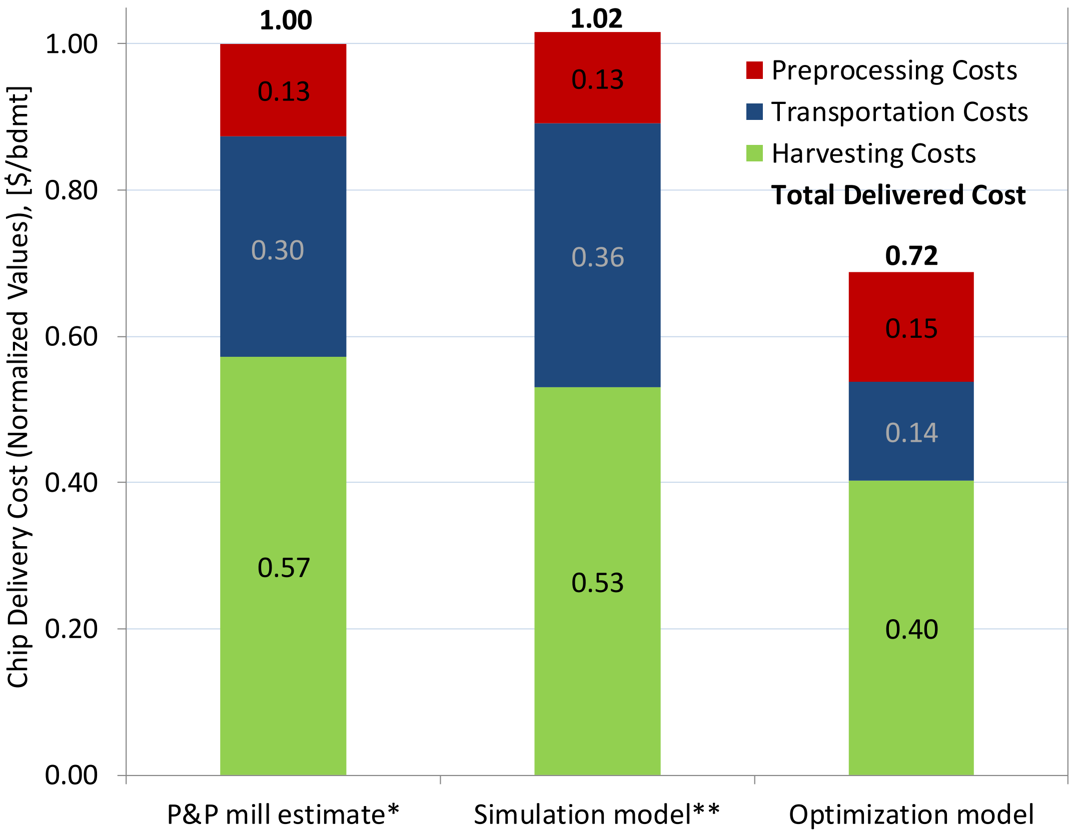
The characteristics and input parameters of the current P&P mill for the optimization model, are presented in Table 5.2.

Table 5.2: Input information for the optimization of the P&P mill’s current operations

	UNITS	VALUE
Pulp & Paper mill's yearly material requirements		
Spruce woodchips required for TMP process	[bdmt/year]	117,600
Fir woodchips required for TMP process	[bdmt/year]	122,400
Biomass boiler hogfuel requirements	[bdmt/year]	50,000
Total optimization time horizon	[years]	20
Optimization run time horizon	[years]	5
Number of optimization runs to complete an optimization scenario		4
Number of cutblocks in database		600
Total number of hectares in database	[ha]	55,927
Initial number of available crews using CTL harvesting		10
Initial number of available crews using FB-CTL harvesting		10
Initial number of available crews using full-tree harvesting		0
% of crews that change to full-tree harvesting in year 6	[%]	50%
% of crews that change to full-tree harvesting in year 11	[%]	100%
Distance from P&P mill to Sawmill 1	[km]	118
Maximum exchange amount with sawmill 1	[bdmt/year]	2,500
Distance from P&P mill to Sawmill 2	[km]	384
Maximum exchange amount with sawmill 2	[bdmt/year]	1,000
Distance from P&P mill to Sawmill 3	[km]	496
Maximum exchange amount with sawmill 3	[bdmt/year]	30,000

5.3.3.1.1 Validation, Normalization and comparison of the optimized data for a single year

Following the same methodology that was carried out to normalize data in the simulation model (see section 5.3.1.2.1 and Figure 5-3), cost data results from the optimization model were also normalized using the same original data, and are presented along in Figure 5-10 along with the original and the simulation data.



*Weighted Average Cost for all Forest Management Areas harvested by the P&P mill in 2010

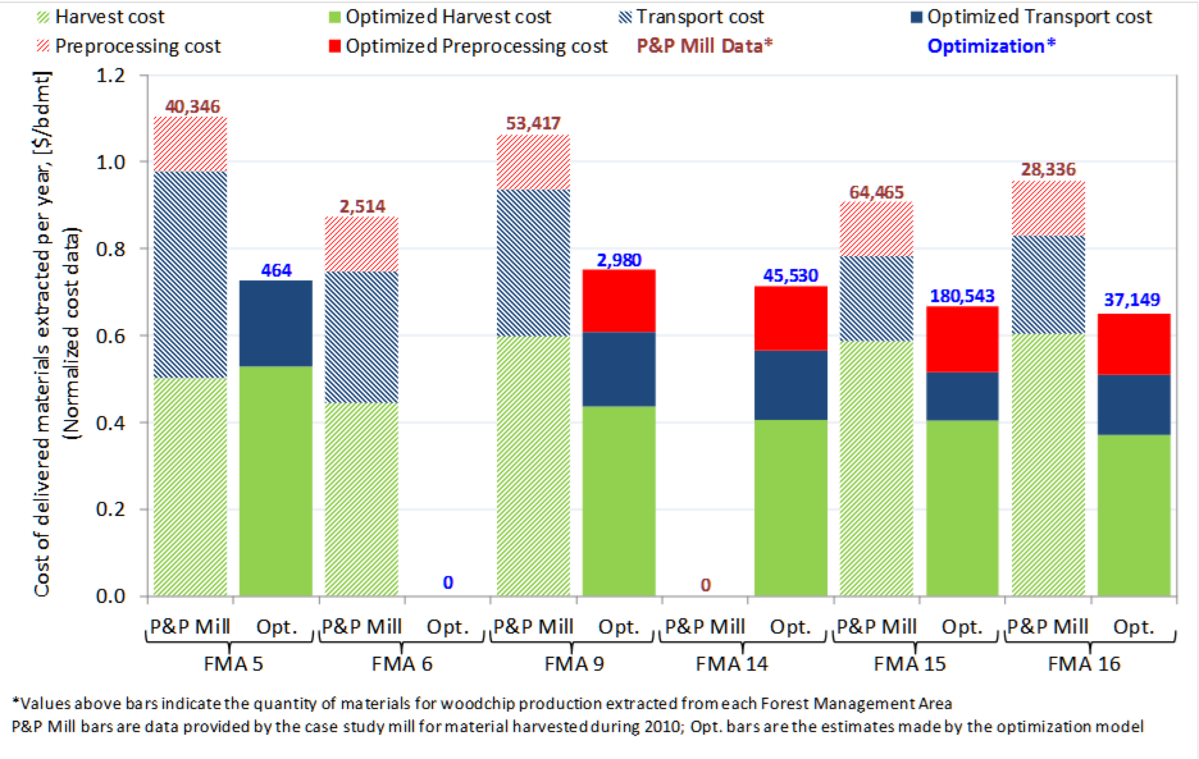
Figure 5-10: Comparison of weighted average chip material costs for all cutblocks harvested to fulfill the P&P mill's demand.

Figure 5-10 show the comparison of the total delivered chip costs to the P&P mill as calculated by the optimization model, the simulation model and the P&P mill's annual total delivered woodchip costs for the year 2010 which was also used as the value of 1 for the normalization. The cost information provided by the P&P mill and the cost derived from the simulation model are both single year based. Thus, a single year cost result is also drawn from the optimization model to validate the model and to compare the results. Any of the first 5 years of the optimization could be used to compare the results. After year 5 the changes made to the harvesting systems available, create a difference with the original data, therefore they cannot be used in this comparison. Year 3 was selected as an example year.

The optimization model differs from the simulation because it searches for the most cost effective way of procuring material for the P&P mill. It seeks out the best solutions to reduce the overall procurement costs. In Figure 5-10, the optimization model accomplishes a reduction in overall chip costs by 28%. Not only does the optimization modeling approach demonstrate the significant cost reduction, but it also confirms that the model is accomplishing its goal.

Coming back to the optimization data represented in figure 5-10, harvesting and transportation seem to be the two main areas where the optimization model is creating a reduction in costs, as compared to the original data. In fact, there is a slight increase in preprocessing costs (from 0.13 $/bdmt in the mill data to 0.15 $/bdmt in the optimization) most likely caused by sending more logs to the P&P mill for woodchip processing instead of sending them to the sawmills and other intermediate locations, that although increases preprocessing cost, reduced the shipment cost significantly.

A lower level visualization of the information presented in Figure 5-10 is shown in Figure 5-11, where the cost information for year 3 of the optimization model is broken down into the different forest management areas (FMAs) harvested by the mill for both the original data and the optimization solution.



*Values above bars indicate the quantity of materials for woodchip production extracted from each Forest Management Area
P&P Mill bars are data provided by the case study mill for material harvested during 2010; Opt. bars are the estimates made by the optimization model

Figure 5-11: Comparison of material costs and quantities extracted from each FMA for woodchip production

The faded bars in Figure 5-11 represent the data provided by the mill, while the solid color bars represent data calculated by the optimization model. Each color in the bar is the average cost for that particular activity in that particular FMA, while the numbers on top of the bars are the total amounts of materials procured from each FMA during year 3 of the optimization or 2010 for the original mill data.

The results show that the optimization model is reassigning the harvesting activities to different FMAs according to the P&P mills feedstock demands, thus it is also re-planning the material transportation and preprocessing activities, to significantly reduce biomass procurement cost in all FMAs.

In FMA 5, the preprocessing cost obtained from the optimization model is reduced down to zero indicating that all the materials harvested from this FMA are to be delivered to the sawmills to avoid additional preprocessing costs. The increase in the harvesting cost from the optimization model (in FMA 5) implies that more materials are to be harvested than what was actually harvested by the mill, subject to the availability of the material. In FMA 6, the total procurement cost from the optimization model is zero indicating that despite the P&P mill’s decision to harvest in this FMA, the optimization model suggests not to harvest materials from this FMA during this particular year. In FMA 14, the actual mill procurement cost from this FMA is zero indicating that no harvesting activities were carried out in this FMA, and thus no shipment and preprocessing costs are associated to the materials from this FMA during the year. Nevertheless, the optimization model suggests that it is economically beneficial to harvest from FMA 14, instead of FMA 6.

The values on top of each bar in Figure 5-11, represent the total quantities of materials extracted from each FMA that will be used to produce woodchips. FMA 15 presents a significant increase in the amounts of materials extracted because it is the closest to the P&P mill. On the opposite end, amounts harvested from FMA 5 should be reduced to around 1% of what was harvested by the mill according to results of the optimization, to reduce transportation costs. The optimization model along with increasing the extraction of material closer to the mill, also increases quantities of materials extracted from areas where the mill was not extracting material from, as is the case for FMA14 while material extraction from FMA 6 was reduced to zero.

From Figure 5-11, it's easy to observe that FMAs 5, 6 and 9, have the highest pre-optimization overall procurement costs, which are in part due to them having the highest transportation costs as they are the areas farthest away from the mill. The optimized costs show that harvesting from these areas was significantly reduced, to avoid high transportation costs; at the same time, harvesting from FMAs closest to the mill (FMA 14, 15, 16) was increased to take advantage of the lower transportation costs. In spite of the increased harvesting of FMAs in close proximity to the mill, because the supply of materials from the forest is much larger than the demand from the mills, a sustainable supply can be provided over each 5-year modeled plan, and over the overall 20-year planning horizon evaluated.

As an example of the results from the optimization model for a year, Figure 5-12 illustrates the flow of materials in year 3 for all final products transferred from intermediate locations over to the final customers, while Table 5.3 summarizes key results to be used as guidelines for upcoming decision making process. Of course these results are an example of the information provided by the optimization model, and the same information can be extracted for all 20 years, with much more detail (selected cutblocks, intermediate locations, flows and costs from each location, etc.) if needed. But for the purposes of this thesis, it would be impractical to show all levels of details for all 20 years.

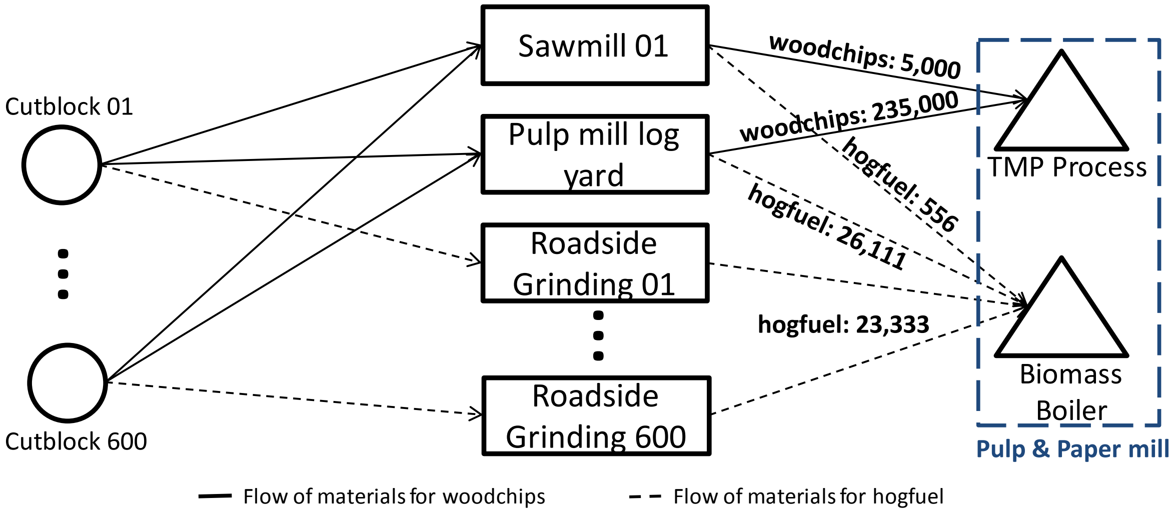


Figure 5-12: Flow of materials to final customers during year 3 of the optimized harvest

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Table 5.3: Key results for year 3 of the optimized harvesting network

	UNITS	VALUE
Number of sawmills used to exchange material		1
Amount of chips provided by sawmills	[bdmt/year]	5,000
Number of contractor crews used		15
Total area harvested	[ha/year]	4,567
Largest amount of hectares assigned to single contractor	[ha/year]	700
Smallest amount of hectares assigned to single contractor	[ha/year]	173
Percentage of hogfuel demand procured from the sawmills	[%]	1.1
Percentage of hogfuel demand procured from the P&P mill log yard	[%]	52

Figure 5-12 and Table 5.3 show that the optimization model only uses one of the three sawmills, with which it exchanges fibre. This sawmill is the closest one to the P&P mill while the other two were not used over the 20-years planning horizon because cheaper woodchips are available elsewhere. This, gives the P&P mill an advantage in contract negotiations with the sawmills if the wish to participate. The sawmills need to provide additional benefit to the P&P mill if they wish to participate in the fibre exchange. One of the unused sawmills is located in a FMA where the company (P&P) has no harvesting activities (or land). The other unused sawmill is located on the outskirts of FMA 5, where the company has little harvesting activities during year 3 (after the optimization). In both cases, agreements could be reached to provide additional woodchips or hogfuel at a reduced cost to the pulp mill, or some other benefit.

The quantity of material exchanged at the sawmill closest to the P&P mill was maximized by the optimization model. A sensitivity analysis was carried out to determine the impacts of changing the exchange limit. The result shows that as the exchange limit increases, the exchanged amount increases linearly up to the exchange limit. This result implies that given the lowest cost option of exchange program for the P&P mill procurement strategy, the optimization model would continuously maximize the exchanged amount subject to the exchange limit.

The storage depot, on the other hand, was not used due to its much higher unit preprocessing and storage costs, along with added unloading, handling and reloading costs. Hogfuel product produced at the storage depot has the highest cost due to these additional costs, and therefore is always avoided by the optimization model. In reality, the P&P mill stopped using the storage depot recently due to this very issue, preferring to process material either at cutblock roadside, or at the P&P mill log yard.

Hogfuels are suggested to be procured from two major sources by the optimization model, the intermediate roadside locations from materials not used for woodchip production, and the P&P mill log yard for processing residues during the chip production. In addition a smaller quantity of hogfuels is supplied from the sawmill as shown in Figure 5-12. Figure 5-13, shows a breakdown of the materials used by the optimization model for hogfuel production in year 3.

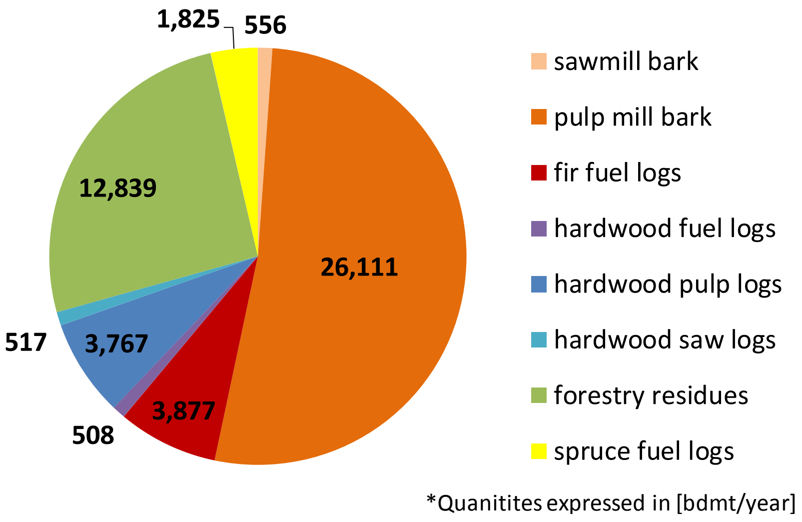


Figure 5-13: Optimized material types and quantities used for the production of hogfuel in Year 3

The bark residues produced at the P&P mill and considered to be “free” compose almost half of the material used by the biomass boiler as hogfuel, the second largest material used for hogfuel, are forest residues. Forestry residues have a lower cost than many of the other materials that can be used as hogfuel, because they are considered a by-product of harvesting operations, and therefore none of the costs from harvesting are assigned to them. These residues still require preprocessing (i.e. grinding) and transportation to the P&P mill which do have a cost associated to the final hogfuel produced.

5.3.3.1.2 Optimization results analysis for multiple years.

Figure 5-14 shows the integrated procurement costs of both woodchips and hogfuels estimated by the optimization model over the 20-year planning horizon. Inflation was not taken into account in these results. The business-as-usual chip and hogfuel costs are derived from the optimization model, in which the same harvesting systems is assumed to be used throughout the 20-year planning horizon. These costs are compared with those in which contractors change their harvesting system over to a full-tree harvesting system as described in the model formulation.

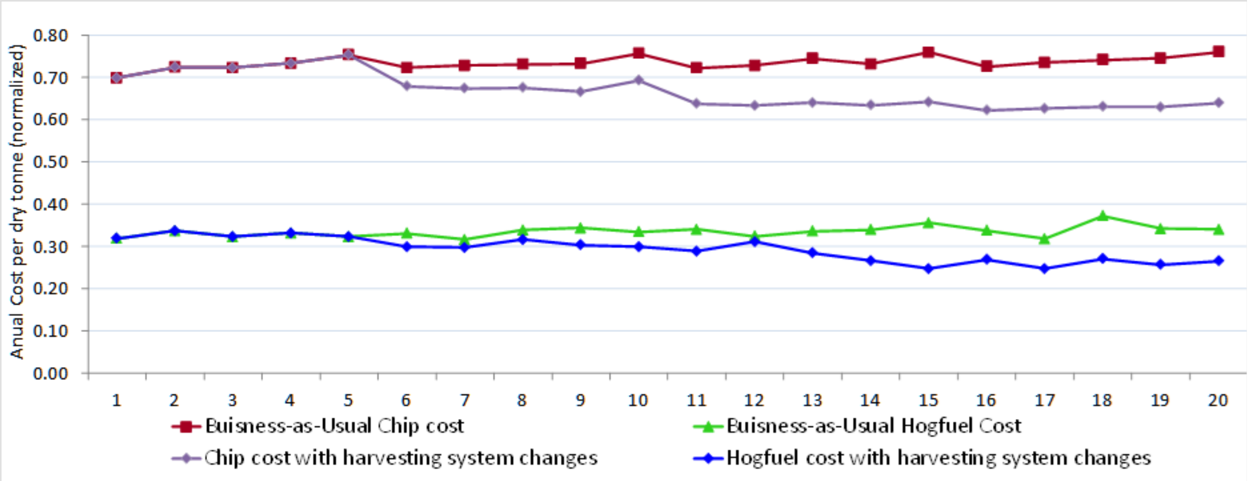


Figure 5-14: Optimized chip and hogfuel costs for the P&P mill with and without harvesting system changes in years 6 and 11.

As shown in Figure 5-14, in the business-as-usual scenario, the costs of both woodchips and hogfuel tend to stay relatively constant, with small increases over time. These small cost increases are most likely due to the fact that as the lower cost materials/cutblocks are harvested during the earlier years. The contractors must move farther away, or harvest higher cost cutblocks (which may have lower quantities of required materials).

Carrying out the harvesting system changes from CTL and FB-CTL to a FT in years 6 and 11, noticeable woodchip and hogfuel cost reductions can be observed at the end of those years. This trend manages to offset the increases caused by the consumption of the lowest cost materials/cutblocks, and reduce the overall cost of materials by the end of the 20-year planning horizon by 12% for woodchips and 7.5% for hogfuel, when compared to the optimized overall costs, without the harvesting system change. The Y-axis in Figure 5-14, shows cost data for the optimization runs still normalized to the un-optimized P&P mill data, therefore the final 20-year value of 0.64 (i.e. a reduction of 36%) for woodchips represents the aggregate cost reductions due to the effects of both the optimization model's re-structuring of the logistical harvesting network and stand selection, as well as the cost reductions caused by the harvesting system change.

5.3.3.1.3 Conclusions

Results show that an optimization model that allows for the study of a large biomass procurement system for the delivery of multiple biomass products (i.e. woodchips and hogfuel) with the use of lower level tactical and operational data, can provide useful information for decision-makers. The use of a forest harvesting simulation model that mimics the characteristics of the real forest, has proven to be an effective tool. When forest data for analysis is not available, and especially when evaluating harvesting systems, or procurement scenarios does not exist, this model can supply that information. These types of tools allow academics and professionals to easily run very realistic scenarios, which if needed, may be adapted to serve the context of multiple case studies, without the need to carry out long intensive data collection operations.

With the optimization results presented, and the evaluation of the current mill's biomass procurement supply, we were able to validate the proper functioning of the optimization model, and thereby complete the third sub-objective of this thesis.

There are of course limitations to the use of this model and its applicability. The created model does have a very economic-centric focus that may require further assessments focusing on environmental and social benefits that may change the final harvesting plan and may increase the final costs.

5.3.4 Evaluation of Biorefinery Scenarios using developed modeling tools

With a the biomass procurement network created using the simulation model, and the optimization of the network for the current mill's biomass feedstock demands, we can now proceed to the final stage in the project, which is to evaluate the developed biorefinery scenarios. Tables 4.2 and 4.3 present the details of each individual scenario along with the changes occurring in each one. Likewise, in Table 5.4 we summarize al the evaluated scenarios and present a short description of each one.

Table 5.4: Description of all biorefinery scenarios evaluated using modeling tools

Identifier	Description
OD	Scenario using the original data provided by the case study mill for a single year's worth of biomass demand
BC1	Data for the current mill's biomass demands, optimized but no changes of any kind have been made to the supply chain.
BC2	Current mill's biomass demands, optimized, with changes made to the harvesting systems used by contractors, moving from the current systems to a full-tree harvesting system
PY1a	Continued production of newsprint at current rates, with the pyrolysis process started up in year 1 and upgraded in year 6 using woodchips as a feedstock
PY1b	Continued production of newsprint at current rates, with the pyrolysis process started up in year 1 and upgraded in year 6 using hogfuel as a feedstock
PY2a	Continued production of newsprint with a 50% reduction in year 6; the pyrolysis process is started up in year 1 and upgraded in year 6 using woodchips as a feedstock
PY2b	Continued production of newsprint with a 50% reduction in year 6; the pyrolysis process is started up in year 1 and upgraded in year 6 using hogfuel as a feedstock
PY3a	Production of newsprint until year 6 when it is shutdown; the pyrolysis process is started up in year 1 and upgraded in year 6 using woodchips as a feedstock
PY3b	Production of newsprint until year 6 when it is shutdown; the pyrolysis process is started up in year 1 and upgraded in year 6 using hogfuel as a feedstock
PY4a	Production of newsprint until year 11 when it is shutdown; the pyrolysis process is started up in year 1 and upgraded in year 6 using woodchips as a feedstock
PY4b	Production of newsprint until year 11 when it is shutdown; the pyrolysis process is started up in year 1 and upgraded in year 6 using hogfuel as a feedstock
PY5a	Production of newsprint until year **16** when it is shutdown; the pyrolysis process is started up in year 1 and upgraded in year 6 using woodchips as a feedstock
PY5b	Production of newsprint until year **16** when it is shutdown; the pyrolysis process is started up in year 1 and upgraded in year 6 using hogfuel as a feedstock
PY6	Production of newsprint with a 50% reduction in year 6, and shutdown in year 11; the pyrolysis process is started in year 1 using hogfuel, and a second reactor is started up in year 6 using woodchips as feedstock
OS7	Continued production of newsprint at current rates, with the organosolv demonstration scale process started up in year 1 using hardwood chips and then in year 6 a full commercial scale plant using softwoods chips as a feedstock
OS8	Continued production of newsprint with a 50% reduction in year 6; the organosolv demonstration scale process is started up in year 1 using hardwood chips and then in year 6 a full commercial scale plant using softwood chips as a feedstock

Table 5.4 continued: Description of all biorefinery scenarios evaluated using modeling tools

Identifier	Description
OS9	Production of newsprint until year 6 when it is shutdown; the organosolv demonstration scale process is started up in year 1 using hardwood chips and then in year 6 a full commercial scale plant using softwood chips as a feedstock
OS10	Production of newsprint with a 50% reduction in year 6, and shutdown in year 11; the organosolv demonstration scale process is started in year 1 using hardwood chips, switched to softwood chips in year 6 with a 500 tpd reactor, and then a second 500 tpd reactor installed in year 11
OS11	Production of newsprint with a 50% reduction in year 6, and shutdown in year **16**; the organosolv demonstration scale process is started in year 1 using hardwood chips, switched to softwood chips in year 6 with a 500 tpd reactor, and then a second 500 tpd reactor installed in year 11

5.3.4.1.1 *Scenario analysis using annual woodchip and hogfuel costs*

The first results for all biorefinery scenarios presented in Figure 5-15, are the scenarios that were determined to be unfeasible.

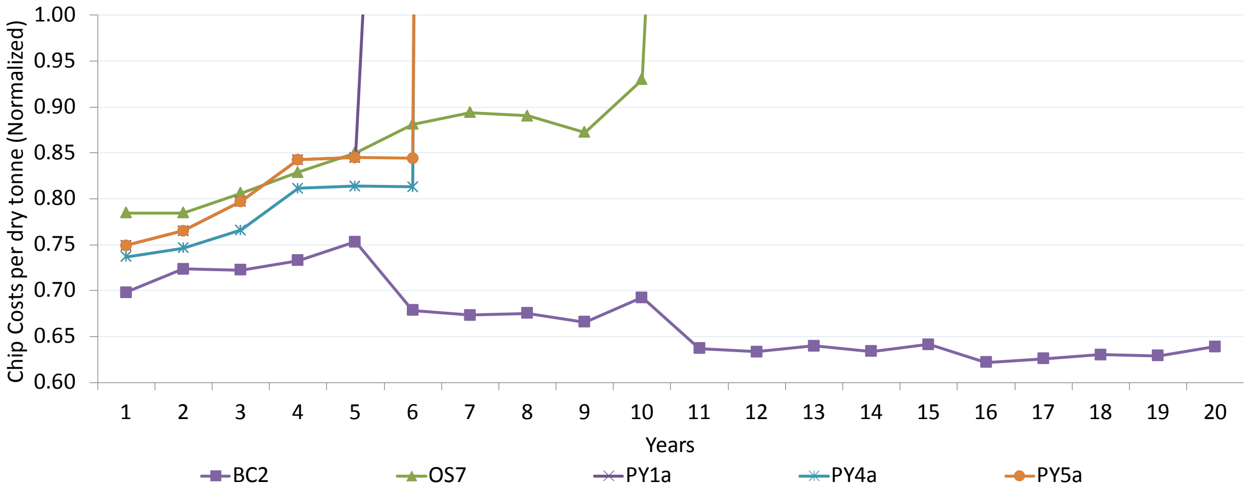


Figure 5-15: Optimized Biorefinery Implementation Scenarios found to be Un-Feasible

As a base point for comparison, BC2 is also presented. Figure 5-15 shows the cost of delivered chips for each scenario for the 20-year time horizon of the biorefinery, and in all of the scenarios, the cost reaches a point where it jumps upwards due to a sudden change in cost of delivered chip product for that year. This sudden change in product cost is caused by the network running out of material to provide the final customer with, and having to resort to spot market purchasing of material. In order to set the spot market as an upper limit in the optimization model the purchase price was set over $1500/tonne so that it would be possible to determine in the results when the model exceeded the material quantities available from the simulated forest. This upper limit is of importance, as it established a limit between sustainable and unsustainable harvesting within the area being evaluated over the 20-year time horizon. If a scenario's demand cannot be sustainably harvested in the local region, the scenario is considered unfeasible and must be discarded.

The other important point to notice in Figure 5-15 is that all of the scenarios eliminated, use woodchips in their biorefinery process, and have an overlap of continued newsprint production at the current rate, while trying to run the biorefinery process at 100% production. This overlap is what causes the unsustainable woodchip demand (above AAC for the region) which ultimately consumes more chip product than is available in the supply chain network; thus the case study supply chain cannot handle both newsprint production and biorefinery production running at 100%.With the elimination of the unviable scenarios, most of the continued newsprint scenarios are removed. Pyrolysis still maintains PY1b as a continued newsprint production scenario that uses hogfuel.

In order to maintain a continued newsprint production scenario in the organosolv biorefinery alternatives, two additional optimization runs of scenario OS7 were carried out with decreased organosolv production, to determine the highest sustainable production capacity alternative to replace the original organosolv size of 1000 tpd. Because OS7's current production capacity is unviable, we want to be determine what the highest sustainable production capacity is, so as to build the biorefinery process as large as possible to take advantage of the economies of scale. The production scale analysis is shown in Figure 5-16. Only the 1000 tpd production scenario is unfeasible, while both 500 tpd and 750 tpd scenarios remain feasible. Therefore the largest production scale was selected to replace the unfeasible scale.

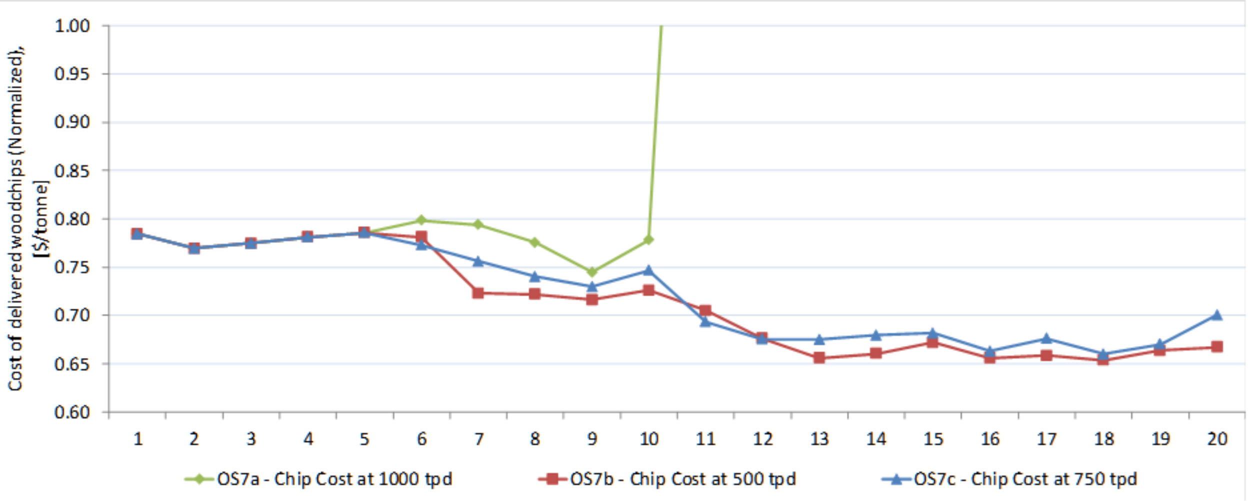
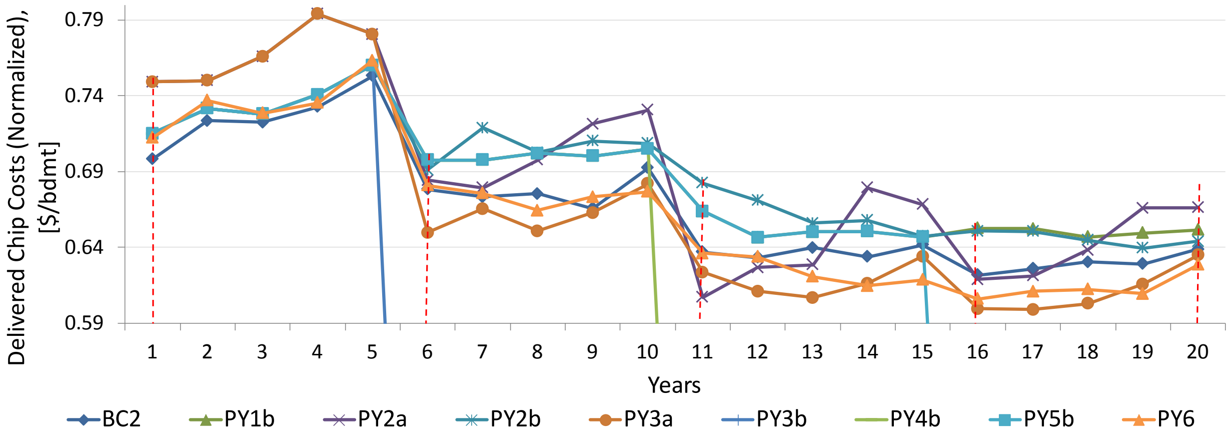


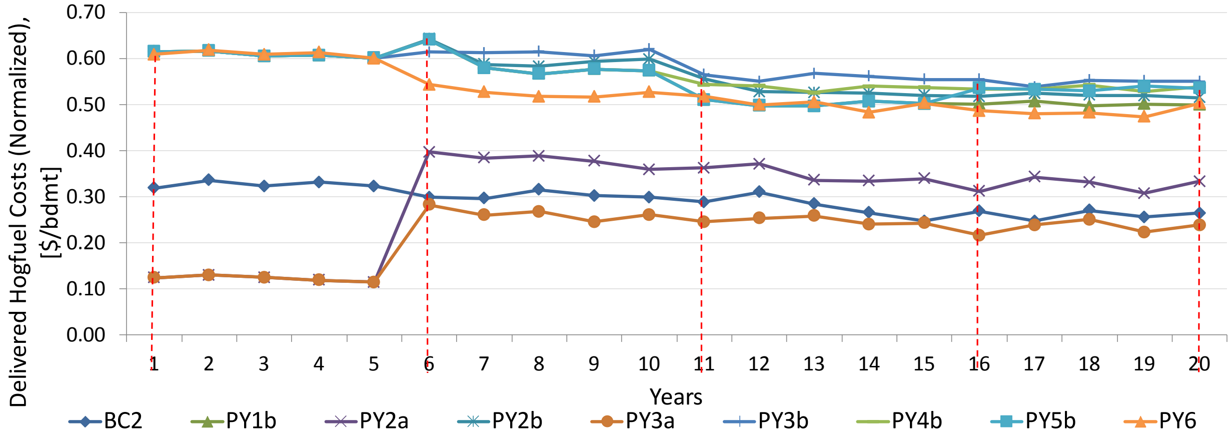
Figure 5-16: Organosolv biorefinery with continued newsprint production at 3 different production scales.

Once the unviable scenarios have been eliminated, we are left with all the viable biorefinery scenarios. Presented in Figures 5-17 and 5-18, the biorefinery scenarios have been grouped according to technology implemented (pyrolysis in Figure 5-17 and organosolv in Figure 5-18). Also in both figures the delivered feedstock costs for both woodchips and hogfuel are shown in individual graphs: a) are the costs for woodchips, and b) are the costs for hogfuels.

Tables 5.5 and 5.6, present the related data for each one of the feasible scenarios for each technology, including the changes in scale made previously to scenario OS7. The blue and green lines present in Tables 5.5 and 5.6 respectively, separate the scenarios into those that continue production of newsprint, and those that do not, for each biorefinery technology implemented. The continued (or not) production of newsprint, is an important distinction to make between our scenarios because whether or not the facility continues to produce paper is a very big decision that will affect all areas of the facility. Providing alternatives for both options of continued (or not) production of newsprint, will allow decision-makers to observe how these changes will affect the traditional business (of papermaking) and the new biorefinery business.



a) Total delivered **woodchip** costs for feasible **pyrolysis** scenarios



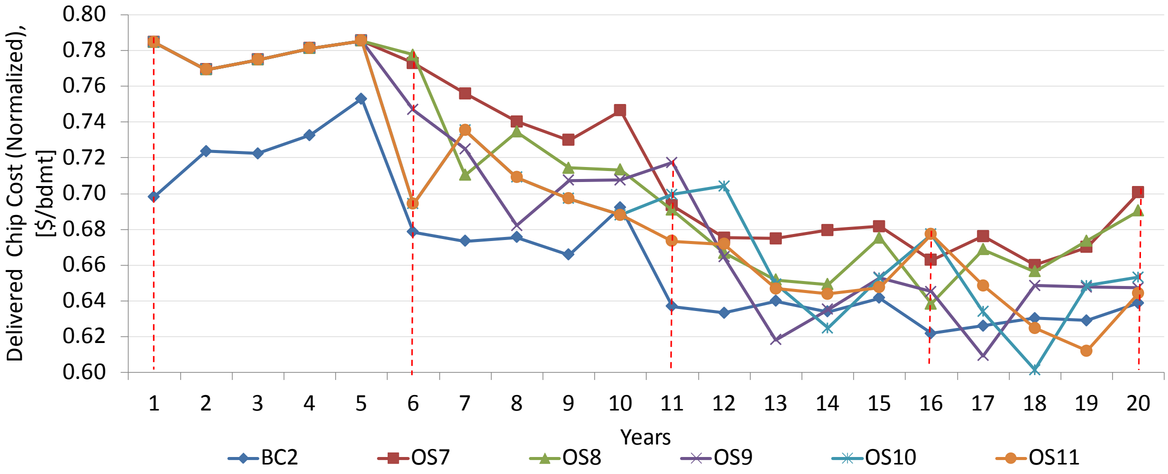
b) Total delivered **hogfuel** costs for feasible **pyrolysis** scenarios

Figure 5-17: Delivered woodchip and hogfuel costs for all viable pyrolysis biorefinery scenarios

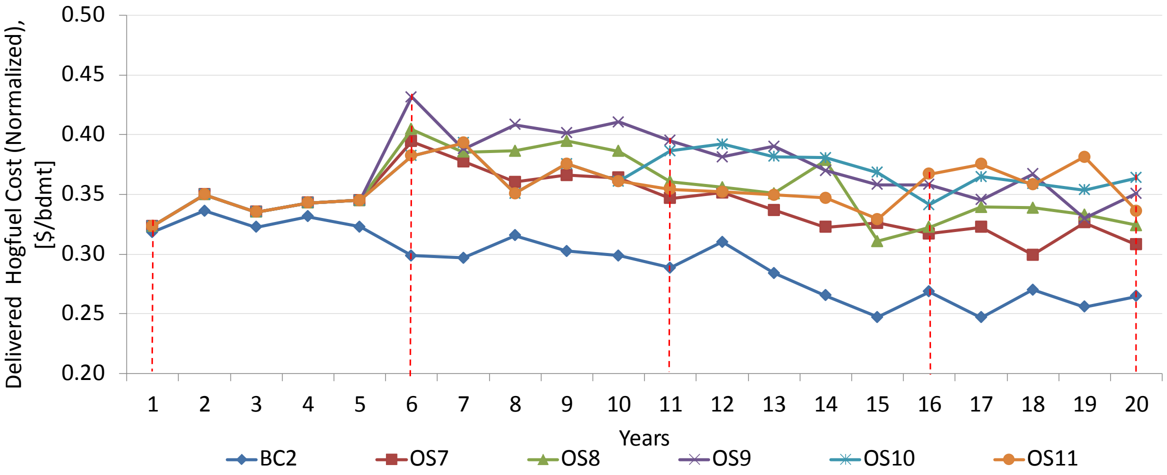
Table 5.5: Viable pyrolysis biorefinery scenarios

	Average Clean Chip demand for all processes [bdmt/day]	Average Hogfuel demand for all processes [bdmt/day]	Feedstock used in 1st 400 tpd Pyrolysis unit (installed year 1)	Feedstock used in 2nd 400 tpd Pyrolysis unit (installed year 6)	Continued Newsprint Production	50% Reduction in Newsprint Production (year of reduction or shutdown)*	Total Shutdown of Newsprint Production
OD	686	143	-	-	yes	no	no
BC2	686	143	-	-	yes	no	no
PY1b	686	930	hogfuel	hogfuel	yes	no	no
PY2a	1,109	250	chips	chips	no	yes (6)	no
PY2b	429	930	hogfuel	hogfuel	no	yes (6)	no
PY3a	851	143	chips	chips	no	no	yes (6)
PY3b	171	823	hogfuel	hogfuel	no	no	yes (6)
PY4b	343	859	hogfuel	hogfuel	no	no	yes (11)
PY5b	514	894	hogfuel	hogfuel	no	no	yes (16)
PY6	549	531	hogfuel	chips	no	yes (6)	yes (11)

*Numbers in parenthesis represent the year in which the reduction or shutdowns are carried out for each scenario



a) Total delivered **woodchip** costs for feasible **organosolv** scenarios



b) Total delivered **hogfuel** costs for feasible **organosolv** scenarios

Figure 5-18: Delivered woodchip and hogfuel costs for viable organosolv biorefinery scenarios

Table 5.6: Viable organosolv biorefinery scenarios

	Average Clean Chip demand for all processes	Average Hogfuel demand for all processes	Initial OrganoSolv unit size using **hardwood** chips (installed year 1)	Final OrganoSolv unit size using **softwood** chips (installed year 6)	Continued Newsprint Production	50% Reduction in Newsprint Production (year of reduction or shutdown)	Total Shutdown of Newsprint Production
	[bdmt/day]	[bdmt/day]	[bdmt/day]	[bdmt/day]			
OD	686	143	-	-	yes	no	no
BC2	686	143	-	-	yes	no	no
OS7	1,256	311	100	750	yes	no	no
OS8	1,181	311	100	1,000	no	yes (6)	no
OS9	924	257	100	1,000	no	no	yes (6)
OS10	889	239	100	500 (6)-1000 (11)	no	yes (6)	yes (11)
OS11	853	221	100	500 (6)-1000 (11)	no	yes (6)	yes (16)

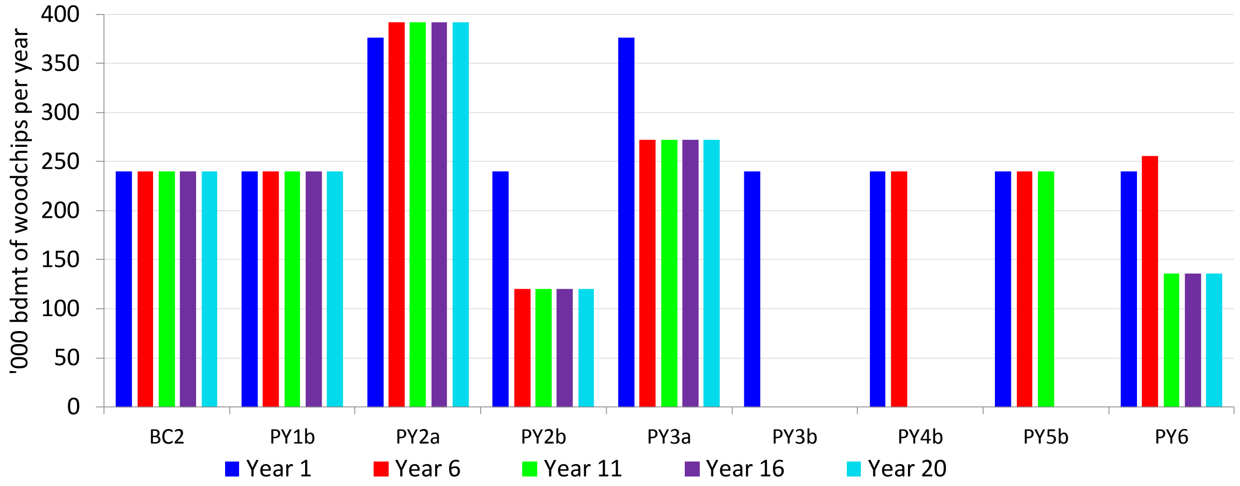
*Numbers in parenthesis represent the year in which the reduction or shutdowns are carried out for each scenario

Results from in Figures 5-17a and 5-18a for woodchip costs present noticeable patterns amongst all the scenarios for each biorefinery technology. In both figures, although more distinguishable in 5-17a, there is a drop in woodchip cost every 5 years during the first 15 years of the projects lifespan. This can be attributed to the change in harvesting systems that is part of all the biorefinery implementation scenarios. Another pattern observed in the costs of woodchips, is the increase in cost that occurs throughout the years due to the consumption by the optimization model of the lowest cost cutblocks. As the years progress, the cost steadily increases; however, it is offset by the change in harvesting technology which reduces the cost of woodchips.

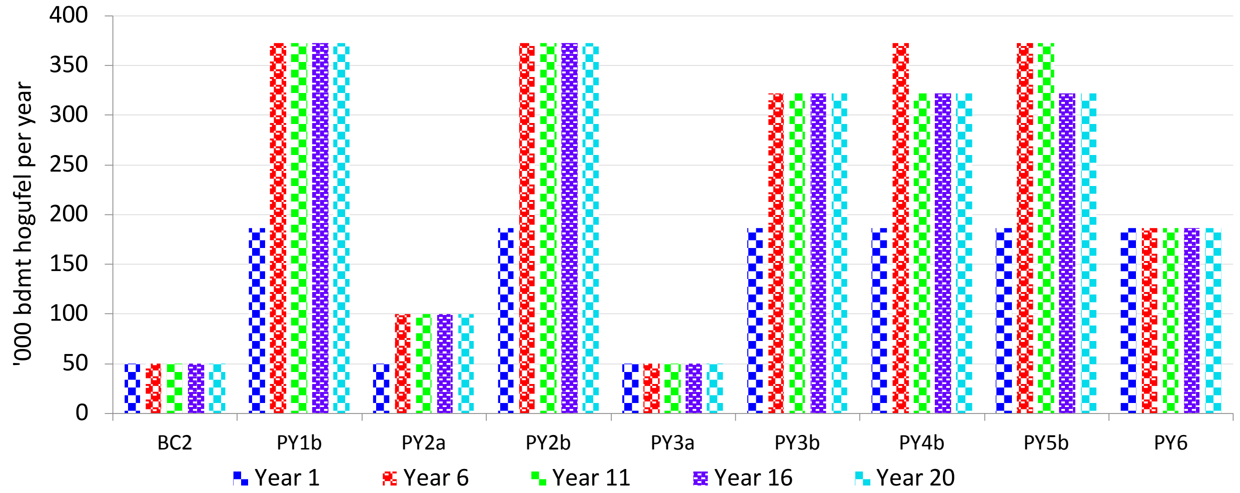
In Figure 5-17a, three of the scenarios show a sudden drop in the cost of woodchips to a value of zero. This happens when the mill's consumption of woodchips stops which occurs in scenarios where the newsprint production is halted and the pyrolysis process uses hogfuel as its feedstock (scenarios PY3b, PY4b, and PY5b). This result is confirmed by Figure 5-19 which presents the biorefineries woodchip and hogfuel demands over the lifespan of the facility. In Figure 5-19 feedstock demands for years 1, 6, 11, 16 and 20 are presented, since these are the years when changes are made in the facility which affect biomass feedstock demands.

Now looking at the information presented by Figures 5-17b, there is distinct difference between the cost of hogfuel in scenarios PY2a and PY3a and all the others. Consider first of all that these two scenarios are the only pyrolysis scenarios to use woodchips in the pyrolysis units. This implies that there will not be much of an increase in the hogfuel demand over the lifespan of the project, as is shown in Figure 5-19b. However, the increases in hogfuel cost in these scenarios are actually being caused by two different issues. In scenario PY2a, the demand for hogfuel is doubled in year 6, and as Figure 5-13 had shown us, during the first 5 years, half of the hogfuel material consumed was actually being produced at the pulp mill log yard at no cost. When the hogfuel demand doubles, but the woodchip demand stays almost the same (Figure 5-19a), no additional "free" hogfuel material is being produced, and must be procured from other locations with the added cost, diminishing the effect the free hogfuel has on the overall averaged hogfuel cost for each year.

In scenario PY3a, the situation is reversed. The hogfuel demand is maintained, but because we reduce the newsprint production by half, the woodchip demand is reduced, and therefore less free hogfuel material is produced at the P&P mill log yard. The reduction in free hogfuel causes the overall average annual cost to increase as is shown in Figure 5-17b.



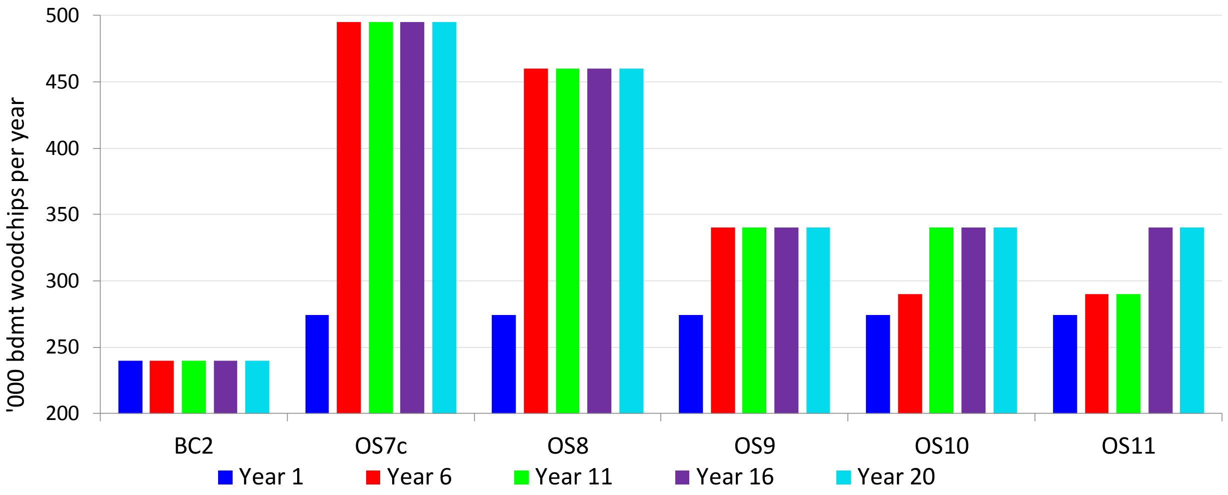
a) **Woodchip** demand by all processes in biorefinery facility for pyrolysis scenarios



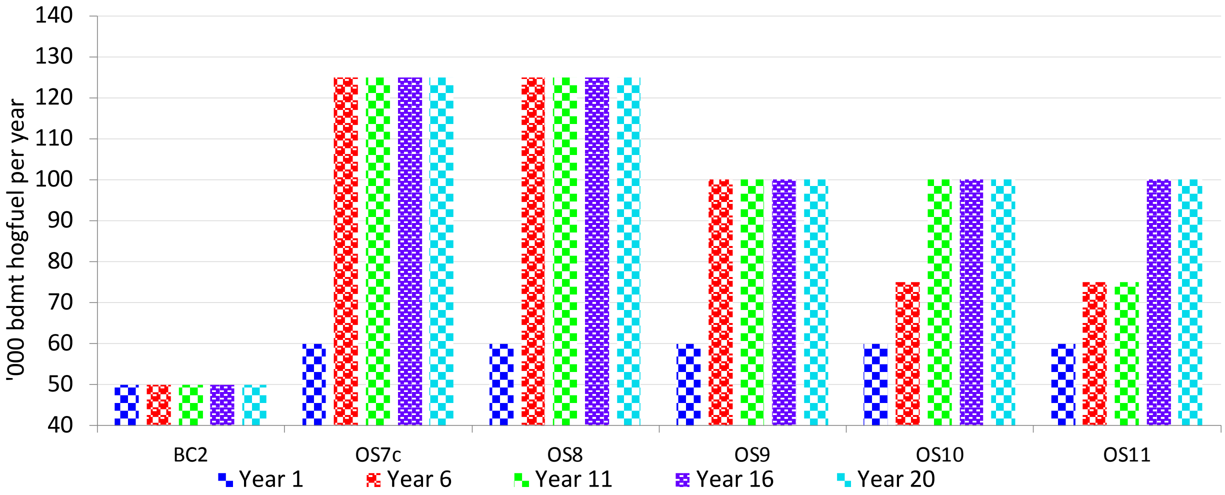
b) **Hogfuel** demand by all processes in biorefinery facility for pyrolysis scenarios

Figure 5-19: Biomass product demands by the biorefinery facilities for pyrolysis scenarios

The changes in costs of hogfuel in other scenarios for both pyrolysis and organosolv, are less dramatic than the ones already discussed. In both cases (Figures 5-17b and 5-18b) increases in hogfuel demand in year 6 increase the cost of hogfuel as can be seen in Figure 5-18b, but since the demand tends to stay the same in the organosolv scenarios as seen in Figure 5-20b, or only slightly reduced in the pyrolysis scenarios (Figure 5-19b), the changes in harvesting systems help reduce the overall hogfuel annual costs as time goes by. Figure 5-20a is pretty.



a) **Woodchip** demand by all processes in the biorefiney facility for all organosolv scenarios



b) **Hogfuel** demand by all processes in the biorefinery facility for all organosolv scenarios

Figure 5-20: Biomass product demands by the biorefinery facilities for organosolv scenarios

5.3.4.1.2 Scenario analysis using averaged costs and quantities over the 20-year lifespan

The year-to-year results presented in the last section have the difficulty of presenting a large amount of information that is hard to distinguish from one scenario to another. This creates difficulties in deciding what scenarios are of use for decision-making. Therefore taking a different approach, and evaluating the averaged costs and quantities for each scenario, may assist in determining which strategy fits best according to the decisions made.

The data presented in Figures 5-21 and 5-22 for each scenario represented the average cost of each material (chips or hogfuel) for all processes in the mill over the 20-year time horizon evaluated.

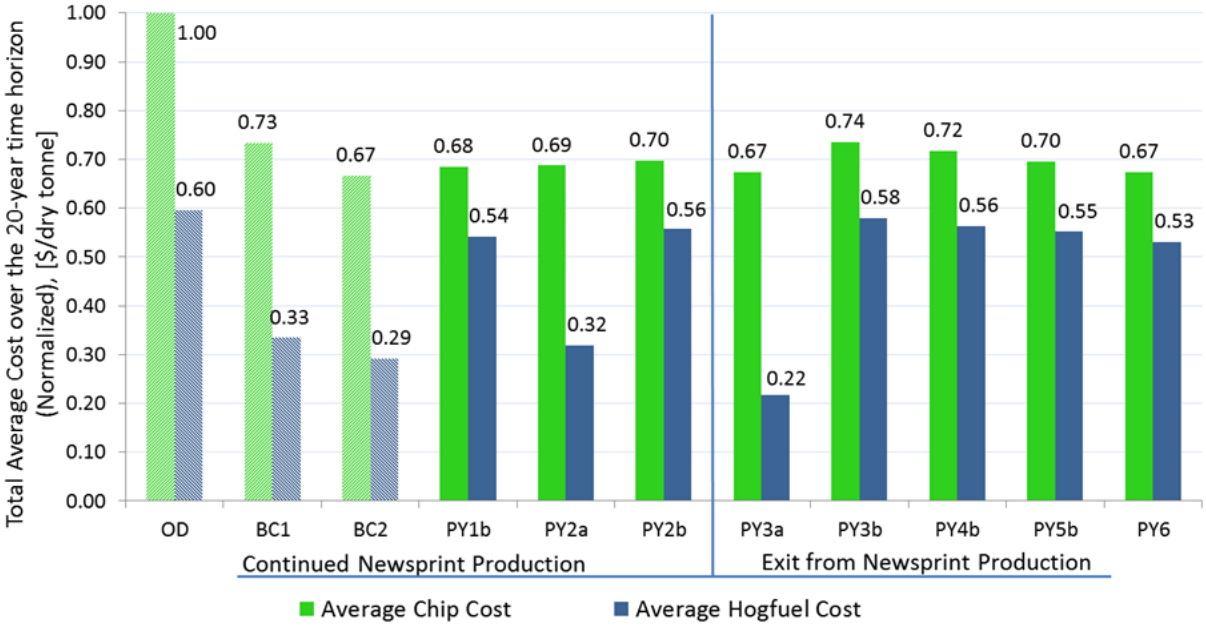


Figure 5-21: Optimized average feedstock procurement costs for the pyrolysis biorefinery during the 20-year time horizon.

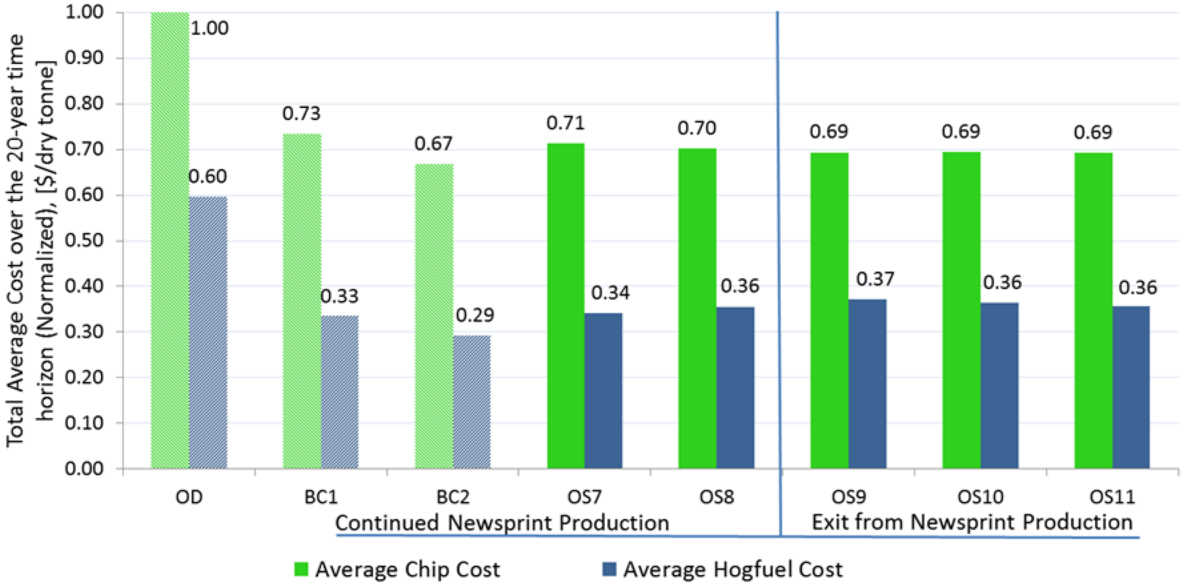


Figure 5-22: Optimized average feedstock procurement costs for the organosolv biorefinery during the 20-year time horizon.

One of the more noticeable aspects of the results shown in Figures 5-21 and 5-22 is that in all biorefinery scenarios, the average cost of chips, once optimized, doesn’t change much from one scenario to another. Although the cost is being lowered over the 20-year period as is shown in Figures 5-17 and 5-18, this reduction is consistent in all the scenarios, therefore when costs are averaged out and compared, the result is not seen, and since it is present in all scenarios, it does not give advantage or disadvantage to any scenario. So the cost information created by the optimization model, is not enough to reach a conclusion as to which scenario is best; however, combining these results with the information on the specifics of each scenario, and sorting the scenarios according to the decisions that must be made by the mill’s decision makers as to what technologies to use, and whether or not to continue production of newsprint, it is possible to reach some conclusions.

Pyrolysis with the continued production of newsprint:

Figure 5-21 and Table 5-5 show the information for scenarios that evaluate the pyrolysis technology. Of the scenarios that continue to produce newsprint (PY1b, PY2a and PY2b), only scenario PY2a uses clean chips in the pyrolysis process. Aside from the potential downstream benefits of using a homogeneous clean material in the pyrolysis unit which will produce a product with less impurities that will require less cleaning operations, the cost of hogfuel is significantly lower than the other two scenarios due to the smaller quantities required for the biomass boiler. Of the other two scenarios for continued newsprint production, PY1b has a lower cost for both chips and hogfuel, and does not reduce newsprint production which will produce larger profits for the mill. However, in order to compare the two selected scenarios, Figure 5-23 presents some additional information that will help in determining which scenario creates a better strategy for the biorefinery facility and the whole supply network.

Figure 5-23 presents the total material inventory amounts that are left in the forest after harvesting each cutblock. In many cases, the majority of materials left are forestry residues that were deemed too expensive to process and transport by the optimization model, or other residual intermediate materials such as hardwoods, or fuel logs that the final mill did not require in any period. But because these materials have already been harvested, they represent invested money to the mill, which should be recovered, by using as much of these materials as possible.

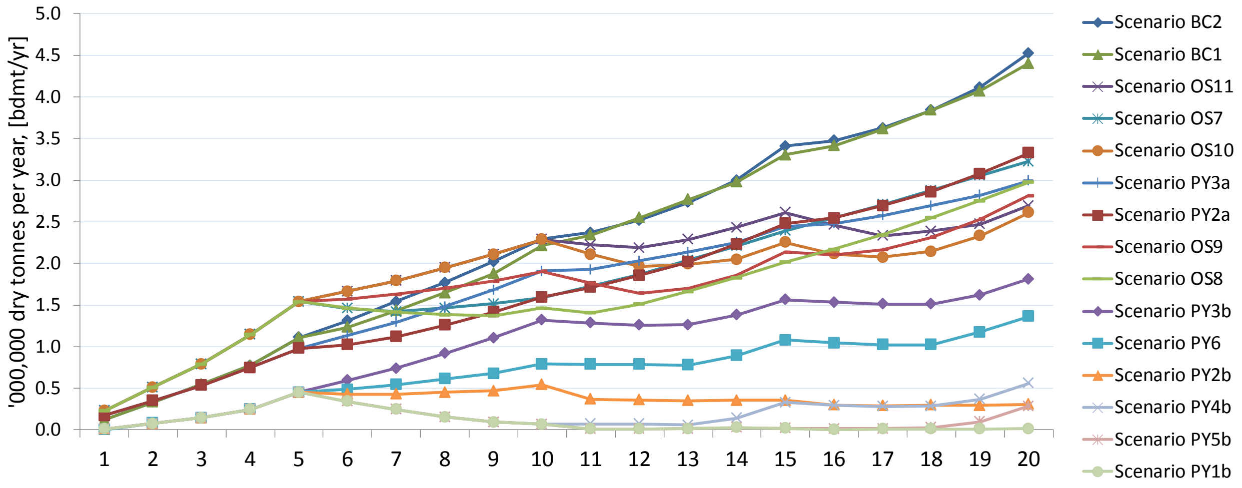


Figure 5-23: Forest material inventories for all feasible biorefinery scenarios during the 20-year time horizon

The scenarios in the legend of Figure 5-23 are organized according to the average inventory amounts over the 20-year period from largest to smallest to make determining which scenarios have the lowest unused inventory amounts of materials. From this figure, we can see that PY2a although a lower material cost scenario, doesn't use up enough material and creates a very large quantity of inventory in the forest; whereas PY1b actually has the lowest amount of inventory accumulation, and will be better for the mill as it allows them to recover much of their harvesting costs which have been assigned to materials left in inventory by the simulation model's ABC accounting system.

Pyrolysis with exit from the production of newsprint:

Figure 5-21 shows that the lowest cost biorefinery scenario is PY3a; nevertheless this is due in part because this scenario does not expand or increase demand for feedstock, and just substitutes the production of one commodity product (newsprint) for another (bio-oil) using the same feedstock.

The second lowest cost scenario that exits newsprint production, would be scenario PY6, which uses a combination of both chips and hogfuel for the production of bio-oil, and at the same time, uses a two-phased shutdown of newsprint production. This type of scenario was developed to reduce the risk involved in each phase of the transformation process, by making the transition in multiple stages, instead of all at once.

The third lowest cost scenario that exits newsprint production, is scenario PY5b, which also uses hogfuel for the pyrolysis process, and does not shut down production of newsprint until year 16. This scenario is worth mentioning, because Figure 5-23 shows that the combination of increased usage of hogfuel and chip demand for newsprint production, maintains a very low inventory (second lowest out of all scenarios) for almost all the time horizon evaluated.

Remember that thermo-chemical processes like pyrolysis, are considered parallel-integrated biorefinery processes, which make them ideal for companies that will not necessarily stay in the P&P industry. **This makes any of the three exit scenarios mentioned above the more likely candidates to be used.**

Organosolv with continued production of newsprint:

The scale of the organosolv process in scenario OS7 as mentioned beforehand, had to be reduced to a consumption of 750 tpd of chips to maintain a sustainable harvest of the forest area. Considering this and the information for scenario OS8 in Figure 5-22, and Table 5-6, it is difficult to reach a conclusion, since OS8 has only a 1% difference in chip cost with OS7. As far as accumulated inventories are concerned, OS8 has a lower quantity of material accumulated than OS7. The one piece of information that may create the biggest difference between these two scenarios, is the decrease in scale in scenario OS7. Because organosolv fractionates biomass into products and by-products which can be used for bio-fuels as well as value-added chemicals, the potential revenues made from this biorefinery process can be assumed to be higher than what would normally be made with the production of newsprint. Therefore the additional 250 tpd of production in OS8 will produce a higher return than what those 250tpd will produce as newsprint. This then makes scenario OS8 the preferred scenario. Also, according to figure 5-23, OS8 has a lower forest inventory of materials than OS7 which also makes OS8 more attractive.

Organosolv with exit from the production of newsprint:

Figure 5-22 indicates that there is little to no difference in costs for all 3 organosolv scenarios that shutdown newsprint production. Table 5-6, indicates that the difference in feedstock quantities per scenario, is also minimal. The main difference between these scenarios, has to do with the uncertainty and risk involved in the scale up to a 1000 tpd process; OS9 assumes the risk and scales up to 1000 tpd in one stage, while OS10 and OS11 do it in a two-stage process, first going to 500 tpd, and then to 1000 tpd. It is this implementation difference which will make the most significant impact in which scenario is selected, assuming that all 3 scenarios produce the same products. Because OS9 commences production at full scale from year 6 onwards, the potential revenues will be higher than the other two scenarios that do not produce at full scale until year 11. Although OS10 and OS11 do continue to produce newsprint longer than OS9, it has already been mentioned beforehand, that the products and by-products from an organosolv process, are expected to bring in more revenues than that of newsprint production.

5.3.4.1.3 Potential revenues from biorefinery scenarios

To test the certainty of the statements made previously regarding potential revenues that can be gained from each biorefinery scenario's final products (in this case we refer to the products of the biorefinery and not the biomass procurement supply chain), a products revenue comparison for all scenarios was set up to determine the biomass cost to revenues ratio. This ratio, also known as a business efficiency ratio, will provide an estimate of the potential of each scenario to create revenues, when compared with the cost of procuring feedstocks for the processes. In simple terms, the efficiency ratio will tell us how much we spend on biomass to make a dollar of revenue from biorefinery products.

Using the results of quantities and costs from the optimization of each of our biorefinery scenarios, the total cost for all biomass materials procured during the 20 year time frame of the biorefinery was calculated. Also using prices for all products produced from the biorefinery and carrying out a calculation of quantities of biorefinery products produced, the total revenue for each biorefinery scenario was estimated. The division of these two numbers created the biomass cost to revenue ratio and all results are presented in Figure 5-24.

Because this ratio, determines how much we spend on feedstocks for each dollar made from products, typically the lower the value of the ratio, the better the result will be. In Figure 5-24, the lowest ratios obtained, were for the base case optimizations were only newsprint is produced. One of the factors that cause this, is the fact that with any biorefinery implementation project, there will be increases in the demand of biomass feedstock to the mill which will affect the biomass cost to revenue ratio.

For the production of pyrolysis bio-oils, the scenarios where production of newsprint is continued, or shutdown is put off until the later years, appear to have better ratios than those in which the facility stops the production of newsprint. In part due to the higher price of $570/tonne used as a base for newsprint as compared to the $130-$150/tonne of bio-oil, and the fact that TMP newsprint process has a higher conversion rate than that of pyrolysis to bio-oil. Bio-oil was priced according to the energy content, and compared to that of heavy fuel oil. In addition, and 10% discount on bio-oil was given, to make its use more attractive to potential buyers. However if future projects upgrade bio-oil to other higher value fuels or chemicals, their potential revenues will increase.

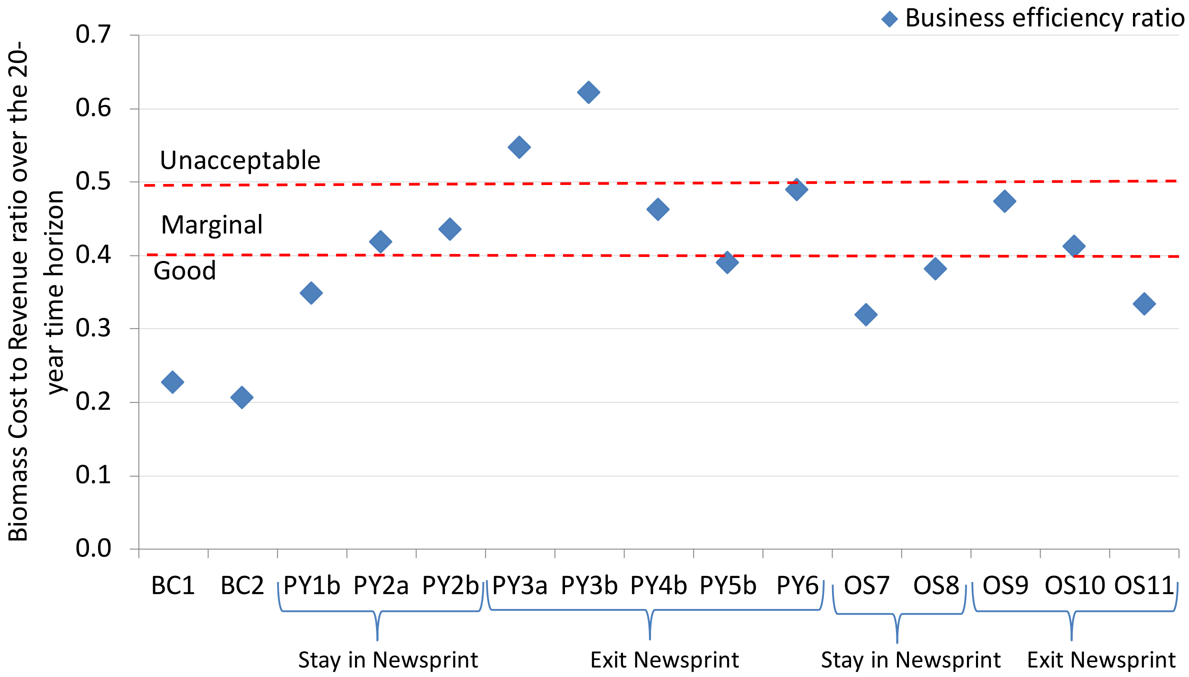


Figure 5-24: Biomass cost to biorefinery product revenues for all biorefinery scenarios

Organosolv scenarios have a lower biomass cost to revenue ratio according to Figure 5-24 due to the higher price that their products obtain compared to the products from the pyrolysis biorefinery. Ethanol sold as fuel at $516/tonne (40 cents/L), and lignin sold for research purposes ($450/tonne) compose the two largest products made and sold at the lowest costs. The other products acetic acid ($600/tonne), furfural ($1500/tonne) would be sold as value added chemicals but produced in much lower quantities (2%, and 0.5% of final product quantities). There is also a stream of organic residues, which would be consumed internally in the plant, fed to the boiler for energy and steam production.

However, the same pattern appears in Figure 5-24 that does for the pyrolysis biorefineries. The scenarios which maintain production of newsprint along with biorefinery options, have lower biomass cost to revenue ratios than those that shut down its production altogether. What this essentially means, is that the scale at which we are producing our biorefinery products, is not large enough to offset the revenues currently being taken in by the P&P mill's newsprint production. Ideally we would increase the biorefinery's production scale, but as was shown in the scenario analysis, many of the alternatives are already putting a strain on the biomass procurement supply chain, and may not be able to provide enough biomass material for a larger scale facility.

Therefore it would be recommended not to shut down newsprint production any time soon, and continue its production for as long as the market price allows it. That being said, it's also not recommended to stay solely with newsprint production, as this is a declining market product which is expected not to recover anytime soon. Therefore if the mill wishes to continue operating, it must diversify its product portfolio according to what the biomass procurement supply chain can supply.

5.3.4.1.4 Conclusions

Evaluating several biorefinery implementation strategies for a newsprint mill using a biomass procurement simulation and optimization models, we were able to recommend what strategies may best fit in with decisions made that will affect the mill during a transitional period when biorefinery processes are being implemented.

Finding the right biorefinery implementation strategy based soley on the biomass procurement supply chain, is not prudent decision, as there are many variables that need to be taken into account such as biomass quantities available, delivered feedstock costs, unused materials produced and left in the forest as inventories, etc. In addition, the variability that comes with a biorefinery product analysis such as the one carried out to calculate the biomass cost to revenue ratio adds additional complexity. The number of variables increases, as product costs may be in a constant state of change, or may also change depending on the application for which they are used.

Decision-makers should be aware of the consequences of introducing new processes and products into an existing mill will have to the up- and down-stream operations, and a biomass optimization model such as the one developed helps provide that information. At the same time, decision-makers cannot focus all their attention of just the cost of feedstocks in order to make decisions because once a system is optimized, costs variations tend to be minimal when evaluating multiple scenarios.

With the scenario analyses carried out, we were able to assess the competitiveness of each biomass procurement strategy and its influence on the overall biorefinery implementation strategy. This completes the fourth sub-objective of this thesis.

CHAPTER 6 GENERAL DISCUSSION

Newsprint mills in Canada, especially those that use thermo-mechanical pulping processes (TMP) are currently facing a shift in their product market place, which has forced many to decrease production, idled or shut down in order to stabilize supply and demand. But others have seen this as an opportunity, to slowly transition their business into new more profitable markets where they can expand their product portfolios and increase their revenues.

Commodity bioproducts as well as value-added products derived from forest materials can allow Canadian newsprint mills to expand their operations by introducing a multitude of products going from bioenergy and combined heat and power generation, to more value-added products such as furfural, lignin, and acetic acids. It is left up to each company (owners of the newsprint mills) to decide which products, and implementation strategies will best be suited for their current needs.

Likewise to the introduction of new products and processes into their facilities, P&P companies are also taking the opportunity to improve the performance of their supply chains (SC), in order to lower operation and logistics costs, and increase their competitiveness. The restructuring of their up- and down-stream activities, investments and financing strategies, is seen as just as big an opportunity to create new value as the introduction of new products.

With so much going on at one time (i.e. introduction of new products, processes, market research into applications, investment decisions into up- and down-stream supply chain activities, etc.), aligning all efforts of a company (and their supply chain) to fit into the long-term strategy of the company is sometimes a troublesome task. It is here that decision support systems (DSS) play a vital role, as they provide decision makers with tactical and operational level information from each stage of the supply chain necessary to develop and implement the most appropriate business strategy to aid in the improvement of their financial performance during the transformation of the facility into a biorefinery.

As this transformation process takes place, the biomass procurement strategy will have to adjust to properly accommodate the mill’s feedstock demands. In addition, these process changes will affect other members of the biomass procurement value chain (suppliers, contractors, sawmill’s, etc.). Simulation and optimization of the biomass procurement value chain for large or small quantities of low and high quality biomass will ensure that feedstock costs remain at minimum levels as the biorefinery transformation process advances.

The main objective of this PhD work was to determine the conditions where different biomass procurement strategies for a retrofit forest biorefinery established within a pre-existing supply chain, result in feedstock procurement cost minimization. This in turn satisfies the facilities quantity and quality requirements and is economically viable for a forestry company in a competitive market.

The theoretical framework of this project is built upon knowledge from multiple disciplines, all of which provide the necessary background information to understand all elements contained within the current supply chain (feedstock characteristics, procurement methods, techno-economics, contracting policies, supply chain management, mathematical optimization, chemical processes, etc.) and potential elements included with the biorefinery transformation (new processes, technologies, integration methods into old systems, etc.). On the other hand, realistic heuristics from a case study mill's supply chain allow us to create realistic modeling tools that simulate existing operations were also used.

The effects of a biorefinery implementation on a P&P facility should be reviewed in as much detail as possible, in order to reduce the risk of failure during the actual transition. However to carry out such activities requires modeling tools that allow to simulate different areas of the P&P mill and their supply chains. Part of the efforts of this PhD project was in the development of these decision support systems which would allow us to evaluate different biorefinery implementations at the same time that supply chain management strategies are taken advantage of, such as the optimization of the entire biomass procurement network.

Two main decision support systems were developed using a systematic methodology in quantitative research to link the two tools together. The development of the forest harvesting simulation model and the optimization model followed the sub-objectives of the research project, and are detailed below.

6.1 Simulating forest resources and their harvesting activities

Efforts to make studies as realistic as possible, sometimes hindered by the lack of practical information that can be found within a reasonable timeframe. Many times the information simply is not collected by industrial partners because it was never thought to be of importance to the mill's operation (e.g. potential residues collected from forest cutblocks).

Hence in order to circumvent these types of situations when designing models for the procurement of biomass resources, a simulation model designed to recreate forest resources, as well as harvesting activities was created.

The forest biomass procurement model simulates forest conditions within a cutblock and determines the materials available, as well as calculate the output product flows (sawlogs, pulp logs, and fuel logs) and costs from each cutblock using one of 4 harvesting systems, with the potential for addition of more harvesting systems if the user wished to research other methods. Costs are initially calculated using the traditional cost accounting system used by the pulp and paper case study mill to estimate delivered-to-mill procurement costs.

Results show that the developed cost model, accurately calculates costs at both the cutblock level, and at the mill level (overall yearly averaged raw material costs). Validity of these results was confirmed by comparing cost data from the mill to the results from the model, and it was observed to be within a reasonable margin of error (under 1% error) for delivered woodchip costs. A sensitivity analysis was carried out on tree heights, tree diameter (dbh), percentage of hardwoods in the cutblock and harvesting productivities, in order to determine their effects on quantities and harvesting costs. Tree diameter has a much larger impact on quantities and costs than does height; decreases in hardwoods in the cutblock double their effect on cost (lower cost) than does an increase, and harvesting productivities have the largest effect on cost. The sensitivity analyses carried out also helped reaffirm the interconnection that all the harvested materials have, and their effects on the quantities and costs of one another, when changes occur in the characteristics of the forest.

But in order to improve currently used harvesting systems, reduce biomass feedstock procurement costs, and allow for a more detailed view of cost allocation, several modifications were made to the original model before using it to evaluate other harevesting systems.

6.2 Application of ABC accounting to the simulation model

More often than not, economical factors will have a larger influence over the selection of harvesting systems than other factors due to their costs being allocated to the materials extracted from the cutblocks. Therefore the cost of materials is always directly affected by the harvesting systems used to harvest, along with other aspects such as the cutblock composition and harvesting system productivity. The decision on which harvesting system to utilize should be based on a thorough understanding of the implications of selecting the different harvesting systems.

But recently, harvesting activities have become complex as the number of material assortments extracted from a cutblock has grown to accommodate multiple customers (i.e. sawmills, pulp mills, bioenergy plants, etc.). Adding to the complexity of typical harvesting activities, the interest for procurement of forestry residues as an alternative source of low-cost material for bioenergy and co-generation creates additional considerations that must be taken into account when selecting the harvesting system, as these add cost to all products harvested. Integrated harvesting of all material including residues has become more important, as it seeks to carry out the minimum number of activities to extract all the materials. However because there is an increase in the number of materials extracted, this makes harvesting work more difficult and affects harvesting system productivities which in turn increase harvesting costs. Thus cost management becomes a more important factor in harvesting activities.

For these reasons, activity-based cost (ABC) accounting methods were implemented as an alternative method of assigning indirect costs to materials extracted from the forest, as they more accurately specify where the costs of each material are coming from by using activities to assign costs to each material. This allows for a much more detailed view of the cost structure of materials which can then not only be used to compare among the extracted materials, but also to determine what harvesting systems produce the material assortment required at the lowest cost.

The introduction of several different harvesting systems into the simulation model showed that ABC accounting methods improve cost allocation systems, and allow to assign indirect costs in a more effective way than was previously done. This allowed not only to determine which harvesting systems could be used in the study of a much larger supply chain network, but also to identify harvesting systems that are not feasible, and where their unfeasibility was coming from.

6.3 Improving the biomass supply chain network with optimization

Simulating forest cutblock on an individual level, has allowed us up to this point to control and improve on operational and tactical level activities being carried out on those individually simulated forest cutblocks. But in order to move a step further, and evaluate the much larger supply chain network for a P&P mill's entire biomass procurement operation with the objective of aligning all activities with the strategic vision of the company, an optimization model would have to be used.

Optimization models have been used many times in the forest industry at many different levels. Their ability to improve upon current systems, has been shown many times, and bring great benefits to the forestry companies that use them. In our study, the focus of the optimization model used, was to optimize biomass procurement activities over a the pulp and paper mills forest supply network, during the transitional period to a biorefinery in which many processes within the mill are started and stopped, creating variable feedstock demands over time.

But as was the case with the simulation and the improvement of the harvesting system, in order to improve upon the existing biomass procurement supply chain for biorefinery scenarios, we must first start by examining and optimizing the existing biomass procurement supply chain network for the demands at the P&P mill. This was carried in multiple steps, first only optimizing with no changes (BC1), then optimizing with changes to the harvesting systems used by contractors (BC2). This stepwise approach allowed us to observe the changes in biomass costs as we included additional changes into the system.

The optimization of the existing system, showed how effective the tool can be at improving the procurement network; and by combining it with the simulation model, both tools create a method for evaluating different mills by adjusting the conditions of the forest, and demands of the mills to the reality of each situation. In addition, since the simulation model uses operational and tactical level information, the optimization model provides not only the optimized strategic level data, but also lower level data which can be used by the mill to assist in the alignment of lower level activities with the strategic overview strategy.

6.4 Evaluating and analyzing biorefinery scenarios

The successful transformation of a P&P mill into a retrofit forest biorefinery is not an easy task to accomplish, and will affect internal as well as external aspect of the mill, including the biomass procurement supply chain. With the modeling tools all set in place, and capable of evaluating different biorefinery scenarios, the focus is on interpreting the results.

Depending on what biorefinery technologies are implemented, and in what scale of production, they may or may not line-up with available forest resources. To add to the problem, because forest harvesting activities normally produce a series of materials for different customers (e.g. sawlogs for saw mills, pulp logs for pulp mills, fuel logs for bioenergy plants, etc.), the introduction of a biorefinery over the course of 20 years will affect the way the mill interacts with other members and may increase the cost of feedstocks for all customers if the biomass procurement strategy does not align properly with the biorefinery implementation strategy.

The analysis of two types of biorefinery technology implementations on a biomass procurement supply chain were reviewed. The two biorefinery technologies (organic solvent pulping and pyrolysis) were implemented in a newsprint mill, in different production scales, using different biomass feedstocks and implementation times. This created 16 biorefinery scenarios to evaluate and compare in order to determine which are best suited for the existing mill. The whole system was optimized for minimized biomass procurement costs, and the effects on the biomass procurement supply chain are reported in terms of cost of material (woodchips or hogfuel) per dry tonne per year.

Results showed that strategies which included the complete shutdown of newsprint production were not favourable, as the scale of the biorefineries implemented did not compensate for the lost revenues when newsprint production was stopped. In addition, the scale of the biorefineries could not be increased in many cases, as the biomass procurement network could not provide sufficient material if the scale of production was to be increased.

The results from the scenario analysis, helped determine that newsprint should not be stopped any time soon, and that the biorefinery technologies evaluated, could both present good alternatives for additional revenues.

CHAPTER 7 CONCLUSIONS

7.1 Contributions to the body of knowledge

The systematic development of a forest/harvesting simulation model:

- Forest characteristics and biomass procurement activities were effectively simulated. By imitating a case study P&P mill's current procurement operations for different biomass demands, harvesting, preprocessing and delivery costs were calculated for all products extracted from a cutblock.
- The integrated harvesting of both traditional feedstocks such as sawlogs and pulp logs, as well as the harvesting of non-traditional materials such as fuel logs and residues was carried out with the purpose of delivering all materials to several intermediate customers: sawmills, pulp mill, roadside grinding operations, storage depot; and then processed or exchanged for final products: woodchips and hogfuel.
- Improvements were made on existing cost allocation systems used by the P&P mill, by implementing activity-based cost accounting methods in the simulation model. This method not only produced a more accurate distribution of indirect costs for procurement activities, but also increased the visibility and traceability of costs from product back to the materials that generated them.
- The comparison of alternative harvesting systems improves the way harvesting activities are carried out, including the addition on new materials such as forestry residues, while also reducing procurement costs for all feedstocks.
- The designed and developed simulation model was used to calculate the costs of a biomass procurement supply chain network that includes 600 forest cutblocks, 3 sawmills, 1 pulp mill, a storage depot, mobile grinding operations, 10 potential products that can be extracted from each cutblock, and 3 different harvesting systems that can be used in each cutblock.

The systematic development of a biomass procurement optimization model:

- The successful integration of a simulation and optimization model to minimize biomass procurement costs for a P&P mill with changing feedstock requirements.

- The integration of tactical and operational level information into an optimization model that can be successfully used to assist decision-makers in making strategic level decisions.
- The use of the optimization model to evaluate the impact of different biomass procurement strategies on tactical and operational level activities (strategy alignment).

The design of biomass procurement strategies for a biorefinery implementation:

- The optimization of biomass procurement activities when demand changes over an extended period of time, due to the implementation of biorefinery processes in several different stages, while maintaining core business activities.
- The use of biorefinery scenario results to determine the limits of application of new processes according to materials that the forest resource network can provide.
- Utilized the developed decision support systems to assist in deciding which biorefinery strategy best suits the existing biomass procurement network.

7.2 Future work

The major opportunities to extend the use of developed tools in this thesis within future works are as follows:

- Combine the biorefinery biomass procurement strategies developed in this thesis with other models that more thoroughly review operational costs (e.g. energy costs) within a biorefinery facility to develop and full biorefinery optimization model that can cover all areas of the supply chain: Procurement, manufacture, distribution and markets.
- Utilize the developed simulation and optimization models to explore additional changes that may be made to the biomass procurement network to improve harvesting activities. This might include the evaluation of even more harvesting systems not reviewed in this project, or the simulation of managed forests, or forest plantations.
- Create a “push” strategy in the optimization model to force the system to utilize all materials harvested, and compare this with the “pull” strategy currently utilized.

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APPENDIX

APPENDIX A – ARTICLE 1: SYSTEMATIC ASSESSMENT OF TRITICALE-BASED BIOREFINERY STRATEGIES: A BIOMASS PROCUREMENT STRATEGY FOR ECONOMIC SUCCESS

Jose Melendez*[a] and Paul Stuart[a]

[a]*NSERC Environmental Design Engineering Chair, Department of Chemical Engineering, École Polytechnique, Montreal, Québec, Canada H3T 1J7*

**To whom all correspondence should be directed*

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1. Abstract

An economical supply of biomass feedstock is an essential part of any biorefinery project. With procurement costs accounting for nearly fifty percent of operating costs, current biomass supply chain and procurement operations must be continuously improved to reduce procurement costs. Strategic negotiations between the farmer (the producer) and the end user (the biorefinery), in which both parties benefit should also take place. This study examines procurement supply chains for triticale, for a biorefinery; as well as proposes a financial model that will satisfy both producer and end user.

A biomass cost model was developed to determine the procurement costs of triticale biomass. Several biomass procurement supply chain alternatives were evaluated. Results from the study determined that a biorefinery would pay $225 per tonne of biomass for the delivery of 250,002 tonnes of triticale grain and 265,791 tonnes of triticale straw per year. In addition, the study shows that increased yields of triticale and its similarities in growing and harvesting methods with currently produced agricultural crops will rapidly enable it to become a viable feedstock source for biorefineries.

The biomass procurement strategy described appears to be an attractive alternative for producers and provides a good basis for furnishing a long-term cost-competitive supply of feedstock to the

triticale biorefinery. This financial model is based on the premise that the risk and cost of developing increasingly engineered triticale crops will be borne by the biorefinery owner.

Keywords: Triticale; biorefinery; biomass procurement; supply chain; techno-economics; yield improvements.

2. Introduction

Biorefining refers to the production of a wide variety of fuels, power, and chemicals from biomass; a biorefinery is the facility or group of facilities where this conversion takes place.[1] Biorefineries enable the diversification of a conventional grain mill, sawmill, pulp mill or paper mill's product portfolio by making better use of incoming raw materials to create higher-value products while still maintaining some production capacity for commodity products.[1-3] Several industries such as pulp and paper, combined heat and power (bioenergy) and electrical energy generation, as well as agricultural crop-based biofuels industries have started to introduce concepts and biorefining processes into their mills. In most cases, conventional products will maintain their production capacities in the mills, and these new processes will be setup alongside. Because of this, there will be a need to increase the raw material supply. Therefore it is important that the development of new feedstock sources and of procurement logistics go hand in hand with the development of biorefineries.

Triticale (*X Triticosecale Wittmack*) is a human-developed agricultural crop. It is a hybrid created from wheat (*Triticum spp.*) and rye (*Secale cereale*) that combines the best characteristics of both parents: the high yields and grain quality of wheat, and the robustness of rye as expressed in adaptability to difficult soils, drought tolerance, cold hardiness, disease resistance, and low input requirements. Unlike many other domesticated crops such as rice and wheat, which have developed over a thousand years, triticale is a "young" crop with only 130 years of history since its first successful breeding.[4] Its current yields are competitive with those of "older", more mature crops, and in certain types of marginal soils, triticale may even outyield wheat cultivars as is discussed by Mergoum et al.[5], and will be further reviewed in section 2.1. But currently, triticale has yet to see the commercial success of other crops because it is stuck in a “chicken-and-the egg” conundrum: producers will not grow large quantities of the grain because there is no one currently purchasing large quantities of it, and mills will not purchase large quantities of it because no one can assure them a large, continuous supply on a long term basis.

Most studies of biomass procurement deal with grain and straw harvesting separately because these two feedstocks may end up at different sites. However, for a biorefinery, the objective is the collection and delivery of both grain and straw, as much as possible at the lowest cost, with a secure supply over a longer-term period (5-10 years). No triticale procurement study has been done which involves the development of economically beneficial strategies by negotiation between the producers and the biorefinery. This study seeks to fill this gap. The main objectives are to assess triticale as a potential biorefinery feedstock, as well as show how to improve on current biorefinery feedstock procurement operations using new harvesting methods, and tools, which will reduce procurement costs, secure long-term feedstock availability, and increase the supply of high-quality biomass by creating a mutually beneficial economic strategy for triticale producers and the biorefinery.

The rest of the article is organized as follows: section 2.1. reviews triticale production yields and qualitative data compared to wheat. Then a literature review of biomass procurement is presented. Subsequently, the methodology and results are presented in two subsections: the first covering the supply-chain mass balances and development of alternatives, and the second covering the techno-economic study. This is followed by an analysis that explains how triticale can be used to benefit both parties involved in procurement. Then a sensitivity analysis of triticale yield is presented and discussed.

2.1 Current Production Status of Triticale

Current world production of triticale stands at approximately 3.9 million hectares harvested, with a production of 14.6 million tonnes of grain. For the most part, European countries are still the largest producers, although countries such as China and Australia have also increased their production in recent years.[6] Canada ranked 27th and 29th in area harvested (11,400 ha) and production (29,600 tonnes) of triticale on a world basis in 2013.[6-8]

Two types of crop yields are typically presented in the literature: country-wide yields based on grain production (tonnage collected) and harvested areas, and site-specific field trial yields. Table 1 shows country-wide crop grain yields as calculated by FAOSTAT[6] for the 2006–2013 period for three different crops in Canada.

Table 1 shows triticale yields to be "better than" or equal to those of one or both of their parent crops. On average, triticale outperforms rye, but still lags behind wheat's yields, however, it has been estimated that yields of triticale are increasing at a rate of 1.5% per year.[9] This increasing yield along with the fact that triticale has a much better tolerance to unfavourable weather and soil conditions, makes it a very robust crop compared to traditional crops. A fact that many producers may favour as it will be less likely to underperform in years when soils and weather are not ideal.

Table 1. Estimated yields for Canadian crops [tonnes/ha]*.

	2006	2007	2008	2009	2010	2011	2012	2013
Triticale	2.20	2.33	2.40	2.48	2.97	2.37	2.74	2.60
Wheat	2.61	2.32	2.85	2.79	2.80	2.96	2.86	3.59
Rye	2.34	2.19	2.40	2.43	2.44	2.47	2.73	2.45

* Estimated yields are calculated by dividing country-wide total grain production by harvested area.[6]

Straw amounts reported[9] for triticale, are calculated based on a grain-to-straw ratio of 1:1.23 which remains steady from year to year, taking into account the need to leave at least 20% (as reported by Stumborg et al.)[10] of produced straw behind for carbon capture and nutrient recycling.

2.2 Qualitative characterization of triticale

Scientists and producers are interested in triticale because it can be adapted to harsh environmental conditions, including acidic and sandy soils, salinity, trace element deficiencies, and drought, among others.[5,11] Other variables have been studied to breed triticale varieties which improve agronomic characteristics: grain-filling duration and rate, earliness, and tillering capacity, as well as quality parameters such as test weight, protein content, and gluten strength enhancement.[5,12] Further improvements, particularly in grain plumpness, grain color (white or amber), and gluten quantity and quality, as well as higher amounts of essential amino acids, are expected to make triticale even more attractive as a food and feed grain.[13]

Triticale has also been found to be a good feedstock for purely industrial uses based on its improved chemical and biochemical composition. It is an excellent source of starch (from the grain) or cellulose (from the straw) for the production of biofuels and biochemicals such as ethanol, polylactic acid, and others. It also presents potential for the production of composites and biomaterials such as fibre-reinforced plastics.[12,14,15]

Qualitative comparisons of triticale with other available crops show that triticale contains about 10% less starch, and 5% less protein, than wheat, but contains more cellulose than its parent crops.[16,17] Starch and protein content in triticale (and traditional crops) are of importance because of the food and feed potential of these crops, therefore if triticale is to substitute many of these crops, it must deliver the same quantity of these components. A recent comparison[18] of triticale and wheat grown under the same conditions showed that the differences in composition between triticale and wheat are small thanks to new varieties of triticale which have improved composition.

Triticale shows potential for improvement and for much faster adaptability than wheat or rye to meet market and customer demands. This will be especially important for biorefineries because product mixes and quantities produced may change over time as they transition from a primarily commodity production (e.g., ethanol) to the production of a range of speciality and commodity products (including various biochemicals).

2.3 Triticale Biomass Procurement

To harvest triticale biomass successfully and deliver it economically to the mill gate, attention must be paid to overall supply chain operations and their integration: harvesting methods, equipment combinations, transportation, and how these are affected by changes in the feedstock (wheat to triticale, improving yields, recovering straw, etc.). Mutually beneficial contracts between the biorefinery and the producers who grow, harvest and deliver the crops will also play a large role in its success.

Traditionally, grain crops such as wheat, corn, barley, and triticale; have been grown specifically for the use of the grains, while the straws and stovers are considered a by-product. In the past, most grains were sold by producers to the Canadian Wheat Board (CWB),[19] while straws and stovers which had no real market, were left up to the producers to deal with.

However, as of 2012, the CWB monopsony on grain purchasing ended,[20] and producers are now free to sell their grains to whomever they choose. The opening of the grain market, plus the increased usage of agricultural residues for purposes such as bioenergy projects, has been seen as a beneficial factor for producers as their residues are now marketable and will likely see multiple buyers for all products.[21] This in turn, means that biorefineries, will need to negotiate directly with producers for their grains and/or residues, by creating mutually beneficial agreements which not only take into account the cost of feedstocks, but also their value in an open market.

From the biorefinery's perspective, feedstock costs typically account for 20%–50% of total production costs[22-24] at biofuel (ethanol) production sites. Changes in feedstock-procurement supply chains which reduce feedstock costs will have a significant impact on plant margins.[14] The application of supply-chain management (SCM) concepts to the procurement of triticale biomass enables the integration and coordination of triticale harvesting operations. Specific studies on growth and harvesting for both grain and straw have been carried out.[25,26] Harvesting operations for a biorefinery will require changes to standard methods because of the interest in co-sourcing both grain and straw.

Sokhansanj et al.[27] carried out a review of the process and field machinery used in the collection of corn stover. In this review, they showed that the typical collection sequence of shredding, windrowing, and round baling of corn stover resulted in collection efficiencies of less than 40%. Also, other studies by the same authors, reviewing feedstocks (e.g. switchgrass, corn stovers and wheat straw), and the techno-economics of biomass harvesting under current and potential scenarios have been carried out.[23,28-31] This research sought to fill the void between the biomass producers and customers and led Sokhansanj et al.[31,32] to develop a model for supply-chain management of biomass. The integrated biomass supply analysis and logistics model (IBSAL) is a modeling tool for determining the costs of harvesting and transporting agricultural residues and energy crops to a mill. The model however, requires large quantities of input information (weather, site, location, yields, etc.) from the user and as of yet, the model has not been used to carry out a study on the integrated harvesting of both grain and straw or stover feedstocks.

Other authors have also studied current collection methods: J.S. Cundiff[33] studied the effects of baling biomass to determine optimal bale size and baling conditions to achieve maximum biomass collection at minimum cost. Atchison and Hettenhaus[34] analyzed biomass procurement scenarios and determined that a one-pass collection system for grain and stover has some advantages over two-pass systems and reduces overall transportation costs to the processing facility. One and two-pass harvesting systems refer to the number of times a producer must pass through the field with equipment in order to collect the desired feedstocks. Most grains harvested with a combine, will use a one-pass system where the combine cuts, separates and collects the grain in a single operation, while residue collection may vary from two or three-pass systems: a first pass when they collect the grain with the combine, and drop the residues on the field; a second pass when they rake the residues into lines, and a third pass when they use a baler to bale up the residues.

J.D. Stephen et al.[35] studied the availability of wheat, barley, and oats to determine whether sufficient quantities would be available for a biorefinery on a yearly basis during a 20-year period. This study concluded that to avoid years with no material available, a single crop with higher potential yields should be planted instead of trying to optimize the combination of crops under unpredictable weather conditions.

In triticale biomass procurement, one report published by the Canadian triticale biorefinery initiative (CTBI)[9] introduced the concept of procuring triticale biomass for the production of value-added products. The report gives examples of the types of procurement operations and individual costs involved in procuring both triticale grain and straw for a biorefinery. Another study by Miller et al.[36] reported the techno-economic costs of growing and harvesting triticale in Iowa, but did not include the costs of transporting triticale to the mill, which represent a very large portion of the final feedstock cost.[37]

3. METHODOLOGY

3.1 Scenario Mass Balance Estimates

In the initial stage, the main goal was to evaluate triticale harvesting scenarios, to determine biomass losses, and to analyze alternative harvesting methods that could improve recovered quantities of grain and straw.

A base-case supply chain for triticale harvesting was developed and is shown in Figure 1. The purpose of this base case, is to set a base-line calculation on harvested quantities of triticale grain and straw using currently used agricultural equipment for wheat harvesting,[12] and supply logistics to deliver as much material as possible to the biorefinery.

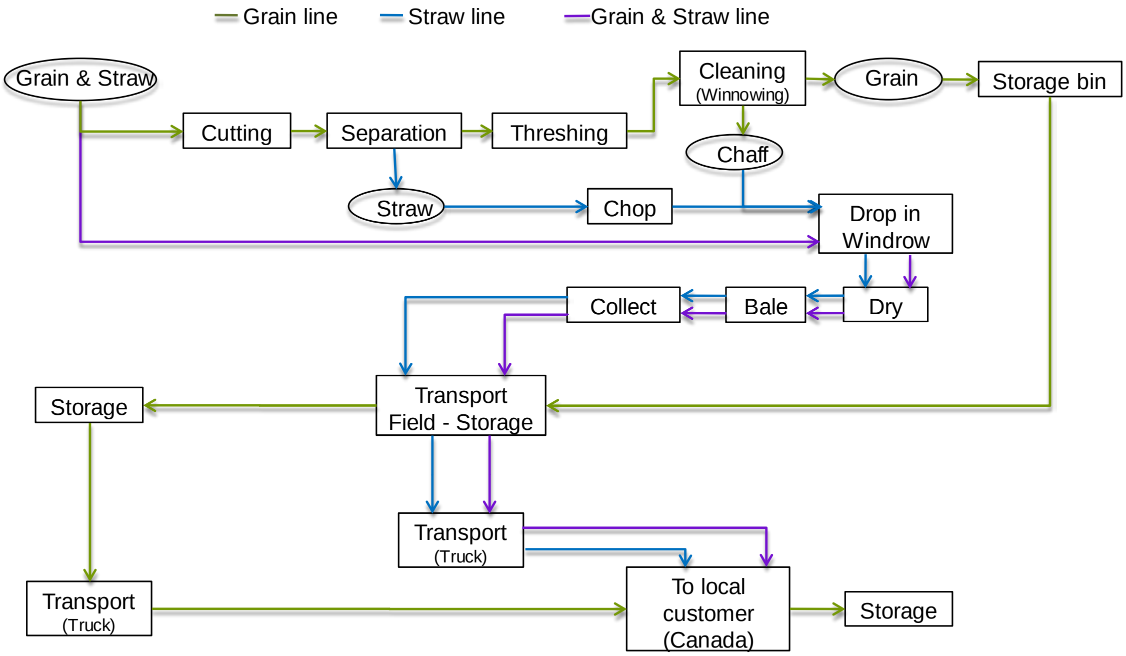

Figure 1. Base-case supply chain for procurement of triticale biomass for a biorefinery.

Once the base-line supply chain was established, changes are made and set up as alternatives 1-3 in order to reduce biomass losses and overall harvesting costs, by modifying the existing supply chain and introducing new technologies which will better densify, and prepare both grain and straw for delivery to the biorefinery. Alternatives 1-3 are described in Table 2.

Mass balance calculations were carried out in the base-case as well as the alternative procurement supply chains assuming a biorefinery demand of 250,000 tonnes of grain per year, along with the produced and recovered straw quantities. Expected biomass losses were estimated using data from various sources.[38-42] Triticale grain yields were obtained from triticale production data in Alberta, Canada,[9] and all other biomass yields (straw and chaff) were derived using production ratios established from the CTBI report[9] (1:1.23 grain: straw ratio and 1:0.31 grain: chaff ratio).

Table 2. Base Case and alternative scenarios description.

	Description
Base Case	In a first pass through the field with equipment, grains are harvested using a combine which cuts, separates (threshes) and cleans the grains before storing them in a bin. Separated straw and chaff are dropped on the field in windrows. With a different piece of equipment, in a second pass, straw and chaff are baled, and wrapped before being moved to the roadside, where they are stacked, stored, and then collected and transported by flatbed trucks to the biorefinery.
Alternative 1	Instead of dropping the straw after collecting the grain, a baler/wrapper attachment is connected to the end of the combine. This way there are fewer losses of straw, and only one pass is needed to collect both grain and straw.
Alternative 2	In an effort to eliminate baling equipment completely, instead of baling straw, the combine is modified so that it can chop (chip) straw and collect it on a straw cart for transport to the roadside, where it is transferred to a chip truck for transport to the biorefinery. Again, this would be a one pass system.
Alternative 3	Since both grain and straw are to be delivered to the biorefinery, instead of separating straw and grain on the field, both are collected in bales which are wrapped and sent to the biorefinery where they can have equipment for separating the grain and straw of much larger size and efficiency. This way, the cost of the feedstock would come down, since there is no longer any need for a combine.

3.2 Techno-economic study of biomass procurement

The second stage of the study was a techno-economic assessment of each scenario alternative to determine the impact of changes on the overall grain and straw costs and how these impact on the overall price paid by the biorefinery. A spreadsheet-based cost model was developed which was used to carry out an engineering cost analysis and estimate the costs associated with the procurement of both triticale grain and straw. Input data used by the model is presented in Table 3. Several references were used in the development of the model, including equipment estimate costs from the John Deere website[43] (most equipment used for calculations was assumed to be purchased new).

The cost model is designed to calculate the delivered costs of both grain and straw, as well as the final price paid by the biorefinery for both feedstocks, based on the following modeling choices and assumptions:

- Market price is the cost of harvesting and delivering grain and straw plus the producer's revenue. Grain has a market price defined by the market which will determine the price the biorefinery pays for that material. Straw, on the other hand, has no defined market price.
- The biomass cost model assumes that the costs involved in seeding and growing of crops represent 40% of the final cost of delivered grain based on work by Brechbill and Tyner.[44]
- Harvesting costs are calculated by the model using the costs of each individual piece of equipment (capital, operational and overhead costs) which in turn are estimated using (but not limited to): purchase price, estimated lifetime, interest rate, salvage value, fuel costs, accessory costs, etc. Similar and more specific information and their respective equations for these calculations may be found in other sources.[43,45-47]
- Transportation costs were estimated using a dollar per tonne per kilometre fixed rate depending on which material was being transported (grain or straw) and assumes a two-way trip within the harvest area, which is a circular area with the biorefinery in the center.
- On-farm storage costs of biomass are assumed to be included in the price paid by the biorefinery.
- Producer participation rates for grains are based on the assumption that most farmers will be willing to sell their grains to the biorefinery, with only a small portion of them (15%) wanting to sell elsewhere. For straw, of the producers participating in grain harvesting, only 15% of them will not be willing to sell their straw to the biorefinery.

When analysing the alternative methods, the land area is kept as a fixed variable and equipment and harvesting methods are changed according to the alternatives described in Table 2. The final paid by a biorefinery for the purchase of triticale feedstock is the sum of both grain and straw prices.

Table 3. Model Input Data[1]

Customer (biorefinery) demand:		
Grain	250,000	mt[2]/year
Straw	276,119	mt/year
Market price:		
Grain	145	mt/year
Straw	15	mt/year
Harvesting yields		
Grain	3.95	mt/ha
Straw	4.74	mt/ha
Producer participation rates[3]		
Grain	85	%
Straw	70	%
Percentage of residues left on field[4]	20	%
Grain transportation		
Truck with Super B Trailer		
Maximum hauling capacity	44	mt
Transportation cost	7.0	$/km/mt
Loading/Unloading cost	0.05	$/mt
Straw Transportation		
Tandem truck with tri-axle flatbed trailer		
Maximum hauling capacity	22	mt
Transportation cost	3.5	$/km/mt
Loading/Unloading cost	0.44	$/mt

[1] Data values extracted from CTBI Producer Value Proposition.[9]

[2] mt: metric tonne

[3] Percentage of lands in the area that are willing to sell to the biorefinery

[4] based on harvesting straw yield

4. RESULTS

4.1 Scenario mass balance estimates

Calculated biomass results from all scenario alternatives are summarized in Table 4. An overall biomass loss percentage for each alternative was estimated to determine whether each alternative improves the amount of actual biomass delivered. The base-case calculation estimated that a total harvest area of 63,152 hectares was necessary to supply the required feedstock quantity with a 22% biomass loss rate.

Table 4. Mass balance results for all product scenarios and alternatives.

			Base Case	**Alt. 1**	**Alt. 2**	**Alt. 3**
Production Area		[ha]	63,152	63,152	63,152	63,152
Potential Biomass	Grain		265,238	265,238	265,238	265,238
	Straw	[tonnes]	407,804	407,804	407,804	407,804
Total potential biomass			673,042	673,042	673,042	673,042
Biomass delivered to biorefinery	Grain	[tonnes]	250,003	250,003	250,003	561,264
	Straw		276,121	295,540	299,076	
Total delivered biomass		*[tonnes]*	526,124	545,543	549,079	561,264
Overall biomass losses		[%]	22	19	18	17

Data represented in Figure 2 and Table 4 show the specific sources of biomass losses throughout the base-case supply chain and the alternatives. . Figure 2a shows that biomass losses are highest in the harvesting of straw due to a number of factors evaluated in the mass balance calculations, which include: uncut biomass left on the field (due to mechanical limitations of the machinery);[39] unrecovered biomass which is not collected by the balers once the biomass has been dropped in a windrow for drying; and in a smaller proportion general losses occurring in the equipment. These factors were taken into account in the development of the alternative scenarios to try to reduce losses by eliminating operations in which biomass is handled by multiple machines in a discontinuous manner. Alternatives 1, 2, and 3 obtained 19%, 18%, and 17% losses respectively.

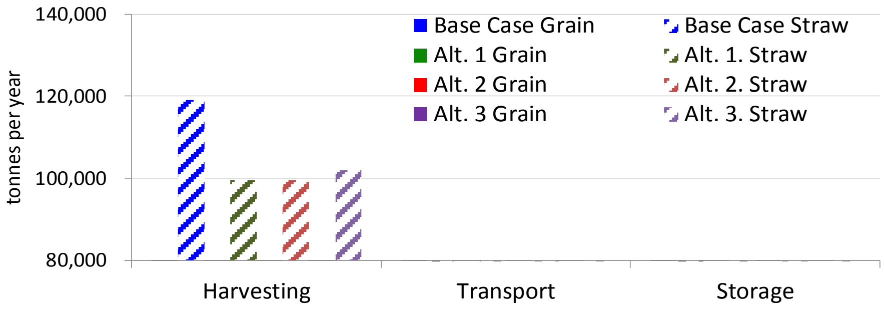

Figure 2a. Biomass losses above 80,000 mt/year

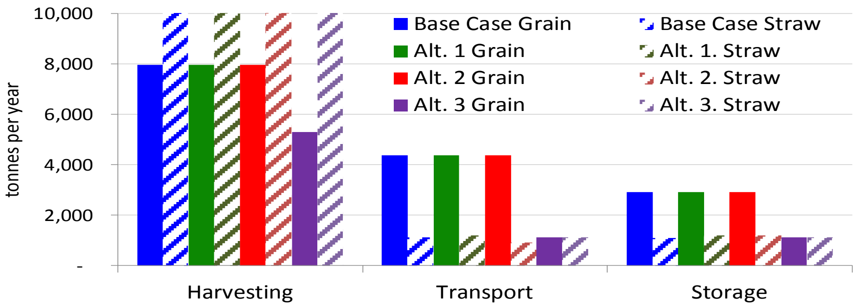

Figure 2b. Biomass losses below 10,000 mt/year

Figure 2. Biomass losses in mass balance calculations

Each alternative method was able to produce some improvements on collection of straw by eliminating steps in the process which produce losses (e.g. the dropping of material onto the field). Alternative 3 showed the largest reduction in biomass losses of 5% (compared to base case); but it's usage is limited to cases were both grain and straw will be delivered to a single customer, and assuming that customer is willing to invest in equipment needed to separate the materials. Alternative 2 presented the second largest reduction (4%) by side-stepping the baling process entirely, but transportation may be more expensive, as the density of unbaled straw will be greater than that of bales. Alternative 1 presents a balance between need for additional equipment and changes in the supply chain, but comes at a cost of only marginally reducing biomass losses (3%).

Of the biomass losses occurring in harvesting, it was determined that the uncut biomass (which can be as high as 30% of straw yields as reported by A. Monti et al.)[39] presents the greatest potential for reducing biomass losses; however in this study, it was not altered as there is no published data on machine modifications which address this issue. However, if the mechanical limitation can be overcome, then biomass losses from uncut material could be further reduced.

Figure 2b show smaller biomass losses (when compared to straw losses in harvesting) in transportation and storage. These values do not change, as no modifications were made in the transportation and storage areas, as most of the effort was centered on harvesting. Grain losses representing about 3% of total grain material harvested presented in Figure 2b, were maintained for most of the scenarios, as they are considered acceptable losses.[40]

Figure 3 presents the quantities of biomass delivered to the biorefinery for each of the alternatives. As can be seen, grain amounts do not vary greatly, but straw quantities collected do increase significantly, with increases of 14%, 15%, and 16% respectively for alternatives 1, 2, and 3.

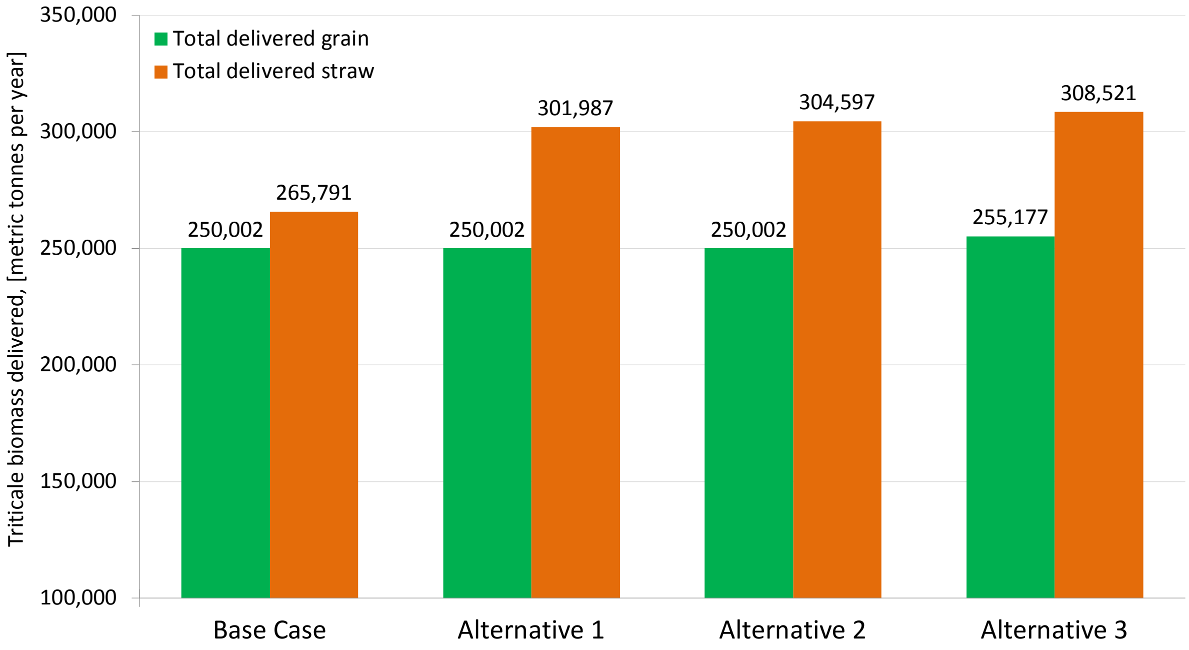

Figure 3. Triticale grain and straw delivered to biorefinery for all scenario alternatives

4.2 Techno-economic study of biomass procurement

Figure 4 summarizes the results of the techno-economic calculation of all costs per tonne associated with the harvesting and transportation of triticale grain and straw to the biorefinery. In the case where a whole-crop harvesting system is used (alternative 4), costs are associated with grain or straw on a weight-percentage basis to compare them with the other alternatives. The whole-crop harvesting method delivers the largest amount of biomass, but has a higher associated cost per tonne. Grain transport increases significantly due the change in truck. Since the grains are mixed in with the straw in bales, transport must be done on a flatbed truck which can only carry 22 metric tonnes of material (44 round bales) as opposed to the 44 tonnes of material carried by a grain trailer as described in Table 4. Because less material can be transported per truck, more trips have to be made to carry all the material, and the transportation cost increases. In straw transportation, this difference is not present because the material is always transported in bales.

Figure 4 also shows that the lowest-cost harvesting scenario alternative for triticale biomass is alternative 2. This, coupled with data presented in Figure 3, shows that in both alternative 1 and 2, it is possible to make changes which will recover more biomass material, and still maintain the same harvesting costs.

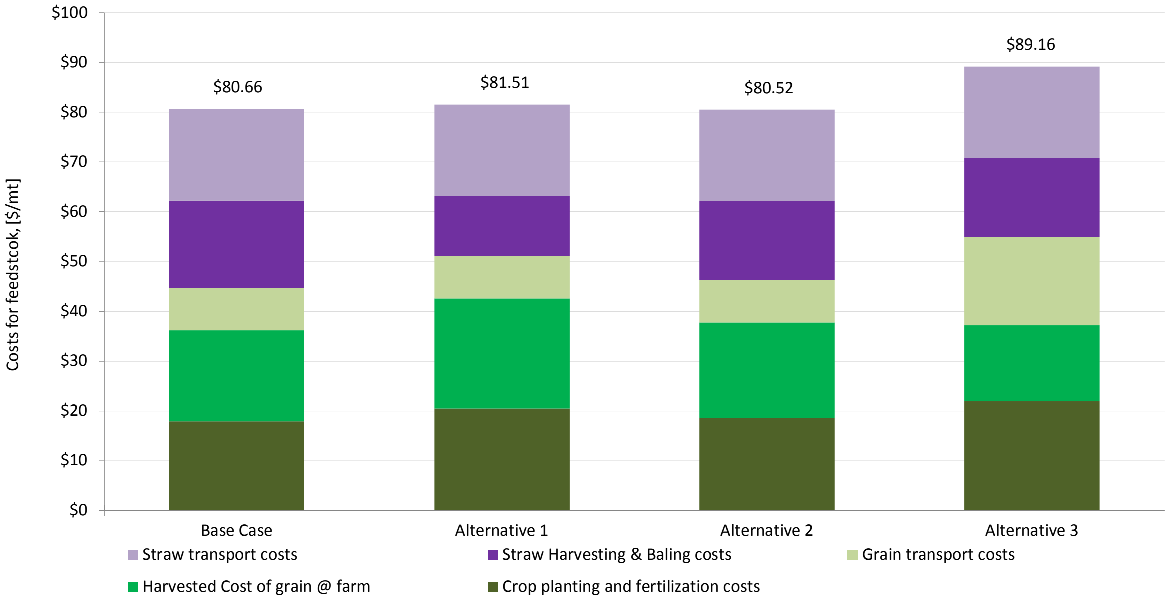

Figure 4. Procurement costs of triticale biomass for all product scenario alternatives

The data presented in figure 4 can also be subdivided into costs per tonne for the individual feedstocks (grain and straw), to show the cost if they were to be sold to different customers as shown in Table 5.

Table 5. Total cost compared to market price for grain and straw

	Base Case	Alternative 1	Alternative 2	Alternative 3
Delivered Cost of grain (producer expenses)	$44.76	$51.13	$46.29	$54.92
Market Price of Grain (paid by customer)	$145.00	$145.00	$145.00	$145.00
Delivered Cost of Straw (producer expenses)	$35.90	$30.38	$34.23	$34.25
Price of Straw (paid by customer)	$50.90	$45.38	$49.23	$49.25

The difference between the cost of each feedstock and the price paid by the customer is the producer's revenues as shown in Figure 5. Revenues for grains are much higher than for straw, because the grain price is controlled by world market demand. As for straw, because there is only a small local market demand, the price may be negotiated between customer and producer, and according to sources[9] straw revenues are maintained around $10-$15 per tonne.

The biomass procurement costs shown in Figure 4 are not the only costs associated with the procurement of triticale biomass feedstocks. Figure 5 presents the costs from figure 4 (shown as producer triticale costs, and transportation costs), along with the additional expenses that would be incurred by the biorefinery. Producer revenues (i.e. the profits earned by selling grains and straw at market price) plus additional payments for triticale will increase the costs per tonne.

If the biorefinery wants to pay less than the market price of competing grain crops, the producer will make more profits, selling their grains elsewhere. Therefore, a biorefinery must always offer more than the market price of wheat grain to secure planting and delivery of triticale. This is part of the reasoning that is used to add a premium payment for triticale, as shown in Figure 5. This premium payment (20% above market price) will assure the producer that the biorefinery will always pay more than what the open market for wheat grain can offer.

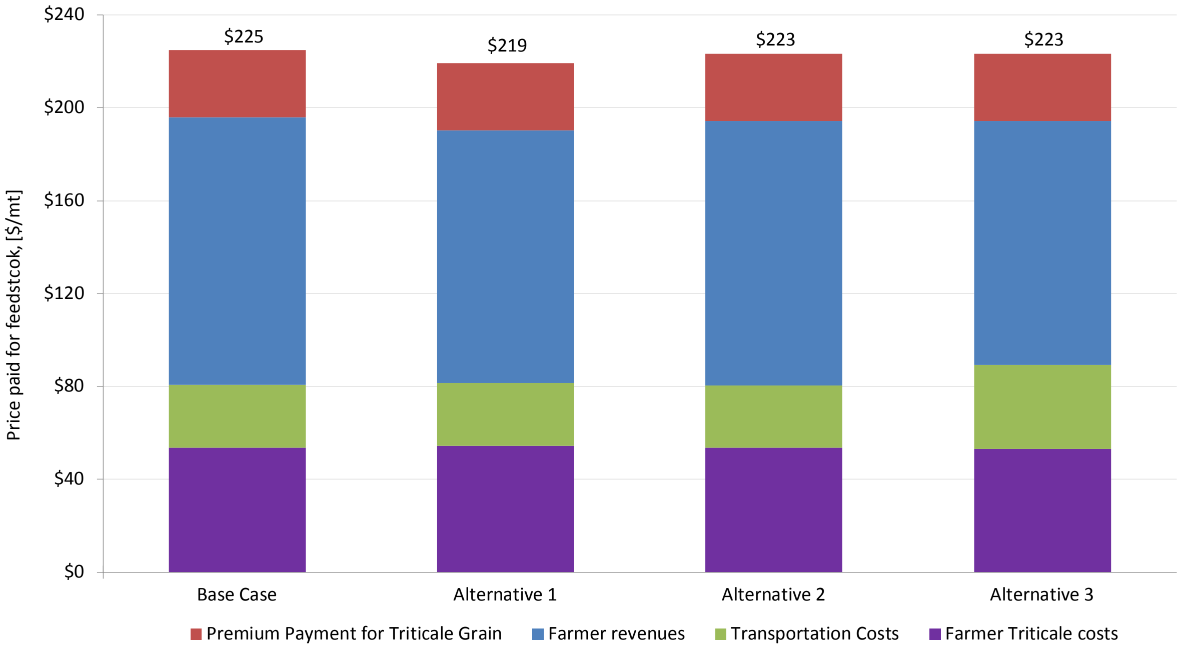

Figure 5. Total biorefinery incurred expenses for triticale biomass

5. DISCUSSION

In current procurement methods for grains and residues of traditional crops, producers assume all the costs and risk involved in the production, harvesting, and transportation. Financial compensation in most cases is not received until the feedstocks are delivered to the mill or regional receiving stations. The customer in turn receives the grain as delivered and has no control over what the local farmers produce. To improve this situation, a new biomass procurement strategy is proposed which seeks to improve bottom-line results for both parties (biorefinery and producer).

The proposed strategy seeks to provide higher revenues than what the producers obtain with current grains by instead planting triticale. In the proposed strategy, the biorefinery assumes control over the inputs and outputs of the farm, i.e., the biorefinery would purchase and deliver the triticale seed to the producer, and after harvesting, would assume all transportation costs of delivering the feedstock to its installations. This strategic model would essentially mean that the biorefinery would assume the costs for triticale seed and shipment of triticale grain and straw to the biorefinery, as well as incremental harvesting costs incurred by the producer for growing, fertilizing, harvesting, and inventorying the triticale biomass. The producer would forego certain activities such as seed purchasing and transportation, but would remain responsible for operations on the farm land. Meanwhile, the biorefinery would realize economies by purchasing seed in bulk and by implementing advanced logistics for grain and straw transportation.

This type of strategy seeks to benefit both the producer and the biorefinery. The benefits for the producer are a better initial cash flow because a large part of his initial costs (seed purchasing) would be covered by the biorefinery. The other important benefit for the producer is increased profit. To motivate producers to plant a relatively new crop such as triticale, the biorefinery would offer a 20% profit premium over the current market price of growing and selling wheat grain. By calculating this value on a year-to-year basis and thus implicitly accounting for market conditions, weather, crop rotation, etc., the mill would guarantee the producer a premium on a year-to-year basis. At the same time, the biorefinery would secure a large supply of triticale feedstocks (both grain and straw) for the duration of the agreement (5-10 years with the potential for renewal after 10 years).

Using this model, and assuming that triticale productivity is 1.06 times that of wheat (based on data from Agriculture Canada), it was found that the biorefinery would pay $225/tonne of biomass for the purchase of 250,002 tonnes per year of grain and the residual 265,791 tonnes per year of straw which would be include in the purchase agreement. This cost can be further reduced, by using one of the alternative methods reviewed, with a minimum cost for both feedstocks sold together of $219 using alternative 1. Additional variations in the feedstock cost can be produced depending on the feedstock demand of the biorefinery (due to transportation distance, competition, etc.), the ratio of straw to grain needed for the biorefinery processes, crop harvesting practices, and other factors.

The second benefit of the biorefinery is that triticale is an ever-improving crop. Every year, triticale breeding programs improve current yields at a rate of 1.5% yield increase per year.[9] With a procurement strategy in which the biorefinery assumes the crop yield risk and pays on a per-hectare basis, the biorefinery will also benefit as yields increase and the cost of biomass per tonne decreases. Further sensitivity analyses examined this effect by analyzing the impact of increased triticale productivity over wheat productivity and the effect on the total price paid by the biorefinery for triticale biomass and on other parameters shown in Figures 6 and 7.

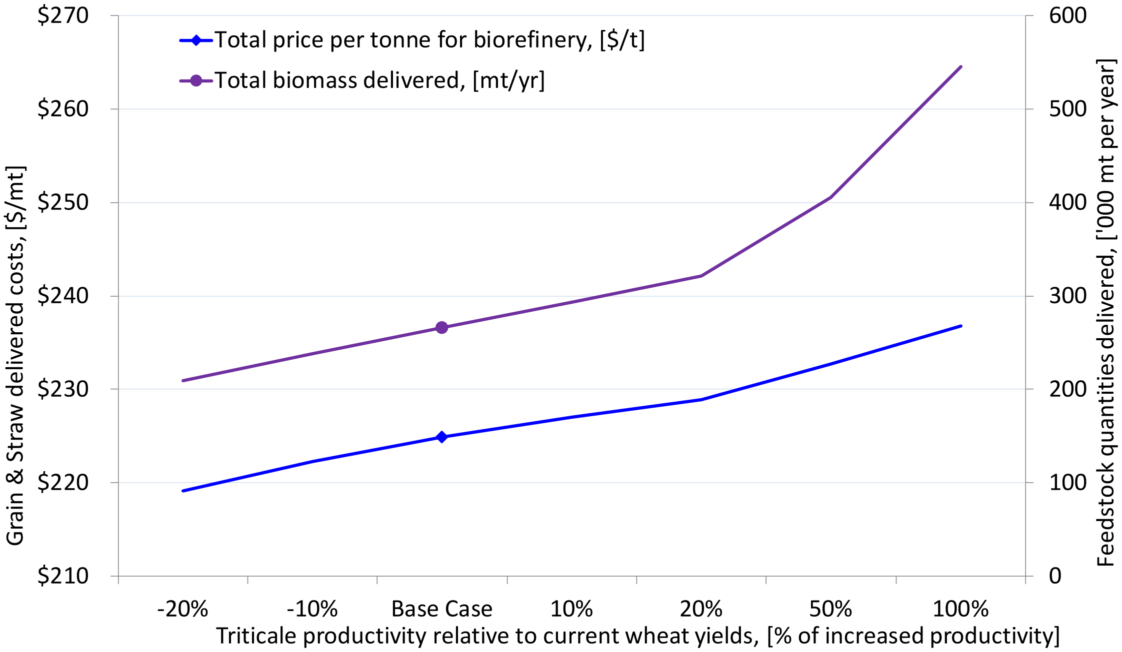

Figure 6. Sensitivity analysis of biomass increase on total price in scenario base case

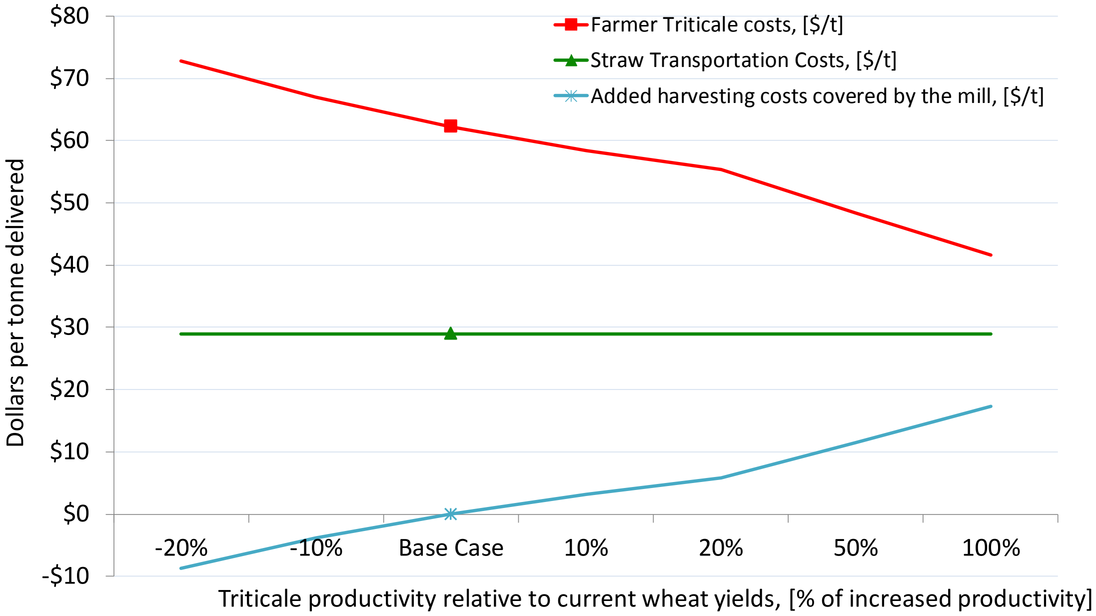

Figure 7. Sensitivity analysis of biomass increase in ethanol scenario base case

Results from the sensitivity analysis shown in Figure 6 reveal that although the costs for biomass still increase because of added harvesting and transportation expenses, the cost does not increase as fast as the amount of biomass being produced due to increased yield. For example, when triticale productivity increases by 20%, the biorefinery will be receiving 20% more biomass from each hectare planted, but only paying approximately $4.00 more per tonne (equivalent to a 2.00% increase in cost) to cover the producer’s extra harvesting and transportation expenses. Because of this, as can be clearly seen in Figure 8, as triticale productivity increases, the producer’s costs will decrease because the biorefinery will be covering all additional harvesting costs.

The benefit of increases in triticale productivity is to be accrued by the triticale biorefinery, ensuring its competitive position over the long term. Thus, the biorefinery invests in increased productivity of triticale and must assume as well the incremental costs accrued by the producer for harvesting. This cost will increase as triticale productivity increases. The specifics of the contract are not the subject of this paper; however, an attempt has been made to allocate costs correctly according to the model as developed. With the strategy proposed here, there are certain trade-offs for both parties that should be considered when negotiating the specifics of the contract. For the biorefinery, aside from the inherent risk of yields on a yearly basis, there are also the increased costs that will have to be paid for assuring their long-term supply of feedstocks. The added cost, will play a defining role in the overall finances of the biorefinery, and may be prohibitive, depending on what final product they are producing. Commodity products such as ethanol, or electricity generation, might not produce enough revenues to balance out the feedstock costs, so additional value-added products may be needed to increase overall profits. As for the producer, the trade-off comes in the form of control of what is being planted on their lands and relinquishing the residues at cost, and accepting long-term agreement which could potentially see them “locked into” a single feedstock for a 5-10 year period.

6. CONCLUSIONS

The goal of this research was to determine a financial model for the delivery of triticale feedstock to a greenfield biorefinery which would ensure that the farming community participates profitably in the value chain and that the biorefinery has a source of feedstock that remains competitive into the longer term.

In the context of this negotiation with the farming community, the biorefinery proponent would offer a 20% profit premium over the profit that the producer would expect from growing wheat. By calculating this value on a year-to-year basis and thus implicitly accounting for market conditions, weather, crop rotation, etc., the mill would guarantee the producer a premium on a year-to-year basis. Based on discussions with the farming community, this type of strategy would be well received because it provides benefits for both parties.

Using the model developed here and assuming triticale productivity 1.06 times that of wheat, it was determined that the biorefinery would pay $225/tonne of biomass for the purchase of 250,002 tonnes per year of grain and 265,791 tonnes per year of straw. This cost obviously varies according to the feedstock demand for the biorefinery (due to transportation distance, competition, etc.), the ratio of straw to grain needed for the biorefinery processes, crop rotation practices, etc.

On the assumption that the productivity of triticale relative to that of wheat will increase in the coming years, the longer-term costs of triticale feedstock were examined. It was found that if triticale productivity over wheat productivity increases by 0.2 (a 20% biomass yield increase), the combined costs of triticale grain and straw will increase only by 2.00%, to $229/tonne of delivered biomass to the biorefinery. Sanaei et al.[48] further reviewed the linkages and their importance between economic and business-oriented strategies and profitability criteria, links which in this article have been reviewed for feedstock procurement costs.

One of the main contributions of this study is the development of an agricultural biomass procurement cost modeling tool which enables the study of various procurement scenarios for different biomass requirements as well as sensitivity analyses for increased yields of triticale biomass.

Typically, the yields from operations across the value chain are not fully recognized. This paper has endeavoured to do this by examining the different steps across the value chain and has found that the yield losses can range between 22% and 17%. Furthermore, the differences between the proposed alternatives were examined. Alternative 3 presented the largest yield losses decrease in harvesting due to less handling of material. Alternative 1 presented the lowest total biomass cost, with a total biomass price of $219 (as presented in Figure 4).

Mass balance calculations and techno-economic estimates were used to develop a biomass costing model, which was then used to develop a strategic biomass procurement model. Use of this model has shown that triticale as a feedstock for biorefineries has the potential to enable significant cost reductions while providing more biomass per hectare than currently produced by other crops. In addition, the alternative scenario analysis showed that there are many ways to improve the current harvesting and procurement of triticale by introducing new technologies into the supply chain, which will ultimately improve efficiencies.

The proposed triticale procurement strategy and model was developed using a thorough biomass procurement analysis. The study of the biomass supply chain and of alternative procurement methods and the subsequent techno-economic analysis were evaluated to find ways to improve biomass harvesting and reduce overall procurement costs. At the same time, the overall strategy secures the production of triticale feedstocks for the biorefinery and provides the producers with increased revenue compared to that from other grain crops.

Future work could be carried out to determine if additional uncut material losses can be reduced in order to increase biomass recovery from the field, as well as work to try and reduce grain losses occurring within the combine during harvesting. In addition, studies could be carried out on other negotiation strategies between customers and producers, and make cost comparisons to the ones established in this study.

7. ACKNOWLEDGEMENTS

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