EVALUATION OF SOCIO-ECONOMIC CONTRIBUTIONS FROM THE PRIMARY FORESTRY SECTOR USING MATERIAL FLOW ANALYSES

by

YU LI

M.Sc., Nanjing Forestry University, 2006 B.Sc., Zhejiang A&F University, 2004

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ABSTRACT

The competitiveness of the global primary forest products industry has been declining consistently compared with many other industrial sectors. This dissertation's goal was to evaluate the performance of primary forestry sector in Canada and use wood utilization and allocation as means to improve the sector's socio-economic outcomes. To achieve this goal, material flow analyses was used as the fundamental methodology to quantify a series of unit input employment and value added indicators to characterize the forestry sector value chains and evaluate socio-economic contributions.

The substantial increase in the international trade of forest products required that trade data should be accounted for when quantifying socio-economic outcomes from national forestry sectors. A parameter termed the Apparent Industrial Input (AII) was developed to measure the wood fibre input at various stages of national primary value chains accounting for the international trade of various forest products. Normalized value added, GDP and employment indicators based on these trade-adjusted fibre inputs were employed to evaluate the comparative performance of Canada and fourteen other countries' forestry sectors at various stages of the value chain.

A primary forestry sector maturation pattern was observed as a nation's commercial forestry sector developed. Nations that created more value per fibre input generally possessed a proportionately smaller forestry and logging subsector and a larger manufacturing subsector. A comparative study between Canada and United States of America (USA) showed that Canada historically had a larger proportional forestry and logging value added and a smaller proportional manufacturing subsector value added than the USA. It was inferred that Canada would achieve lower economic outcomes per input.

Material flow analyses were completed for British Columbia's (BC) primary forestry value chain and an integrated forestry company in BC. Both studies revealed the importance of by-products' role in linking the wood products manufacturing and pulp and paper manufacturing subsectors. Two optimized scenarios revealed that by reallocating fibre flows, value added per unit of input for BC's primary forestry sector could be increased by up to 35.4% compared to the base case. The enterprise level study also showed that material flow adjustment could increase the unit input value added.

PREFACE

I hereby declare that this thesis, as approved by my thesis committee and the Graduate and Postdoctoral Studies, is the product of my original work and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

The core theme of this thesis is evaluating the socio-economic contributions from the primary forestry sector at national and provincial levels using material flow analyses. The contributions of this thesis have resulted in eleven conference oral and poster presentations. Since all of these conference papers and posters were co–authored by other colleagues, I would like to clarify my contributions to these publications, particularly those related to Chapter 5.

In all publications, I contributed through reviewing the literature, developing the research idea, analyzing the problem, and writing the report/paper.

For the material flow research presented in Chapter 5, I collaborated with Dr. Jerome Alteyrac and Mr. Hugues Petit-Etienne on communication with related institutions, data collection and interpretation, laboratory work, analyzing results, material flow model design and writing reports. For the enterprise case study described in Chapter 7, I collaborated with Dr. Jerome Alteyrac on communication with related institutions, data collection for the material flow development.

Except for Chapters 5 and 7, all other parts of the thesis, including the data collection, indicators selection, development of mathematical models and writing up of all chapters were my sole responsibility, working within the Department of Wood Science, under direct supervision of Dr. Paul McFarlane and Dr. Christopher Gaston. The thesis, and the research to which it refers, contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution.

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LIST OF ABBREVIATIONS

- AII: Apparent Industrial Input
- AVA: Apparent Value Added
- **BP**: By-Products
- C&P: Chips and Particulates
- FJ: Finger Joint
- FL: Forestry and Logging
- FP: Final Products
- FS: Forestry Sector
- FTE: Fulltime Equivalents
- GRWE: Green Roundwood Equivalent (underbark or whitewood volume)
- GSWE: Green Solid Wood Equivalent (underbark or whitewood volume)
- GVA: Gross Value Added
- I-O Factor: Input/Output Factor
- InRw: Industrial Roundwood
- LRF: Lumber Recovery Factor
- MFA: Material Flow Analysis
- MS: Manufacturing Subsector
- **OM**: Other Mills
- **OSB**: Oriented Strand Board
- Ply: Plywood
- PM: Pulp and Paper Manufacturing
- PNL: Panel
- PP: Pulp and Paper
- **PS**: Primary Sawmilling
- PW: Pulpwood
- S&S: Shake and Shingles

SP: Structural Panels

- SPF: Spruce-Pine-Fir
- SS: Sawdust and Shavings
- SV: Sawlogs and Veneer Logs

VNR: Veneer

- VS: Veneer Sheets
- v/v: Volume/Volume
- WP: Wood Pulp
- WPM: Wood Products Manufacturing

WR: Wood Residues

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CHAPTER 1 INTRODUCTION

1.1 Background

Forests provide a diverse range of goods to meet society's needs, including structural lumber, furniture, packaging, printing, hygiene products and energy. There are several reasons to develop, analyze, depict and optimize the forestry sector structure including socio-economic (e.g. economic, social and ecological drivers), political-economic (e.g. basis for political decisions), or technological reasons (technological innovation drivers) (Teischinger, 2009). The development and quantification of suitable criteria and indicators for important outcomes along the value chain are needed to better manage the value chain, provide policy relevant information and enable decision makers to undertake comparisons (Adamowicz, 2003; Dale et al., 2013; Franc et al., 2000; Lindner et al., 2010).

The economic and social contributions of the primary forestry sector (FS) to nations are important aspects of sustainable forest management (Lebedys, 2008, 2004) and many countries are seeking to increase the socio-economic benefits delivered by this sector. The forestry sector's socio-economic benefits have traditionally been collected from the following three subsectors: forestry and logging (FL), wood products manufacturing (WPM) and pulp and paper manufacturing (PM) (MoFR, 2011; StatsCans, 2009a). The manufacturing subsector is considered to consist of the aggregated wood products manufacturing and pulp and paper manufacturing in this way, what the primary manufacturing subsector represents is economically and socially important to many countries, especially those nations with well-developed forestry sectors (Carlsson and Rönnqvist, 2005; Rönnqvist, 2003).

From a material flow perspective, the forestry and logging subsector provides industrial roundwood to both the wood products manufacturing and pulp and paper manufacturing subsectors (FAO, 1990). Within the wood products manufacturing subsector, sawmills represent the primary fractionation phase of wood processing. They consume logs and produce lumber as the major commercial product. The lumber produced typically comprises 45-55% of roundwood input by volume and the yield of wood by-products including chips, sawdust, shavings and bark is approximately 55-45% of the roundwood volume (Parikka, 2004). In many nations with a significant sawmilling industry, wood by-products, especially chips, flow from the wood products manufacturing to the pulp and paper manufacturing subsector and provide an important link between these two subsectors (Alteyrac et al., 2008a, b). In addition, sawdust, bark, and other residues are used for pellet and bioenergy production. These links improve the forestry sector's material utilization efficiency.

Material flow analysis (MFA) may be used to quantify the industrial roundwood input to the forest products industry and more comprehensively understand how industrial roundwood flows from the timber harvest to a diverse range of products. MFA measures how materials flow into, through, and out of a

system (Hendriks et al., 2000) and it can be employed to quantify each component of the wood flow from forest harvest to final products. In addition, most historical studies on wood flow or primary forest product contributions have been undertaken on mixed input and output basis using different measurement systems (Lebedys, 2008; 2004; Lebedys and Li, 2014). Traditionally, final forest products from the manufacturing subsector have been quantified using a diverse range of units (Lebedys, 2008; 2004). For instance, industrial roundwood harvested in the forest has usually been measured in green cubic metres (m^3) , wood pulp and paper have been quantified in air dry tonnes (ADT), whereas, in North America, sawn lumber has been measured in million board feet (Mbfm) and panels have been assessed using thousand square feet (msf) with various thicknesses measured in inches, e.g. msf (3/8"), whereas in Europe and much of the rest of the world, metric volumetric units are usually used. Quantifying the wood supply from the forestry and logging subsector and its distribution in the wood products manufacturing and pulp and paper manufacturing subsectors when products are measured in different units has been difficult. Therefore, it has been challenging to complete a material flow analysis for the entire forestry sector using one unit basis. To the best of the author's knowledge, a few studies have completed a comprehensive forestry sector MFA at the national level either on a volumetric or dry mass basis. All of these studies have taken place recently and they have been undertaken for China (Cheng et al., 2010a, b; Su and Cheng, 2004), Finland (Sokka et al., 2015), Austria (Lang and Nemesthoty, 2013), Netherland (Kwant et al., 2014) and the European Union (Mantau, 2012). Considering that the majority of forest products along the value chain are measured in a volumetric unit, it is more favorable to use volumetric based socio-economic indicators to characterize the forest value chain at the national scale based on MFA. However, a lack of information on the quantities of wood by-products flowing from the wood products manufacturing subsector to support the pulp and paper manufacturing subsector has traditionally made it difficult to measure the total wood material consumed by both the wood products manufacturing and pulp and paper manufacturing subsectors. Therefore, as an alternative to comprehensive MFA studies, it would be useful to investigate whether a series of volumetric material input indicators could be developed to quantify the fibre input at stages of the value chain. Based on these values, unit input socio-economic indicators may be further used to investigate socio-economic outcomes created along the value chain.

To the author's knowledge, there has been no published research that has focused on completing a comprehensive input-based MFA of a primary forestry value chain for any Canadian province in order to quantify the material utilization efficiency and evaluate the socio-economic benefits delivered. To better understand the manufacturing infrastructure's impact on the socio-economic benefits from the primary forestry sector and search for socio-economic improvement from the means of alternating manufacturing infrastructure for Canada, a detailed MFA study is needed to quantify the socio-economic benefits on a common volumetric input unit for Canada's provincial primary forestry sector given that provincial data are available.

MFA has been identified as an important methodology that may be used to characterize how an industry value chain functions at a range of different levels (e.g. national, provincial/state, organizational) (Chambers et al., 2005; Lang et al., 2006), and optimization studies in the literature have been developed to support the forestry sector planning (Beaudoin et al., 2007; Bredström et al., 2004; Carlsson and Rönnqvist, 2005; Grladinović et al., 2003; Palander and Voutilainen, 2013; Rönnqvist, 2003; Shabani et al., 2013). Most of these optimization studies have focused on either a part of the entire forestry value chain or certain manufacturing plants by considering various factors, such as material procurement, storage, transportation and production. To the extent of the author's knowledge, no study has focused on identifying the potential value increase that may be achieved by fibre supply reallocation within an entire provincial primary forestry sector. Thus, it will be an important goal for this study to explore whether the reallocating wood fibre flows within existing constraints can improve the socio-economic benefits produced at a provincial level.

1.2 Research Objectives

In order to fill these gaps, the research presented in this dissertation consisted of the following four objectives:

Objective 1: To Assess the Forestry Sector's Socio-Economic Contributions Using Input Based Indicators

Many traditional forest products, such as industrial roundwood and intermediate products (i.e. veneer sheets, chips and particulates, wood residues and wood pulp) are traded internationally as commodities (Sathre and Gustavsson, 2009). The ongoing globalization of forest products markets and increased forest products trade (Lebedys and Li, 2014) require more effective indicators to determine the net input to the forest products industries. Therefore, an important objective of this research was to develop a series of input indicators to quantify apparent wood fibre inputs at points along the primary forest products value chain and based on this to assess subsectors' socio-economic benefits.

Objective 2: To Investigate Value Structure's Impact on Forestry Sector Socio-Economic Contributions for Canada and Other Forestry Countries.

Preliminary research undertaken by MFLNRO and UBC (MoFR, 2009a) has shown that Canada's primary forestry sector has historically obtained lower socio-economic benefits per unit of input than that of the USA. There was significant interest in assessing and comparing the forestry sector's unit socio-economic contribution in Canada to gain an improved understanding of the potential causes of the variations in the socio-economic contributions among the forestry subsectors in Canada and other important forestry nations. Potential means of improving socio-economic contributions could be investigated based on studies that assessed the impact of various industrial value structures.

Objective 3: To Develop and Optimize Material Flows of British Columbia's Forest Products Industry

British Columbia (BC) is one of most important forestry provinces in Canada. Forests have been economically, culturally and spiritually significant to BC residents. The province is well known for its abundant forest resources, high forest coverage rate, advanced forest management practices and forest products (MoFR, 1995). As an important component of Canadian forest products industry, socio-economic contributions study for BC would reflect the means to improve socio-economic contributions at the nation's level. Material flow analysis and a reallocation of fibre flows were selected to be the approach to evaluate how substantially the value structure impacts on the provincial socio-economic outcomes achieve.

Objective 4: To Optimize Material Flow for an Integrated Company in BC

National and provincial forestry sector socio-economic benefits are essentially the aggregation of the outcomes achieved by many forest products manufacturing enterprises and improved national and provincial socio-economic benefits will only occur if better outcomes are delivered at the enterprise level. Forest product companies are continuously pursuing profitable manufacturing patterns and with cyclical price conditions for various commodity forest products and increasing concerns over socio-economic outcomes, the forest products industry needs to be responsive to changing market and societal conditions. It is therefore of interest to undertake an MFA case study at the enterprise level to investigate the potential economic benefits that an integrated forest products company could achieve under different supply and demand scenarios.

1.3 Preliminary Material Flow Studies for British Columbia

British Columbia (BC) is Canada's westernmost province, occupying about 10% of Canada's total land area (FII, 2008; MoFR, 1995, 2008a), and it is an important element of the Canadian forest products industry (FII, 2008). BC is well known around the world for abundant forest resources, a high forest coverage rate and advanced forest management practices and forest products (MoFR, 1995).

A simplified conceptual material flow framework for BC's primary forestry sector was initially developed for British Columbia and is presented in Figure 1-1 (Alteyrac et al., 2008a). The three major subsectors in the value chain, namely the forestry and logging (FL), wood products manufacturing (WPM) and pulp and paper manufacturing (PM) subsectors (introduced in Section 2.2.2), are indicated in this figure. Alteyrac et al. (2008a) concluded that, in BC, the wood products manufacturing consumed the major proportion of roundwood harvested from BC forests to produce lumber and panels. Historically, BC's pulp and paper value chain has directly consumed less than 10% of BC's roundwood harvest by volume. The industrial roundwood chipped directly for pulp and paper manufacturing mainly consists mainly of low quality, small diameter pulpwood. Wood by-products produced by the lumber and panel mills accounted for almost

half of the log input in the structural wood product value chain and most of these by-products were used to make pulp and paper. This substantial flow of by-products therefore linked the two manufacturing subsectors of the value chain (Figure 1-1). The by-products used by the pulp and paper industry included chips and a portion of the shavings and sawdust. The remainder of the shavings and sawdust were used for the production of medium density fibreboard (MDF), pellets and bioenergy.



Figure 1-1: Conceptual Framework for Material Flow Analyses

(Alteyrac et al., 2008a)

This flow of wood by-products from the wood products manufacturing subsector to the pulp and paper manufacturing subsector has resulted in increased material use efficiency and an interdependence of the two forest products manufacturing subsectors (Alteyrac et al., 2008a).

Several major companies have integrated structural wood products and pulp and paper operations for strategic reasons, including a desire to ensure certainty of the by-products supply in BC. Other pulp and paper companies have protected their supply chain by developing by-products supply contracts with independent sawmills (Alteyrac et al., 2008b). Value chain integration, such as that described above, may reduce the risk for stakeholders but it has been reported to limit the ability of the manufacturing operations to adapt to environmental and market turbulences (D'Aveni and Ilinitch, 1992). This situation may have been experienced in 2007 and early 2008 as the structural wood products industry in BC decreased its production in response to the substantial reduction in the number of houses constructed in the USA during the global economic recession in the latter part of the first decade in the 2000's (Alteyrac et al., 2008b; Peters et al., 2012; Sianchuk et al., 2008, 2012). Consequently, there was a restricted supply of wood chips for the pulp and paper industry at a time when the demand for pulp and paper products was strong and prices were firm. Under these circumstances, the pulp and paper industry was seeking to obtain substantial volumes of sawmilling by-products at a time when it was uneconomical for

most sawmills to produce lumber. Therefore, despite the benefits of closely integrated value chains from a material use perspective, the asynchrony between the structural wood products and pulp and paper markets may create significant problems for the optimized operation of such tightly related manufacturing operations (Alteyrac et al., 2008a). Thus, it would be insightful to use this conceptual material flow as the base to further investigate the conjunctive function of wood by-products from an MFA viewpoint and to analyze the influence of altered wood material flows on the forestry sector's economic and social benefits in this study.

1.4 Organization of the Dissertation

In addition to the introduction presented in this Chapter 1, this dissertation includes a literature review chapter, five research chapters to address the four objectives, and a chapter on conclusions, limitations, and future work.

Chapter 2 provides a literature review of the application of material flow analysis to the forestry sector and the previous research conducted on conversion factors to enable the comparisons on a common basis, and the use of indicators for forest products industry's socio-economic benefits.

Chapter 3 summarizes a series of volumetric indicators to evaluate the net fibre inputs at different stages of the value chain. These indicators account for the international trade of industrial roundwood and intermediate forest products. A series of volume based economic indicators, GDP and value added per apparent fibre input, are adapted to provide a detailed analysis of the economic contributions achieved by different subsectors in fifteen important forestry countries. Employment per apparent fibre input and employment and apparent productivity by subsector have been evaluated and compared at an international scale.

In Chapter 4, the influence of the different forestry subsectors on the economic benefit from each unit of wood fibre input is evaluated at an international level. Detailed comparisons of the national economic benefits attained per unit of fibre input are made between Canada and the USA. A forestry sector maturation pattern is proposed based on the correlation of value structure denoted as proportional subsector GVA and value added per unit fibre input in fifteen forestry countries.

Chapter 5 presents detailed material flow models for BC's forest products industry and analyzes changes in the provincial value structure from 1991 to 2007. Input/output (I-O) factors and conversion factors are determined to balance material flows.

In Chapter 6, a material flow model of BC's forestry sector in 2007 is completed to demonstrate how the economic benefits at the provincial scale may be improved. Material utilization efficiency and socio-economic benefits are quantified in two alternative scenarios and compared with the base scenario.

Chapter 7 evaluates how economic benefits may be increased by optimizing the by-products flow at an enterprise level. The economic benefits of more effectively using the wood by-products that provide the link between the wood products manufacturing and pulp and paper manufacturing subsectors are highlighted.

Finally, Chapter 8 provides the final conclusions, indicates research limitations and provides suggestions for future research.

CHAPTER 2 LITERATURE REVIEW

2.1 Synopsis

Material flow analysis (MFA) has been used in the literature to analyze the flow and distribution of raw material in industrial value chains (Ciacci et al., 2013). This dissertation will examine the use of indicators linked with MFA methodology as a means of assessing socio-economic benefits from nations with large forest resources. It will also explore whether the adjustment of fibre flows within the primary forestry sector may increase the economic outcomes.

The purpose of this chapter is to introduce and provide a review on the background, methods and approaches used in the research chapters to follow. First, Section 2.2 provides an overview of the primary forestry sector. Section 2.3.2 which provides the basis for Chapter 3, 4 and 5, explains conversion factors applied in the forestry industry. In Section 2.3.3, most common socio-economic indicators applicable to the forest products industry were discussed. Section 2.3.1 discusses the implication of MFA in the forestry sector and Section 2.4 briefly explains the optimization of MFA in the forest products industry to provide the background for Chapter 7.

2.2 Primary Forestry Sector Overview

2.2.1 Primary Forestry Sector's Socio-Economical Benefits Overview

The forest products industry impacts the lives of every person in the world, either directly or indirectly. Our world depends heavily upon the ecological functions of forests and society consumes a diverse range of forest products including energy, structural lumber and panels, furniture, flooring, newsprint, packaging and hygiene papers.

Canada is the world's second largest country, with an area of 9,984,670 km² (MoFR, 1995). It is a nation rich in natural resources, with more than 15% of the world's entire softwood forest stock (FII, 2008). Forest resources form an important part of Canada's economy, history, culture, tradition and lifestyle (Natural Resources Canada, 2006).

British Columbia (BC) is Canada's most important forestry province (FII, 2008). The forestry sector continues to make an important contribution to BC's economy although the economic growth rate of the forestry sector has been lower than those of other industrial sectors. The contribution of the forestry sector's GDP to the provincial economy decreased from 10.3% to 2.50% from the late 1980s to 2013 (BC Stats, 2008; MoFR, 2008a; Natural Resources Canada, 2016). However, the absolute value generated by the forestry sector increased over the same period. The average number of jobs in the forestry sector also

decreased substantially. Between 1990 and 2013, the total employees within the provincial primary forestry sector decreased from 94,300 to 63,500 full time equivalents (FTE), or a 32.7% reduction (CanSim, 2011; StatsCan, 2016a).

This declining trend in socio-economic benefits was also observed in the forestry sector at a global level. The industrial roundwood and lumber production per unit of global GDP has consistently declined from 1961 to 2011 and both have decreased about 80% over this period (McFarlane and Sands, 2013). In particular, there was a significant decrease in the contribution of the forestry sector to GDP in the developing Asia-Pacific region during the 1990s (Lebedys, 2008). However, the forestry sector remains a relatively important generator of GDP in many developing regions and Eastern Europe.

The dwindling proportional contribution of the forestry sector to GDP does not mean that the forest industry did not expand in absolute terms. Production, consumption and trade volumes of forest products increased in real terms in most countries, but the growth of the forest products sector was slower than that of most national economies. Thus, at the global scale, the forest industry's relative contribution to GDP is currently less important than it used to be. Very few countries have focused on the development of the forestry sector, preferring instead to promote the development of other industries and it is generally the case that the growth rate of the forestry sector has not kept pace with other swiftly developing sectors, particularly in rapidly growing economies (Lebedys, 2008).

In addition, the preliminary study by MoFR (2009a) concluded although Canada's forestry sector GDP has been strong amongst forestry nations (Lebedys and Li, 2014; Lipsey et al., 1991; Mankiw et al., 1999; StatsCan, 2009), its economic benefits per unit input have been consistently low. Therefore, it is important to analyze the cause of the low contribution and assess the potential of increasing value creation from each cubic metre of the tree harvested from Canada's forest.

2.2.2 Primary Forestry Sector Structure

A full value chain for the primary forest products industry consists of a wide range of economic activities ranging from forestry logging, diverse wood products manufacturing, to wood fibre reutilization. Due to this complexity, detailed analysis of the value chain is frequently conducted at the subsector scale and several categorization systems have been used, including the North American Industry Classification System (NAICS), the Canadian System of National Accounts (CSNA) and the Food and Agriculture Organization (FAO) of the United Nations. Importantly, the forestry sector definitions used by these categorization systems are consistent.

According to NAICS, the forestry sector has traditionally been divided into three major subsectors for statistical purposes: forestry and logging (FL) for all forest management and harvesting activities; wood

products manufacturing (wood products manufacturing) which includes all activities involved in the production of lumber, panels and other commodities made of wood; and pulp and paper manufacturing (PM) for all endeavours associated with manufacturing pulp and paper products (StatsCan, 2009). As shown in Figure 2-1, the forestry and logging subsector is a precursor to both the wood products manufacturing and pulp and paper manufacturing subsectors as it provides them with industrial roundwood.

The FAO has published subsector level data on the forestry sector's contributions to various nations' employment and GDP values (Lebedys and Li, 2014). It has used different terminologies compared to NAICS to characterise the subsectors, namely, roundwood production, wood processing and pulp and paper (Lebedys, 2008). These definitions are consistent with the forestry and logging, wood products manufacturing and pulp and paper manufacturing subsector terminologies used by NAICS. Other names for the three subsectors have also been used in some publications. For example, the CNSA used the respective terms logging and forestry industries, wood industries and paper and allied products industries (Alteyrac et al., 2007). However, the scope of each subsector defined by the CNSA is consistent with NAICS's.

Based on NAICS's definition, the forestry sector is defined as the sum of forestry and logging (FL), wood products manufacturing (WPM) and pulp and paper manufacturing (PM) subsectors.



Figure 2-1: A Schematic Representation of the Three Subsectors of the Forestry Sector

The three subsectors are connected by the supply of wood fibre (Figure 2-1). Industrial roundwood is harvested in the forestry and logging subsector and then sent into both wood products manufacturing and pulp and paper manufacturing subsectors to produce primary wood products. The net volume of wood fibre

flowing through a value chain may also be influenced by the trade of industrial roundwood and intermediate forest products. Five intermediate forest products are traded internationally, namely, wood chips and particles (C&P), wood residues (WR), veneer sheets (VS) and wood pulp (WP) (FAO, 2011). The pulp and paper manufacturing subsector may be then divided into pulp manufacturing and paper manufacturing sub-components with a flow of wood pulp linking the two sub-components. The definitions of these forest products are listed in the Glossary.

2.2.3 Primary Forestry Sector Manufacturing

2.2.3.1 Lumber Manufacturing

Sawmilling is an important component of primary wood manufacturing in most nations. Within the primary forestry sector, sawmills frequently play a central role in fractionating the industrial roundwood. The objective of a sawmill is to produce a set of saleable products that maximize net revenue by converting industrial roundwood into lumber as the principal product (Wessels et al., 2006). Several by-products, including chips, sawdust, shavings, trim ends and bark are also produced. The mix of by-products is dependent upon the characteristics of the mill and the industrial roundwood. Lumber manufacture consists of a sequence of interrelated operations resulting in an end product of specific dimension and grade. A flow chart illustrating a typical manufacturing process for lumber products is presented in Figure 2-2. The manufacturing process consists of unloading and sorting, debarking, sawing, drying, planing, wrapping and shipping stages, although some sawmills may only consist of a selection of these processes. Four types of market softwood lumber products (green rough, green dressed, kiln rough and kiln dry) may be produced by a sawmill. In this figure, the sequence of manufacturing steps and the process from which each type of softwood lumber product and wood by-product are obtained are also indicated (Figure 2-2).



Notes: BP= By-products; P = Products; GR= Green rough lumber; KR= Kiln rough lumber; GD= Green dressed lumber; KD= Kiln dried dressed lumber



2.2.3.2 Lumber Recovery

Lumber recovery quantifies the proportion of the roundwood that is converted into lumber. It is an important parameter for sawmills to maximize. Lumber recovery can be measured using several variables. The simplest is the lumber yield which is the lumber volume produced as a percentage of the industrial roundwood volume consumed. In BC, which has annually used about two thirds of the provincial roundwood harvest for lumber production, its average lumber yield at sawmills was 44.8% by volume (volume/volume (v/v)) in 2013 (MoFR, 2015). Within the North American industry, lumber recovery is more commonly expressed using the lumber recovery factor (LRF), which is defined as the nominal board feet (bf) of lumber recovered per scaled cubic metric of log input (Nielson et al., 1985).

Several factors influence the lumber recovery factor including log diameter, length, taper, quality, kerf width, sawing variation, rough green-lumber size, size of dry-dressed lumber, product mix, decision making by sawmill managers, condition of mill equipment and sawing methods (Steele, 1984). The trend in BC's LRF over a 24-year period is presented in Figure 2-3. Generally, the LRF has increased fairly steadily during these 24 years from 232 bf/m³ in 1990 to 277 bf/m³ in 2013 (Figure 2-3). The major driver for the increased LRF has been the technological improvement in BC sawmills. For instance, computer controlled laser scanning, log optimization and process control systems have delivered lumber recovery

benefits and significantly increased sawmill efficiency by giving an accurate scale input and determining the optimized cut patterns for logs (Martin, 2004; Stirling, 1998).



Figure 2-3: BC Average Annual LRF, 1991-2013 (MoFR, 1995, 2000, 2011, 2015)

2.2.3.3 Sawmill By-Products

As noted above, five by-products may be created at a sawmill, namely, chips, sawdust, shavings, trim ends and bark. The yields of the various wood by-products are dependent upon the volume of lumber produced from the industrial roundwood and they are therefore affected greatly by the LRF. Higher LRF values will result in a lower quantity of by-products.

2.2.3.4 Wood By-Products Utilization

Successful by-products utilization requires a beneficial use, an adequate market, and a suitable economic return (FAO, 1990). Originally, BC's sawmills generated all their revenue from lumber sales and most mills regarded mill by-products as troublesome residues that incurred costs by needing to be landfilled or incinerated in beehive burners. In BC, mill by-products started being used as a feedstock for the pulp and paper industry in the 1950's and the financial success of this development prompted two further waves of by-products based pulp mill developments in 1955-1960 and 1965-1975 (Christie, 2004). Landfilling and the use of beehive burners were expensive and raised contentious environmental issues. Together with the rising cost of energy, mill owners have been forced to seriously consider the merits of effectively using all

the by-products and this has led to the exploration of a diverse range of utilization options, including energy production or secondary product manufacturing (Table 2-1).

In addition to serving as the raw material for pulp and paper and panel productions, wood by-products are frequently used to produce bio-energy. Many manufacturing facilities have installed co-generation systems to produce electricity to operate their plants. Several panel mills and sawmills have installed boilers to produce steam to dry wood products. In a few instances, gasifiers have been used to produce a combustible gas to be used in the manufacturing plant or for electricity production. There is also active research in producing ethanol and biodiesel from these materials. Sawmill by-products may also be utilized for the production of a diverse range of products (Table 2-1). A substantial wood pellet industry has developed in North America over the last twenty years (MoFR, 2008c). Wood ash and particles can be used to manufacture bricks, cement blocks and slabs, roof planks, exterior wall panels, highway noise barriers, and asphalt (Alderman, 1998). In addition, pilot plant studies are investigating the production of higher value organic compounds, such as cellulose nanocrystalline (Brinchia et al., 2013) and carbon fibres (Zhang and Zhang, 2013).

Table 2-1: Mill Types Suitable for Sawmill By-Products Utilization

Mill types	By-Products Utilization
Pulp Mill	Pulping to fibre
MDF Mill	Defibring for MDF
Finger-Joint Plant	Finger-joint lumber and block board raw material
Power Plant	Hog fuel for combustion
Pellet Plant	Pellets production for combustion or animal bedding
Ethanol Plant	Ethanol production
Gasification Plant	Converting to synthetic natural gas
Cogeneration Plant	Energy producing
Others	Adhesives, charcoal briquette horticulture, landfill
	cover, landscape mulch, packaging filler

(Alderman, 1998; IWMB, 1999; Shirek, 2007; Wyoming Business Council, 2008)

Note: MDF: Medium density fibreboard

Sawmill by-products therefore perform an important role by linking a diverse range of forest product mills in a material flow network that is becoming increasingly complex as the number of by-products utilization options increase. Furthermore, the utilization of wood by-products is often an important factor in determining whether a mill operates at a profit or loss. By using low cost by-products as a substitute for roundwood, the total cost of the fibre input may be reduced and the overall material utilization efficiency increased.

In summary, this section presents the sawmill manufacturing and by-products utilization options. The material flow preliminary study in BC concluded that sawmill by-products play an important role in connecting the wood products manufacturing and pulp and paper manufacturing subsectors and greatly influence the material flow efficiency of the value chain. Changes in industrial roundwood supply entering the wood products manufacturing and pulp and paper manufacturing subsectors will also affect the flow of sawmill by-products, the final product range manufactured, the structure of the forestry sector and the socio-economic outcomes achieved. Consequently, further research quantifying fibre on a common basis is required to better facilitate measuring the fibre flows at stages of the value chain and structural changes in the forestry sector.

2.3 Material Flow Analysis and Its Applications in the Forestry Sector

2.3.1 Applying Material Flow Analysis in the Forestry Sector

Material flow analysis (MFA) is a method for describing and analyzing the material balances of a system such as an industry, a region or global resource management (Chambers et al., 2005; Lang et al., 2006). It is based on the law of conservation of matter. It provides a quantitative picture of resource use at various scales by connecting the sources, the pathways, the intermediate and the final sinks of a material (Ciacci et al., 2013). MFA was developed by Baccini and Brunner during the 1980s to systematically assess flows and stocks of materials within a well-defined system with the intent of obtaining an understanding of materials flowing through an industry and connected ecosystems, to calculate indicators, and to develop strategies to improve the material flow systems (Brunner and Rechberger, 2003).

Over the last 30 years, MFA has become an important component of industrial ecology (Hendriks et al., 2000) and has been applied as a basic tool in diverse fields, such as economic management (Mäenpaää and Juutinen, 2002; Marco et al., 2001), environmental management (Côté et al., 2002; Müller et al., 2004), resource management (Cheng et al., 2010a; Park et al., 2011), and waste management (Cochran and Townsend, 2010; Lau et al., 2013).

MFA is of prime importance in resource management for analyzing, planning, allocating, exploiting and upgrading resources. Two resource categories have usually been considered in resource management: 1) Natural resources such as minerals, water, air, soil, information, land, and biomass, and 2) Anthropogenic resources such as manufactured materials, energy, information and manpower (Brunner and Rechberger, 2003). To date, many MFA case studies have focused primarily on the minerals industries (Brunner and

Rechberger, 2003; Graedel and Allenby, 2010) with nickel, chromium, copper, iron and aluminum being some of the most thoroughly investigated materials (Bonnin et al., 2013; Mathieux and Brissaud, 2010; Müller et al., 2011; Reck and Gordon, 2008; Reck et al., 2008). The reason for the intensive analysis of metals is their critical role in human societies and technological systems, energy consumption and emissions during their production, their non-renewable attributes, relatively high recyclability, and potential toxicological effects. In addition, metals can be transformed but not destroyed (Müller et al., 2011). Several authors have highlighted that MFA may be applied to analyze anthropogenic resource stocks and flows in order to evaluate the current "metabolism" of human societies, supporting recycling activities and estimating future needs based on socio-economic trends (Ciacci et al., 2013; Graedel and Allenby, 2010).

Top-down and bottom-up approaches are two MFA approaches used to estimate material stocks (Hirato et al., 2009; Kytzia, 2004). The top-down approach is more applicable when analyzing high jurisdictional level material flows, e.g. the global or a national level. The throughput of the whole economy can be disaggregated and attributed to specific industrial sectors by this approach. A bottom-up approach may be more often applied to analyze the material flows of lower jurisdictional level, e.g. a city level, a specific industrial sector and an industry (Bringezu and Moriguchi, 2002; Shi, et al., 2010). In the bottom-up approach, product outputs within a system are firstly quantified. Then, material inputs of the system are calculated based on certain conversions and also to give an estimate of material stocks (Bringezu and Moriguchi, 2002; Hirato et al., 2009). However, MFA of specific industrial sectors often use a combination of both approaches and related data sources (Bringezu and Moriguchi, 2002; Shi, et al., 2010).

The broad and successful application of MFA in the mineral industry has inspired interest in applying MFA to the study of renewable materials, including those within the forestry sector. In contrast to metals, forests, which cover almost 30% of the Earth's total land area, provide important renewable and carbon-intensive natural resources (Boever and Acker, 2008). A growing number of MFA studies have paid attention to forest resources management from harvesting to wood products production (Boever and Acker, 2008; Korhonen et al., 2001; Zhao et al., 2008), from energy balance (Gustavsson and Sathre, 2011; Sathre and Gustavsson, 2006) to carbon sequestration in harvested wood products (Bache-Andreasse, 2009; Pingoud et al., 2003).

• Wood Fibre Balancing

There has been significant interest in undertaking material flow studies in the forestry sector (Beaudoin et al., 2007; Carlsson and Rönnqvist, 2005; Hendriks et al., 2000). Because of the law of conservation of mass, a material flow can be determined by completing a material balance of all inputs, stocks and outputs of processes within the industrial system being studied. Wood fibre balancing may therefore be considered to be the earliest and one of the most important applications of MFA in the forestry sector (Mantau, 2008).

Wood balancing is an essential element in measuring the gap between the supply and demand of wood-based resources. Pandey and Rangaraju (2008) predicted the wood harvest supply according to the demand determined by market conditions and influences from global trade. Further research done by Piškur and Krajnc (2007) and Binder et al. (2004) forecast the scarcity or underutilization of wood-based materials by analyzing the gap between the demand and supply of wood resources.

Developing a wood fibre balance is the most fundamental task when undertaking a forestry sector MFA and this stage should be completed prior to undertaking a complete material flow analysis and further studies based on stock information. The similar conception of MFA's top-down and bottom-up approaches could be applied to balance wood fibre flow in a predefined region for a certain time period (Parobek and Palus, 2008).

Several studies have analyzed wood fibre flows at the national or enterprise levels (Audy et al., 2011; Cheng et al., 2010a, b; Hekkert et al., 2000; Kastner et al., 2011; Kwant et al., 2014; Laga and Réh, 2008; Lang and Nemesthoty, 2013; Mantau, 2008, 2012; Parobek and Palus, 2008; Sokka et al., 2015; Su and Cheng, 2004; Ulvas, 2008). Many of these investigations focused on developing wood fibre flows to interpret the fibre balance or identify the gaps between wood fibre supply and demand in the forestry and logging and wood products manufacturing subsectors (Laga and Réh, 2008; Parobek and Palus, 2008). Amongst these studies, many reported to date developed material flows that represent only one or two subsectors of the industry (Mantau, 2008; Parobek and Palus, 2008). Very few studies have been devoted to developing detailed material flow analyses for the entire forest products industry in a common unit (Cheng et al., 2010a; Kwant et al., 2014; Lang and Nemesthoty, 2013; Mantau, 2012; Sokka et al., 2015). To the best of the author's knowledge, no detailed material flow has been developed to depict the structure of Canada or BC's entire primary forest products industry and highlight the conjunction function of by-products. This stresses the need for a comprehensive understanding of forestry sectors' fibre flows in Canada and its provinces. With this fundamental information can aAny further analysis of socio-economic benefits achieveding from this sector can be undertaken with this fundamental information.

• Volume and Mass Approach Comparisons

After being harvested in the forestry and logging subsector, industrial roundwood is consumed in the manufacturing subsector within the forest products industry to produce various final and intermediate forest products. Inputs to, outputs from and intermediate flows within the forest products industry are measured in a wide range of volumetric and mass units. Many attempts have been made to quantify and characterize each component of a wood material flow with most studies being completed in either mass or volumetric measurements (Alteyrac et al., 2008a; Cheng et al., 2010a, b; Grladinović et al., 2006; Hekkert et al., 2000; Joosten et al., 1999; Mantau, 2008; Parobek and Palus, 2008; Su and Cheng, 2004; Ulvas, 2008).

A review of previous research demonstrated that three bases have been most frequently used to assess the wood raw material input to forest products manufacturing: mass (Hekkert et al., 2000; Meil et al., 2007), volume (Cheng et al., 2010a; Alteyrac et al., 2008a) and carbon content (Gingrich et al., 2007; Houghton, 2003; Kastner et al., 2011; Kwant et al., 2014; Lang and Nemesthoty, 2013; Mantau, 2012; Sokka et al., 2015). Carbon contents can be directly calculated from oven dried mass of forest products in various forms and can therefore be considered as a sub-set of the mass approach. The strengths and weaknesses of the volume and mass approaches are addressed in this section.

Hekkert et al. (2000) quantified the supply and demand flows of paper and wood fibre in the Netherlands using the mass unit of kilotons. This study used STREAMS, a method proposed in 1998 (Joosten et al., 1999), to analyze wood and paper flows through the Netherland's economic system. This research has been recognized as one of the first studies to show that MFA was able to be used in the forest products industry. The use of a mass-based MFA was rational for this study given its emphasis on the pulp and paper manufacturing subsector, which generally quantifies its inputs and outputs in mass units. Subsequently, Kwant et al. (2014) developed wood flows for the Netherlands using the dry ton of woody biomass as the unit to depict the masses of raw material production, consumption, import and export. This research revealed that except for the industrial roundwood, considerable amounts of forest products were imported, especially pellets. The study suggested that cascading use of wood products should be considered from the perspective of the whole wood-using cycle (Kwant et al., 2014).

In contrast, several studies have quantified wood material flows using volumetric measurements (Alteyrac et al., 2008a; Cheng et al., 2009, 2010a; Grladinović et al., 2006; Mantau, 2008; Su and Cheng, 2004; Ulvas, 2008). Mantau and Ulvas used a volumetric approach to develop material flows for Europe's wood processing industry with the wood resource flow being converted into roundwood equivalent units (Mantau, 2008; Ulvas, 2008). Their research indicated that wood resource balances can be used to fill some important gaps of knowledge about the actual calculated resources consumed and the apparent consumption.

Besides the studies on a part of the forestry sector listed above, the first published MFA of a nation's forestry sector on a volumetric basis was conducted by Su and Cheng (2004). They completed an MFA for China's national forestry sector using timber volume equivalents (m³) to quantify all the components of the material flow (Su and Cheng, 2004). Log equivalent ratios were developed and applied to convert the original units of lumber, plywood, chips, particleboard and pulp to m³ (Cheng et al., 2010a, b; Su and Cheng, 2004). A material flow framework was developed and used to evaluate resource utilization efficiency. This research has provided a scientific basis to support China's decision makers in the forestry sector (Cheng et al., 2010a). With the increasing focus on the wood uses to address environment concerns, many studies claimed that the wood resources should be used in a way that helps to store carbon or to replace the most emission intensive fossil fuels, while securing development of forest carbon sinks at the same time. Several

recent studies (Lang and Nemesthoty, 2013; Mantau, 2012; Sokka et al., 2015) incorporated material flows to understand the cascading uses of wood material in Finland, Austria, Germany, and the EU to achieve the most effective climate change mitigation impacts. These national wood material flows are presented in the volumetric unit m³ green solid wood equivalent (GSWE).

As discussed above, material inputs are generally measured in mass or volumetric units. A unified measuring system is very important as it enables the comparisons of every segment along the flow. In the mineral industry, inputs are exclusively measured in mass units. However, wood products are measured in both volumetric and mass units. Wood densities may be used to convert between volume and mass units. However, wood density varies with the moisture content and wood absorbs and desorbs moisture. In a living tree, wood contains a large quantity of water. However, the moisture content of the final products varies depending upon its manufacturing process and utilization (Bergman, 1993). When the moisture content of wood is less than the fibre saturation point (FSP), several physical properties, including volume, are changed. When wood absorbs moisture, the cell wall swells significantly, whereas when wet wood dries, the volume of a wood fibre is reduced. Below the FSP, the relationship between fibre volume and moisture content follows a pattern which is close to linear (Suchland, 2004). Above the fibre saturation point, the dimensions of a wood fibre become stable as the additional water accumulates in the lumen rather than the cell wall (Suchland, 2004). The fibre saturation point varies with species and generally lies between 21% (w/w) and 32% (w/w), and Siau (1984) assumed an average value of 30%. Wood is categorized as "green" when its moisture content is greater than the fibre saturation point (Hill, 2006).

The mass of wood varies substantially with its moisture content. Several studies have used units of mass to balance material flows within the forestry sector (Hekkert et al., 2000; Meil et al., 2007; Parobek and Palus, 2008). Mass units are especially common when a study focusses on the pulp and paper manufacturing subsector, bio-energy products or by-products, all of which are usually measured by mass. The mass of green logs depends largely on the wood species and their moisture contents, which can vary widely in accordance with the seasons, the geographic locations where logs were harvested, how they have been stored and how long they have been stored. However, the moisture contents of industrial roundwood are usually significantly above the fibre saturation point and, under these conditions (i.e. at moisture contents (MC) >30% (w/w)) the volumes of industrial roundwood and forest products are stable. For this reason, amongst others, the green fibre inputs, in the form of industrial roundwood, are usually measured by volume. When mass units are used to balance fibre flows, the green industrial roundwood volume must be converted to oven dried tonnes or kilograms by multiplying the basic density (oven dried mass/green volume) to green volume (Nielson, 1985).

Where fibre inputs, intermediate and final products are measured in volumetric units (e.g. industrial roundwood supply and various wood products in the wood products manufacturing subsector), a volumetric

approach to develop material flows becomes more practical and it simplifies the calculation process. Despite the large variety of the moisture contents, the green volumes only need to be adjusted for forest products with a moisture content less than 30%. Under these circumstances, the volumetric shrinkage or swelling may be considered proportional to the maximum volume changes from 0% to 30% (w/w) moisture content. The green volume of fibres in the pulp and paper manufacturing subsector that have been reported in mass units may be obtained by applying their basic densities, prior to which the mass should be converted to an oven dried basis. Conversion factors and input/output factors that convert the various output units to a common green volumetric unit may be derived from these calculations and further used to convert various output units to a common green volumetric unit. Accurate and applicable conversion factors for jurisdictional forestry sector are usually difficult to obtain. The uses of conversion factors are discussed in section 2.3.2.

In summary, the undertaking of MFAs for a jurisdiction's forestry sector offers several benefits that have been described in the preceding sections. However, the development of MFAs on a common unit basis is a complex exercise that presents major challenges for many forestry nations, especially those with incomplete or inaccurate data. Both mass (oven dried basis) and volume (green basis) approaches could be applicable to unify all the material flows along a value chain on a constant unit. In BC's forestry products industry, the major fibre source, industrial roundwood has been measured in green m³. More industrial roundwood has historically flowed through the wood products manufacturing value chain than the pulp and paper manufacturing subsector (Alteyrac et al., 2008a) and a greater proportion of forest products was reported in volumetric units than mass units, inferring that volumetric units should be preferred. Furthermore, the use of volumetric units would minimize the need for conversions between the two systems of units and should therefore maximize the accuracy of the calculations.

2.3.2 Conversion Factors in the Forestry Sector

Manufacturing efficiencies are usually less than 100% and therefore the total raw material inputs are usually greater than the quantity of the output products created (Kovanda and Weinzettel, 2013). The concept of raw material equivalents has been developed to link outputs to inputs (Eurostat, 2001; OECD, 2008; Weisz, 2007). As discussed in Section 2.3.1, products from the wood products manufacturing and pulp and paper manufacturing subsectors are quantified in a variety of units and therefore conversion factors are needed to convert the various units for by-products and final products into a consistent unit that will then allow any further comparisons to be on a common basis.

Forest product conversion factors were defined as the values that converted the original units of output products to one common input unit (Fonseca, 2009; Nielson et al., 1985; Su and Cheng, 2004; UNECE/FAO, 2010a). They have been utilized as a tool for analyzing material production and consumption at forest
product manufacturing facilities for an extensive period (UNECE/FAO, 2010a). Forest products conversion factors have been defined as "using a known figure to determine or estimate an unknown figure via a ratio" and they are essential elements in completing material balances for the forestry sector (Fonseca, 2009). Sometimes these ratios may be exact, such as the conversion of feet to metres or kilograms to metric tonnes. However, when inputs and outputs from a manufacturing process are presented in different units (e.g. volume and mass), several other variables such as density, moisture content and shrinkage can influence the conversion. Usually, an average conversion factor can be calculated using the wood fibre balance. Conversion factors vary considerably depending upon many factors, including the quality of the raw material, methods and efficiency of processing, desired characteristics of the products and other operational, economic and technical parameters (UNECE/FAO, 1991).

Conversion factors that relate the input of raw material to output of forest products are a good indication of efficiency levels and thus are often used to benchmark a manufacturing facility's effectiveness (UNECE/FAO, 2010a). The UNECE/FAO has been collecting and reporting conversion factors since 1963. The first major report on conversion factors in the UNECE region countries was published in 1991 (UNECE/FAO, 1991). Following that, two documents were published to highlight the various approaches that may be used to estimate industrial roundwood consumption based on the output of wood products and the challenges in converting these varied data into harmonized international units (Thivolle-Cazat, 2008; UNECE/FAO, 2010b). Following an FAO/UNECE workshop, the UNECE/FAO Timber Section was mandated to lead a cooperative effort to develop accurate conversion factors for UNECE regions as an aid to developing wood balances at the national or sub-regional levels (UNECE/FAO, 2010a). Conversion factors were collected and published for a range of final products and intermediate products including industrial roundwood, sawnwood, veneer and plywood, panels, wood pulp and paper, wood particles, round and split wood products and energy wood products (UNECE/FAO, 2010a).

It should be noted that, the conversion factors published in UNECE/FAO reports (Fonseca, 2009; UNECE/FAO, 2010a, b) were input/output factors (I-O factors) according to the terminology used in this dissertation. The relation between input/output factors and conversion factors is depicted in Equation 2-1.

Conversion Factor (m³ GSWE/Original Unit) = Input/Output Factor (m³ GRWE/Original Unit) x Yield (m³ GSWE/ m³ GRWE) Equation 2-1

Green roundwood equivalent (GRWE) volume is a measure of the green volume of logs (industrial roundwood) required as material input to produce wood-based products. Such assessments depend partly on the reliability and comprehensiveness of published statistics, and partly on the reliability of the factors used when estimating GRWE volume from wood volume or product mass (Global Timber, 2010). It is the sum of solid wood equivalent (GSWE) and manufacturing losses or other residues. Conversion factors quantify the

wood fibre contained in the product and the roundwood equivalent volume needed to produce the product when there are no losses or other residues (UNECE/FAO, 2010a).

Relatively few reports have presented conversion factors for countries outside of the United Nations Economic Commission for Europe (UNECE). In Canada, Forintek has reported on conversion factors for the forest products industry in western Canada (Nielson et al., 1985) and eastern Canada (Kostiuk and Pfaff, 1997). In addition, Su and Cheng (2004) used log equivalent ratios for China to estimate the material input in cubic metres.

A few publications have used conversion factors to predict the amount of material required from forests to supply a given quantity of manufactured forest products or used the conversion factors to estimate the quantity of forest products manufactured (Cheng et al., 2010a, b, Mantau, 2008; Su and Cheng, 2004; Ulvas, 2008) and to present the cascading use of the wood material within the fibre flow (Kwant et al., 2014; Lang and Nemesthoty, 2013; Mantau, 2012; Sokka et al., 2015).

In conclusion, wood fibre flows through a complex material flow network to produce a wide range of forest products consumed by society. The wood products manufacturing and pulp and paper manufacturing subsectors are connected by a flow of by-products which creates an inter-dependence between these two subsectors. Forest products are quantified using a diverse range of units. This creates challenges for undertaking material consumption comparisons amongst product types in different forestry subsectors, constrains the estimation of upstream industrial roundwood inputs and leads to difficulties in balancing the fibre supply and demand along the value chain. Applying conversion factors to develop measurements on a unified input basis (e.g. m³ GSWE) is the most straightforward way to solve the challenges created by the diversity of output units used by the sector.

2.3.3 Socio-Economic Indicators for the Forestry Sector

Sustainability within the forestry sector has evolved from a rather narrow focus on sustainable wood production to a much broader evaluation of social, economic and environmental sustainability for the entire value chain (Lindner et al., 2010; Zhou et al. 2000). The development of adequate criteria and indicators for sustainable forest management has been an important element in the evolutionary process and a variety of indicators have been created (Castañeda et al., 2001; Franc et al., 2000; Lindner et al., 2010; Montreal Process, 2009; Nussbaum et al., 1996).

Evaluation of socio-economic benefits differs with the jurisdictional levels at which the outcomes are assessed. For example, the indicators used to assess socio-economic benefits for the forest products industry at national and provincial levels usually differ from those that applied at the level of an individual forest products company (hereafter termed the enterprise level). Indicators that have been used to provide useful

insights on socio-economic benefits from the forestry sector at national, provincial and enterprise levels are discussed below.

2.3.3.1 Indicators of the Forestry Sector's Economic Benefits at Different Jurisdictional Levels

The quantification of economic contributions is considered in this section and the estimation of social outcomes is discussed in Section 2.3.3.2. Evaluation of economic outcomes is crucial as the industry must be profitable if it is to operate in the long term. The importance of economic outcomes is confirmed by a study of the literature which revealed that economic indicators are well developed compared with social indicators (CIBC, 2010; Binder, 2007; Lethbridge and Forel, 2011).

The economic indicators by the Montreal Process (Montreal Process, 2009) and the Pan-European Forest Process (Castañeda et al., 2001) provided the most extensive information on the contribution of forest products industry to national economies.

Montreal Process has used production and consumption, investment in the forestry sector and their sub-indicators to evaluate the economic benefits from a forest products industry (Table 2-2). Among these, two indicators were given in roundwood equivalents input basis. The Pan-European Process has used the forestry sector's share of the gross national product (GNP) as one of the most important quantitative indicators (Castañeda et al., 2001).

(Montreal Process, 2009)				
Economic Indicators	Economic Sub-Indicators			
Production and consumption	 Value and volume of wood and wood products production Revenue from forest based environmental services Total and per capita consumption of wood and wood products in roundwood equivalents Total and per capita consumption of non-wood forest products Value and volume in roundwood equivalents of exports and imports of wood products Exports as a share of wood and wood products products consumption Recovery or recycling of forest products as a percent of total forest products consumption 			
Investment in the forest sector	 Value of capital investment and annual expenditure in forest management Annual investment and expenditure in forest-related research Extension and development, and education 			

2000 1 D

In addition to the indicators used by both international processes, other economic indicators that have been used at different jurisdictional levels are described below.

• Enterprise Level Economic Indicators

From the perspective of an enterprise, the economic outputs for a certain time period are commonly evaluated by using indicators that include: earnings before interest, taxes, depreciation, and amortization (EBITDA), earnings before interest, taxes (EBIT), value added, profits and selling prices, operational profit margin, return on capital employed (ROCE), return on capital investment (ROCI), return on equity (ROE), net debt/capital, market capitalization and export revenues (CCFM, 2006; FPAC, 2012; Lebedys, 2008; 2004; Nelson et al., 2006). One way of measuring profitability in a forestry sector is through an evaluation of value added. Value added is a simple unencumbered profit measure of converting raw materials into products (Meil, 1990). From a value chain perspective, the value added and its supplementary indicators are useful economic indicators at an enterprise level.

Value creation may occur at any production stage in the forest products value chain. The value of a forest product usually increases as it proceeds along the value chain from forest harvesting to product uses by customers. Sathre and Gustavsson (2009) developed a conceptual framework to quantify the value adding from a manufacturing process in a forest products enterprise with multiple inputs and outputs (Figure 2-4). The total value added could therefore be calculated using Equation 2-2 (Sathre and Gustavsson, 2009). Value added from a forestry enterprise may be considered to be the aggregate value of forest product outputs less the total value of intermediate forest products consumptions. Alternatively, it can also be expressed as the total value of sales from the enterprise less the total value of purchases of that enterprise from other businesses (Lebedys, 2004).



Figure 2-4: Conceptual Diagram of Value Adding Process in a Forest Products Firm

(Sathre and Gustavsson, 2009)

Total Value Added by the Operation= Value of (PP+MBP+EBP) - Value of (BI+OI+EI)

Note: The abbreviations used in Equation 2-2 are defined in Figure 2-4.

Equation 2-2

By capturing the maximum value added from all manufacturing processes, a firm's economic benefits may be increased, as long as these economic benefits outweigh the costs. Several researchers have analyzed changes in production and other potential factors on increasing the value added from the forest products industry (Bridges et al., 1997; Lantz, 2005, 2001; Lee et al., 1999; Maness, 1993; Michelsen et al. 2008; Ringe and Hoover, 1987; Roos et al., 2000, 2002). Their research illustrated that indicators that assess the value added achieved at various points along the value chain increased our understanding of the incremental improvements in wood fibre value from logs to various forest products.

National and Provincial Level Economic Indicators

Economic contributions from a nation or a province can be evaluated by various indicators including: gross value added (GVA), gross domestic product (GDP), and gross national product (GNP). Simplistically, GVA is the grand total of all revenues, from final sales and (net) subsidies, which are incomes into businesses. Those incomes are then used to cover expenses (wages & salaries, dividends), savings (profits, depreciation), and (indirect) taxes). This definition is consistent with that of Statistics Canada's. Statistics Canada defines gross value added as the value of output less the value of intermediate consumption before deducting consumption of fixed capital (StatsCan, 2016b). It is an important indicator that measures the total contribution of all firms to the national or provincial economy and it is useful to avoid the statistical double counting that may occur with GDP (Lipsey et al., 1991; Mankiw et al., 1999).

Lantz (2001) and Meil (1990)'s investigated value added production in the Canadian forest products industry. In their studies, they highlighted that Statistics Canada's definition of value added includes energy costs as an additional cost to materials and supplies and Statistics Canada defended value added as the difference between the shipment value of a good sold in the market and the costs of primary resource inputs. As such, value added provides a measure for the amount of processing that primary resources endure before being shipped and sold (Lantz, 2001; Meil, 1990).

In Lantz (2001) and Meil (1990)'s calculations, energy cost has been excluded from the calculation of value added in order to concentrate on resource conversion efficiency. Later, Lantz (2004) included the energy cost component to examine value added and variable cost trends across Canadian forest regions and sectors. The formula Lantz used in his latter publication (Lantz, 2004) is presented in Equation 2-3.

Value Added = [Value of Output] – [Cost of Materials Supplies] – [Cost of Purchased Energy]

Equation 2-3

The Pan-European Process used the contribution to national GNP as a quantitative indicator (Castañeda et al., 2001), whereas, the Montreal Process (1999) used indicators on wood production value, the contribution to national GDP, and export and import values. The commonly used economic indicators are GDP, GVA and their normalized indicators which may be also determined on a material input or product output basis (Bringezu et al., 2003; Teischinger, 2009). The statistics on these indicators can often be readily accessed from various public sources and they are generally calculated using standardized methodologies.

2.3.3.2 Indicators of the Forestry Sector's Social Benefits at Different Jurisdictional Levels

Social impacts cover a broad area and usually take into account the benefits for individuals, communities, politicians, and regulators (Montreal Process, 2009). Many social indicators have been applied to assess the social contributions from the forest products industry and, in contrast to the economic indicators, the same set of social indicators may be used to analyze social contributions at all scales of the forestry sector.

The following five important indicators are commonly used for studies of social benefits: employment, labor productivity, labor cost, tax contribution to local communities, occupational safety and health (CCFM, 2006; Lindner et al., 2010; Nelson et al., 2006; Teischinger, 2009). In official national statistics, employment is usually reported on a full time equivalent (FTE) basis. Labor productivity, also called apparent productivity, can be measured by either the output per employment or value added per employment (Lebedys, 2008). Value added per employment also indicates the level of salaries and wages in an industry. It reflects the general level of benefits and conditions of employment (Lebedys, 2008). Labor productivity can also be used to assess the efficiency of workers using GDP/working hour as an indicator. Tax income/mill type or tax income/m³ of roundwood can be used to indicate the tax contribution to local communities.

In summary, employment, apparent productivity, GDP and GVA are important components of a broad range of socio-economic statistics that are collected to monitor trends in the forest products industry at national and provincial levels (Lebedys, 2008). These parameters are very useful because standard methodology is used globally and long term national and provincial data are readily available. At the enterprise level, employment and value added are also considered to be important socio-economic indicators.

2.3.3.3 Normalized Socio-Economic Indicators

Several secondary indicators may be derived from these core indicators using a material input or product output basis to reveal more information on various aspects of the value chain (Lebedys, 2008). Several normalized socio-economic indicators are discussed in the following sections.

• Normalized GDP and GVA Indicators

The following normalized indicators have been used previously to quantify the economic benefits from the forestry sector and its three subsectors: Forestry sector or subsectors' GVA; GVA per unit of forest products output; value added from forest product imports and exports and GVA per unit of material input (Bringezu et al., 2003; Cheng et al., 2009, 2010a; Lebedys, 2008).

Sathre and Gustavsson (2009) concluded that manufacturing products with greater added value is increasingly a strategic goal of forest products industries. They argued that GVA achieved depends on the products manufactured and their measurement units. This implies that GVA from different segments of the value chain may not be directly comparable unless all materials, energy and products are expressed in the same unit (e.g. \$/ton, \$/m³, \$/GJ) (Sathre and Gustavsson, 2009). Therefore, manufacturing processes that produce dissimilar products quantified in different units may only have their GVAs compared by normalizing the GVA to a consistent series of units.

Similar to the previous input and output discussions, GVA may be related either to the total output product's value and quantity or to the total input of materials. Output based indices show the proportion of value in the finished product that has been added during the process (Sathre and Gustavsson, 2009) and GDP or GVA per forest products output value or quantity has been utilized to analyze the added value contained in the final products (Bringezu et al., 2003; Lebedys, 2008; Teischinger, 2009). Sathre and Gustavsson (2009) used the total value added per output value (in $\in \in$) and the total value added per production (\in /output units) to analyze the value addition by various forest products manufacturing processes. A variety of mass, volume and energy units were used to characterize the inputs and outputs. They showed that the value added per unit of product output was difficult to compare amongst a variety of product types quantified in several different units. This study demonstrated that instead of mixing product output based indicators, it was more useful to compare normalized indices, such as the value added per unit of biomass input. Lebedys (2008; 2004) also observed the disadvantage of using output-based economic indicators when evaluating the value added per unit of output in three forestry subsectors by region. His studies highlighted that outputs in the pulp and paper subsector were quantified in mass units while the forestry and logging and wood products manufacturing subsectors used volumetric units (Lebedys, 2008; 2004). This lack of consistency in output units limited the comparisons of performance among subsectors.

In addition to GVA per unit of output, other indices of added value which provide additional insights on the economic contributions in the forestry sector may also be envisioned. First, value added from forest product imports and exports could be used to determine a surrogate forest products price in the international market (Lebedys, 2008). Second, the value added per hectare-year may be used to assess the productivity of a forest stand (Sathre and Gustavsson, 2009; Teischinger, 2009). Third, another useful indicator is GVA per unit value or quantity of material input. This index assesses how the value of the material input is related to an increase in total value (Sathre and Gustavsson, 2009; Teischinger, 2009).

Input based economic indicators should overcome the barriers to undertaking comparisons for different products and subsectors. To the author's knowledge, only one study has analyzed the economic contribution using wood fibre input normalized value added as the indicator for fourteen primary and secondary forest products (Sathre and Gustavsson, 2009). In this study, Sathre and Gustavsson (2009) employed value added per unit of biomass input, in the forms of sawlogs, pulpwood and forest residues, as the indicator to compare value added from fourteen existing and potential forest-based industry processes. The study concluded that it is useful to compare normalized indices, such as value added per unit of input, to compare different forest products manufacturing operation systems. However, the volumetric unit they used for biomass in forms of sawlogs, pulpwood input was m³, whereas biomass in the form of forest residues was quantified in GJ lower heating value. This variability in raw material input units constrained value added analyses on a common volumetric input basis. Furthermore, this study focused on finding the combination of the grade of raw material input and the type of forest product processing operation that had the potential for adding the greatest value. However, not all of the fourteen processing operations existed in Sweden at the time when this study was undertaken and the study was not case-specific to reflect the particularities of a forestry sector. These limitations provided a chance for a study on value added on a common volumetric input basis for all forest products processing using different raw material inputs within a current jurisdictional forestry sector. The input based value added studies can provide insights on the where and how much the values are created within the forestry sector.

• Normalized Employment Indicators

Input and output versions of economic indicators may also be used to evaluate the forest products industry's social contributions. In contrast with output per employee (Lebedys, 2008) which has traditionally been used to measure productivity, the number of employees per unit of material input provides information on the labour required to handle various material inputs to manufacture different products. Other indices of employment, such as value added per employee or value added per hour of labour may also be used (Teischinger, 2009).

However, social indicators are generally considered to be less accurate than GDP and GVA data (Lebedys, 2008; Slee, 2007). Full time equivalent employment data in the forestry sector are also relatively more difficult to obtain from official statistics than economic information. In particular, the substantial informal forest activities that are likely to occur in the developing countries increase the difficulty of collecting precise employment data for these nations (Lebedys, 2008).

In summary, MFA may be considered to provide a fundamental conceptual model of the industrial system prior to further considering socio-economic aspects (Bringezu et al., 2003), energy uses (Sokka et al., 2015) or carbon sequestration (Bache-Andreasse, 2009; Pingoud et al., 2003; Sokka et al., 2015). Regarding this dissertation, once the material flow model has been developed, socio-economic indicators could be linked to the material flow data to provide more detailed information at every stage along the value chain. For instance, GDP, value added and employee per unit of material input (Bringezu et al., 2003) could be used as indicators derived from MFA.

However, frequently data unavailability, in particular the quantity of by-products linking the two manufacturing subsectors, limits the material flow development for the entire forest product industry. Developing indicators representing aggregated quantity of material input or output at stages of the value chain would be an alternative method to quantify the wood fibre flow. A major advantage of input based socio-economic indicators is that unifying wood-based material inputs in one common unit enables straightforward comparisons of socio-economic benefits to be made amongst the three forestry subsectors and various stages of the value chain.

2.4 Optimization of Primary Forestry Sector Material Flow

The results of MFA may be used in diverse ways. For example, the outcomes of an MFA can be used to quantify the gap between the supply of wood fibre from forest harvests and the market demand for wood products, evaluate distribution of log resources, assess the structure of resource flows, measure resource utilization efficiency and investigate associated environmental implications (Cheng et al., 2010a, b; Pandey and Rangaraju, 2008; Sokka et al., 2015; Su and Cheng, 2004). When linked to socio-economic indicators, MFA may be used to assess the socio-economic contributions from the various stages of the value chain and thereby assist decision makers to estimate the likely effects of policy or operational changes (Binder, 2007).

In addition, MFA is a useful tool to support strategic planning in the forestry sector. Many planning exercises involve the evaluation of a range of material flow scenarios. Strategic planning frequently involves considering alternative scenarios and considering their consequences (Grladinović et al., 2003). Thus, MFA may be used to evaluate existing systems as well as supporting the design of new and more efficient ones (Brunner and Rechberger, 2003). An assessment of the socio-economic benefits produced by

a given material flow scenario may be used to assess how good that material flow option is in comparison with others. For example, Su and Cheng (2004) developed and compared historical material flows for China's forestry sector in the sixth, seventh, eighth and ninth five-year plan periods (1981-2000). They concluded that the material flow pattern that operated in the Ninth Five-Year Plan was better than those in the earlier periods. The improvement in material flow was attributed to allocating increased proportion of the wood resources to pulp, paper and veneer manufacturing (Su and Cheng, 2004).

MFA results have been also used quite successfully to optimize material flows in production processes, within an industry and across different industrial sectors (Binder, 2007; Najm and El-Fadel, 2004; Sikdar, 2008; Silen, 2008). Recently, modelling the entire value chain has received more attention and there has been a significant interest in optimizing the forestry sector value chain (Beaudoin et al., 2007; Bredström et al., 2004; Carlsson and Rönnqvist, 2005; Grladinović et al., 2003; Palander and Voutilainen, 2013; Rönnqvist, 2003; Shabani et al., 2013). Most of these optimization studies have focused on either a part of the entire forestry value chain or certain manufacturing plants by considering various factors, such as material procurement, storage, transportation and production. To the best of the author's knowledge, it appears that no research has been devoted to comparing and optimizing wood material flows within an entire forestry sector on a common input basis to achieve the greatest socio-economic benefits. The absence of such studies motivates this research to use MFA as a tool to evaluate the suitability and flexibility of the existing forestry sector in a given socio-economic system. In addition, as discussed in Section 2.2.3, the role of wood by-products in linking different subsectors within the forestry value chain is likely to create substantial opportunities for improving the material resource utilization and increasing socio-economic outcomes.

2.5 Discussion and Conclusions

In many parts of the world, the competitiveness of the forest products industry has been consistently declining in comparison to many other industrial sectors. In addition, the economic contribution per unit of fibre input in Canada has been historically low (MoFR, 2009a). This observation motivated this research to investigate mechanisms that the forestry value chain may use to capture more socio-economic benefits at different jurisdictional levels of the sector (i.e. nationally, provincially and at the enterprise level). To the best of the author's knowledge, none of the previous studies exert pressure on understanding the value structure in Canada or in BC, one of the major forestry provinces in Canada and its potential for socio-economic benefits increase from the perspective of value structure adjustment.

The broad and successful uses of material flow analysis in the mineral industry have promoted its application in the forestry sector. A branch of the literature has proposed material flow analysis as one means to interpret forestry sector value structure and serve as a fundamental model prior to further

considering socio-economic behaviors. Given sufficient data availability, MFA could be used to quantify the wood fibre fluxes through the value chain. Subsequently MFA could be linked to socio-economic indicators to evaluate forestry sector outcomes. In the literature, MFA could be completed on a volumetric or a mass input basis and the former approach was concluded to be more precise as most forest products are quantified in volumetric units and consequently, an input-based material flow balance should be more accurate when the conversions between mass and volumetric units are reduced. For a primary value chain dominated by the wood products manufacturing sector, such as in BC, it is therefore logical to use a volumetric input unit.

In addition, the sub-optimal socio-economic benefits from Canada's primary forest products industries provided an opportunity to assess the suitability and flexibility of the existing forestry sector in a given socio-economic system and interpret the impacts of material resource allocations on the socio-economic outcomes from an entire forestry sector for Canada's most important forestry province.

CHAPTER 3 ASSESSING THE FORESTRY SECTOR'S SOCIO-ECONOMIC BENEFITS FROM STAGES OF THE PRIMARY FORESTRY SECTOR VALUE CHAIN

3.1 Introduction

Socio-economic benefits make forest products one of the most important commodities in our daily lives (Natural Resources Canada, 2006). In 2011, the global forestry sector generated 13.2 million employment positions, created US\$ 605 billion in value added and US\$ 364 billion from exported forest products (Lebedys and Li, 2014). Despite the increased total global value added and value from forest products exports increasing by 10.7% and 60.2%, respectively, between 1990 and 2011, employment decreased by approximately 15.1% over the same period. Overall, the growth in the global forestry sector's employment, value added and trade was less than most other industrial sectors (Lebedys and Li, 2014). Consequently, the FAO has concluded that the forestry sector was not a major driving force for economic growth and development in many developed countries, except in specific circumstances (Lebedys, 2008; Lebedys and Li, 2014). Further analysis of the socio-economic benefits from the forestry sector is warranted to increase our understanding of the causes of these low contributions and to assist the development of potential solutions.

When comparing socio-economic outcomes from nations with different sized forestry sectors, it is essential to normalize outcomes using an input or output basis. Volume input basis approach has been highlighted as one of the methods enabling the comparisons of every segment along the flow (Section 2.3.2). As a consequence of globalization, the national harvest volume, which has traditionally been used as the key input variable, may now be an inadequate measure of the net raw material inputs to a nation's forestry sector supply chain (Brooks et al., 2004). The international trade of various commodity forest products has increased substantially over the last sixty years as nations seek to address wood fibre shortages, protect national forests or take advantages of fibre surpluses. This trade affects a nation's forestry sector inputs at different points along the value chain depending upon the products traded. For instance, industrial roundwood can be imported and directly used at the beginning of the supply chain to produce structural lumber, whereas, the import of wood pulp as an intermediate product could be used as the additional fibre input to produce paper in the middle of the supply chain. A series of indicators that determine the net wood fibre input at various points along the value chain would therefore be beneficial for a detailed analysis of the socio-economic contributions from a nation's primary forest products industry on an input basis and may provide additional knowledge on where and how socio-economic benefits are delivered.

This chapter assessed Canada's socio-economic contributions along the primary forestry sector value chains and benchmarked them internationally. The primary objectives of this Chapter are to: 1) Select and assess a series of socio-economic indicators, 2) Provide an understanding of the forestry sectors' socio-economic contributions and investigate the diversity of these subsector contributions within the primary forestry sector value chain in a selection of important forestry nations.

3.2 Methodologies and Data Sources

Fourteen important forestry nations, namely, Australia, Austria, Brazil, Canada, Chile, China, Finland, France, Germany, Indonesia, Japan, Malaysia, New Zealand, Sweden and the USA are chosen to provide useful benchmarks with Canada's performance. These are representative forest nations with significant forestry sectors and a range of forest products trade linkages. For the purpose of this study, ten countries, including Australia, Austria, Canada, Finland, France, Germany, Japan, New Zealand, Sweden and the USA were categorized as developed countries, whereas, five nations, including Brazil, Chile, China, Indonesia and Malaysia were classified as developing countries. This categorization is consistent with that used by the Organisation for Economic Co-operation and Development (OECD). Chile joined OECD in 2010 and is presently one of the most advance developed nations (OECD, 2013). However, for this study which considered the period from 1990 to 2011, Chile has been categorized as a developing country.

3.2.1 Methodologies

In this chapter, GDP, value added, employment and apparent productivity were selected as the most important indicators with which to evaluate a forest products industry's economic and social contributions. The availability of data at the national level was an important consideration in choosing these indicators.

3.2.1.1 Indicators of the Primary Forestry Sector Structure

Production, export and import levels are important components of a value chain (Breitman and Lucas, 1987). With increasing globalization, it is important to account for the trade of forest products as it may influence greatly the net input to a nation's forestry sector. Apparent consumption, which is synonymous with demand, is frequently used to quantify the net input to a sector. Apparent consumption is calculated by adding a country's production to its imports and subtracting its exports (Equation 3-1).

Apparent Consumption = Production + Imports - Exports Equation 3-1

Volumes of apparent consumption are usually not adjusted for levels of stocks (UNECE/FAO, 2008) and this approach will be used in this dissertation. In practice, determining the apparent consumption of a nation's primary forest products industry is rather more complex than outlined in Equation 3-1 due to the variety of forest products that must be quantified and the range of units that are used to measure these products. In this chapter, the concept of apparent industrial input (AII) was developed to account for the net volume of wood fibre entering the supply chain. A country's AII was determined by adding the national

domestic industrial roundwood harvest to the imports of various forest products and by subtracting the exports of those forest products.

As noted in Section 2.2.2, the forest products industry is usually divided into three subsectors for statistical purposes: forestry and logging (FL), wood products manufacturing (WPM) and pulp and paper manufacturing (PM) (StatsCan, 2009). These three subsectors are connected by flows of industrial roundwood and several intermediate forest products (Figure 3-1) which adds complexity to Equation 3-1. In the forestry and logging subsector, the absolute quantity of industrial roundwood consumed by the domestic primary forest products industry is the sum of industrial roundwood from domestic harvests and international industrial roundwood imports less industrial roundwood exports (Equation 3-1). Similar calculations can be made for the wood products manufacturing and pulp and paper manufacturing subsectors to obtain the net volumes of wood fibre supplied to those subsectors.

Industrial roundwood (InRw), chips and particulates (C&P), wood residues (WR), veneer sheets (VS) and wood pulp (WP) are traded as raw and intermediate products. As reported annually in FAO statistics (FAO, 2015), these products may enter the value chain at different points. A general model indicating the three primary subsectors of the forestry sector and the points at which traded wood fibre may enter and leave the value chain is presented in Figure 3-1. Four different AIIs were defined and used to analyze historical data on primary forest products manufacturing at a national level. Each AII accounted for the import and export of industrial roundwood and intermediate forest products at different points along the value chain. The calculations for the four AIIs used in this study are presented in Equations 3-2 to 3-5.



Notes: InRw: Industrial roundwood; VS: Veneer sheets; C&P: Chips and particulates; WR: Wood residues; WP: Wood pulp

Figure 3-1: Schematic Diagram of Primary Forest Subsectors and Traded Fibre Inputs

AII1: AII1 accounts for the total volume of national industrial roundwood harvest before taking into account of any international trade of forest products (Equation 3-2).

AII1 = InRw Harvest

AII2: AII2 accounts for the national harvest, imports and exports of industrial roundwood and it represents the net volume of industrial roundwood entering the country's forestry sector (Equation 3-3).

AII2 = InRw Harvest + InRw Imports - InRw Exports

AII3: The wood products manufacturing subsector produces several intermediate forest products, including veneer sheets, chips and particulates and wood residues. Veneer sheets are intermediate forest products from the plywood and veneer component of the wood products manufacturing subsector. They are principally used to produce plywood or laminated veneer lumber (Stark et al., 2010). Chips and particulates and wood residues can be obtained from the wood products manufacturing subsector as manufacturing by-products or from imports. The pulp and paper manufacturing subsector consumes industrial roundwood, chips and particulates and wood residues to produce so produce pulp and paper. AII3 measures the net wood material inputs for wood products and pulp manufacturing by taking into account of the international trade of intermediate products in the wood products manufacturing subsector, namely, veneer sheets, chips and particulates, and wood residues (Equation 3-4).

AII3 = InRw Harvest+ InRw Imports - InRw Exports + VS Imports - VS Exports + C&P Imports - C&PExports + WR Imports - WR ExportsEquation 3-4

AII4: Wood pulp is not included in the AII3 calculation and because it is an important commodity product that has undergone a substantial increase in trade over the past four decades (Figure 3-1), it was decided to evaluate its importance using AII4. By taking account of the international trade of industrial roundwood and all intermediate forest products, AII4 quantifies the net total volume of wood material supply to a nation's primary forest products sector (Equation 3-5).

AII4 = InRw Harvest + InRw Imports - InRw Exports + VS Imports - VS Exports + C&P Imports - C&PExports + WR Imports - WR Exports + WP Imports - WP ExportsEquation 3-5

3.2.1.2 Economic Indicators

In the forestry sector, GDP has been the most commonly used economic indicator. However, to avoid "double-counting" in cases where the outputs of one enterprise are intermediate goods rather than final goods, the concept of "value added" has been used as the principal economic indicator in this chapter. Gross value added (GVA) is a measure of the contribution to GDP made by an individual producer, industry or sector. It is an economic measure of the value of goods and services produced in an area or a sector of an economy (Lebedys, 2004; United Nations, 2002). In a sector, GVA is defined as the value of output less the value of intermediate consumption. GVA in a sector may be calculated using Equation 3-6.

Equation 3-2

Equation 3-3

Gross Value Added = Sum of values added by all enterprises = Sales of goods - purchases of intermediate goods used to produce the goods sold¹ Equation 3-6

In order to quantify the value added created from each unit of fibre input, the concept of apparent value added (AVA) has been used in this chapter by taking into account the value changes from the trade of industrial roundwood and intermediate forest products. GVA data have been published for the three subsectors specified in Figure 3-1 (Lebedys and Li, 2014). Therefore, AVA could be obtained by subtracting value added and operating expenses from industrial roundwood and intermediate forest product exports and adding value added and operating expenses from industrial roundwood and intermediate forest product imports to the total GVA for each subsector.

Compared to GDP, the use of GVA data provided additional information on the economic contributions at the subsector level. In order to enable AVA calculations to be made along the value chain, two GVA terms were defined: The gross value added in the forestry and logging subsector (termed forestry GVA) and gross value added in the primary forest products manufacturing subsector (termed manufacturing GVA), which is the sum of the gross value added from the wood products manufacturing and pulp and paper manufacturing subsectors (termed wood products manufacturing GVA and pulp and paper manufacturing GVA, respectively). The manufacturing subsector is enclosed within the rectangular frame outlined in dashed green in Figure 3-1. The relationships between these subsectors and the flow of intermediate forest product associated with them are presented in Figure 3-2.

Despite the existence of individual subsector GVA data, aggregated GVA information for the wood products manufacturing and pulp and paper manufacturing subsectors were used due to a lack of wood by-products flow information. Wood by-products play a very important role connecting the wood products manufacturing and pulp and paper manufacturing subsectors (Chapters 5, 6 and 7) and without detailed information on the fibre flows between these subsectors, it was not possible to quantify the net fibre inputs to each subsector. AIIs could therefore not be determined at the level of the wood products manufacturing subsector could be determined and therefore this study was limited to comparing the AVA/AII of the forestry and logging and manufacturing components of the supply chain.

This terminology also enabled the AVAs to be correlated with the four AIIs developed in Section 3.2.1.1. Value added changes from industrial roundwood trade were considered to impact on the forestry and logging subsector, whereas, value added changes from trade of all intermediate forest products were assumed to occur in the manufacturing subsector.



Notes: InRw: Industrial roundwood; VS: Veneer sheets; C&P: Chips and particulates; WR: Wood residues; WP: Wood pulp

Figure 3-2: Material Flow Conceptual Framework for an Integrated Forest Products Primary Manufacturing Subsector

The four apparent industrial inputs (AIIs) were used to account for the influence of international trade of wood materials consumed by the primary forest products value chain. In association with these four AIIs, five AVAs were developed to evaluate the net value added created at different stages of the primary forestry sector value chain. The definitions and calculations of the four AIIs and the associated five AVAs are presented in Table 3-1.

AVAs	Definition		Definition
AVA1	The value added from the domestic InRw harvest excluding changes from international InRw trade.		The total volume of domestic InRw harvest excluding international trade of InRw.
AVA2-1	The value added from the net InRw input to forest product manufacturing accounting for InRw trade.		The net volume of InDuces the new metanical
AVA2-2	The value added from WPM and PM subsectors accounting value added changes from the international trade of intermediate products (VS, C&P, WR and WP).	AII2	The net volume of InRw as the raw material input to a nation's primary forestry secto accounting for international trade of InRw.
AVA3	The value added from WPM and PM subsectors accounting the value added changes from international trade of intermediate products (VS, C&P and WR) and excluding value added changes from the international trade of WP.	АПЗ	The net volume of wood fibre inputs for forest products manufacturing accounting for international trade of WPM intermediate products (VS, C&P and WR).
AVA4	The value added from WPM and PM subsectors accounting for value added changes associated with the international trade of all intermediate products (VS, C&P, WR and WP).	АП4	The net volume of wood fibre inputs for forest products manufacturing accounting for international trade of all intermediate products (VS, C&P, WR and WP).

Table 3-1: Definition of AVAs and their Corresponding AIIs

Notes: InRw: Industrial roundwood; C&P: Chips and particulates; WR: Wood residues; VS: Veneer sheets; WP: Wood pulp.

Given the parametric definitions presented in Table 3-1, each AVA was calculated using Equations 3-7 to 3-11:

$$\mathbf{AVA1} = \mathbf{GVA}_{FL} + (\mathbf{VA}_{InRw\ Imports} - \mathbf{VA}_{InRw\ Exports}) + (\mathbf{OE}_{InRw\ Imports} - \mathbf{OE}_{InRw\ Exports})$$

$$= AVA2-1 + (VA_{InRw Imports} - VA_{InRw Exports}) + (OE_{InRw Imports} - OE_{InRw Exports})$$
Equation 3-7

$$AVA2-1 = GVA_{FL}$$
 Equation 3-8

$$\begin{split} \mathbf{AVA2-2} &= \mathbf{GVA_{WPM}} + \mathbf{GVA_{PM}} + (\mathbf{VA_{C\&P\ Imports}} - \mathbf{VA_{C\&P\ Exports}} + \mathbf{VA_{WR\ Imports}} - \mathbf{VA_{WR\ Exports}} + \mathbf{VA_{VS\ Imports}} - \\ & \mathbf{VA_{VS\ Exports}} + \mathbf{VA_{WP\ Imports}} - \mathbf{VA_{WP\ Exports}}) + (\mathbf{OE_{C\&P\ Imports}} - \mathbf{OE_{WR\ Imports}} - \mathbf{OE_{WR\ Imports}} - \mathbf{OE_{WR\ Exports}} + \\ & + \mathbf{OE_{VS\ Imports}} - \mathbf{OE_{VS\ Exports}} + \mathbf{OE_{WP\ Imports}} - \mathbf{OE_{WP\ Exports}}) \end{split}$$

= AVA3+ (VA_{C&P Imports} - VA_{C&P Exports} + VA_{WR Imports} - VA_{WR Exports} + VA_{VS Imports} - VA_{VS Exports} + VA_{WP Imports} - VA_{WP Exports}) + (OE_{C&P Imports} - OE_{C&P Exports} + OE_{WR Imports} - OE_{WR Exports} + OE_{VS Imports} - OE_{VS Exports} + OE_{WP Imports} - OE_{WP Exports}) Equation 3-9

 $AVA3 = GVA_{WPM} + GVA_{PM} + (VA_{WP Imports} - VA_{WP Exports}) + (OE_{WP Imports} - OE_{WP Exports})$

$$= AVA4 + (VA_{WP Imports} - VA_{WP Exports}) + (OE_{WP Imports} - OE_{WP Exports})$$
Equation 3-10

 $AVA4 = GVA_{WPM} + GVA_{PM}$

Equation 3-11

Where

AVA is apparent value added;

GVA is gross value added;

VA is trade value;

OE is operating expenses.

In Equations 3-7 to 3-11, AVA2 and AVA4 were calculated directly from the subsector GVA. The other three AVAs were determined by accounting for the changes of value added and associated operating expenses for the traded intermediate forest products to the subsector GVAs. AVA1 and AVA2-1 denote the value added achieved by the forestry and logging subsector. In contrast, AVA2-2, AVA3 and AVA4 represent different elements of the value added within the manufacturing subsector.

Indicators of value added per unit of wood fibre at the subsector level within the primary value chain, termed return of logs were developed by associating the value added parameters defined above with the four AII values (Table 3-1). AVA1/AII1 and AVA2-1/AII2 were developed as indicators of value added per unit of industrial roundwood input in the forestry and logging subsector (termed forestry return of log). AVA1/AII1 represents the value added created from each unit of domestic harvest, whereas, AVA2-1/AII2 denotes value creation from net industrial roundwood input when the trade of industrial roundwood is accounted for. Both AVA2-1 and AVA2-2 were associated with AII2. AVA2-2/AII2, AVA3/AII3 and AVA4/AII4 were categorized as value added from each unit of material flowing through manufacturing subsector (termed manufacturing return of log), and these indicators respectively describe the value added from their associated net wood material inputs when the international trade of intermediate forest products was ignored, the trade of wood products manufacturing intermediate forest products was accounted for and the trade of all intermediate forest products was quantified.

3.2.1.2 Social Indicators

Employment is an important macroeconomic statistic that is used to monitor economic trends (Lebedys, 2008). In this chapter, the employment associated with the forestry and logging, wood products manufacturing, and pulp and paper manufacturing subsectors was analyzed to compare the social contributions achieved by the fifteen important forest countries studied.

Apparent productivity, defined as the value added from each employee (Lebedys, 2008) was assessed for forestry and logging and manufacturing subsectors. Apparent productivity was calculated by dividing the GVA for each subsector by the corresponding employment data for that subsector. It is expressed as the level of value added per employee from each subsector of the primary forest products industry in units of 2011 US\$/ full time equivalent (FTE).

The acronyms used in this chapter and their meanings are summarized in Table 3-2.

Acronym	Descriptive Term	Meaning	Equation	
AII1	National harvest	National harvest production	InRw Harvest	
AII2	Apparent harvest	Apparent InRw input to manufacturing	InRw Harvest+ InRw Imports - InRw Exports	
		subsector		
AII3	Apparent fibre input-pulp	Apparent fibre input to MS excluding	InRw Harvest + InRw Imports - InRw Exports + VS Imports - VS Exports + C&P Imports - C&P Exports	
	trade	wood pulp trade	+ WR Imports - WR Exports	
AII4	Apparent fibre input	Apparent fibre input to MS considering	InRwHarvest + InRw Imports - InRw Exports + VS Imports - VS Exports + C&P Imports - C&P Exports	
		national harvest, by-products and pulp	+ WR Imports - WR Exports + WP Imports - WP Exports	
		trade		
AVA1	National harvest value added	FL national harvest value added	GVA _{FL} + (VA _{InRw Imports} - VA _{InRw Exports}) + (OE _{InRw Imports} - OE _{InRw Exports})	
AVA2-1	Apparent harvest value added	FL apparent harvest value added	GVA _{FL}	
AVA2-2	MS apparent harvest value	MS apparent harvest value added	GVAWPM + GVAPM + (VAC&P Imports - VAC&P Exports + VAWR Imports - VAWR Exports + VAVS Imports - VAVS Exports +	
	added		VAWP Imports - VAWP Exports) + (OEC&P Imports - OEC&P Exports + OEWR Imports - OEVS Imports - OEVS	
			Exports + OE _{WP Imports} - OE _{WP Exports})	
AVA3	MS-pulp trade AVA	MS apparent fibre input excluding pulp	$GVA_{WPM} + GVA_{PM} + (VA_{WP\ Imports} - VA_{WP\ Exports}) + (OE_{WP\ Imports} - OE_{WP\ Exports})$	
		trade value added		
AVA4	Apparent fibre input value	MS apparent fibre input value added	$\mathrm{GVA}_{\mathrm{WPM}}+\mathrm{GVA}_{\mathrm{PM}}$	
	added			
AVA1/AII1	Return of log_1	FL national harvest value added per m ³	$(GVA_{FL} + (VA_{InRw\ Imports^{-}}\ VA_{InRw\ Exports}) + (OE_{InRw\ Imports^{-}}\ OE_{InRw\ Exports})\)/\ InRw\ Harvest$	
AVA2-1/AII2	Return of log_2-1	FL apparent harvest value added per m ³	GVA _{FL} / (InRw Harvest + InRw Imports - InRw Exports)	
AVA2-2/AII2	Return of log_2-2	MS apparent harvest value added per m ³	$(GVA_{WPM}+GVA_{PM}+(VA_{C\&P\ Imports}-VA_{C\&P\ Exports}+VA_{WR\ Imports}-VA_{WR\ Exports}+VA_{VS\ Imports}-VA_{VS\ Exports}+VA_{VS\ Imports}-VA_{VS\ Exports}+VA_{VS\ Imports}-VA_{VS\ Exports}+VA_{VS\ Imports}+VA_{VS\ Imports$	
			$+ VA_{WP\ Imports} - VA_{WP\ Exports}) + (OE_{C\&P\ Imports} - OE_{C\&P\ Exports} + OE_{WR\ Imports} - OE_{WR\ Exports} + OE_{VS\ Imports} - OE_{VS\ Imports})$	

Table 3-2: List of Acronyms and Explanations

Exports + OE_{WP Imports} - OE_{WP Exports}))/ (InRw Harvest + InRw Imports - InRw Exports)

Acronym	Descriptive Term	Meaning	Equation
AVA3/AII3	Return of log_3	MS excluding pulp trade value added per	$(GVA_{WPM}+GVA_{PM}+(VA_{WP\ Imports}-\ VA_{WP\ Exports})+(OE_{WP\ Imports}-\ OE_{WP\ Exports}))\ /\ (InRw\ Harvest+InRw)$
		m ³	Imports - InRw Exports + VS Imports - VS Exports + C&P Imports - C&P Exports + WR Imports - WR
			Exports)
AVA4/AII4	Return of log_4	MS apparent fibre input value added per m^3	$(GVA_{WPM} + GVA_{PM}) / \ (InRw \ Harvest + InRw \ Imports - InRw \ Exports + VS \ Imports - VS \ Exports + C\&P$
			Imports - C&P Exports + WR Imports - WR Exports + WP Imports - WP Exports)
FL	Forestry subsector	Forestry and logging subsector	GVA _{FL}
WPM	Wood products subsector	Wood products manufacturing subsector	GVA _{WPM}
РМ	Paper subsector	Pulp and paper manufacturing subsector	GVA _{PM}
MS	Manufacturing subsector	Manufacturing subsector	GVA _{WPM} + GVA _{PM}
FS	Forestry sector	Sum of all three subsectors	$GVA_{FL}+GVA_{WPM}+GVA_{PM}$

Table 3-2: List of Acronyms and Explanations (Cont'd)

Notes: AII: Apparent Industrial Input, AVA: Apparent Value Added, GVA: Gross Value Added

InRw: Industrial roundwood; VS: Veneer sheets; C&P: Chips and particulates; WR: Wood residues; WP: Wood pulp

3.2.2 Data Sources

3.2.2.1 Apparent Industrial Input Data Sources

The data used in this study were obtained from a variety of sources. Production, imports and exports volumes of industrial roundwood, chips and particulates, wood residues, veneer sheets and wood pulp were obtained from the FAOSTAT database from 1961 to 2011 for the world and fifteen important forestry countries specified in Section 3.1 (FAO, 2015).

It is important to quantify forest products manufacturing inputs and outputs using a common unit to enable any further comparisons. The importance of international trade for the forestry sector is clearly demonstrated by considering the proportion of global industrial roundwood production that is exported as industrial roundwood or intermediate forest products. Data provided by FAOSTAT were presented in a wide range of mass and volume units. For example, wood pulp was measured in air dry tonnes (ADT), industrial roundwood were given in m³ green roundwood equivalent (GRWE) and chips and particulates were quantified in m³ green solid wood equivalent (GSWE). The unit GSWE describes the green volume of wood prior to any shrinkage. It quantifies the wood fibre contained in the product and is the roundwood equivalent volume needed to produce the product when there are no losses or wood by-products created. GRWE volume is a measure of the green volume of logs used to manufacture wood-based products. It is the sum of GSWE and manufacturing losses or wood by-products (Global Timber, 2010; UNECE/FAO, 2010a). In this chapter, the five raw and intermediate forest products considered were all converted to m³ green roundwood equivalent (GRWE) or m³ solid roundwood equivalent (GSWE) (GRWE and GSWE can be used interchangeably for chips and particulates and wood residues). Yield and moisture content values were used to convert all mass based and volumetric data for all five forest products to m³ GRWE (Nielson et al., 1985). Weighted national average wood pulp input/output factors (I-O factors) from 1961 to 2013, were calculated based on the production and input/output factors of four wood pulp categories, including chemical pulp, mechanical pulp, semi-chemical pulp and dissolving pulp (FAO, 2015; UNECE/FAO, 2010a, b).

Detailed assumptions and conversions for different forest products considering moisture contents (MC), volumetric variation with MC changes, wood yield and input/output factors to obtain AIIs are presented in Appendix A.

3.2.2.2 GDP and Apparent Value Added Data Sources

Macroeconomic statistics including total national GDP (2011 US\$), historical global GDP deflators from 1969 to 2011 were obtained from the FAO finance report (Lebedys and Li, 2014). The proportions that the forestry sector GDP (termed forestry sector GDP) contributed to national economies from 1990 to 2011 were obtained from FAO finance report (Lebedys and Li, 2014). The forestry sector GDP for each country

was obtained by multiplying the economic contribution proportion of the forestry sector by the national GDP. To be corresponsive to the GDP values, net input volume could be calculated for the same time period. Each nation's apparent consumption was calculated using Equation 3-1 for each forest product category.

AVAs were calculated using published data on GVA for the three subsectors and value added and operating expenses of the trade of industrial roundwood and intermediate forest products. GVA, at the price levels and exchange rates prevailing in the year 2011, for the three subsectors for fifteen countries from 1990 to 2011 were obtained from the FAO (Lebedys and Li, 2014). The forestry sector GVA for each nation was calculated by aggregating GVAs from all three subsectors. The primary manufacturing subsector (MS) AVA was the sum of both the wood products manufacturing and pulp and paper manufacturing GVA.

Global export values of the forest products (in current US\$) were obtained from 1969 to 2011 (FAO, 2015). Due to the unavailability of global export deflators, the GDP deflators from 1990 to 2011 were applied to convert global forest products export values in current US\$ to the values at the price levels and exchange rates prevailing in the year 2011 (constant 2011 US\$).

Export and import value data for industrial roundwood and intermediate products in the manufacturing subsector from 1990 to 2011 were obtained from the FAOSTAT database for the fifteen countries studied (FAO, 2015). Trade statistics are reported in current US\$. Other macroeconomic statistics including exchange rate (local currency (LOC) per US\$), import deflators (LOC) and export deflators (LOC) for fifteen countries from 1990 to 2011 were obtained from the FAO finance report (Lebedys and Li, 2014). These exchange rates and deflators were applied to convert import and export values in current US\$ to constant 2011 US\$. The real 2011 US\$ trade value series were calculated by deflating the local currency series to obtain a constant local currency value with 2011 as the base year. The resultant values were then converted to US dollars at a fixed exchange rate to realize the conversion from current US\$ to the 2011 US\$ series. In essence, the real dollar series removes both exchange rate fluctuations and price changes from the series (Equations 3-12 and 3-13).

Export (Constant 2011 US\$) = Export (current US\$) × Exchange rate (LOC per US\$)/ Export Deflator (LOC) × Export Deflator (2011) / Exchange rate (2011) Equation 3-12

Import (Constant 2011 US\$) = Import (current US\$) × Exchange rate (LOC per US\$)/Import Deflator (LOC) × Import Deflator (2011) / Exchange rate (2011) Equation 3-13

3.2.2.3 Operating Expenses Data Sources

Intermediate goods used to produce the goods sold in the forestry sector comprise the wood fibre cost and operating expenses including energy, maintenance, non-fibre material, other various costs and other fixed

costs (FPAC, 2012). It is a cost component to calculate the gross value added. Operating expenses as the proportions of traded intermediate forest product value for each traded intermediate forest product in Canada are summarized in Appendix B. These ratios are used for all other fourteen forestry nations studied due to the unavailability of the operating expenses in these countries. Operating expenses can therefore be obtained by multiplying these proportions to the value of the traded products. It should be noted that operating expenses for traded intermediate forest products are the costs required to convert intermediate products to final products (except for pulp production). Therefore, operating expenses for traded veneer sheets are these costs required to convert veneer sheets to plywood rather than from veneer logs to plywood. The same rule applies to traded chips and particulates and wood residues to produce pulp and traded wood pulp to produce paper.

Some assumptions and estimations used to calculate these proportions are summarized below:

- It was assumed that all traded veneer sheets were used for plywood production. All traded chips and particulates and wood residues were used for pulp manufacturing. All traded wood pulp was used for paper production.
- It was assumed that the proportion of operating expenses for veneer production to plywood production using veneer logs as the material input was the same as the proportion of the manufacturing cost of veneer to plywood manufacturing cost.
- The production of chemical and mechanical pulps varied by country and by year (Appendix B). The average proportion of chemical pulp and mechanical pulp production (1990-2011) was used to get weighted ratios of operating expenses to traded intermediate products values for the fifteen countries studied.
- It was assumed that the operating expenses of chipping were 1/5 and 1/10 of the total operating costs needed to produce chemical and mechanical pulp from pulpwood, respectively.
- It was estimated that logging's operating expenses (excluding labor and capital) were 42.2% of the total logging cost and average logging cost is 40.4% of the traded industrial roundwood value (FPI, 2015; MoFR, 2007b, c).

3.2.2.4 Employment and Productivity Data Sources

Employment data from 1990 to 2011 for the three subsectors in the fifteen countries studied were obtained from the FAO (Lebedys and Li, 2014). The employment values were given in FTE for "formal" and "visible" activities in the forestry sector. The data provided by the FAO finance report deliberately excluded all

informal forestry sector activities (Lebedys, 2008; Lebedys and Li, 2014). Due to this exclusion, the employment data are likely to underestimate the total forestry sector's social contribution, especially in some developing countries where informal activities may be significant.

Apparent productivities for the three subsectors in the fifteen countries were obtained by dividing the subsector's GVA by the subsector's employment. Manufacturing subsector's apparent productivity was determined by dividing the manufacturing subsector's GVA by the total employment for both wood products manufacturing and pulp and paper manufacturing subsectors (Lebedys, 2008; Lebedys and Li, 2014).

3.3 Results and Discussion

This section initially weights the relative importance of forest products that are traded globally and confirms which products need to be accounted for in AII calculations. Subsequently, this section evaluates forestry sector GDP and AVA per unit input and highlights the benefits of using these indicators developed in this dissertation. Forestry sector employment (FTE) per unit input was then used to understand the job creation in forestry nations before assessing both employment and apparent productivity by subsector.

3.3.1 International Trade of Intermediate Forest Products

The transition to post-Fordism during the latter part of the twentieth century resulted in globalization and a substantial increase in international trade (Brooks et al., 2004). There are a number of benefits of international trade. Economically, it allows producers and consumers to buy and sell products at the best available prices. From a development perspective, it may be a driving force for economic growth, particularly when the domestic market is small or prices are low. Greater export or import substitution can also increase or protect foreign currency reserves, which are a concern in some developing countries (Brooks et al., 2004). The global forestry sector has been influenced by these drivers and there have been substantial increases in volumes and values of forest products traded since the 1960's (Lebedys and Li, 2014). As mentioned earlier, this study hypothesized that imports and exports of industrial roundwood and intermediate forest products should be accounted for when determining the flows of materials through a nation's forestry value chain. In order to show the trends in the international trade of industrial roundwood and intermediate products, the global historical exports of five forest products including industrial roundwood, wood chips and particulates, wood residues, veneer sheets and wood pulp have been assessed (Figure 3-3).



Figure 3-3: Trends in Industrial Roundwood Production and Global Forest Products Exports, 1961-2013

Note: Global industrial roundwood production data refer to the right hand axis, while the lines for the rest refer to the left hand axis.

Global industrial roundwood harvests increased fairly steadily from 1.02 billion m³ per year in 1961 to 1.70 billion m³ per year in 1989 (Figure 3-3). The pronounced decrease in the early 1990's has been attributed to the collapse of the Soviet Union (USSR) during 1989 and 1990 (Strayer, 1998), economic recessions in the early 1990's (Walsh, 1993) and the reduced harvest from public lands in the USA (Raettig and Christensen, 1999). After a substantial decrease in early 1990s, there was an erratic upward trend in industrial roundwood production from 1994 until 2005, although at a lesser rate than occurred from 1961 to 1989 (Figure 3-3). Since 2005, there has been a substantial decrease in production which has been attributed to the global economic recession and shrinking housing markets (Shepard and Sitar, 2010). The harvesting started to increase steadily back to 1.70 billion m³ in 2013 after it reached the lowest of 1.51 billion m³ in 2009 (Figure 3-3).

The importance of international trade for the forestry products is clearly demonstrated by considering the proportion of global roundwood production that is traded as industrial roundwood or intermediate forest products (FAO, 2015). The global export volumes of industrial roundwood and the four important intermediate forest products increased significantly from 1961 to 2013. For example, the cumulative export volumes of these five forest products increased from less than 5.0% of the total global industrial roundwood production in 1961 to 27.0% in 2013, and reached a maximum value of 27.1% in 2011 (FAO, 2015). This more than fivefold increase in the trade of raw and intermediate forest products, and the observation that

about a quarter of the global industrial roundwood harvest is traded internationally, make it imperative that assessments of material flows through national value chains should take account of the imports and exports of these products.

A consideration of trends in the global export volumes of individual forest products reveals a shift in importance from industrial roundwood to intermediate products, especially wood pulp (Figure 3-3). The trend of industrial roundwood export follows a similar pattern of industrial roundwood production. Until the early 1980's, industrial roundwood was the principal wood product traded before being surpassed by wood pulp in 1982. Notably, exports of all intermediate product volumes increased relatively steadily over the period considered, irrespective of global economic conditions, whereas the industrial roundwood trade appeared to be much more influenced by periods of recession (Figure 3-3).

Amongst the five forest products considered here, wood pulp exhibited the most substantial increase, by more than threefold from 63.1 Mm³ GRWE in 1968 to 247.5 Mm³ GRWE in 2013 (Figure 3-3) (Wood pulp data prior to 1968 were considered to be unreliable). Despite the slow growth of industrial roundwood production from 1989, wood pulp export followed a more steady growth pattern with the most pronounced increase occurring from 1982 to 2013 and its growth rate was more than five times that of industrial roundwood export (Figure 3-3). Wood pulp accounted for 54.0% of the total volume of wood products exported in 2013 (FAO, 2015) and this large increase in trade was mostly driven by structural changes in the pulp and paper industry. There has been a decrease in the number of large integrated mills being located on one site and an increase in the number of pulp mills being strategically sited close to fibre resources and paper mills close to consumer markets (Hylander, 2009; Välikauppi et al., 2006). These developments have resulted in wood pulp becoming an internationally traded commodity that links the forest resources to the consumers of paper products. North and Latin America have become major pulp exporting regions. Asia, and to a lesser extent Europe, have become major pulp importing regions (Letohnen, 2009).

The by-products from manufacturing and the virgin fibre supply for pulp manufacturing, chips and particulates and wood residues' shares of exported wood product volumes increased from 2.08% in 1964 (data on chips and particulates volumes prior to 1964 are not available) and 0.73% in 1961 to 15.3% and 2.03% in 2013, respectively. Export volumes of both intermediate product categories increased almost thirtyfold from 1964 to 2013. However, with the steady growth of global trade of forest products, the share of both intermediate products to global exports only quadrupled between 1964 and 2013. Chips and particulates is the third most traded forest product. The traded volume has been steadily increasing with time in a slower growth rate than wood pulp (FAO, 2015) (Figure 3-3).

The export volume of veneer sheets was historically the lowest amongst the five products studied, increased steadily from 0.64 Mm³ GRWE in 1961 to 5.10 Mm³ GRWE in 2013. Its share of total global forest products exports averaged at 1.70% (FAO, 2015) (Figure 3-3).

3.3.2 Forestry Sector's Economic Contributions

3.3.2.1 Forestry Sector GDP Contributions by Apparent Industrial Inputs

GDP has been used as one of the most important indicators to evaluate an industry's economic contribution and its widespread use enables international comparisons to be easily made (Lebedys and Li, 2014; Lipsey et al., 1991; Mankiw et al., 1999; StatsCan, 2009). This section compares the forestry sector GDP created per cubic metre of green roundwood equivalent input flowing through the primary forestry value chains of the countries studied. Four different apparent industrial inputs (AIIs) were developed to assess green roundwood equivalent volumes entering the value chain at four different stages of manufacturing and to calculate the average forestry sector return of logs (FS GDP/AII) values from 1990 to 2011. Data are presented in Figure 3-4 in an alphabetic sequence for each of the fifteen countries studied.

Irrespective of which forestry sector GDP/AII was evaluated, Japan, Germany and Australia consistently exhibited high GDP/AII values and Canada, Sweden, Finland, Brazil and Indonesia tended to attain the lowest GDP/AII values in the range of 198 to 330 US\$/m³ GRWE (Figure 3-4). There were obvious differences amongst the four GDP/AII values in some countries, particularly Japan, indicating that the international trade of industrial roundwood and intermediate forest products strongly influenced its forestry sector GDP.

Nations which exhibited greater GDP/AII1 values than their GDP/AII2 values were net roundwood importers and those with GDP/AII1 values less than GDP/AII2 were net roundwood exporters. For example, using national industrial roundwood harvest as the input to Japan's primary forestry sector showed that it achieved a GDP/AII1 of 2,521 US\$/m³ GRWE, by far the highest of any country studied (Figure 3-4). However, its GDP/AII2 was almost halved to 1,475 US\$/m³ GRWE due to the large volume of industrial roundwood imported. The national harvest volume therefore substantially underestimated the true wood fibre inputs for the entire value chain and resulted in an erroneously high estimation of the GDP created per unit of roundwood processed. Austria was another important industrial roundwood importer with its forestry sector GDP/AII1 value of 131 US\$/m³ GRWE being greater than its forestry sector GDP/AII2 due to the 5.91 Mm³ GRWE/year average net industrial roundwood imports over the study period (FAO, 2015) (Figure 3-4). In contrast, New Zealand, Malaysia, Germany and France, important industrial roundwood exporters, followed an opposite trend. GDP/AII1 values, respectively. In these nations, using the national industrial

roundwood harvest as the input value to primary manufacturing would underestimate the GDP created per unit volume processed.



Figure 3-4: Forestry Sector GDP/AII Values in 15 Countries, Average 1990-2011

Japan also imported chips and particulates as indicated by its GDP/AII3 value being greater than the GDP/AII2 value. In contrast, nations that exported intermediate products from the wood products manufacturing subsector displayed a greater GDP/AII3 than GDP/AII2. This trend was most evident in Australia which is a noted exporter of chips (Figure 3-4).

Germany and Japan are two important wood pulp importers as revealed by the lower GDP/AII4 values compared to the GDP/AII3 values. In contrast, the greater GDP/AII4 values compared to those for GDP/AII3 indicated that Chile and New Zealand were two of the most important wood pulp exporters (Figure 3-4).

Canada's rankings of GDP/AII values were consistently the lowest for all AII-based economic indicators. Notably, the GDP/AIIs in the USA were almost one and half times those of Canada. While GDP/AII values reveal very useful information about the economic outputs obtained from comparable industrial roundwood inputs and the importance of trade in generating these outputs, further data are required to give an accurate explanation of the causes of the differences between the primary forestry sectors in these two North American countries. 3.3.2.2 Return of Log (Average Apparent Value Added/Apparent Industrial Input)

To further the forestry sector GDP/AII study, average unit input apparent value added (AVA/AII, termed return of log) is employed to analyze the value creation from stages of value chain.

A variety of return of logs indicators may be used to show the value created per unit volume of wood fibre input at different stages along the primary value chain to identify the stage that achieved the greatest value added per unit of fibre input and to facilitate comparisons of the economic contributions produced by each nation's forestry sector (Figure 3-5). The five AVA/AIIs described in Section 3.2.1.1 were allocated into two categories. First, the raw material value added category was attributed to the forestry and logging subsector and termed forestry return of log. Hence, AVA1/AII1 and AVA2-1/AII2 were attributed to this category. Second, the manufacturing subsector unit input value added category was termed manufacturing return of log and all the remaining AVA/AII values (i.e. AVA2-2/AII2, AVA3/AII3 and AVA4/AII4) were attributed to this category.

The average return of logs values attained by each nation between 1990 and 2011 are presented in Figure 3-5. This figure ranks countries by their AVA2-2/AII2 values. Average return of logs for all nations studied are presented in Appendix C.





The manufacturing return of logs was greater than the forestry return of logs in all countries studied, other than Chile and Malaysia. In some developed countries, there were large differences between the forestry and logging and manufacturing return of logs which showed that substantial value addition was created per unit of fibre passing though the manufacturing subsector (Figure 3-5 and Appendix C). The highest manufacturing return of logs was observed in Japan, Germany, France and Australia (Figure 3-5). The value created by each unit of fibre input in the manufacturing subsector of these four nations accounted for more than 81.9% of their total primary forestry sector unit input value added. Other developed nations that focussed primarily on lower value added commodity products such as Canada, New Zealand and Sweden achieved lower manufacturing return of logs (Figure 3-5 and Appendix C). The differences between the forestry and logging and manufacturing return of logs were quite small, especially amongst some developing countries. For example, the differences between two subsector AVA/AII values in Indonesia were within 10%.

The return of logs also reflected the scale of international trade of industrial roundwood, intermediate forest products and by-products at various points along the value chain. Irrespective of the subsector considered, an increasing return of logs along the value chain indicates that the nation is a net exporter, since exports increase AVA and decrease AII. In contrast, return of logs declines along the value chain if the nation is a net importer. Japan displayed the most significant differences between the various return of logs and serves as a

good case study to reveal the significant influence that international trade of industrial roundwood and intermediate forest products may have on a nation's forest products sector. Japan has historically been a large net importer of various forest products to supplement the roundwood provided by its national harvest. Over the study period, Japan's forestry and logging subsector imported an average of 15.2 Mm³ GRWE industrial roundwood annually with negligible exports averaging at 0.02 Mm³ GRWE annually (FAO, 2015). This volume accounted for 76.2% of the total roundwood inputs to its manufacturing subsector. The increased total industrial roundwood input and the associated expenses significantly decreased Japan's return of log 2-1 to 91.3 US\$/m³ GRWE, which was one fifth of its average return of log 1 (Appendix C). The large proportion of industrial roundwood imports may be explained by several factors. Japan's forest protection policy and continuous introduction of higher forest taxes has highly constrained its domestic harvesting (FAO, 2010; Forestry Agency, 2010). In 2005, the area of protected forests in Japan was 11.65 million ha, which was equivalent to 46% of its total forest area (FAO, 2010). Most Japanese forest products firms own no forest land and have no long-term harvesting rights which cause them to buy wood from local and global markets. Those private companies which own forests must pay high land taxes and they have obligatory replanting and silvicultural costs which are frequently higher than the harvest value. Japan's average wage rates for silvicultural and logging workers are high in an international context. These factors all place pressure on Japan's domestic industrial roundwood production and they also contribute to the high return of log 1. In addition, the Japanese government has reduced tariffs on intermediate forest products, by-products and wood, which further encouraged Japanese forest products companies to import industrial roundwood and intermediate forest products from forestry nations with lower return of log_1s (Iwai, 2002; Marchak, 1995; Sedjo and Simpson, 1999). The use of cheaper imported intermediate forest products appears to have enable Japan to protect a substantial proportion of its forests while continuing to have a competitive forest products sector.

Historically, Japan has also been the largest global importer of wood chips (FAO, 2015). Consumption of chips has increased rapidly from the mid-1960's with Japanese pulp mills increasing imports of these materials because local supplies were insufficient and costly (Iwai, 2002; Marchak, 1995). Therefore, large imports of by-products to the wood products manufacturing subsector lowered Japan's return of log_3 to 894 US\$/m³ GRWE, or 47.1% lower than its return of log_2-2. Japanese papermaking companies have been investing in pulp mills and in pulpwood plantations to obtain their virgin fibre in addition to high quantities of recycled waste paper (Marchak, 1995). As a consequence of these developments, the volume of imported pulp has halved between 1990 and 2011 and by 2011 pulp imports only accounted for about one seventh of the imported volumes of chips and particulates and wood residues (FAO, 2015). Despite the decreasing volumes of wood pulp imported by Japan, it remained a net wood pulp importer for the duration of the study period. Over this time frame, Japan's return of log_4 averaged 673 US\$/m³ GRWE which another 24.7%

reduction in comparison with return of log_3 is observed by importing wood pulp as the intermediate to Japan's pulp and paper industry (Figure 3-5 and Appendix C).

Conversely, the opposite trend in return of logs was observed in nations that were net exporters including Australia, Germany, Chile, Malaysia and New Zealand. In particular, Australia has historically been a large net exporter of by-products, especially wood chips and particulates (Industry Edge, 2013). Its wood products manufacturing subsector, showed a 416 US\$/m³ GRWE or 133% increase in its return of log_3 compared to its return of log_2-2. Chile also displayed a substantial difference of 343 US\$/m³ GRWE between its return of log_4 and return of log_3 values due to its substantial exports of wood pulp which have increased steadily as a proportion of total forestry sector volumes since the early 1990's (FAO, 2015).

International trade has little impact on the return of logs for some nations. For example, there was little significant international trade in intermediate products in the USA as revealed by the relatively trivial differences amongst the three return of logs for the USA's manufacturing subsector (Figure 3-5 and Appendix C).

The return of log data also enabled international comparisons of the different forest value chains to be made. For example, a comparison of the results for the USA and Canada is informative. Despite the closely linked markets and some similarities between both nations' forest products industries, the economic benefits generated per unit of input were quite different. Canada has consistently been a net exporter of industrial roundwood and intermediate forest products, with the majority of these exports traditionally being imported by the USA. The value added achieved per unit input in both countries' forestry and logging subsectors was quite similar between 1990 and 2011, with the USA's average return of log 1 being approximately 10.6% lower than that of Canada at 46.7 US\$/m³ GRWE (Figure 3-5). However, the USA's average return of log_2-1 was 6.91% greater than that of Canada. The manufacturing subsector further increased the differences between the return of logs in both countries with the USA's average return of log 2-2 of 253 US\$/m³ GRWE being 4.70 times that of Canada as a consequence of its larger scale of industrial roundwood export. In contrast, Canada's greater proportional exports of wood pulp narrowed the gap between the two countries return of log_4, with the USA's return of log_4 of 262 US\$/m³ GRWE being 1.48 times that of Canada (Figure 3-5 and Appendix C). In order to further understand the causes of the differences between these two nations return of logs and to inform Canadian forestry policy development, a detailed analysis of Canada's and the USA's return of log data have been undertaken in Section 4.3.2.

3.3.3 Forestry Sector's Social Contributions

3.3.3.1 Forestry Sector Employment/AIIs

Employment statistics provide insights on the social contributions from a nation's forestry sector. In general, forestry sector employment declined between 1990 and 2011 in most countries studied. Detailed employment statistics and analyses are provided in Appendix D. In this section, forestry sector employment is normalized by AIIs and used as a social contribution indicator to evaluate the forestry sector's social benefits from each unit of wood material input at the four points of the value chain in each country. The employment/AIIs created by the forestry sector for the fifteen countries studied are listed in alphabetic order in Figure 3-6.



Figure 3-6: Employment/AIIs in 15 Countries, Average 1990-2011

Irrespective of which employment/AII parameter was evaluated, China, the nation with highest forestry sector employment, consistently exhibited the highest employment/AII values, whereas, some developed nations, including Canada, Sweden, Finland, New Zealand and the USA consistently had the lowest employment/AII values (Figure 3-6). There were clear differences amongst the four employment/AII values in some countries, particularly Japan, China, Chile and Germany indicating that the international trade of industrial roundwood and intermediate forest products strongly influenced the forestry sector employment in these countries.

China and Japan displayed the highest employment/AII1 (Figure 3-6). China's employment/AII1 averaged 35.1 FTE/1000 m³ GRWE of industrial roundwood harvest, while, Japan attained 25.4 FTE/1000 m³ GRWE. The influence of trade on employment/AII was apparent in Japan and was a consequence of the large volumes of imported industrial roundwood and intermediate forest products used to supply its wood products manufacturing and paper manufacturing industries together with Japan's efforts on educating introductory skills and knowledge of forestry to the new entrants to forestry (FAO, 2015; Forestry Agency, 2010). In contrast, average values of employment/AII3 and employment/AII4 in Australia, Chile and New Zealand were greater than the data for employment/AII1 and employment/AII2, indicating that these three nations were net exporters of industrial roundwood and/or intermediate forest products (Figure 3-6).

In general, developed countries had lower employment/AII values than developing countries. This observation is consistent with the developed nations substituting labour with capital (Binkley, 1993). Forestry sector employment/AII may be influenced by many factors, including scale of the forestresources, size of the primary forest products industry, national population and manufacturing technologies utilized. In industrialized countries, the application of state-of-the-art technologies is likely to result in a decreased number of labour intensive jobs in the forestry sector. Whereas, a reduced application of capital and technologies in developing countries is likely to be associated with higher levels of employment per unit volume roundwood processed. In addition, it has been noted that in some Asian developing countries, illegal logging has been estimated to account for about one fifth of the total harvest (WWF, 2005) and therefore reported roundwood harvest volumes may underestimate the true volumes of roundwood entering the value chain.

3.3.3.2 Employment by Subsector

For each country, an analysis of the employment in forestry and logging and manufacturing subsector as a function of the value added per unit input can also reveal useful insights (Figures 3-7 and 3-8). The four quadrants are created by using the average values for unit value added and employment for the forestry and logging subsector and the manufacturing subsector.

Top right green quadrant represents the most desirable situation from a governmental perspective (i.e. higher employment and higher unit value added) and the lower right quadrant describes the most favorable situation for industry (i.e. higher unit value added with lower employment) (Figures 3-7 and 3-8). Return of log_2-1 and return of log_4 represent the value added per unit of fibre input in m³ GRWE from forestry and logging subsector and manufacturing subsector, respectively.

Blue and double green dashed lines respectively represent the average values of unit value added and employment of fifteen forestry nations. Double green dash line represents the average forestry and logging subsector employment of fourteen forestry countries excluding China. Over the study period, China's
forestry sector had the largest labor market and the trend in China's forestry sector employment has a large influence on global forestry sector employment as, globally, one in every four employees working in the primary forest products industry was employed in China (Appendix D). China's absolute high employment brought the average forestry and logging subsector and manufacturing subsector employment from 54.5 to 150 thousand FTE and from 270 to 397 thousand FTE, respectively. The average value added per unit fibre input attained 89.4 US\$/m³ GRWE at the level of Japan and Germany (Figure 3-7).

Two thirds of the forestry nations studied fall in the bottom left and top right quadrants where China is not included in the average forestry and logging employment calculation. In general, nations with rich forest resources obtained lower value added per cubic metre. Indonesia and Malaysia are the two exceptions presumably because of their high value tropical logs. However, the data quality from these nations may be questioned. Forestry and logging employment has been low in the nations which have developed the most advantage from forest operations technologies (Figure 3-7).



Figure 3-7: Forestry and Logging Employment in Relation to Return of Log_2-1 from Apparent Harvest in the Forestry and Logging Subsector

The trend of employment versus unit value added in manufacturing subsector revealed that most of the nations are distributed in two low manufacturing employment quadrants with developing forest nations

consistently fall in the lower per m³ value added quadrants. Japan, Germany, France, Chile and Australia, the manufacturing focused forestry countries, obtained higher value added per m³ input (Figure 3-8).



Figure 3-8: Manufacturing Subsector Employment in Relation to Return of Log_4 from Apparent Fibre Input in the Manufacturing Subsector

In general, employment in the primary forest products industry has been decreasing with the exceptions of Brazil, Malaysia and Chile over the study period (Lebedys and Li, 2014). The trends in employment in the three subsectors over the last seventeen years in the fifteen countries studied are presented in Appendix D.

3.3.3.3 Apparent Productivity by Subsector

Apparent productivity expressed by value added per employee has been used as an indicator of social contribution. It denotes the level of salaries and wages in an industry and reflects the general level of benefits and conditions of employment in an industrial subsector (Lebdeys, 2008; Lebdeys and Li, 2014). For each country, apparent productivity performance in forestry and logging and manufacturing subsectors as show by the correlated value added per unit input can also reveal useful insights. Four quadrants represent the changes of productivity performances in terms of per unit value added and productivity as shown in the top right green quadrant representing the most desirable productivity outcome by industry at subsector level (Figure 3-9 and 3-10). Blue and green dash lines represent the average values of unit value added and

productivity of fifteen forestry countries, respectively. Higher productivity with higher value added per unit input is the most favorable situation for both government and industry.

The average forestry and logging productivity (87,1000 US\$/FTE) and average unit value added in forestry and logging subsector amounted at 89.4 US\$/m³ GRWE divided the productivity in terms of unit forestry and logging subsector value added into four quadrants (Figure 3-9). Most nations fall in the top left and bottom right quadrants. Developed nations that utilized more mechanized forest harvesting technologies obtained lower value added per cubic metre, whereas nations with lower harvesting operation productivity were associated with higher unit value added. In particular, important log exporting nations (e.g. Canada, New Zealand and Australia) had the most advantageous forest operations technologies, but because the logs are traded as the commodity products, these countries did not achieve high unit value added. China and Japan, which both have extensive forest conservation regulations, had limited investment on their national harvesting practices and they achieved below average productivity in this subsector and above average unit value added (Figure 3-9). High value tropical forests in Malaysia and Indonesia contributed to the high unit input value added despite their relative low productivities.



Figure 3-9: Forestry and Logging Productivity in Relation to Return of Log_2-1 from Apparent Harvest in the Forestry and Logging Subsector

The trend of productivity versus unit value added in manufacturing subsector revealed differences between developing and developed countries. Developed nations with higher manufacturing productivity are mostly distributed in the top left and right quadrants with France as the only exception. France obtained lower than average productivity and its manufacturing subsector was located in the right bottom quadrant (Figure 3-10). All the developing nations studied including China, Brazil, Indonesia and Malaysia together with Canada were located in the left bottom quadrant indicating their low manufacturing productivity and low unit value added obtained. Canada's manufacturing sector productivity was below average (84.2 thousand US\$/FTE) indicating that it still has room to improve its productivity of this subsector. Japan, Australia and Germany once again demonstrated their high value creation with these three nations obtaining the greatest unit value added in the manufacturing subsector.



Figure 3-10: Manufacturing Subsector Productivity in Relation to Return of Log_4 from Apparent Fibre Input in the Manufacturing Subsector

In summary, the differences in apparent productivities reflect the level of automation in the industry, the extent to which capital has been substituted for labor, and market conditions. Technology adoption, resource quality, trade in intermediate forest products and market conditions are important factors influencing a nation's achievements in the forestry and logging productivity and unit input value added quadrant. High

resource quality in tropical countries appeared to benefit their unit value added in the forestry and logging subsector.

The range observed in manufacturing productivities was substantial. Developing nations showed their limited abilities to add value, and high manufacturing productivity was not consistently associated with high unit value added. Many other factors, including product type, product grade and selling price are likely to influence the unit value added in the manufacturing subsector.

Comparisons of the apparent productivity in the three subsectors of the fifteen countries studied are presented in Appendix D.

3.4 Conclusions

The economic and social contributions of the forest products industry are important aspects of sustainable forest management. Due to a substantial increase in the international trade of industrial roundwood and intermediate forest products over the last fifty years, the domestic harvest volumes do not provide an adequate estimate of the total wood fibre entering a nation's forest products value chain. This study used four AIIs to more accurately characterize the wood fibre inputs to a country's value chain and to analyze the influences of international trade of industrial roundwood and intermediate forest products on socio-economic contributions from a nation's forestry sector.

Economic and societal indicators (GDP/AII, return of log, employment/AII and employment and apparent productivity by subsector) were evaluated for fifteen forest products nations between 1990 and 2011. Differences between the developed and developing countries revealed useful trends and information on how the value chain functioned.

The use of AIIs enabled the various national forestry supply chains to be compared on a green equivalent roundwood input basis and these analyses revealed clear differences amongst the forestry sector GDP/AIIs, return of logs (AVAs/AIIs) and forestry sector employment/AIIs in some countries. In particular, Japan's primary forest products industry was shown to be strongly dependent on the import of industrial roundwood and intermediate forest products.

The AVA indicators reflected the size of the forestry sector in each nation. In contrast, return of logs provided information on where the value addition occurred along the value chain and revealed the importance of international trade of forest products irrespective of the size of the industry. Manufacturing processes, indicated by the difference between return of log_2-2 and return of log_2-1, added the greatest value to every unit of fibre input in all nations. In particular, the differences between these values were

substantially greater in developed countries compared to developing nations. The importance of international trade was also highlighted in the economic contribution analyses.

China had the highest forestry sector employment/AIIs amongst the fifteen countries studied. Three countries: Finland, Sweden and Canada displayed the lowest forestry sector employment/AIIs. These observations supported the premise that the industrialized nations that focus on the production of commodity primary forest products have substantially substituted capital for labor.

The trends of employment and productivity versus unit value added in two subsectors revealed clear differences between the developing and developed countries. Most developing nations, which had higher employment and lower apparent productivity, obtained higher unit input value added from the forestry and logging subsector compared with developed nations. In contrast, despite the high forestry and logging productivity in several nations, the majority of the developed countries displayed low unit input value added and low employment indicating as the primary forestry industry in these nations relied less on their forest and logging subsectors and more on their manufacturing subsectors.

From the perspective of manufacturing subsector, unit input value added varied substantially among nations. The analysis of employment trends in relation to unit input value added revealed that, apart from Chile, the manufacturing subsector was more labor intensive than forestry and logging operations. This unit input value added achieved by the manufacturing subsector was greater than that for forestry and logging in all nations except Malaysia. Nations that relied heavily on their forest resources generally achieved low unit input value added from their manufacturing subsector. An assessment of apparent productivity in relation to unit input value added in the manufacturing subsector revealed two trends: First, the unit input value added produced in all the developing nations except Chile was consistently lower than the average of 306 US\$/m³ GRWE. Second, despite the wide range of unit input value added obtained from the manufacturing subsector, all developed nations, together with Chile, consistently displayed higher productivities than the developing countries.

Socio-economic analyses in fifteen forestry countries using indicators of GDP/AII, return of log, employment/AII and employment and apparent productivity in relation to the subsector unit input value added concluded that developing countries' forestry sectors tended to deliver lower socio-economic values. Many factors could be considered to elevate these contributions, in particular, for developing countries. First of all, apparent productivities could be enhanced by adopting more advanced techniques to add further value to each unit of fibre input. Secondly, greater value could be captured within the nation rather than exporting industrial roundwood or intermediate products. The focus of the industry should be shifted from being heavily reliant on raw material provision to an emphasis on higher value added creation.

In summary, by decomposing gross value added production and wood fibre input at points along the value chain, a more thorough understanding of socio-economic benefits created national primary forestry sectors has resulted.

CHAPTER 4 ASSESSMENT OF THE INFLUENCE OF THE FORESTRY SECTOR'S STRUCTURE ON ITS ECONOMIC CONTRIBUTIONS PER UNIT OF INPUT

4.1 Introduction

Chapter 3 assessed and used indicators to evaluate the socio-economic contributions of fifteen important forestry countries. The comparisons revealed that, in general, the primary forest products manufacturing (MS) subsector was a more important component of the forestry sector in developed countries than in developing nations. In the latter countries, the forestry and logging subsector tended to predominate and lower levels of socio-economic outcomes were usually achieved. In addition, it was noted that despite the USA and Canada having broadly similar forest products manufacturing technologies, management and markets, the two countries had different return of logs. The USA's return of logs were 1.10 to 2.62 times greater that of Canada (Figure 3-5).

In order to better understand the influence of the value structure on the socio-economic benefits generated by a jurisdiction's forestry sector, this chapter aimed to 1) investigate the forestry sector structure in Canada and fourteen other forestry nations to explore value chain attributes that enhance the economic benefits achieved per unit of material input, 2) understand the causes of the discrepancies in economic benefits per material input amongst countries, in particular, between the USA and Canada.

The two principal variables evaluated in this chapter were the primary forestry subsector GVA and the value structure measured by the proportional value added by the forestry and logging and manufacturing subsectors. Other factors, such as land ownership, forestry tenure and labour costs may also influence economic benefits. However, evaluation of these parameters was beyond the scope of this study.

4.2 Methodologies and Data Sources

4.2.1 Methodologies

In Chapter 3 (Section 3.2.1), the forestry sector was divided into the forestry and logging, wood products manufacturing and pulp and paper manufacturing subsectors (Lebedys, 2008; StatsCan, 2009) and AVA was used to calculate the value added at four points along the value chain. This chapter characterized the forestry sector value structure in the same manner. Forestry and logging AVA represented the value added by the forestry and logging subsector and the aggregated AVA from both the wood products manufacturing and pulp and paper manufacturing subsectors was used to determine the value added achieved by the

primary forest products manufacturing subsector. This latter value was termed the manufacturing subsector AVA (manufacturing AVA). The total value added of the forestry sector was assessed by adding together the forestry and logging and manufacturing GVAs.

4.2.2 Data Sources

4.2.2.1 AII Data Sources

AII calculations were undertaken for the fifteen important forestry countries in Chapters 3, namely, Australia, Austria, Brazil, Canada, Chile, China, Finland, France, Germany, Indonesia, Japan, Malaysia, New Zealand, Sweden and the USA for the study period of 1990 to 2011. Export and import volumes for industrial roundwood and intermediate products (wood chips and particulates, veneer sheets, wood residues and wood pulp) were obtained from the FAO database (FAO, 2015, 2011). Quantities of production and trade were obtained in various mass or volume units (FAO, 2015). These units were converted to an m³ GRWE basis. The conversion methodologies have been described in Chapter 3 (Section 3.2.2 and Appendix A).

4.2.2.2 GVA Data Sources

The GVAs for the forestry and logging, wood products manufacturing and pulp and paper manufacturing subsectors in fifteen countries from 1990 to 2011 were obtained from FAO (Lebedys, 2008). Forestry sector GVAs were calculated by aggregating GVA from all the three forestry subsectors. Export and import value added data for industrial roundwood and intermediate products in manufacturing subsectors were obtained from the FAOSTAT databases (FAO, 2015). The trade values were presented in current US\$ and were converted to constant 2011 US\$. The conversion methodologies have been described in Section 3.2.2.2.

4.2.2.3 Operating Expenses Data Sources

Operating expenses as the proportions of traded intermediate forest product value for each traded intermediate forest product were obtained for Canada. These ratios were then used in all other fourteen forestry nations studied due to the data unavailability in these countries. The methodologies of calculating the operating expenses have been described in Section 3.2.2.3.

4.3 Results and Discussion

Previously, the value structure has been considered to be a useful indicator of the general development level of a nation's forestry sector (Lebedys, 2008). This chapter hypothesized that a nation could potentially improve the economic contributions from its forestry sector by adjusting the industry's value structure. This section sought to explore this hypothesis by first assessing its validity by undertaking a study of fifteen

countries with important forest product industries. Chapter 3 concluded that forestry sectors in developing countries tended to be dominated by the forestry and logging subsector and produce lower economic outcomes. In contrast, return of logs achieved by developed countries were greater, and their forestry and logging GVAs were generally smaller as a proportion of their forestry sector GVAs. This chapter therefore hypothesized that the proportional subsector GVA could be used to analyze the industry's value structure. In general, it was expected that a larger proportional forestry and logging subsector (e.g. percentage forestry and logging GVA/forestry sector GVA) would be associated with lower economic outcomes per unit of input and a larger proportional manufacturing subsector (e.g. percentage manufacturing GVA/forestry sector GVA) would be associated with lower economic outcomes per unit of input and a larger proportional manufacturing subsector (e.g. percentage manufacturing GVA/forestry sector GVA) would be associated with lower economic outcomes per unit of input and a larger proportional manufacturing subsector (e.g. percentage manufacturing GVA/forestry sector GVA) would be associated with higher outcomes.

4.3.1 Impacts of the Value Structure on the Economic Benefits Attained from Unit of Input

4.3.1.1 International Assessment of Value Structure on Return of Log_4

Regardless of the absolute total forestry sector GVA, the GVAs produced by individual subsectors varied substantially from nation to nation over the study period (Figures 4-1, 4-3 and 4-5). Temporal trends in return of log_4 from 1990 to 2011 are presented in Figures 4-2, 4-4 and 4-6.

Figure 4-1 presents the effect of the proportional size of the forestry and logging subsector GVA on return of log_4 and it revealed a curvilinear power relationship with a negative slope indicating that a larger forestry and logging subsector, as a proportion of the total forestry sector was associated with a lower value added per unit volume of total net input (Figure 4-1). Simplistically, those nations with a predominant forestry and logging subsector, such as many developing nations, produced lower economic outcomes per unit input than nations with large manufacturing subsectors (wood products manufacturing and pulp and paper manufacturing). Whereas, the negative correlation was more substantial for nations with forestry and logging GVA% lower than 20% (Chapter 3 and Figure 4-1). Malaysia had the lowest value at 139 US\$/m³, and Japan had the highest at 673 US\$/m³. The curvilinear power relationship noted above showed relatively little increase in return of log_4 until the forestry and logging subsector GVA decreased below 20% of the GVA of the forestry sector. Below this proportion, return of log_4 tended to increase substantially and three countries, Japan, Australia and Germany with forestry and logging forestry and logging GVA less than 12% of the forestry sector GVA displayed highest return of log_4 values. A curvilinear power trend gave higher level of significance than linear (Figure 4-1).



Figure 4-1: Average National Return of Log_4 from 1990 to 2011 as a Function of Forestry and Logging GVA%

Substantial structural changes were noted in several nations' forestry sectors over the 22 year study period. In addition to average values, temporal trends were therefore investigated. Relevant data for the forestry and logging subsector are presented in Figure 4-2, and several trends were apparent. In many developing nations, namely, China, Malaysia and Indonesia, the proportional forestry and logging GVA decreased substantially and there was an associated increase in return of log_4. This trend has been especially apparent in China. In 1990, China's proportional forestry and logging GVA was 68.2% and its return of log_4 was 58.9 US\$/m³. These values had changed as its manufacturing subsector expanded over time. By 2011, its proportional forestry and logging GVA was reduced to 25.9% and the return of log_4 was increased to 359 US\$/m³ (Figure 4-2).



Figure 4-2: National Return of Log_4 Trends as a Function of Forestry and Logging GVA%, 1990-2011

Several developed nations that have substantial primary forest product industries focused on manufacturing commodity products (e.g. New Zealand, Austria, Canada and the USA) exhibited less clear temporal trends. For example, in 1990, New Zealand's proportional forestry and logging GVA was 26.6% and its return of log_4 was 232 US\$/m³. In 2011, the respective values were 39.3% and 223 US\$/m³. In contrast, nations with a proportional forestry and logging GVA of less than 20% were also able to substantially increase their return of log_4 values over the study period. For instance, Japan decreased its proportional forestry and logging GVA from 11.9% in 1990 to its lowest 2.80% in 2003, and its return of log_4 varied from 641 in 1996 to the highest 742 US\$/m³ in 2009. Japan had the lowest proportional forestry and logging GVA of any nation studied and this was indicative of the small national forestry and logging and the extensive raw and intermediate forest product imports into that country (Figure 4-2).

In contrast to the negative curvilinear relationship between return of log_4 and the proportional forestry and logging GVA, both wood products manufacturing and pulp and paper manufacturing displayed increasing linear trends as a proportion of forestry sector GVA although neither trend was statistically significant (Figures 4-3 and 4-5). These relationships indicated that a proportionately large primary manufacturing subsector was an important element in achieving a high value added per unit net input.

Of the countries studied, Australia had the largest average proportional wood products manufacturing at 50.0% and China had the smallest at 17.4%. There was a large scatter in the data with several nations displaying substantial differences in return of log_4 at the same proportional wood products manufacturing GVA values. For example, France and Indonesia both had a proportional wood products manufacturing GVA of approximately 30% with France achieving an average return of log_4 of 424 US\$/m³ and Indonesia 180 US\$/m³. Similarly, Japan and Brazil both had proportional wood products manufacturing GVAs of approximately 26% and their return of logs_4 were 673 US\$/m³ and 219 US\$/m³, respectively (Figure 4-3). Clearly other variables, such as the specific products produced by the wood products manufacturing subsector, labour and raw material costs and the markets within which they are sold and their proportional forestry and logging and pulp and paper manufacturing subsector GVAs are also important in determining the value added per unit input.



Figure 4-3: Average National Return of Log_4 from 1990 to 2006 as a Function of Wood Products Manufacturing GVA%

Temporal trends in national return of log_4 as a function of proportional wood products manufacturing GVA from 1990 to 2011 are presented in Figure 4-4. Excluding part of Japan's extraordinary data, data in all countries fell into the light blue field (Figure 4-4).

The figure revealed that a larger wood products manufacturing subsector, as a proportion of the total forestry sector, the greater the return of log_4 achieved. Several developing nations (e.g. China, Malaysia and Brazil) substantially increased their proportional wood products manufacturing GVA over the study period. However, their value added per input remained consistently less than most of the developed nations studied.

China exhibited the most substantial percentage increase in wood products manufacturing GVA% despite the wood products manufacturing subsector in China being less important than in any other country studied in terms of value adding. Despite the relatively large absolute size, China's wood products manufacturing GVA was consistently less than 33% of its national forestry sector GVA (Figure 4-4). In 1990, China's proportional wood products manufacturing GVA was 6.52% and its return of log_4 was 58.9 US\$/m³. In 2011, the respective values were 32.7% and 359 US\$/m³. In contrast, Malaysia's proportional wood products manufacturing GVA was 20.0% in 1990 and its return of log_4 was 65.9 US\$/m³, by 2011, these values had increased to 28.3% and 186 US\$/m³ (Figure 4-4). These data are consistent with the conclusions delineated in Chapter 3 with a generally positive relationship between the manufacturing GVA share and the return of log_4 achieved by a nation.

In contrast, temporal trends were less clear for most developed nations and the positive correlation between return of log_4 and wood products manufacturing GVA% was statistically weak with an R² less than 30% (Figure 4-4). One relatively consistent trend was that the wood products manufacturing GVA% decreased with time in most of the developed nations with Japan and Germany being leading examples of this observation.

Australia and Austria had the greatest wood products manufacturing GVA% of all the nations studied but their wood products manufacturing GVA% increased relatively little or showed negative growth over the study period. For example, Austria's proportional wood products manufacturing GVA increased by 6.05% but Australia had a decrease of almost 0.10% in its proportional wood products manufacturing GVA (Figure 4-4).

The variation of wood products manufacturing GVA% in developed countries was relatively less than for developing nations. This may be due to the forestry sector value structure in developed countries being relatively stable and the manufacturing technologies more fully developed leaving less room for improvement compared developing nations which might have been experiencing substantial industrial structural and technological changes.



Figure 4-4: National Return of Log_4 Trends as a Function of Wood Products Manufacturing GVA%, 1990-2006

Although a relatively high data scatter was appeared, the relationship of return of \log_4 to the proportional pulp and paper manufacturing GVA was broadly linear (Figure 4-5). Despite the low R² of 29%, the ascending trend in return of \log_4 as function of proportional pulp and paper manufacturing GVA followed a similar pattern as proportional wood products manufacturing GVA (Figure 4-5). This broad trend indicated that a proportionately larger pulp and paper manufacturing subsector had a weak influence on increasing the value added per unit net input but to a lesser extent than an equivalent increase in the size of the wood products manufacturing sector. However, this correlation is not statistically significant as well.

The proportional pulp and paper manufacturing GVA in fifteen countries ranged from 11.7 % to 67.9% with Malaysia having the lowest value and Japan having the highest (Figure 4-3). As observed from the pulp and paper manufacturing results, there was a large scatter in the data with several nations displaying substantial differences in return of log_4 at similar proportional pulp and paper manufacturing GVA values. For example, Finland, Germany, Brazil, Chile, France and Sweden had a proportional pulp and paper manufacturing values of approximately 50%. Germany and France achieved an average return of log_4 of

575 and 460 US $/m^3$, respectively, while the comparable value in the other four countries was less than one third of that Germany.



Figure 4-5: Average National Return of Log_4 from 1990 to 2011 as a Function of Pulp and Paper Manufacturing GVA%

The distribution of countries' return of log_4 correlated with their pulp and paper manufacturing GVA% from 1990 to 2011 is presented in Figure 4-6. Data in all countries enclosed in a light blue envelope to show the broad increasing trend with the increasing proportional pulp and paper manufacturing GVA size (Figure 4-6).

This figure revealed that a larger pulp and paper manufacturing subsector, as a proportion of the total forestry sector, the greater the return of log_4 achieved. Most developed countries obtained high proportional pulp and paper manufacturing GVAs and these were frequently associated with low forestry and logging subsector proportional contributions. All the developing countries studied, with the exception of Brazil (Bracelpa, 2014; Kilpp, 2012), demonstrated a lower proportional pulp and paper manufacturing GVA than all the developed nations studied (Figure 4-6).

An analysis of temporal trends showed that Indonesia, China and Malaysia significantly increased their proportional pulp and paper manufacturing GVA over the study period by 33.4%, 16.0% and 12.9%, respectively. These trends were also associated with an increase in economic contributions per unit input. Indonesia achieved the most notable increase with its proportional pulp and paper manufacturing GVA approximately tripling from 13.7% in 1990 to 47.1% in 2011 and its return of log_4 increasing by one third

(Figure 4-6). However, despite these substantial increases in proportional pulp and paper manufacturing GVA, the value added per unit input obtained by these developing nations was still less than those for most of the developed nations studied (Figure 4-6).



Figure 4-6: National Return of Log_4 Trends as a Function of Pulp and Paper Manufacturing GVA%, 1990-2011

The temporal trends in developed nations were less clear than most of the developing countries. Seven developed countries decreased their pulp and paper manufacturing GVA% substantially over the study period while proportional pulp and paper manufacturing GVA increases were observed in the following four developed countries: Japan, Germany, Finland and Austria. The growth rates of the subsector were relatively low compared to those of the developing countries. Japan had the highest proportional pulp and paper manufacturing GVA share of its pulp and paper manufacturing subsector increased from 60.7% in 1990 to 71.9% in 2011 and it averaged at 67.9% over the study period (Figure 4-6).

In summary, most developing nations increased the proportional GVA of their pulp and paper manufacturing subsector relatively rapidly and achieved improved economic benefits from their forest products industries per unit input. In contrast, more than half of the developed nations studied decreased the proportional GVA of their pulp and paper manufacturing subsectors. These observations are consistent with

published trends on the pulp and paper sectors in many developed countries facing challenging market conditions and numerous mills being closed. In contrast, new pulp and paper mills are being opened in developing nations to satisfy increased demand and to respond to changes in the global pulp and paper supply network (Hylander, 2009).

4.3.1.2 Comparisons of Forestry Sector Value Structure in Fifteen Countries

Many factors, including selling prices, market conditions, material costs may influence the value added produced by a nation's forest products industry. However, this analysis has shown that the forestry sector's value structure, expressed by the relative contributions of the three subsectors to GVA, is one important indicator with which to evaluate economic outcomes. As discussed in Section 4.3.1.1, although there was substantial scatter in the data and the correlation for wood products manufacturing GVA% and pulp and paper manufacturing GVA% to return of log_4 were not statistically significant, the value added per unit of material input decreased with an increasing proportional forestry and logging GVA and increased with larger proportional manufacturing GVA

In order to further assess these effects, the fifteen countries studied were divided into high, medium and low return of log_4 groups with high return of log_4 values defined as being greater than 518 US\$/m³, and low return of log_4 values considered to be less than 219 US\$/m³. Any value greater than 219 US\$/m³ and smaller than 518 US\$/m³ was categorized as medium. The results are summarized in Table 4-1.

Using this categorization, Japan, Australia and Germany were identified as high return of log_4 countries. In each of these nations, the manufacturing GVA was at least 85% of the forestry sector GVA, and the forestry and logging GVA% was less than or equal to 15%. Eight nations including Malaysia, China and Canada were categorized as low return of log_4 countries. In each of these nations, the forestry and logging GVA% was greater than or equal to 25%, and the manufacturing GVA was less than or equal to 75% of the forestry sector GVA. The remaining four countries were categorized as medium return of log_4 nations. In these cases, the forestry and logging GVA ranged between 15% and 50% of the forestry sector GVA and manufacturing GVA% varied from 75% to 85%.

Return of Log_4	a	Return of Log_4	FL GVA	MS GVA	GVA% Ranges by
Group	Countries	(US\$/m ³ GRWE)	(%)	(%)	Country Group
High Return of	Japan	673	7%	93%	ELCMA0/ < 150/
	Australia	647	11%	89%	FL GVA% <= 15%,
Log_4	Germany	518	12%	88%	MS GVA%>=85%
	France	424	23%	77%	
Medium Return of Log_4	Chile	375	18%	82%	25%>FL GVA%>15%,
	Austria	266	22%	78%	75%>MS GVA%<85%
	USA	262	16%	84%	
	Brazil	219	26%	74%	
Low Return of Log_4	New Zealand	219	32%	68%	
	Indonesia	180	42%	58%	
	Canada	177	26%	74%	FL GVA%>=25%,
	China	168	48%	52%	MS GVA%<=75%
	Sweden	164	33%	67%	
	Finland	161	32%	68%	
	Malaysia	139	61%	39%	

 Table 4-1: Forestry Sector Value Structure in Fifteen Countries Studied by Group, Average

 1990-2011

In addition, the temporal trend analyses of the three subsectors GVA% in relation to return of log_4 also revealed that developed countries have generally been increasing the proportional GVA of their manufacturing subsectors while simultaneously decreasing their proportional forestry and logging GVAs more quickly than the developing countries. Supported by the literature findings on the trend toward more value added production in the Canadian forest industry (Lantz, 2004, 2001), a simple forestry sector maturation pattern is proposed below to characterize and explain the different forestry sector trends observed in developing and developed nations. Historically, as forests were initially exploited and the manufacturing subsector was undeveloped, the forestry and logging subsector would have dominated the forestry subsector. With time, it may be envisaged that the manufacturing subsector developed to meet society's needs for forest products and as more valuable products were manufactured the value achieved per unit of input increased. Eventually, as these developments proceeded, and the more developed economies exploited their own forest resources, the manufacturing subsector may be expected to eventually become larger than the forest and logging subsector. In time, if forests became over-exploited or societal values changed in the more advanced economies, the values of forest conservation may eventually exceed those of

exploitation. Consequently, imported industrial roundwood and intermediate products, facilitated by increased globalization, may become a significant component of the national material flow of forest products.

Using this framework, the data in Figures 4-1 to 4-6 show where different nations lie on the curves depending upon the state of maturity of their forestry sectors. The developed nations tend to possess more mature forestry sectors and their national characteristics (e.g. abundance of forest resources, importer or exporter, market conditions) determine where they lie on the curve. These countries also tend to be changing less quickly than the developing nations because their manufacturing subsectors are more fully developed and there are reduced opportunities for further growth. Many of the less developed nations (Malaysia, China and Indonesia) are maturing rapidly reflected in the changing characteristics of the forestry sector as they grow their proportional manufacturing GVAs and shrink their proportional forestry and logging GVAs.

In conclusion, the distribution of GVA between the forestry and logging and the manufacturing subsectors of a nation's forest products industry influences its net economic benefit per unit of input. Increasing the value share of the manufacturing subsector to the forestry subsector is an effective way of increasing the value added per unit input. Increasing the proportional GVA of the forestry and logging subsector within a country's forestry subsector resulted in a reduced return of log_4, whereas, increasing the proportional GVA of the wood products manufacturing and pulp and paper manufacturing subsectors raised the return of log_4 value. Countries with high return of log_4 (i.e. >518 US\$/m³) had forestry and logging subsectors that accounted for less than or equal to 15% of the total forestry sector GVA, whereas, nations with low return of log_4 (i.e. <219 US\$/m³) had forestry and logging proportions that were more than 25% of that country's forestry sector GVA. Canada is categorized as a low return of log_4 nation (Table 4-2).

In the following section, a detailed analysis of the forestry value chains for the USA and Canada is undertaken using the methodology applied previously in this Chapter. The purpose of this section is to gain further insights into how the differences of value added per unit of input have been impacted by the industry value structure between the two neighbouring nations and to assess how Canada may improve its value creation per unit of input.

4.3.2 Comparison of the Forestry Sector Gross Value Added between Canada and the USA

4.3.2.1 Introduction

Canada and the USA have abundant forest resources and they both possess substantial primary forest products industries. In Table 4-1, the USA was categorized as a medium return of log_4 nation and it generated substantially more net GVA per unit of net material input than Canada which was one of the low return of log_4 nations (Table 4-2). Further analysis showed that Canada and the USA's primary forest

products industries have historically had different value structures with Canada tending to have a proportionally larger forestry and logging subsector GVA and a proportionally smaller manufacturing subsector GVA to those of the USA (Figure 4-6 and Table 4-2). On this basis, Canada may be expected to achieve a lower level of value creation per unit input return of log_4 and this section undertakes a detailed analysis of the influence that the primary forestry sector value chain has on subsector GVAs in the USA and Canada.

4.3.2.2 Data Comparisons

Over the study period the USA had a larger primary forestry sector than Canada with the net total material input (AII4) averaging 2.78 times that of Canada (Table 4-2). In addition, the USA created substantially more total value added averaging 97.2 billion US\$, which was 4.03 times Canada's value of 24.1 billion US\$. Therefore, the USA created an average of 1.48 times of value per unit of input (return of log_4) compared to Canada (Table 4-2).

			and I	Tverage 1770-2	2011			
Country	Year	AVA4	AII4	Return of	FL	MS	WPM	PM
				Log_4	GVA%	GVA%	GVA%	GVA%
		(Billion 2011	(Mm ³	(2011 US\$/m ³	(%)	(%)	(%)	(%)
		US\$)	GRWE)	GRWE)				
Canada	1990	20.0	124	160	24.28%	75.7%	25.2%	50.5%
	2011	14.0	107	131	29.10%	70.9%	33.8%	37.1%
	Average 1990-2011	24.1	134	177	25.54%	74.5%	34.5%	39.9%
USA	1990	95.9	395	243	13.12%	86.9%	27.8%	59.0%
	2011	75.4	281	269	21.18%	78.8%	23.1%	55.7%
	Average 1990-2011	97.2	372	262	16.11%	83.9%	27.8%	56.1%
Ratio of USA/Canada	Average 1990-2011	4.03	2.78	1.48	0.63	1.13	0.81	1.40

 Table 4-2: Forestry Sector Value Structure Comparisons between Canada and the USA, 1990, 2011

 and Average 1990-2011

A comparative analysis revealed several differences in the structure of the value chains. Based on the average proportional GVA data, the USA had a smaller forestry and logging subsector and a larger manufacturing subsector as the proportion of the total forestry sector GVA than Canada (Table 4-2). Using the assessment methodology described in Section 4.3.1.1, this observation is consistent with the USA having a higher return of log_4 than Canada, especially, as the USA's proportional forestry and logging

GVA was located close to a region of the curve where a decrease in proportional forestry and logging GVA resulted in a significant increase in return of log_4 (Figure 4-6).

The use of average data conceals several important temporal trends that occurred over the study period and the temporal data by subsector are presented in Figures 4-2, 4-4 and 4-6. The proportionate GVA of Canada's forestry and logging subsector increased by approximately 20% (Figure 4-8), whereas, its manufacturing GVA% declined by 6.37% (Table 4-2) and therefore, the return of log_4 decreased by 18.1% from 1990 to 2011. In contrast, the proportionate size of the USA's forestry and logging subsector GVA was more than doubled (Figure 4-7) while its manufacturing subsector decreased by 10%. Therefore, its return of log_4 only reduced 10.5% (Table 4-2). These trends in both North American countries are also broadly consistent with the relationship between the proportional forestry and logging GVA, manufacturing GVA and return of log_4 presented in Section 4.3.1.1.

This assessment masks substantial changes in the individual manufacturing subsectors. Although manufacturing GVA in both countries showed decreases to some extent from 1990 to 2011, within manufacturing subsector, the proportionate size of the wood products manufacturing GVA and pulp and paper manufacturing subsector GVA in Canada and the USA presented different trends (Figures 4-8 and 4-9). Two manufacturing subsectors in Canada tended to be more balanced after variations over the study period. The wood products manufacturing subsector in Canada exhibited some growth over the study period, increasing from 25.2% to 33.8% of the total forestry sector GVA. In contrast, a decreasing trend occurred in the USA with its wood products manufacturing subsectors in both the USA and Canada decreased proportionately over the study period. In the USA, it reduced from 59.0% to 55.7% of the forestry sector GVA, while in Canada this decrease was much more substantial, from 50.5% to 37.1% (Table 4-2 and Figure 4-9).

The more substantial reduction of pulp and paper production in Canada may contribute to a lower return of log_4 compared with the USA. Conceptually, the larger manufacturing subsector, the greater unit input value added that could be achieved and therefore Canada could potentially examine means of increasing the size of its pulp and paper industry. However, over the last twenty years in North America, many paper grades have displayed declining consumption trends, in large part due to the substitution of printing and writing papers by electronic products (FAO, 2015). Hence, increasing the size of the Canadian pulp and paper manufacturing subsector would not be feasible if the market was focused on North America.



Figure 4-7: Return of Log_4 as a Function of Forestry and Logging GVA% in the USA and Canada, 1990-2011



Figure 4-8: Return of Log_4 as a Function of Wood Products Manufacturing GVA% in the USA and Canada, 1990-2011



Figure 4-9: Return of Log_4 as a Function of Pulp and Paper Manufacturing GVA% in the USA and Canada, 1990-2011

The same trends were also reflected in the absolute subsector GVA (Figures 4-10 and 4-11). In 1990, the pulp and paper manufacturing GVA was twice that of the wood products manufacturing GVA in both countries. By 2011, pulp and paper manufacturing GVA has decreased to be only 10% greater than the wood products manufacturing GVA in Canada. In contrast, in the USA, the pulp and paper manufacturing GVA was 2.41 times of the wood products manufacturing GVA at the end of the study period (Figures 4-10 and 4-11).

These observations match market conditions in North America. Over the study period, the USA housing market, which drives demand for solid wood products in North America, was very strong with annual starts of single and multi-family houses increasing from 1.01 million to 2.07 million from 1991 to 2005 (Sianchuck et al., 2012). It is not surprising that the wood products manufacturing subsectors in Canada, the main wood products supplier to the USA, expanded to meet this increased market demand, with a disproportionate amount of the growth occurring in Canada's wood products manufacturing subsector.

In contrast, as discussed previously, the consumption of printing and writing paper has decreased substantially over the past years in North America, largely due to increased use of digital media despite expanded demand on packaging paper and sustained hygiene paper uses (FAO, 2015). Pulp and paper manufacturing GVA in Canada was almost halved from 13.3 billion US\$ in 1900 to 7.35 billion US\$ in 2011 (Figure 4-10). Although the USA's pulp and paper manufacturing subsector is seven times of that of Canada,

its pulp and paper manufacturing GVA has also decreased by 18.2% from 1990 to 2011 (Figure 4-11). Pulp and paper manufacturing has been decreased dramatically in Canada and the USA as the demand for some products has reduced. Also, in general, Canada is a relatively high cost pulp and paper manufacturing nation, particularly in comparison with other emerging large paper producers associated with low fibre and manufacturing costs, such as Brazil (Bracelpa, 2014; Kilpp, 2012). Additionally, structural changes observed in the global pulp and paper industry favoured an increased trade in wood pulp rather than paper (Hylander, 2009). These trends may provide an opportunity for Canada to increasingly focus on market pulp production and to diversify its international markets rather than having its traditional focus on the USA as its major market. However, major infrastructural and cost challenges remain within the Canadian pulp and paper sector that constrain its ability to meet these strategic challenges.

These findings of the differences between forest products industries between the USA and Canada are broadly consistent with the hypothesis discussed in Section 4.3.1.1 that variations in value structure may influence the economic outcomes per unit of material input. It is meaningful to investigate how Canada and its major forestry provinces can take some actions to improve the economic benefits from the forestry sector. British Columbia is one of the most important Canadian provinces from a forest products manufacturing perspective. It is therefore of interest to analyze its value chain using MFA and identify how Canada could capture greater economic benefits from each unit of input at a provincial level. These topics are addressed in the subsequent chapters.



Figure 4-10: Value Structure in Canada's Forestry Sector, 1990-2011

Note: The line for FS GVA refers to the right hand axis.





Note: The line for FS GVA refers to the right hand axis.

4.4 Conclusions

An analysis of international trends in return of log_4 as a functions of the proportional GVA in three forestry subsectors revealed that value structure (denoted by the proportion of these three forestry subsector GVAs) influenced the national economic benefits gained from unit input. It was concluded that nations with smaller proportional forestry and logging GVAs (lower end of the value chain), and higher proportional manufacturing GVAs (higher end of the value chain) achieved higher economic benefits per unit of input.

An assessment of how economic benefits per unit of input were influenced by the proportional subsector GVA showed that developing and developed countries studied followed different patterns. Developing countries with low return of log_4 generally had a large proportional forestry and logging GVA and a low proportional manufacturing GVA. In contrast, developed countries with a high return of log_4 generally had a low proportional manufacturing GVA and a low proportional forestry and logging GVA.

Forestry sector maturation pattern was suggested based on the study of relationships between return of log_4 and forestry sector value structure. The pattern indicated that all nations studied with commercially oriented forestry sector tend to change from an initially dominant forestry and logging subsector to a higher value framework in which the manufacturing subsector tends to dominate. Most developing countries were changing rapidly as they grew their proportional manufacturing GVA and shrank their proportional forestry and logging GVA. In contrast, most developed nations tended to be evolving less quickly because their manufacturing subsector were often more fully developed.

National return of log_4 comparisons showed that Canada and the USA's forestry sectors have historically had different proportionately sized value structures with Canada tending to have 9.13% larger forestry and logging and consequently, 9.13% smaller manufacturing subsector GVAs than those of the USA.

In summary, Canadian forest products industry's economic outcomes per unit of input from the aspect of value structure could be improved from many directions. Amongst all, according to the forestry sector maturation pattern proposed in Section 4.3.1.2, as the industry "maturation" proceeded, the dominant role of the forestry and logging subsector would be replaced by the manufacturing subsector with time as the more valuable products were manufactured, the greater value achieved per unit of input can be increased. Therefore, instead of heavily relying on the low value added structural lumber commodity and logs production and exports, it would be recommended to produce more valuable solid wood products to increase the price competitiveness and drive up value added per unit of input.

CHAPTER 5 MATERIAL FLOW MODELING OF BRITISH COLUMBIA'S FOREST PRODUCTS INDUSTRY

5.1 Introduction

British Columbia (BC) occupies about 10% of Canada's total land area and it has historically been one of Canada's most important forest provinces (FII, 2008; MoFR, 1995; 2008a). From 1990 to 2009, it accounted for between 36.1% to 46.4% of Canada's industrial roundwood harvest and its average forestry sector GVA and employment accounted for approximately one third and one quarter of the national values, respectively (CanSim, 2011; Natural Resources Canada, 2011).

Chapter 4 demonstrated that the structure of the forestry sector value chain influenced the total GVA created from each unit of net material input. Generally, increasing the proportion of GVA within the manufacturing subsector at the expense of the forestry and logging subsector increases a nation's per unit value added.

Material flow analysis (MFA) which quantifies all elements along a value chain is an important way of evaluating and interpreting the historical changes in the forestry sector's value structures (Section 2.2.2). This chapter builds on the previous sections of this dissertation by undertaking a detailed material flow analysis of the BC forestry sector. Wood fibre flows through BC's forestry value chain to produce intermediate and final forest products and these flows vary in response to fluctuating market demands and manufacturing capacities. Over the past decade, BC's forest products industry has confronted several serious challenges. A widespread mountain pine beetle outbreak (Goldring, 2008; Natural Resources Canada, 2006), the softwood lumber dispute with the USA, a fluctuating \$C:\$US exchange rate and the downturn in the USA housing market have dramatically impacted the sector and affected how BC's forestry value chain functioned (Alteyrac et al., 2008b; Bazett, 2000; Sianchuk et al., 208, 2012; Sierra Club Canada, 2006). Therefore, it is useful to analyze the variations in wood fibre flows in response to changing resource availability, manufacturing capacities and market demands and to estimate the utilization of provincial industrial roundwood resources in the primary forestry value chain. Such an analysis is a prerequisite to assessing approaches that may be used to improve the sector's socio-economic outcomes.

Sawmills in BC represent the primary fractionation phase of wood processing. They consume logs and produce lumber as the major commercial product. A BC sawmill typically converts about 45-55% of roundwood input by volume into lumber. It also produces a range of wood by-products including bark, sawdust, chips, shavings and trim ends that account for about 55-45% of the roundwood input volume (MoFR, 2008b). The by-products produced by sawmills are valuable resources that serve as an extra source of income. In BC, the flow of wood by-products from sawmills to other manufacturing plants, such as pulp

and paper mills is important as it enables efficient material utilization and links the different components of the primary forest products industry. Consequently, a complex material flow web exists within the sector and MFA is a useful tool for analyzing these flows. In addition, MFA may be used to evaluate how efficiently the provincial value chain is functioning in order to assist government and industry to achieve their economic and social objectives. The objectives of this chapter were to: 1) develop annual material flow models for BC's primary forestry sector, and to 2) analyze historical performances and changes in material flow through this sector on an input basis.

5.2 Data Sources and Methodologies

5.2.1 Data Sources

The data used in the material flow model development were obtained from two sources. Most of the data used were from a confidential database developed from annual surveys carried out by the BC Ministry of Forests, Lands and Natural Resources Operations (MFLNRO). This report provided information on all the primary forest product mills in BC from 1991 to 2007. The data were provided by mill types using the following categories: lumber mills, chip mills, log home mills, pellet mills, pole and post mills, pulp and paper mills, shake and shingles mills, veneer mills, plywood mills, other panel mills and other primary processing mills. Re-manufacturing plants were not included in the report. Pulp and paper mills, panel plants and pellet mills were included even though some did not have primary log processing capabilities. All mills were listed with their names, locations, roundwood input volumes, production capacities, lumber production, chip outputs and the local forests that supplied the logs. The original data were in a wide variety of units. For example, industrial roundwood volume input, production capacity, lumber production and chips output were given in thousand cubic metres (green), million board feet (Mbfm), and thousand bone dry units (Bdu), respectively. Therefore, a common input unit: m³ green solid wood equivalent (m³ GSWE) was required to quantify all the elements along the value chain and enable the comparisons amongst elements, sub-levels, subsectors and flows.

Additionally, all volume data provided by MFLNRO were underbark. Recycled pulp fibre was excluded in its database as it was not considered as a primary forest product according to MFLNRO. Input data listed by MFLNRO accounted the net fibre input volume for each individual mill in BC during the year of study. This implied that the inventories, imports and exports were already accounted.

The second major data source was the series of "Major primary timber processing facilities in British Columbia" reports (MoFR, 2007a, 2006, 2009b,). These are publicly available reports published annually by the MFLNRO. However, these published reports only provided estimations of annual capacities for all

mills in BC. Validation of the data quality was undertaken by comparing values with other resources related to this research (John, 2006; Nielson et al., 1985, StatsCan, 2009; Suchland, 2004).

5.2.2 Methodologies

5.2.2.1 Research Variables

Wood fibre yield and material utilization efficiency were two important variables used to analyze the temporal changes of material flows in BC's primary forest products industry. In this study, the wood fibre yield was defined as the ratio of the equivalent green volume of a product (in m³ GSWE) to the equivalent volume of green roundwood utilized to manufacture this product (in m³ GRWE) as shown in Equation 5-1.

Wood Yield (m³ GSWE/m³ GRWE) = Product Output (m³ GSWE) / Industrial Roundwood Input (m³ GRWE) Equation 5-1

The difference between the two volumetric units green roundwood equivalent (GRWE) and green solid wood equivalent (GSWE) is of importance to this study. To reiterate, the unit m³ GRWE quantifies the underbark volume of roundwood required to manufacture a given product and it incorporates both the final product volume and the volume of all the by-products or material losses created by the manufacturing process. In contrast, the unit m³ GSWE quantifies only the volume of the final product at the same density and moisture content as the original wood used to manufacture the product (Section 3.2.2.1). The conversion scheme between GRWE and GSWE are provided in Appendix E.

Material utilization efficiency was defined in this study as the ratio (%) of the total forest products output over the total wood fibre input using m^3 GSWE as the unit for both outputs and inputs (Equation 5-2).

Material Utilization Efficiency (%) = Total Forest Products Output (m³ GSWE) / Total Wood Fibre Input (m³ GSWE) Equation 5-2

Final outputs, which consisted of the final forest products from both the wood products manufacturing and the pulp and paper manufacturing subsectors, were measured by volume of green solid wood fibre contained in the final forest products. The total input was the net green industrial roundwood entering the manufacturing subsector. In this study, material utilization efficiency of BC's forest product industry was equivalent with the weighted average yield of all final forest products excluding the chip mills, which were not included because they only produced chips as an intermediate product.

Material flows were balanced by using wood fibre input data and verified by wood products output data. A range of conversion factors was used in the material balancing process. To facilitate the material flow balancing, material flow in BC's forest products industry was broken down into four sub-levels categorized

by MFLNRO, namely, primary sawmilling (PS), structural panels (SP), pulp and paper (PP), and other mills (OM). Models were developed for these four levels prior to being balanced and integrated into a provincial level model. Primary sawmilling, structural panels and other mill models were the three sub-levels of the wood products manufacturing subsector, whereas, the pulp and paper sub-level model represented the pulp and paper manufacturing subsector.

5.2.2.2 Material Flow Boundary

A complete forest products life cycle is presented in the black rectangular box in Figure 5-1. However, the boundary conditions for this study were defined by the rounded rectangular frame outlined in dashed blue (Figure 5-1) and ranged from the point at which industrial roundwood was extracted from the forests to the point at which the final products left the primary mills. Pre-consumer recycling and reuse flows within the manufacturing subsector were incorporated into the material flow model. In contrast, secondary manufacturing and recycling of post-consumer wood and paper wastes were not included.



Figure 5-1: Material Flow Analysis Boundary Conditions for BC's Forest Products Industry

5.2.2.3 Time Scale

Material flow models of BC's forestry sector material flows were completed for the years 1991, 1999, 2005, 2006 and 2007.

5.2.2.4 Conversion Factors and Input/Output Factors

As mentioned in Section 5.2.1, conversion factors that transformed final outputs in various units to one common input unit were used to quantify the wood fibre flowing from forest harvest to final forest products manufacturing.

As discussed in Section 2.3.1, both green volume and oven dry mass could be used to quantify the fibre input on a uniform basis. The fact that more roundwood flowed through the wood products manufacturing value chain than the pulp and paper manufacturing subsector in BC and a greater proportion of products were reported in volumetric units than mass units also inferred that volumetric units should be used. In this study, the unit m³ GSWE was chosen for input and output calculations. All original units were converted to cubic metres on a GSWE basis to enable the volume and mass data to be comparable within the system.

In material flows, the final forest product's original units were converted to the equivalent green volume of wood fibre by applying the conversion factors after taking account of the wood fibre yields and other factors affecting the final products volumes, including MC, pressing and densification processes and other non-wood content from various manufacturing processes. In this study, the industrial roundwood inputs have units of either m³ GRWE or m³ GSWE and can be used interchangeably, and industrial roundwood input data provided in all MFLNRO reports were underbark volumes.

5.2.2.5 Material Balance at the Primary Sawmilling Sub-Level

The primary sawmilling sub-level consisted of all BC lumber mills. The approaches used to create the material balance and develop conversion factors are discussed below.

• Material Balance

The schematic material flow diagram for the primary sawmilling sub-level is shown in Figure 5-2. The sawmill within the box represents all the sawmills in BC. The aggregated annual average input and output data from each lumber mill in BC were used to develop the general flow of wood fibre for this sub-level. Green underbark industrial roundwood (whitewood) was used as the raw material input. Outputs were lumber, trim ends and a range of by-products, including chips, sawdust and shavings and trim ends. In this study, chips, sawdust and shavings were considered to be wood by-products, and trim ends were considered

to be a final product. This definition is consistent with the BC MFLNRO categorization. Volumes of by-products were found by balance calculations using the input and output data.



Figure 5-2: Material Flow Schematic for the Primary Sawmilling Sub-Level

Five models for this sub-level representing the years of 1991, 1999, 2005, 2006 and 2007, were developed and compared. Conversion factors used for the PS sub-level are presented below.

- Conversion Factors Development
- a. Lumber Conversion Factors

In North America, lumber products are most frequently quantified using board feet. Measurements are made when the lumber is rough and green to get the nominal volumes. Actual volume measurements may also be undertaken after lumber is dried and planed. The volume of lumber becomes smaller due to the shrinkage and material loss after the drying and planing processes. Therefore, the actual volume will be smaller than the nominal volume. For the primary sawmilling sub-level, all lumber volumes given in the MFLNRO reports in nominal board feet were converted into actual volumes with an average MC of 19% and planed (Nielson et al., 1985).

Conversion factors accounting shrinkage were required to convert Mbfm of lumber to m³ GSWE lumber. A shrinkage factor was used to adjust the actual volumes (19% MC) into green volumes. The fibre saturation point (FSP) averages about 30% MC and it is considered to be the moisture content below which the physical and mechanical properties of wood begin to change as a function of moisture content. The volume of wood is relatively stable when the MC is greater than 30% (Simpson and TenWolde, 1993; Suchland, 2004). This important characteristic of wood and the ability to account for shrinkage enabled the study to use one common volumetric unit to describe all the products in the material flow system.

The shrinkage factors vary with wood species. Average shrinkage factors were correlated to the proportion of species used by BC's forest products industry. Two main assumptions were made in the primary sawmilling sub-level material flow balancing. Firstly, the MC of the roundwood input was assumed to be always above the fibre saturation point (30% MC) and thereby considered to be green (Simpson and TenWolde, 1993). Secondly, the average final MC for lumber products was assumed to be 19% (Nielson et al., 1985).

A list of the main species used by BC forest products industry, the proportion of each wood species and the shrinkage adjustment factors from green to dry are presented in Table 5-1.

Species	Volumetric Shrinkage (%, Green to Oven Dry)	Average Estimated Proportion of Species Input (%)
Western Hemlock	12.4	6%
Balsam Fir	11.2	6%
Western Cedar	6.8	8%
Douglas-Fir	12.4	8%
Larch	14.0	2%
Amabilis Fir (Pacific Silver)	13.0	15%
White Spruce (Black)	12.7	16%
Lodgepole Pine	11.1	35%
Other (11 Species Average)	10.7	4%
	Volumetric Shrinkage	Proportion of species input in BC
	(%, From 19% MC to green)	industry (%)
Average Shrinkage	4.23	100%

Table 5-1: Estimated Average Volumetric Shrinkage for Wood Species in BC

The volumetric shrinkage from green to 19% MC could be calculated as the volume changes were
considered linear from oven dry (0% MC) volume to green (30% MC) volume. The average shrinkage from
green to 19% MC was 4.23% (Table 5-1). Since information on the annual changes in wood consumption by
species in BC was not available, this shrinkage correction factor was used for each material flow model at
the primary sawmilling sub-level.

(Alteyrac et al., 2008c; Suchland, 2004)

The m³ GSWE calculated from the original output volume obtained from MFLNRO data was therefore adjusted for shrinkage and this enabled the conversion of the actual volume at 19% MC to green wood fibre volume. The final lumber conversion factors after the shrinkage adjustment from oven dry to 19% MC are presented in Table 5-2.

Year	m ³ SWE dry (19%	Shrinkage Correction	m3 CSWE/Mhfm	
	MC)/Mbfm	(19% MC to Green)		
1991	1.72 (Estimation)	1.042	1.792	
1999	1.72 (Estimation)	1.042	1.792	
2005	1.752	1.042	1.826	
2006	1.752	1.042	1.826	
2007	1.680	1.042	1.740	

Table 5-2: Final Lumber Conversion Factors for BC

In 2005, 2006 and 2007, the MFLNRO reported actual conversion factors for m³ dry SWE/Mbfm (Table 5-2). Data were not available for 1991 and 1997, so a value of 1.72 m³ dry SWE/Mbfm was assumed for each year, based on the size of lumber products manufactured (Nielson et al., 1985).

b. By-Product Conversion Factors

In order to complete the material flow balance, the wood by-products output must be known. The quantity of by-products is most frequently given in Bdu which is equivalent to 2400 pounds of oven dried wood fibre (Nielson et al., 1985). The volume of roundwood (m³GSWE) required to obtain a Bdu of chips varies with the density of the wood species.

The conversion factor (m³ GSWE/wood by-products output unit (Bdu)) depends on the type of wood by-products and the fibre compaction which is affected by the loading method (e.g. orientation of chips, impact, and layering), particle size distribution, wood species, and MC. Basic densities of wood species used in BC are presented in Table 5-3 (Nielson et al., 1985). The average basic density of industrial roundwood input to lumber manufacturing in BC was 391 kg/m³ or 0.391 ODT/m³ (green) (Table 5-3).

	Industrial Doundwood Input	Basic Density	
Wood Species		(kg (Oven Dry)/m ³	
	(%)	(Green))	
Western Hemlock	6%	423	
Balsam Fir	6%	335	
Western Cedar	8%	329	
Douglas-Fir	8%	450	
Larch	2%	450	
Amabilis Fir	15%	377	
White Spruce	16%	360	
Lodgepole Pine	35%	409	
Other (soft and hardwood)	4%	418	
Total/Average	Total: 100%	Average: 391	

Table 5-3: Total Average Basic Density of BC Industrial Roundwood Inputs

The factors used to convert a Bdu to m³GSWE for wood by-products (chips, sawdust and shavings) are shown in Table 5-4.

The conversion factors used for chips in 1991 and 1999 were 2.33 m³ GSWE/Bdu and 2.38 m³ GSWE/Bdu, respectively, using 0.90 as the average yield for both years (Appendix F). Therefore, using these conversion factors, basic densities of 467 and 457 (kg/m³ GSWE) were obtained for 1991 and 1999, respectively (Table 5-4).

Year	Chips Conversion Factor	Average Basic Density	
	(m ³ GSWE/Bdu)	(Lb/ ft ³)	(kg (Oven Dry)/m ³
			GSWE)
1991	2.33	29.17	467
1999	2.38	28.55	457
2005	2.78	24.41	391
2006	2.78	24.41	391
2007	2.78	24.41	391

Table 5-4: Chips Conversion Factors and Average Basic Density in BC

The volumes of wood by-products produced, including sawdust and shavings, were calculated using equation mass balance: mass in = mass out, as the basic density (oven-dry mass/green volume) for both the inputs and outputs was consistent.
The conversion factors, unit definitions and volumetric shrinkages discussed above facilitated the primary sawmilling sub-level material flow to be developed on a volumetric basis. In addition to the primary sawmilling sub-level fibre balancing, material flow balances for the other three sub-levels (SP, OM and PP) of the BC's forestry industry were completed for each of the five study years. Details of these sub-level models are presented in the Appendix F. In the next section, four sub-level models are integrated into a provincial wood fibre balance.

5.2.2.6 Material Used to Produce Energy at Chemical Pulp Mills

The material inputs (i.e. the mix of pulpwood and by-products from wood products manufacturing subsector) to the pulp mill category were back calculated by multiplying the average pulp yields which represent various processing types by the output values of the various pulp products. There were two main categories of pulp mills in BC, namely, chemical pulp mills (bleached kraft pulp mills and unbleached kraft pulp mills) and mechanical pulp mills. Chemical pulp which has lower yield than mechanical pulp, accounted more than 67% of the annual pulp output in BC by mass (MoFR, 2009b, 2007a, 2006).

The output from the pulp mills consisted of two major components, namely, pulp products and pulping by-products, termed waste losses in this study. In the kraft chemical pulping process, waste losses were the wood components, specifically, lignin, hemicelluloses and extractives dissolved and converted to black liquor which is used for energy production, turpentine and tall oil. The data used in material flow balancing were all underbark volumes. Therefore, the energy recovery from hog fuel, which largely arises from bark, was excluded from this study.

The detailed material flow balancing, annual average yield and conversion factors used for pulp and paper mill sub-level are presented in Section 3 of Appendix F.

5.3 Results and Discussion

5.3.1 Number and Average Capacity of Primary Manufacturing Mills in BC

The number and capacity of mills in BC's primary forest products sector is quite dynamic due to the sector's responses to changing technologies, resource characteristics and market conditions. The total number of primary mills in BC ranged from 382 to 433 over the study period (Table 5-5).

On average, the wood products manufacturing subsector accounted for about 94% of the total number of mills and the pulp and paper manufacturing subsector accounted for 6%. Within the wood products manufacturing component of the industry between 46% and 52% of the total mills were sawmills and lumber was the predominant primary forest product manufactured in the province. Between 1991 and 2007,

the number of lumber mills increased by 10.1% and the average mill capacity decreased by 13.9% (Table 5-5).

Veneer and plywood mills were the second most numerous mill type within the wood products manufacturing subsector, accounting for approximately 5% of the total number of mills. Between 1991 and 2007, the number of veneer and plywood mills reduced by 24.0% and average mill capacity increased by 29.8% (Table 5-5).

Mill\Year	No. of Mills and Capacity	1991	1999	2005	2006	2007	Change 1991 to 2007
	No. of mills	178	227	192	193	196	10.1%
Lumber	Avg Capacity per mill (Mbfm)	93.4	69.3	88.9	84.3	80.5	-13.9%
	Province Capacity (Mbfm)	16,629	15,734	17,076	16,275	15,770	-5.17%
	No. of mills	0	3	3	4	4	33.3% (1999-2007)
OSB	Avg Capacity per mill (Msf)	0	287	490	564	566	97.2% (1999-2007)
	Province Capacity (Msf)	0	860	1,471	2,256	2,265	163% (1999-2007)
¥7 0	No. of mills	25	18	20	19	19	-24.0%
Veneer&	Avg Capacity per mill (Msf)	95.2	120	134	133	124	29.8%
Plywood	Province Capacity (Msf)	2,381	2,155	2,674	2,529	2,349	-1.34%
Other Mills	No. of mills	142	132	120	129	126	-11.30%
	No. of mills	3	5	4	4	4	33.3%
Other Panel	Avg Capacity per mill (Msf)	152	125	194	188	127	-16.6%
	Province Capacity (Msf)	457	626.4	774	751	508	11.2%
	No. of mills	0	0	5	8	8	60.0% (2005-2007)
Pellet	Avg Capacity per mill (000 Tonne)	0	0	31	101	141	359% (2005-2007)
	Province Capacity (000 Tonne)	0	0	153	810	1,125	635% (2005-2007)
	No. of mills	9	24	13	14	13	44.4%
Chip	Avg Capacity per mill (000 Bdu)	145	145	134	127	147	1.50%
-	Province Capacity (000 Bdu)	1,594	3,487	1,738	1,780	1,913	20.0%
	No. mills	25	24	23	23	23	-8.00%
Pulp&Paper	Avg Capacity per mill (000 ADT)	341	329	329	341	288	-15.5%
	Province Capacity (000 ADT)	8,537	7,905	7,557	7,835	6,627	-22.4%
TOTAL	No. of mills	382	433	380	394	393	2.88%

Table 5-5: Number and Average Capacity of Primary Manufacturing Mills in BC, 1991-2007

(MoFR, 2008c)

The total mill number, total capacity and per mill capacity of both OSB mill and pellet mill categories increased significantly over the study period. Between 1999 and 2005, one new OSB mill was built and the total annual capacity and average capacity per OSB mill increased by 163% and 97.2%, respectively. Between 2005 and 2007, three additional pellet mills were constructed and the provincial pellet production capacity increased sixfold and the average mill capacity was 3.59 times greater (Table 5-5).

The annual capacity of the pulp and paper manufacturing subsector decreased by 22.4% from 1991 to 2007, while the average mill capacity also decreased by 15.5% (Table 5-5). The data reflected the systematic decline in the pulp and paper industry in North America over the study period (FAO, 2015).

In general, the data on mill numbers and capacities revealed the large scale of the primary forest products industry in BC and the increasing importance of the structural wood product, panel and pellet industries (Table 5-5). It also demonstrated the wide range of primary forest products manufactured, the substantial mill numbers and the capacity changes over the 17-year period, which confirms the large, dynamic and complex network that makes up the BC primary forest products industry.

5.3.2 Material Flow Balances

Provincial material flow balances for the years of 1991, 1995, 2005, 2006 and 2007 were undertaken to quantify changes of in volumetric flows through the value chain over a 17-year period. To support this analysis, a large range of data for key materials and products that appeared along the wood fibre supply chain was collected. To simplify the material balancing process for each sub-level, the annual input and output data from all mills in BC's forestry sector were used. Each mill category was considered as one combined mill by using the aggregated annual data for each individual mill in the category. The following section describes the material flow analysis undertaken for the primary sawmilling (PS) sub-level. Similar analyses were also undertaken for the other three sub-levels (structural panels (SP), other mills (OM) and pulp and paper (PP) (Appendix F).

5.3.2.1 Wood Fibre Balance Assessment

Material flow models for BC's primary forestry sector were developed for 1991, 1999, 2005, 2006 and 2007 by combining the four sub-level models described in this section (Figures 5-3 to 5-7) and Appendix F. This modeling approach converted all product masses and volumes to equivalent roundwood inputs in Mm³ GSWE and validation of each annual model was undertaken by comparing the roundwood requirements determined by the material flow model with the reported volumes of the primary logs provided by the provincial harvest. The total roundwood input requirements calculated using both approaches, together with the percentage differences between the values, are presented in Table 5-6. For the most recent four assessments, the differences were less than 5% whereas the 1991 material flow model overestimated the

roundwood requirements by 6.7% (Table 5-6). However, this was considered to represent an adequate level of precision in the models.

	Total Wood Fibre Input from	Total Wood Fibre Input from	Difference
Year\Unit	MFLNRO Database	Material Balancing*	
_	(Mm ³ GSWE)	(Mm ³ GSWE)	(%)
1991	68.8	73.4	6.7%
1999	69.8	73.2	4.9%
2005	78.7	80.2	1.9%
2006	78.5	77.6	-1.1%
2007	71.1	70.7	2.3%

Table 5-6: Balance Difference for the Wood Fibre Utilization, 1991, 1999, 2005, 2006 and 2007

Notes: Data availability for wood fibre volume balancing is listed below:

1991: Industrial roundwood input volumes for both other panel mills and pulp and paper mills were not available.

1999: The input sources for the others panel mills and the industrial roundwood input for pulp and papers manufacturing were unavailable.

- 2005: All data were available.
- 2006: Industrial roundwood input volumes for pulp and paper manufacturing was insufficient. 8% of the total roundwood used was assumed to be used as the input to pulp and paper manufacturing.
- 2007: Industrial roundwood input volume for the other panels mills was unavailable. 8% of the total roundwood used was assumed to be used as the input to other panels manufacturing.

5.3.2.2 Conversion Factors and Input/Output Factors

The conversion and input/output (I-O) factors calculated from the material flow balancing processes for the various products and their variations by year are presented in Tables 5-7 and 5-8. These conversion factors enabled the original production data in a diverse range of units to be converted into product volumes in the consistent unit of m³ GSWE.

In contrast, I-O factors enabled the original data to be converted into the equivalent green industrial roundwood required as the input. Conversion factors (Table 5-7) and I-O factors (Table 5-8) listed were determined after taking into account mathematical conversions, extraction of the non-wood components of products, compression and shrinkage effects depending on the type of the final product.

The conversion factors and I-O factors varied with time, average density of material input and MC (Tables 5-7 and 5-8). Conversion factors and I-O factors listed in Tables 5-7 and 5-8 can be applied to convert forest products quantified in mass units (e.g. pellets, pulp and paper and chips) and forest products needed to consider compression effects (e.g. OSB and other panels) to a volumetric unit. Additionally, standard size was an important factor affecting conversion factor values for lumber products. Pellet conversion factors

and I-O factors were not included for the year of 1991 and 1999 in the both Tables 5-7 and 5-8 due to a lack of adequate data. OSB's conversion factors and I-O factors were not available for the year 1991 as the first record for OSB in BC was in 1994 (Tables 5-7 and 5-8). Detailed conversion factors and I-O factors are presented in Appendix G.

Product	Original Unit	Conversion Factors (m ³ GSWE/Original unit)							
	original child	1991	1999	2005	2006	2007			
Lumber	Mbfm	1.792	1.792	1.826	1.826	1.74			
OSB	Msf (3/8" basis)	/	1.123	1.313	1.313	1.313			
Veneer	Msf (3/8" basis)	0.957	0.957	0.957	0.957	0.957			
Plywood	Msf (3/8" basis)	0.956	0.956	0.956	0.956	0.956			
Other Panels	Msf (3/8" basis)	1.035	1.058	1.237	1.237	1.237			
Pellet	Tonnes	/	/	2.467	2.467	2.467			
Pulp & Paper	Tonnes (ADT)	1.946	1.988	2.322	2.322	2.322			
Chips	Bdu	2.33	2.38	2.78	2.78	2.78			

Table 5-7: Selected Conversion Factors for BC's Forest Products, 1991-2007

Note: "/" indicates that data were unavailable.

Product	Original Unit	Input/Output Factors (m ³ GRWE/Original unit)						
	original crist	1991	1999	2005	2006	2007		
Lumber	Mbfm	4.398	3.969	3.712	3.69	3.694		
OSB	Msf (3/8" basis)	/	2.483	2.657	2.641	2.781		
Veneer	Msf (3/8" basis)	1.846	1.684	1.714	1.627	1.714		
Plywood	Msf (3/8" basis)	1.846	1.684	1.714	1.627	1.714		
Other Panels	Msf (3/8" basis)	3.355	1.536	1.699	1.938	1.771		
Pellet	Tonnes	/	/	2.543	2.543	2.543		
Pulp & Paper	Tonnes (ADT)	4.14	4.23	4.739	4.739	4.739		
Chips	Bdu	2.589	2.587	2.989	3.39	3.022		

Table 5-8: Selected Input/Output Factors for BC's Forest Products, 1991-2007

Notes: "/" indicates that data were unavailable.

All inventories were considered in the net input and output calculations.

5.3.2.3 Temporal Wood Material Flows in BC

Based on the data sources and analytical methods described above, provincial wood material flow balances have been developed for each of the five years studied (Figures 5-3 to 5-7).



* This key applies to Figures 5-3 to 5-7.

Figure 5-3: Wood Material Flow in BC, 1991 (Unit: Mm³ GSWE)



Figure 5-4: Wood Material Flow in BC, 1999 (Unit: Mm³ GSWE)



Figure 5-5: Wood Material Flow in BC, 2005 (Unit: Mm³ GSWE)



Figure 5-6: Wood Material Flow in BC, 2006 (Unit: Mm³ GSWE)



Figure 5-7: Wood Material Flow in BC, 2007 (Unit: Mm³ GSWE)

Important points arising from the changes of material input and forest products output along BC's wood fibre supply chains over the study period are listed below:

• Harvest: Over the study period, the harvest volume of industrial roundwood ranged from 75.3 to 86.7 Mm³ GRWE. The harvests increased substantially by 11.4 Mm³ or 15.1% from 1991 to 2005, largely due to the mountain pine beetle (MPB) outbreak that prevailed in the early 2000's. The harvest decreased after 2005 to 83.5 Mm³ GSWE in 2006 and 75.4 Mm³ GRWE in 2007, in response to the reduced demand for structural wood products due to the decreased number of houses constructed in the USA (Shepard and Sitar, 2010) (Table 5-9).

1991 1999 2006 2007 Year 2005 86.7 Harvest 75.3 76.0 83.5 75.4 1.51 1.76 1.70 Waste and Rejects 1.52 1.51 0.00 Log Import 0.36 0.46 0.04 0.11 Log Export 0.77 1.45 4.77 4.26 3.53 73.2 80.2 77.6 70.7 Net Wood Fibre Input to the MS Subsector 73.4

Table 5-9: Net Industrial Roundwood Input to the Manufacturing Subsector (m³ GRWE), 1991-2007

Quantities of waste and rejects, log imports and exports must be considered when determining the net industrial roundwood volumes that entered the manufacturing boundary set in this study. The volume of waste and rejects was proportional to the industrial roundwood harvest and it typically accounted for approximately 2% of the annual harvest. Industrial roundwood exports in 1991 and 1999 were lower than in the 2000s. Log exports increased from 0.77 in 1991 to 3.29 Mm³ GSWE in 2007, peaking at 4.77 Mm³ GSWE in 2005. Conversely, log imports (less than 0.5 Mm³ GSWE) were negligible in all years studied. The net input of total industrial roundwood to BC's forestry sector increased from 1991 to 2005 when it peaked at 80.2 Mm³ GSWE. It subsequently decreased to reach 70.7 Mm³ GSWE in 2007.

• Chip Exports: Exports of wood chips ranged from 2.24 to 4.39 Mm³GSWE between 1991 and 2007. Chip exports accounted for 1-3% of the total chips production.

• Structural Changes: Over the study period, BC's primary forest products sector diversified its product range. OSB was first produced in BC in 1994 and pellets were first included in the MFLNRO reports in 2005. The production of both of these products has increased in response to increasing market demands. Over much of the study period, North American OSB markets grew as this product displaced plywood from the structural panels market (Sianchuk et al., 2012; Spelter et al., 2006). In contrast, growing

demand from European residential heating markets was the primary driver of growth for the pellet industry (Bradburn, 2014).

BC's industrial roundwood harvest mainly flowed into the wood products manufacturing subsector throughout the study period. However, the proportion of wood fibre supplied to lumber production has been reduced and the wood input was increasingly used to manufacture plywood and veneer, OSB and pellets. The fibre input to the pulp and paper sub-level increased from 1991 to 2005 and decreased in 2006. Throughout the study period, wood by-products from the wood products manufacturing subsector remained the dominant fibre source for the pulp and paper sub-level.

5.3.3 Material Flow Analysis in BC's Forestry Sector

In this section, the distribution of wood fibre input into a range of mills and the output of various forest products are discussed.

The percentages of wood fibre input by final products output type are presented in Figure 5-8. All the input and output calculations were in Mm³ GSWE. Later in this section, the linkage role of wood by-products, the impact of yields in manufacturing and material utilization efficiency will be considered.

5.3.3.1 Industrial Roundwood Input Distribution

Sawmills were the largest consumer of industrial roundwood in BC throughout the study period. Total net industrial roundwood input to the manufacturing subsector increased substantially from 1999 to 2005, reaching 80.2 Mm³ GSWE, as the result of the increased harvest and the use of MPB killed wood. Subsequently, the industrial roundwood input fell to 70.7 Mm³ GSWE in 2007, the lowest value in the period due to the economic recession and the poor USA housing market (Figure 5-8). Wood fibre inputs to the wood products manufacturing subsector decreased from 59.6% to 53.4% of total manufacturing subsector, increased from 40.4% to 46.6% over the same time interval (Table 5-10).

From 1991 to 2007, lumber mills consumed between 55.1% and 61.2% of the total wood fibre flowing into the manufacturing subsector reflecting the key role that this sub-level fulfills in roundwood breakdown. With the introduction of both OSB as a structural panel in 1994 and pellets as a new energy resource in 2005, the share of wood fibre consumed directly by lumber manufacturing reduced steadily from 61.2% in 1990 to 55.1% in 2007. Total net wood fibre input to OSB manufacturing increased substantially from 1.86% in 1999 to 2.46% of manufacturing subsector inputs in 2007 (Figure 5-8).

The proportion of wood fibre entering the plywood and veneer mills ranged from 3.98% in 1991 to 5.67% in 2005. Pellets mills consumed 1.45% of net wood fibre input in 2005 and increased to 2.51% in 2007. The increased diversity of wood products manufactured was also evident in the greater number of horizontal bars in 2007 than 1991 (Figure 5-8).

The pulp and paper manufacturing subsector was the second largest consumer of wood fibre with the main source being wood by-products. The proportion of manufacturing subsector fibre input entering the pulp and paper mills was relatively stable from 1991 to 2007, accounting for approximately one third of the total fibre input (Figure 5-8). Chip mills, an important raw material provider for the pulp and paper manufacturing subsector, consumed between 2.35% to 4.45% of the total wood fibre input. The reduced availability of wood by-products from sawmills in 1999 resulted in an increased proportion of wood fibre input to chip mills. In that year, it reached 4.45% of manufacturing subsector inputs, the highest proportion over the study period.



Figure 5-8: Comparisons of Wood Fibre Input by Product Type (%)

Wood Fibre Input Distribution	1991	1999	2005	2006	2007
WPM (Mm ³ GSWE)	43.8	38.5	43.8	42.0	37.7
PM (Mm ³ GSWE)	29.6	34.7	36.4	35.6	33.0
Manufacturing Subsector	72 4	72.0	80.2	77 (70.7
(Mm ³ GSWE)	/3.4	13.2	80.2	//.0	/0./
WPM%	59.6%	52.5%	54.6%	54.1%	53.4%
PM%	40.4%	47.5%	45.4%	45.9%	46.6%
Difference between WPM% and PM%	19.2%	5.08%	9.23%	8.14%	6.72%

 Table 5-10: Net Wood Fibre Input Distribution in Wood Products Manufacturing and Pulp and

 Paper Manufacturing Subsectors

In summary, sawmills have been historically the largest consumer of the wood fibre input in BC. However, the percentage of fibre input entering sawmills has decreased with time. Simultaneously, the wood fibre input to structural panels has increased significantly. Its share of total manufacturing subsector input ranged from 3.98% in 1991 to 4.94% in 2007 and peaked at 5.67% in 2005. Pulp and paper mills have historically been the second largest consumer of wood fibre input. They consumed approximately one third of the total manufacturing subsector fibre input over the study period with the proportion peaking at 30.8% in 1999.

5.3.3.2 Forest Products Output distribution

Wood fibre distribution in the outputs from both BC's wood products manufacturing and pulp and paper subsectors are presented in Figure 5-9 and Table 5-11.

Total forest products output from BC's manufacturing subsector increased steadily from 43.0 Mm³ GSWE in 1991 and peaked at 58.9 Mm³ GSWE in 2006, before decreasing to 51.8 Mm³ GSWE in 2007 (Table 5-11). Wood products manufacturing outputs have consistently dominated BC's forest products manufacturing by accounting for more than two thirds of the total volume over the study period. Wood products manufacturing inputs as a percentage of the total output increased from 66.5% in 1991 to 71.7% in 2007 with a slight drop in 2006. In contrast, the proportion of pulp and paper products decreased substantially from 33.5% of the total output in 1991 to 28.3% in 2007. The volume of pulp and paper output increased from 14.4 Mm³ GSWE 1991 to 17.4 Mm³ GSWE in 2006 before a 2.72 Mm³ GSWE reduction in 2007. However, the volumetric increases in wood products manufacturing outputs were much greater, from 28.6 Mm³ GSWE in 1991 to 41.5 Mm³ GSWE in 2006 (Table 5-11).

Lumber, the predominant forest product over the study period averaged 53.8% of the total primary forest products industry output. The proportion of lumber products declined from 55.2% in 1991 to 51.4% in 2007, although the absolute lumber output slightly increased in 2007 compared to 1991 (Figure 5-9).

Pulp and paper products averaged 30.3% of the total output over the study period, decreasing from 33.5% in 1991 to 28.3% in 2007 (Figure 5-9 and Table 5-11). Market pulp averaged 58.7% of the total pulp and paper production, with its proportion of total pulp and paper manufacturing subsector production increasing very slightly by 0.79% from 1991 to 2007. In response to North America's decreased demand for important grades of paper, such as newsprint and printing paper and writing paper, paper production decreased significantly from 15.6% 1991 to 9.7% in 2007 (FAO, 2015).

Notably, with the reduced proportional production of lumber and pulp and paper products, other wood products have been increasingly important components of BC's primary forest products sector over the study period (Figure 5-9). The aggregated proportions of these products almost doubled over the study period, increasing from 11.3% to the total outputs in 1991 to 20.3% in 2007.



Figure 5-9: Comparisons of Wood Fibre Output by Product Type (%)

Veneer and plywood contributed 5-6% of the total output over the study period. Between 2005 and 2007, the volume of veneer products, which was sent to the veneer market for sale rather than directly used for further manufactured to plywood, almost doubled. The quantities of pellets and OSB manufactured increased substantially over the study period. Pellet production expanded every year after 2005, reaching 2.5 Mm³ GSWE or 4.53% of total output in 2007, with most of the production exported to meet the growing demand from Europe (Bradburn, 2014). The proportion of OSB also increased from 2.91% of total outputs in 1999 to

4.53% in 2007 to supply for the demand for structural panels for house construction in the USA (Spelter et al., 2006)

i uper manufacturing Subsectors							
Wood Fibre Output Distribution	1991	1999	2005	2006	2007		
WPM (Mm ³ GSWE)	28.6	31.4	40.6	41.5	37.2		
PM (Mm ³ GSWE)	14.4	14.4	16.3	17.4	14.7		
Manufacturing Subsector	42.0	15 9	56.0	58.0	51 9		
(Mm ³ GSWE)	45.0	43.8	30.9	38.9	51.8		
WPM%	66.5%	68.5%	71.4%	70.5%	71.7%		
PM%	33.5%	31.5%	28.6%	29.5%	28.3%		
Difference between WPM% and PM%	33.0%	37.1%	42.8%	41.0%	43.4%		

 Table 5-11: Forest Products Output Distribution in the Wood Products Manufacturing and Pulp and

 Paper Manufacturing Subsectors

In summary, two main trends were observed in BC's primary forest products output over the study period. Firstly, lumber and pulp and paper products were consistently the two predominant forest product categories, but they have become smaller components of the output. Consequently, the proportions of other products, especially structural panels and pellets, have increased over time. Secondly, BC's forest product outputs became more diversified, with increased production of OSB and pellets to supply offshore markets.

5.3.3.3 Linkage Function of Wood By-Products

Within the material flow network, wood by-products (predominantly wood chips) from both lumber and structural panel mills served as the additional fibre input for pulp and paper production. In addition to pulp and paper production, sawdust was also used as an input for pellet manufacturing. Wood by-products therefore played an important role in linking both wood products manufacturing and pulp and paper manufacturing subsectors and improving the efficiency of material utilization.

The annual total volume and proportions of chips produced from various sources are presented in Figure 5-10. Overall, the production of chips increased over the study period. After a slight decrease in 1999, the volume rebounded to reach 30.3 Mm³ GSWE in 2005, resulting from the large quantity of industrial roundwood input to the lumber manufacturing and pulpwood input to chip mills. Impacted by the reduced quantities of lumber produced after 2005, the production of chips in 2007 declined to 26.8 Mm³ GSWE. Lumber manufacturing accounted for an average of 79.3% of the total chips produced over the study period making sawmills the largest chip producer. Chip mills were the second largest source of chips, with an average of 10.6% of production. Veneer and plywood mills produced 3-7% of the total chips (Figure 5-10).



Figure 5-10: Chips Output from BC's Manufacturing Subsector, 1991-2007

Sawdust and shavings are another important category of wood by-products from lumber and structural panel mills. They may be utilized as raw materials for pulp and paper, panels and pellet manufacturing. The proportions of sawdust and shavings produced by primary mills and the total volumes of sawdust and shavings produced over the study period are presented in Figure 5-11. The total volumes of sawdust and shavings were 15.9 and 13.5 Mm³ GSWE in 1991 and 1999, respectively, approximately half the volume of the chips produced in the same years. The production of sawdust and shavings in 2005, 2006 and 2007 reduced significantly to be approximately 60% that in 1991 as the consequence of the improved LRF within the sawmilling industry (Figures 2-3 and 5-11; MoFR, 1995, 2000, 2011). Sawmills were the largest source of sawdust and shavings and they accounted for an average of 86.7% of the total sawdust and shavings produced 10.1% of the total sawdust and shavings on average. Chip mills provided 1.4-5.6% of the sawdust and shavings over the study period (Figure 5-11).



Note: SS: Sawdust and shavings

Figure 5-11: Sawdust and Shavings Output from BC's Manufacuring Subsector, 1991-2007

Total wood by-products and the proportions of chips, sawdust and shavings from 1991 to 2007 are presented in the Figure 5-12. Total by-products products production decreased from 41.0 Mm³ GSWE in 1991 to 38.4 m³ GSWE in 1999. After a slight rebound in 2005, the total by-products produced continued to decline steadily to reach a value of 36.6 m³ GSWE in 2007. Many factors contributed to this decrease, including the higher wood fibre yield of final products (e.g. lumber and structural panel products), less industrial roundwood input to the manufacturing subsector and reduced pulp and paper demand.

Generally, chips are considered to be a more valuable by-product than sawdust and shavings and, despite the decreased total volume of wood by-products, the proportion of chips increased from 63.1% in 1991 to 73.3% in 2007, peaking at 76.0% in 2005 (Figure 5-12). In contrast, sawdust and shavings accounted for approximately one third of the total by-products products on average and its share reduced from 38.7% in 1991 to 26.7% in 2007.



Figure 5-12: The Composition of By-Products in BC's Manufacturing Subsector, 1991-2007

Notes: 1. The pulp and paper yield was an average of all pulping processes.

2. The pellet yield was estimated using the yield provided by one of the eight pellets mills in BC in 2007.

In conclusion, the volume of wood processing by-products produced decreased over the study period. The proportion of chips, which averaged 70.0% of the total by-products, increased with time. In contrast, the proportion of sawdust and shavings declined with time.

5.3.3.4 Summary of Wood Yields

The volumes of final products and wood by-products produced in all mills were determined by product yields. A yield may be influenced by many factors, including the type of products manufactured, the quality of the raw materials, manufacturing technologies and manufacturing equipment (Martin, 2004; Steele, 1984; Stirling, 1998).

The wood yield for each component of BC's primary forest products value chain is presented in Figure 5-13. Overall, the wood yield improved over the study period, which resulted in a proportional increase in the final products manufactured and a proportional reduction in wood by-products (Table 5-12).



Figure 5-13: Yields Used in BC's Material Flow Balancing, 1991-2007

Notes: 1. The yields for pulp and paper manufacturing were the weighted average yield (v/v) of all pulping processes.

2. The yields for pellet mills were estimated based on the confidential data from one of the eight mills in BC.

3. The yields for other mills were assumed to be 0.55 (v/v) for years studied.

Pellet mills had the highest yield amongst all the primary forest product mills, averaging 0.97 (v/v) over the study period. The high pellets yield was the result of low material losses during the material handling and compressing processes. Chip and OSB mills had the second and third highest yield, averaging 0.90 and 0.89 (v/v), respectively over the study period, due to low material losses from pulpwood chipping and OSB manufacturing (Figure 5-13).

Sawmills had the lowest yield comparing with other types of mills in BC, mainly because of the large quantities of by-products created during the sawing, edge trimming and handling processes. The average sawmill's yield increased considerably from 0.41 (v/v) in 1991 to 0.47 (v/v) in 2007 peaking at 0.50 (v/v) in 2006. This improvement reflected the technological improvement in BC's sawmills (Figure 2-3; Martin, 2004; Stirling, 1998) while the decrease was most probably due to log quality deterioration that occurred when the MPB affected trees were harvested (Figure 5-13; Goldring, 2008). Losses of lignin, hemicelluloses, and extractives during the chemical pulping process were the principal cause of the low pulp mill average yield of 0.48. These compounds contribute to black liquor, turpentine and tall oil and are used to produce energy and pulping by-products. The pulp yield increased from 0.45 (v/v) in 1991 to 0.47 (v/v) in

2007 and peaked at 0.49 (v/v) in 2005 and 2006 (Figure 5-13). Many factors may influence pulp yield including the specific pulping and bleaching technologies and the wood species used.

5.3.4 Material Utilization Efficiency

Material utilization efficiency defined in section 5.2.2.1 is an important indicator of many material flow analyses (Cheng et al., 2010a). The average utilization efficiency of wood fibre within BC's forest products industry has steadily increased from 58.6% in 1991 to reach 75.9% by 2006 (Figure 5-14).





Note: WPM included chips exports but excluded the chip products from chip mills.

Material utilization efficiency is correlated to the yields and the distribution of raw materials to each component of the forest products manufacturing industry. It also reflects the overall industry structure. The material utilization efficiency did not directly account for the amount of energy (recovered from wood material used at the province's pulp mills) in the pulp and paper subsector's final fibre output.

This material flow analysis demonstrated that wood by-products provided a strong link between BC's wood products manufacturing and pulp and paper manufacturing subsectors. The wood fibre yield played a crucial role in determining the volumes of final products and it also influenced wood fibre fluxes by adjusting the proportions of industrial roundwood flowing to final products and by-products in each component of the manufacturing subsector. The material flow was also affected by market demands for wood products

manufacturing and pulp and paper manufacturing products and manufacturing capacity constraints. For instance, in the case of a high demand and profit for lumber products, the majority of industrial roundwood could be utilized in sawmills to maximize the total profit from the provincial forest products industry. However, in the case of high demand and profit for pulp and paper products, the flow of chips may be increased by distributing more industrial roundwood to chip mills or increasing chip production at sawmills. Consequently, providing sufficient manufacturing capacity existed, the material flow could potentially be adjusted to meet fluctuating market conditions to ensure that the industry optimizes its socio-economic benefits. Historically, BC's wood products and pulp and paper manufacturing subsectors have rarely operated at fully capacity (MoFR, 1995, 2000, 2008c, 2011, 2015), there is therefore an opportunity to examine whether a more flexible flow of wood materials through the manufacturing subsector could deliver improved socio-economic outcomes.

In summary, several factors have contributed to the increased material utilization efficiencies over the past seventeen years. Firstly, wood yields have increased with time, resulting in a greater volume of final forest products output per unit of input. This has especially been aided by the application of improved log scanning, sawing and planing technologies within sawmills. Secondly, the development of the OSB and pellet industries within the wood products manufacturing subsector has improved the material use efficiency because they both have high yields. Thirdly, the pattern of wood by-products utilization has changed with time. Although the increased wood yields for final forest products reduced the volumes of wood by-products products yielded were used more efficiently as the additional input for pulp, pellets and some structural panel productions rather than being landfilled or burnt. The utilization of wood by-products has increased the material utilization efficiency and it has also made material flow more complex. Additionally, the composition of the forest products manufactured has changed with time. Although lumber and pulp and paper products continued to dominate BC's forestry sector, the increased proportions of OSB, pellets and other structural panels have resulted in a more diverse set of outputs.

5.4 Conclusions

A framework for evaluating wood fibre flow and utilization efficiency for BC's primary forest products industry has been developed in this chapter. Material flows for 1991, 1999, 2005, 2006 and 2007 were created by aggregating four sub-level models. These subsector models (primary sawmilling, pulp and paper, structural panel and other mills) used a top down approach and their accuracy was validated using a bottom up approach. Input/output factors (m³ GRWE)/units of final forest products) and conversion factors (m³ GSWE)/units of final forest products) were developed and applied to convert regular volumetric and mass data to m³ GSWE. This approach enabled the volume and mass data to be comparable for each element along the supply chain and the subsequent development of the volume based sub-level models.

More than 90% of industrial roundwood was consumed in the wood products manufacturing subsector and less than 10% was utilized directly as raw material for the pulp and paper manufacturing subsector. Approximately one third of by-products (chips, sawdust and shavings) from the wood products manufacturing subsector flowed to the pulp and paper manufacturing subsector. This flow of wood by-products played an important linking role between the two major subsectors of BC's forest products industry and resulted in the increased interdependence of the two forest product manufacturing subsectors and a 14.7% increase in the material use efficiency from 1991 to 2007. Temporal structural changes of the provincial primary forest products utilization over the study period. The wood fibre yield and the average material utilization efficiency of wood fibre resources in BC's forest products industry continuously increased over the period investigated.

CHAPTER 6 OPTIMIZATION MODELING OF BC FORESTRY SECTOR'S MATERIAL FLOW

6.1 Introduction

In Chapter 5, wood material flow analysis was undertaken for British Columbia (BC)'s forest products industry to quantify the material flow changes from 1991 to 2007. It provided a framework with which to evaluate opportunities for BC's primary forest products industry to further optimize resource allocation in the manufacturing subsector to maximize economic outcomes while meeting fluctuating market demands. This chapter seeks to utilize these MFA data by evaluating potential opportunities to improve the economic contribution of BC's forest products industry through better resource utilization.

Social benefits are another important contribution from BC's forest products industry. In 2007, BC's forest products manufacturing subsector employed 552,000 full employment equivalents (FTE) and accounted for 24.4% of the province's industrial employment (MoFR, 2009b; StatsCan, 2009). This chapter also considers the changes of social benefits associated with the economic outcomes from the solutions found. As discussed in earlier chapters, the value structure impacts the economic benefits produced by the forest products industry at national and provincial levels. This chapter aimed to use the material flow model of BC's forest products industry developed in Chapter 5 to investigate whether the economic benefits produced by the forestits produced by the forestry sector could be increased by adjusting wood allocations through the value chain.

6.2 Methodologies and Data Sources

6.2.1 Methodologies

Fully utilizing wood by-products and increasing the socio-economic benefits of the forestry sector became increasingly important for BC's forest products industry as it experienced one of the worst cyclical downturns in its history from 2005 to 2010 (Alteyrac et al., 2008b; Sianchuk et al., 2008, 2012). In this study, a linear model of BC material flow was developed using the cvx optimization toolbox of Matlab software. This model was then used to simulate the material flow in 2007 and evaluate the economic benefits of material reallocation to the wood products manufacturing and pulp and paper manufacturing subsectors in various market conditions. The optimized alternative material flow sought to achieve the greatest economic benefits while maintaining adequate employment outcomes for BC's primary forest products industry.

6.2.1.1 Product Definitions

Industrial roundwood, the raw material source for forest products production, is defined as all roundwood except wood fuel (FAO, 2011). It is an aggregate input comprising sawlogs and veneer logs (SV), pulpwood (PW), round and split, and other industrial roundwood (FAO, 2011). Sawlogs and veneer logs have been defined as roundwood that will be sawn (or chipped) lengthways for the manufacture of sawnwood or railway sleepers (ties) or used for the production of veneer (mainly by peeling or slicing) (FAO, 2011). Pulpwood has been defined as that part of the industrial roundwood that will be used for the production of pulp, particleboard or fibreboard. It includes roundwood (with or without bark) that will be used for these purposes in its round form, as splitwood or wood chips made directly (i.e. in the forest) from roundwood and is reported in cubic metres solid volume underbark (FAO, 2011). These definitions have been applied in this chapter and the industrial roundwood input in 2007 was subdivided into two categories: 1) sawlogs and veneer logs, and 2) pulpwood.

6.2.1.2 Scenarios

Three scenarios were established to study the material flows for BC's forest product industry, namely, the base scenario, scenarios 1 and 2. In this study, the sector's material flow model for 2007 presented in Chapter 5 was chosen as the base scenario. It illustrated BC's primary forestry sector structure in 2007. This base scenario served as the reference for the further comparisons with the optimized scenarios. Two additional optimization scenarios (scenario 1 and scenario 2) were developed to simulate two different market conditions. Both scenarios were evaluated and compared to the base scenario. Scenario 1 was set with a constant industrial roundwood supply as that of 2007 with flexible production outputs (fixed supply and variable demand). Scenario 2 analyzed the economic outcomes from a material flow which had fixed forest product outputs with a flexible industrial roundwood supply (variable supply and fixed demand). To avoid the 2.3% discrepancy in input from top down and bottom up approaches (Section 5.3.3.1), a total industrial roundwood input volume of 71.7 Mm³ GSWE obtained from using the top down approach was used in all scenarios.

6.2.1.3 Material Flow Boundary

The province of BC was established as the boundary of the material flow analysis and optimization modeling. All 393 forest product mills that operated in BC in 2007 were included in the study assuming no extra mills were added and no current mills were shut down. The mill capacities used were the aggregated capacities of the same categories of mills.

6.2.1.4 Time Scale

The optimization model was developed to simulate the forest products manufacturing in all the mills within the study region in the 2007 fiscal year.

6.2.1.5 Conversion Factors

In order to facilitate material flow balancing and evaluation of socio-economic contributions, conversion factors (m³ green roundwood equivalent (GSWE)/unit of final forest product) were applied to convert all the volumetric and mass data to m³ GSWE basis values. A detailed explanation of the conversion factors used was presented in Chapter 5 (Section 5.3.2.2; Appendices F and G).

6.2.2 Data Sources

BC's initial material flow in 2007 was based on the MFLNRO confidential database and the MFLNRO public report (MoFR, 2008c, 2009b). Various other resources were used to confirm the conversion factors calculations (Nielson et al., 1985; StatsCan, 2009; Suchland, 2004).

Earnings before interest, tax, depreciation and amortization (EBITDA), a useful measure in particular for large companies with significant assets (Grant and Parker, 2002), gross value added (GVA) and value added per unit of input (return of log_4) discussed in Chapters 3 and 4 were the economic benefits indicators used in this study. Economic data including prices, manufacturing costs, labor costs and logistic costs were obtained from a range of published sources and personal consultation with industry representatives and research professionals (Bradley, 2009; Canfor, 2008; CIBC, 2010; FPAC, 2012; Gystafson, 2010; MacDonald, 2006; Magelli et al., 2009; Mani et al., 2006; MoFR, 2007b, c, 2008c; Wood Markets, 2009, 2005; RISI, 2008). Prices and costs were average values for the BC industry in 2007. Estimations were applied to get the average prices, manufacturing costs, labor costs and transportation cost for the forest products when data were unavailable (Appendix H).

The manufacturing cost for forest products mills typically consists of the delivered wood fibre inputs, labor (direct operations and maintenance), energy, supplies (operations and maintenance) and other non-wood material costs (CIBC, 2010; RISI, 2008). EBITDA was calculated by subtracting the manufacturing cost (excluding interest, taxes, depreciation and amortization) from the final products and by-products sales. The labor cost (i.e. staff labor and production labor), which was accounted for in the manufacturing cost, needed to be added to the EBITDA when the GVA is calculated for a forest products manufacturing system. Therefore, GVAs from all forest product operations were obtained by adding the labor cost to the EBITDA.

Employment data, on a full employment equivalent basis, for each mill were obtained from the BC MFLNRO confidential database and personal communication with the representatives who operated with the database (MoFR, 2008c).

Other data used in the scenario comparisons study, including mill categories, mill names, mill locations and mill capacities were obtained from MFLNRO confidential database (MoFR, 2008c). The average yields for BC's forest product mills in 2007 that determined in Chapter 5 were used (Appendix G).

6.3 Base Scenario: BC's Wood Material Flow in 2007

BC's forest products material flow in 2007 was used as the base scenario. It served as the baseline for further comparisons to understand the economic benefit and material utilization efficiency changes. A detailed overview of BC's material flow and correlated conversion factors, input/output factors is presented in Appendix I. The volume balance of wood fibre in BC's forest products industry in 2007 is presented in Figure 5-7.

When BC's forestry sector material flow model for 2007 was developed, it was assumed that the industrial roundwood inputs to the pulp, chip, other panel, OSB and pellet mills were in the form of pulpwood. Therefore, the pulpwood inputs to these five mills were 2.71, 2.78, 0.08, 2.53 and 0 Mm³ GRWE, respectively (Figure 6-1). Consequently, the total pulpwood input to the manufacturing subsector was 8.1 Mm³ GSWE, or 13.9% of the total industrial roundwood input.



Figure 6-1: Wood Material Flow in BC Using Sawlogs and Veneer Logs and Pulpwood as Inputs, 2007 (Unit: Mm³ GSWE)

Varying the material flows in response to the changing conditions in structural wood products and pulp and paper markets provided material flow optimization opportunities to increase the industry's economic performance. In this chapter, an optimization model was developed based on BC's wood fibre flow in 2007 with the objective of maximizing the economic contributions (EBITDA) under two sets of constraints. The best wood fibre distributions to structural wood products and pulp and paper manufacturing were evaluated under the constraints in scenario 1 and 2 and the constraints applied in each scenario are described in the following section.

6.4 Scenario Optimization

Two important influences on the primary forestry sector structure are the fibre input supply and the market demand for forest products. Market conditions are major influences on the quantities and prices of wood and pulp and paper products manufactured and they may therefore be expected to influence provincial wood fibre flows. In this section, a linear programming model was developed and used to maximize the economic outcomes in "supply push" and "market pull" scenarios. Scenario 1 was set up to investigate a situation of fixed supply with variable demand according to the market conditions. In contrast, material supply is another constraint that affects economic returns by impacting the fibre quality, quantity and price. For instance, the mountain pine beetle attack in BC decreased the wood quality, increased the roundwood harvest and decreased the supply cost (Goldring, 2008). Therefore, scenario 2 was used to evaluate the impact of fixed demand with flexible supply conditions.

In BC, lumber is the predominant forest product from the wood products manufacturing subsector, whereas the pulp and paper manufacturing subsector mainly produces various pulp and paper products. Lumber and pulp and paper markets may move counter-cyclically as they generally supply different sectors of the economy (Lethbridge and Forel, 2009, 2011; Roberts et al., 2004). Historical prices of selected forest products from 2002 to 2011 (Appendix J) indicated that when the price of lumber products increased, pulp and paper markets may be in a downturn. Also, there have been periods when paper products have had good market conditions and lumber prices have been at relatively low levels.

The annual manufacturing capacity is one of the most important constraints to be considered in the optimization modeling. The capacities of BC's forest product mills in 2007 are presented in Table 6-1. For this optimization study, the forest products industry was broken down into the ten mill categories used by MFLNRO (Table 6-1). Measurement units, annual capacities and conversion factors for 2007 discussed in Chapter 5 were used and details are presented in Appendix K. The total capacity of BC's manufacturing subsector in 2007 was 148 million m³ GSWE (Table 6-1). Given that the total wood fibre input was 71.7 million m³ GSWE, the overall capacity utilization of BC's primary forest products manufacturing subsector in 2007 was 64.1% (Figure 6-1) and conceptually there were substantial opportunities to vary the flow of wood fibre through the installed manufacturing capacity (MoFR, 2008c).

	Number of	Aggregated Annual	Consoity Original	Annual Input	Input in 2007	Capacity
Mill Category	mill	Output Capacity in		Capacity	(Mm ³ GSWE)	Utilization
	111111	Original Unit	Unit	(Mm ³ GSWE)		
Lumber	196	15,770	Mbfm	58.19	56.6	97.3%
OSB	4	2,265	Msf (3/8" basis)	3.19	2.53	79.3%
Veneer	8	895	Msf (3/8" basis)	4.02	2.24	55.7%
Plywood	11	3734	Mef (3/8" basis)	3.04	2.83	03 104
(Including Veneer)	11	3234	WISI (3/8 Dasis)	5.04	2.65	93.170
Other Panel	4	510	Msf (3/8" basis)	0.90	1.00	111%
Chip	15	1,913	000 Bdu	5.82	2.78	47.8%
Pellet	8	1,125	000 Tonnes	2.86	2.58	90.2%
Other Mill	126	12,693	/	23.10	1.97	8.5%
Pulp	12	4,100	000 Tonnes (ADT)	32.54	19.9	61.2%
Paper (Including	11	5 302	000 Toppes (ADT)	14.06	10.3	73 30%
Pulp)	11	5,592	000 Tonnes (ADT)	14.00	10.5	13.3%
Sum	393	/	/	147.7	120.7	64.1%

Table 6-1: Mill List and Aggregated Mill Capacities by Category in BC, 2007

Notes: "/" indicates that data were unavailable.

6.4.1 Optimized Scenario 1: Fixed Supply with Flexible Demand

Scenario 1 assumed that the total wood fibre supply to the ten forest product mill categories (Table 6-1) was fixed while the demand for final products could vary between the minimum and maximum values to simulate how the material flow could be adjusted in response to the changes of market demand of structural wood products and pulp and paper products. Market conditions, product demands and manufacturing capacities change with time. Given the fact that BC's wood products production, including lumber and OSB, was reduced by approximately 45% from 2004 to 2011 and 30% from 2008 to 2011, respectively (Ainsworth Lumber Co., 2011; Kayne, 2011), it is reasonable to assume that sufficient capacity existed to enable the production of BC's wood products to vary substantially in response to fluctuating market demand. In this model, the maximum demand for various forest products in BC was set as 30% greater than the productions in 2007. This was a reasonable increase given the overall capacity utilization of 69.5% in 2007 (MoFR, 2008c). In order to provide symmetry in the scenario analysis, the minimum market demand for each forest product was established at 30% below 2007's production value.

The conceptual optimized model is shown in Figure 6-2. Wood by-products from all mills were considered to be transferred to a pool before being consumed in the mills or sold to external customers beyond the MFA boundary (Figure 6-2).

Suppliers	By-Products	By-Products Pool	Consumers
S ₁	Chips	lool	$Z_1^{\text{Chip, out}}$ $Z_2^{\text{Chip, out}}$
S ₂	Shavings Chips Sawdust	Chips F	Z ^{Chip, out}
	and Shavings Chips	SS &	Z ₁ SS, out
	Sawdust and Shavings	⇒	$Z_2^{SS, out}$

Figure 6-2: Conceptual Flows in the By-Products Pool

6.4.1.1 Optimization Modeling

It was assumed that each final product was produced by each individual mill and the indices presented in Table 6-2 were assigned to those mills. In this model, veneer and plywood mills and pulp and paper mills were separated into four individual mill categories: namely, veneer mills, plywood mills, market pulp mills and paper mills to enable each final product to be correlated to a forest product mill category. In 2007, BC had nineteen veneer and plywood mills. Eight of them produced only veneer and eleven manufactured both veneer and plywood (Table 6-1). The yield of plywood from veneer was assumed to be 100% and all plywood was assumed to be produced from locally manufactured veneer. To facilitate the modelling, veneer and plywood mills were considered to be two individual mill categories despite several plywood mills being located on the same site as veneer mills. Therefore, in addition to annual capacity constraints for each individual aggregated mill, an additional annual capacity constraint was set for the veneer mill. This annual capacity was the sum of the wood input for veneer and plywood. The same constraint concepts were also applied to the pulp and paper mills. In 2007, there were 23 pulp and paper mills in total, with eleven of them only producing market pulp as the final product (Table 6-1). The yield for paper from pulp was also assumed to be 100%.

			Table	e 0-2. mue	A Assign		ne mins			
Mill	Sawmill	OSB	Vanaar	Plywood	Other	Chip	Other	Dallat	Market	Dapar
IVI111	Sawiiiii	OSD	v eneer	riywood	Other	Chip	Panel	renet	Pulp	raper
Index (i)	1	2	3	4	5	6	7	8	9	10

Table 6-2: Index Assigned for the Mills

Mills 1-6 only consumed industrial roundwood as their input, while mills 7-10 consumed both industrial roundwood and wood by-products.

The model variables and parameters are defined in Table 6-3. Prices, manufacturing costs and unit by-product transportation cost and the average by-product transportation distances are presented in Appendix H.

Parameter/Variable	Definition
S	Total supply of logs to all mills
X_i	The amount of input logs at mill <i>i</i>
Y_i^{FP}	The final product output from mill <i>i</i>
$Z_i^{ ext{Chip, in}}$	The amount of chips entering mill <i>i</i>
$Z_i^{\text{Chip, out}}$	The amount of chips produced by mill <i>i</i>
$Z_i^{ m SS,in}$	The amount of sawdust and shavings entering mill <i>i</i>
$Z_i^{SS, out}$	The amount of sawdust and shavings produced by mill <i>i</i>
$D_i^{ m FP,\ min}$	Minimum demand for final product <i>i</i>
$D_i^{ m FP,\ max}$	Maximum demand for final product <i>i</i>
Cap_i	Capacity of mill <i>i</i>
P_{sv}	Price of delivered sawlogs and veneer logs (industrial roundwood excluding pulpwood)
P_{pw}	Price of delivered pulpwood
P_i^{FP}	Price of final product <i>i</i>
$C_i^{ m FP}$	Manufacturing cost of final product <i>i</i>
C^{chip}	Processing cost of chips
$E^{ m chip}$	Export/external sale price of chips
E^{SS}	Export/external sale price of sawdust and shavings
α_i^{FP}	Yield of final product from mill <i>i</i>
$\alpha_i^{ m Chip}$	Yield of chips from mill <i>i</i>
α_i^{SS}	Yield of sawdust and shavings from mill <i>i</i>
Ι	Total number of supplier mills
Т	Transportation cost (per distance and volume)
D	Average transportation distance of by-products to pulp mills

Table 6-3: Variables and Parameters in the Model

Notes: FP: Final products; SS: Sawdust and shavings

6.4.1.2 Objective Function

The object of this optimization problem was to maximize the total EBITDA (for simplicity, EBITDA is referred to "earnings" in all subsequent text) from BC's primary forestry sector in 2007. This is the sum of

all the earnings from each forest product mill category within BC. The total industrial roundwood input, average transportation costs and other market conditions including forest product prices, manufacturing costs, labor costs, exports and imports were unchanged in the model and the final output volumes, industrial roundwood input volumes distributed amongst manufacturing facilities and by-products flows were varied. The total EBITDA was obtained from the formula below:

Maximize Total EBITDA¹ = Revenue from final product sales

- + Revenue from exporting/selling wood by-products (chips and SS)
- Cost of purchasing delivered sawlogs and veneer logs
- Cost of purchasing delivered pulpwood
- Cost of manufacturing final products (excluding wood fibre material cost)
- Cost of processing chips at the chip mill
- Cost transporting by-products (chips and SS)

Each of the above terms can be expressed using the parameters and variables defined in Table 6-3 as shown in Equations 6-1 to 6-7:

Revenue from selling final products =
$$\sum_{i} P_{i}^{FP}$$
. Y_{i}^{FP} Equation 6-1

Revenue from exporting/external selling by-products (chips and SS)

$$= E^{\text{chip}} \cdot \sum_{i} (Z_i^{\text{Chip, out}} - Z_i^{\text{Chip, in}}) + E^{\text{SS}} \cdot \sum_{i} (Z_i^{\text{SS, out}} - Z_i^{\text{SS, in}})$$
Equation 6-2

Cost of purchasing delivered sawlogs and veneer logs (industrial roundwood excluding pulpwood)

$$=\sum_{i} P_{sv} X_{i}$$
 Equation 6-3

Cost of purchasing delivered pulpwood = $\sum_{i} P_{pw}$. X_i Equation 6-4

Cost of manufacturing final products = $\sum_{i} C_{i}^{\text{FP}}$. Y_{i}^{FP} Equation 6-5

¹ Note that chips from chip mills were considered to be wood by-products rather than the final products, i.e. $a_6^{FP}=0$. Also, the revenue from intra-provincial by-products sales did not contribute to the total earnings of the provincial forestry sector.

Cost of processing chips at the chip mill = C^{Chip} . $Z_6^{\text{Chip, out}}$	Equation 6-6
--	--------------

By-products transportation cost= T. $(Z_i^{\text{Chip, in}} + Z_i^{\text{SS, in}})$.D Equation 6-7

To facilitate cost calculations for fibre inputs in various forms, the manufacturing costs used in this optimization model (Appendix H) excluded the cost of delivered wood material input. In this model, delivered wood fibre input costs were accounted for individually. The total industrial roundwood input cost for the entire industry was the combined cost of delivered saw logs and veneer logs and pulpwood. Intra-provincial sales of wood by-products were not accounted for when the total revenue from all provincial forest product mills was considered. Whereas, the transportation cost of by-products is an important part of the total cost for the provincial forest products industry (Equation 6-7). In addition, the transportation costs of sawlogs and veneer logs, pulpwood purchases, exports and imports have already been accounted for in the delivered log sales prices (Equations 6-3 and 6-4). Furthermore, the transportation of final products was beyond the material flow boundary.

6.4.1.3 Constraints

The major constraints applied in the optimization model were supply and demand constraints and other quantity limitations Equations 6-9 to 22.

• Supply Constraints

In scenario 1, the supply of industrial roundwood (sum of sawlogs and veneer logs and pulpwood) to the industry in 2007 was a constant value. Volumes of final products and by-products were obtained by multiplying the yields of final products and by-products by the total material inputs to the mills. The yields used were those presented in Chapter 5 for 2007 (Appendix G). In addition, the by-products supply was assumed to be greater than, or equal to, the demand. The following equations were used in the model.

Total supply of logs was fixed:
$$\sum_i X_i = S$$
 Equation 6-8

The outputs of final products:
$$Y_i^{\text{FP}} = \alpha_i^{\text{FP}} \cdot (X_i + Z_i^{\text{Chip, in}} + Z_i^{\text{SS, in}})$$
 Equation 6-9

Chips produced in wood products manufacturing subsector mills: $Z_i^{\text{Chip, out}} = \alpha_i^{\text{Chip}} \cdot (X_i + Z_i^{\text{Chip, in}} + Z_i^{\text{SS, in}})$ Equation 6-10

Sawdust and shavings produced in wood products manufacturing subsector mills:

$$Z_i^{\text{SS, out}} = \alpha_i^{\text{SS.}} (X_i + Z_i^{\text{Chip, in}} + Z_i^{\text{SS, in}})$$
Equation 6-11

The quantity of chips produced by all wood products manufacturing mills could not be less than the quantity consumed in total:

$$\sum_{i} (Z_{i}^{\text{Chip, out}} - Z_{i}^{\text{Chip, in}}) \ge 0$$
Equation 6-12

The quantity of sawdust and shavings produced by all wood products manufacturing mills could not be less than the quantity consumed in total:

$$\sum_{i} (Z_i^{\text{SS, out}} - Z_i^{\text{SS, in}}) \ge 0$$
 Equation 6-13

• Demand Constraints

In the scenario 1, the minimum demand of final products was set 30% below the final product outputs in 2007, whereas, the maximum demand was set at 30% above the final products output in 2007:

The minimum demands for all final products should be met: $Y_i^{\text{FP}} \ge D_i^{\text{FP, min}}$ Equation 6-14

Final products produced should not exceed the maximum demands: $Y_i^{\text{FP}} \le D_i^{\text{FP, max}}$ Equation 6-15

• Other Quantity Limitations

Some other quantity limitations were considered in the model. First, mills 1-6 didn't utilize by-products as their fibre inputs. Second, the total fibre input to any mill was set to be less than or equal to the input capacity. Furthermore, veneer and plywood mills were considered to be two separate mill categories with plywood mills only consuming veneer produced by BC's veneer mills. Therefore, the total input of veneer logs to the aggregated veneer and plywood mills should be less than the aggregated manufacturing capacity of the veneer mills. This quantity constraint was also applied to pulp and paper mills. Consequently, the total wood material input to both pulp mills and paper mills should not exceed the manufacturing capacity of the aggregated pulp mills. These limitations are stated mathematically in Equations 6-17 to 6-22.

Mills 1-6 did not take any chips as input: $Z_i^{\text{Chip, in}} = 0; i = 1, 2,, 6$	Equation 6-16
Mills 1-6 did not take any sawdust and shavings as input: $Z_i^{SS, in} = 0; i = 1, 2,, 6$	Equation 6-17
The input capacity of each mill could not be exceeded: $X_i \leq Cap_i$	Equation 6-18

The total input for veneer and plywood mill could not exceed the capacity of the veneer mill:

$$X_3 + X_4 \le Cap_{3}$$
 Equation 6-19

The total input for pulp and paper mills could not exceed the capacity of the pulp mill: $X_9 + X_{10} \le Cap_9$

Equation 6-20

All variables were non-negative: $X_i \ge 0, Y_i \ge 0, Z_i^{\text{Chip, out}} \ge 0, Z_i^{\text{Chip, in}} \ge 0, Z_i^{\text{SS, out}} \ge 0, Z_i^{\text{SS, in}} \ge 0$

Equation 6-21

In summary, scenario 1 is mathematically expressed as:

Maximize:
$$\sum_{i} P_{i}^{\text{FP}} \cdot Y_{i}^{\text{FP}} + E^{\text{chip}} \cdot \sum_{i} (Z_{i}^{\text{Chip, out}} - Z_{i}^{\text{Chip, in}}) + E^{\text{SS}} \cdot \sum_{i} (Z_{i}^{\text{SS, out}} - Z_{i}^{\text{SS, in}})$$

- $\sum_{i} P_{sv} \cdot X_{i} - \sum_{i} P_{pw} \cdot X_{i} - \sum_{i} C_{i}^{\text{FP}} Y_{i}^{\text{FP}} - C^{\text{Chip, out}} \cdot Z_{6}^{\text{Chip, out}} - \text{T.} (Z_{i}^{\text{Chip, in}} + Z_{i}^{\text{SS, in}}).\text{D}$
Over $X_{i}, Y_{i}, Z_{i}^{\text{Chip, out}}, Z_{i}^{\text{Chip, in}}, Z_{i}^{\text{SS, out}}, Z_{i}^{\text{SS, in}}$

Subject to:

$$\begin{split} \sum_{i} X_{i} &= S \\ Y_{i}^{\text{FP}} &= \alpha_{i}^{\text{FP}} \cdot (X_{i} + Z_{i}^{\text{Chip, in}} + Z_{i}^{\text{SS, in}}) \\ Z_{i}^{\text{Chip, out}} &= \alpha_{i}^{\text{Chip}} \cdot (X_{i} + Z_{i}^{\text{Chip, in}} + Z_{i}^{\text{SS, in}}) \\ Z_{i}^{\text{SS, out}} &= \alpha_{i}^{\text{SS}} \cdot (X_{i} + Z_{i}^{\text{Chip, in}} + Z_{i}^{\text{SS, in}}) \\ \sum_{i} (Z_{i}^{\text{Chip, out}} - Z_{i}^{\text{Chip, in}}) \geq 0 \\ \sum_{i} (Z_{i}^{\text{SS, out}} - Z_{i}^{\text{SS, in}}) \geq 0 \\ Y_{i}^{\text{FP}} \geq D_{i}^{\text{FP, min}} \\ Y_{i}^{\text{FP}} \leq D_{i}^{\text{FP, max}} \\ Z_{i}^{\text{Chip, in}} = 0; i = 1, 2, \dots, 6 \\ Z_{i}^{\text{SS, in}} = 0; i = 1, 2, \dots, 6 \\ X_{i} \leq Cap_{i} \\ X_{3} + X_{4} \leq Cap_{3} \\ X_{9} + X_{10} \leq Cap_{9} \\ X_{i} \geq 0, Y_{i} \geq 0, Z_{i}^{\text{Chip, out}} \geq 0, Z_{i}^{\text{Chip, in}} \geq 0, Z_{i}^{\text{SS, out}} \geq 0, Z_{i}^{\text{SS, out}} \geq 0, \end{split}$$

6.4.2 Optimized Scenario 2: Fixed Demand with Flexible Log Mix Supply

In this scenario, in contrast to scenario 1, it was assumed that the outputs of all the final products were the same as those for the base scenario and the total industrial roundwood input to the mills was adjusted if the

material flow was reconstructed in the model. The objective function in optimizing scenario 2 was the same as scenario 1 which was to maximize the total EBITDA from BC's forest products industry. Most of the constraints in scenario 1 were also applied to this scenario, except for the supply of sawlogs and veneer logs and pulpwood and the demands for final products. In particular, the variable Y_i^{FP} was fixed to D_i^{FP} , where D_i^{FP} was the demand for final product *i*. Therefore Y_i^{FP} could not be used as an optimization variable. The total earnings were obtained from the maximizing total EBITDA formula. Each term in the equation is explained in Appendix L and could be expressed using the parameters and variables defined in Table 6-3. However, the constraints on the total supply of industrial roundwood and the minimum and maximum demands for final products used in scenario 1 were removed.

A detailed explanation of the terms in the objective function, the supply and demand constraints together with limitations and quality constraints are presented in Appendix L. The terms in the objective function and constraints for this scenario are listed in Appendix L. The optimization problem can be mathematically expressed as:

$$\begin{aligned} \mathbf{Maximize:} & \sum_{i} P_{i}^{\text{FP}} \cdot D_{i}^{\text{FP}} + E^{\text{chip}} \cdot \sum_{i} (Z_{i}^{\text{Chip, out}} - Z_{i}^{\text{Chip, in}}) + E^{\text{SS}} \cdot \sum_{i} (Z_{i}^{\text{SS, out}} - Z_{i}^{\text{SS, in}}) \\ & - \sum_{i} P_{sv} \cdot X_{i} - \sum_{i} P_{pw} \cdot X_{i} - \sum_{i} C_{i}^{\text{FP}} D_{i}^{\text{FP}} - C^{\text{Chip}} \cdot Z_{6}^{\text{Chip, out}} - \text{T.} (Z_{i}^{\text{Chip, in}} + Z_{i}^{\text{SS, in}}) \cdot D \\ \text{Over} & X_{i}, Z_{i}^{\text{Chip, out}}, Z_{i}^{\text{Chip, in}}, Z_{i}^{\text{SS, out}}, Z_{i}^{\text{SS, out}}, Z_{i}^{\text{SS, in}} \end{aligned}$$

Subject to:

$$D_i^{\text{FP}} = \alpha_i^{\text{FP}} \cdot (X_i + Z_i^{\text{Chip, in}} + Z_i^{\text{SS, in}})$$

$$Z_i^{\text{Chip, out}} = \alpha_i^{\text{Chip}} \cdot (X_i + Z_i^{\text{Chip, in}} + Z_i^{\text{SS, in}})$$

$$Z_i^{\text{SS, out}} = \alpha_i^{\text{SS}} \cdot (X_i + Z_i^{\text{Chip, in}} + Z_i^{\text{SS, in}})$$

$$\sum_i (Z_i^{\text{Chip, out}} - Z_i^{\text{Chip, in}}) \ge 0$$

$$\sum_i (Z_i^{\text{SS, out}} - Z_i^{\text{SS, in}}) \ge 0$$

$$Z_i^{\text{Chip, in}} = 0; i = 1, 2, ..., 6$$

$$X_i \le Cap_i$$

$$X_3 + X_4 \le Cap_3$$

$$X_9 + X_{10} \le Cap_9$$

$$S \ge 0, X_i \ge 0, Z_i^{\text{Chip, out}} \ge 0, Z_i^{\text{Chip, in}} \ge 0, Z_i^{\text{SS, out}} \ge 0, Z_i^{\text{SS, out}} \ge 0, Z_i^{\text{SS, in}} \ge 0$$

6.5 Results and Discussions

6.5.1 Optimized Material Flow Results

Material flow for BC's forest products industry in 2007 was amended by using the mill indices in the optimization model (Table 6-2). BC's base scenario and optimized wood material utilizations in scenarios 1 and 2 are depicted in Figures 6-3 to 6-5, respectively. To ensure consistent comparisons, the total industrial roundwood inputs in both the base scenario and the optimized scenario 1 were 71.7 Mm³ GSWE and the total forest products outputs in both the base scenario and the optimized scenario 2 were 50.8 Mm³ GSWE (Figures 6-3 to 6-5 and Table 6-2). It should be noted that GRWE and GSWE can be used interchangeably only when the green volume of industrial roundwood is totally accounted for.

The most significant change in both optimized scenarios was the allocation of industrial roundwood flowing to the ten aggregated mill categories.

First, in both optimized scenarios 1 and 2, the supply of pulpwood to chip mills decreased and was reallocated to other mill categories. The costs incurred by chip mills consist of the delivered pulpwood cost, the chipping manufacturing cost and the by-products transportation cost from the chip mill to the other mills that utilize these by-products. The principal driver to reduce the input to chip mills was the reduction in by-products transportation costs which would be avoided if the chipping facility was located at the pulp mill. The total pulpwood input into the pulp and paper mill to be directly chipped in optimized scenarios 1 and 2 were nine and eight times that of the base scenario, respectively. Therefore, it was unprofitable to chip the pulpwood at chip mills given the conditions that existed in both optimized scenarios.

Second, the industrial roundwood input to the pulp and paper manufacturing subsector increased with unchanged or decreased inputs to the wood products manufacturing subsector. In scenario 1, with the fixed total input constraint, 19.0 Mm³ GSWE of the industrial roundwood input in the wood products manufacturing subsector was reallocated to the pulp and paper manufacturing subsector. In contrast, under the flexible total input conditions of scenario 2, the industrial roundwood input to the pulp and paper manufacturing subsector was tripled with an unchanged wood products manufacturing input. The focus on maximizing production in the pulp and paper manufacturing subsector was driven by the higher revenue margin in that subsector compared to the wood products manufacturing subsector (Appendix H).



* This key applies to Figures 6-3 to 6-5.

Figure 6-3: BC's Wood Material Flow in the Base Scenario, 2007 (Unit: Mm³ GSWE)


Figure 6-4: BC's Wood Material Flow in the Optimized Scenario 1, 2007 (Unit: Mm³ GSWE)



Figure 6-5: BC's Wood Material Flow in the Optimized Scenario 2, 2007 (Unit: Mm³ GSWE)

6.5.1.1 Comparisons of Wood Material Flows in Three Scenarios

Comparisons of wood fibre allocation and utilization amongst the base scenario and optimized scenario 1 and 2 are presented in Table 6-4.

Comparing with the base scenario, with the fixed supply in the optimized scenario 1, the total industrial roundwood flowing into the wood products manufacturing subsector was reduced by 31.5%. Most of the reduction was occurred in sawmills and structural panel mills and this resulted in the total pulpwood input to the pulp and paper manufacturing subsector being approximately eight times that of the base scenario. Consequently, the proportional pulpwood input increased from 11.3% in the base scenario to 37.8% in the optimized scenario 1. The entire input to chip mills has been reallocated to pulp mill in optimized scenario 1.

The distribution of final products outputs between the two predominant manufacturing subsectors has been adjusted in the optimized scenario 1 to obtain the maximum earnings for BC's primary forest products industry. With the fixed supply, the total output of the forest products in 2007 declined by 6.02 Mm³ GSWE, or 11.9%, in the optimized scenario 1, wood products manufacturing products decreased by 10.4 Mm³ GSWE, whereas, the output from the pulp and paper manufacturing subsector increased by 30.0% in this scenario. This may have resulted from the higher earnings in the pulp and paper manufacturing subsector than for structural products in 2007 (Table 6-4).

In optimized scenario 2, all ten mill categories used the same outputs and yields as in the base scenario and there was less room to optimize the industrial roundwood supply compared with optimized scenario 1. Therefore, finding the best use of by-products became an important means of maximizing the total earnings. The increased wood fibre input for this scenario arose from the additional 18.3 Mm³ GSWE pulpwood input to the pulp and paper manufacturing subsector, which caused the total industrial roundwood input to increase by 25.6% compared with the base scenario. Consequently, the proportional pulpwood input in the optimized scenario 2 exhibited an 18.9% increase beyond that of the base scenario (Table 6-4).

Scenarios		Base	Scenario			Optimize	d Scenario 1	l		Optimize	d Scenario 2	2
N.4211	InRw	Log_SV	Log_PW	FP	InRw	Log_SV	Log_PW	FP	InRw	Log_SV	Log_PW	FP
IVIIII	Input	Input	Input	Output	Input	Input	Input	Output	Input	Input	Input	Output
Lumber	56.6	56.6		26.7	39.7	39.7		18.7	56.7	56.7		26.7
OSB	2.53		2.53	2.35	1.77		1.77	1.65	2.53		2.53	2.35
Veneer	2.24	2.24		1.25	1.56	1.56		0.88	2.23	2.23		1.25
Plywood	2.83	2.83		1.58	1.98	1.98		1.11	2.82	2.82		1.58
Other Mills	1.97	1.97		1.08	1.37	1.37		0.76	1.96	1.96		1.08
Other Panel	0.08		0.08	0.69	0.31		0.31	0.90	0.30		0.30	0.69
Chip	2.78		2.78									
Pellet				2.50	0.58		0.58	1.75	0.95		0.95	2.50
Pulp	1.79		1.79	9.65	18.2		18.2	12.5	16.0		16.0	9.65
Paper	0.92		0.92	5.01	6.29		6.29	6.51	6.58		6.58	5.01
WPM	69.0	63.6	5.39	36.1	47.3	44.6	2.66	25.7	67.5	63.7	3.78	36.1
PM	2.71		2.71	14.7	24.5		24.5	19.1	22.6		22.6	14.7
Total	71.7	63.6	8.10	50.8	71.7	44.6	27.1	44.7	90.1	63.7	26.4	50.8

 Table 6-4: Industrial Roundwood Input and Final Products Output Comparisons in the Three Scenarios (Mm³ GSWE)

Notes: InRw: Industrial roundwood; SV: Sawlogs and veneer Logs; PW: Pulpwood; FP: Forest products

"--" Refers to 0.

6.5.1.2 Comparisons of By-Product Flows in Three Scenarios

By-products are supplied from mills in the wood products manufacturing subsector and chip mills in the pulp and paper manufacturing subsector. However, this study did not consider chips, sawdust and shavings that from directly chipped pulpwood were by-products to pulp and paper mills. Total by-products produced in the optimized scenarios 1 and 2 were decreased by 34.7% and 7.41%, respectively, compared to the base scenario (Table 6-5). The reduction in by-products flows in the optimized scenario 1 resulted mainly from a reduced volume of lumber production. In contrast, in optimized scenario 2, the decreased supply of by-products supply in optimized scenario 1, the additional 19.0 Mm³ GSWE of the pulpwood supplied to the pulp and paper manufacturing subsector caused the total pulp and paper output to be increased by 30.0%.

M:II	Base S	cenario	Optimized	Scenario1	Optimized	l Scenario2
	S_chip	S_SS	S_chip	S_SS	S_chip	S_SS
Lumber	21.4	8.55	15.1	5.95	21.5	8.51
OSB		0.18		0.12		0.18
Veneer	0.78	0.18	0.56	0.13	0.80	0.18
Plywood	1.05	0.23	0.71	0.16	1.02	0.23
Other Mills	0.63	0.25	0.44	0.18	0.63	0.26
Other Panel		0.30		0.40		0.31
Chip	2.55	0.24				
Pellet						
Pulp						
Paper						
Total Supply	26.4	9.93	16.8	6.94	24.0	9.65
Total By-Products Supply	36	.3	23	.7	3.	3.6
Total External Sales	1.0)6	7.1	10	24	4.0
Total By-Products Loss	4.2	27				
By-Products Utilized in BC Mills	31	.0	16	.6	9.	.66

Note: A blank field infers that the value is 0.

The gap between the demand and supply of by-products in all three scenarios was the combined volume of chips sales and by-products losses (Tables 6-5 and 6-6). In the base scenario, 1.06 Mm³ GSWE chips were sold to users outside the study region and 4.27 Mm³ GSWE by-products, consisting 0.27 Mm³ GSWE chips

and 4.00 Mm³ GSWE sawdust and shavings, were accounted for as material losses. This part of the by-products was considered to be either land-filled or burnt without energy recovery. In both optimized scenarios, materials losses were minimized to zero. In both optimized scenarios, all the available by-products were used as an additional raw material by BC mills to reduce raw material costs or sold to external users for an income (Table 6-5).

After external sales and losses were accounted for, the total by-products utilized as an additional fibre input in BC mills were 16.6 and 9.66 Mm³ GSWE in the optimized scenarios 1 and 2 respectively. Therefore, in all three scenarios the total by-products supply and demand was balanced (Tables 6-5 and 6-6).

	Base Scenario		Optimized	Scenario1	Optimized Scenario2	
Mill	D_chip	D_SS	D_chip	D_SS	D_chip	D_SS
Lumber						
OSB						
Veneer						
Plywood						
Other Mills						
Other Panel		0.92	0.51	0.48		0.70
Chip						
Pellet		2.58	0.64	0.58		1.63
Pulp	16.5	1.60	4.41	3.02		3.68
Paper	8.52	0.83	4.14	2.86		3.65
WPM	0.00	3.50	1.15	1.06		2.33
PM	25.1	2.43	8.55	5.88		7.33
Total Demand	25.1	5.93	9.70	6.94		9.66
Total By-Products Demand	31.	0	16.	6	9.60	5

Table 6-6: Comparisons of By-Products Demand amongst Three Scenarios

Note: A blank field infers that the value is 0.

Chips were categorized as higher value by-products than sawdust and shavings due to their higher sale price (Appendix H). In both optimized scenarios, the demand for by-products declined due to the increased supply of pulpwood. In particular, the volume of chips consumed in the optimized scenario 1 was 38.7% of that base scenario. In the optimized scenario 2, rather than being utilized in BC mills, the chips from the wood products manufacturing subsector and chip mills were sold to external mills beyond the studied material flow boundary to gain extra income.

6.5.2 Material Utilization Efficiency

Material utilization efficiency has been defined as the ratio of total output to the total industrial roundwood input when both variables are measured in Mm³ GSWE (Section 5.2.2.1). The total output is comprised of all forest products outputs, including those by-products that were sold externally.

The cumulative fibre input is considered to be the total fibre input in various forms to all of the province's forest products manufacturing facilities (Table 6-7). This fibre input comprised the virgin fibre from industrial roundwood (sawlogs and veneer logs) and that part of by-products created from the upstream mills and re-utilized by the downstream mills. The cumulative fibre input (excluding chips external sales) decreased by 14.7 and 3.2 Mm³ GSWE, respectively, in the two optimized scenarios. The decreased cumulative fibre input volume doesn't necessarily indicate that the by-products products manufacturing subsector relying more on pulpwood supplies than by-products provided by the wood products manufacturing subsector. Therefore, revenue from external sales of chips might be an important driver that would reduce by-products utilization in the BC manufacturing subsector. Additionally, the wood by-products losses from the manufacturing subsector in both optimized scenarios 1 and 2 were reduced to zero from 4.27 Mm³ GRWE in the base scenario (Table 6-7).

	Dece G	Optimized Optimized				
Input and Output	Dase Scenario	Scenario 1	Scenario 2	Changes in Optimized	Changes in Optimized	
(Mm ³ GSWE)	(Mm ³ GSWE)	(Mm ³ GSWE)	(Mm ³ GSWE)	Scenario 1 (%)	Scenario 2 (%)	
Total Industrial Roundwood Input	71.7	71.7	90.1	0.00%	25.6%	
Total By-Products Utilized	31.0	16.6	9.66	-46.5%	-68.8%	
Cumulative Fibre Input	102	00 2	00.8	14.00/	-2.90%	
(Excluding External Chip Sales)	105	88.5	99.8	-14.0%		
AII4 (Excluding External Chip Sales)	70.7	64.6	66.1	-8.63%	-6.51%	
Total Final Products Output	50.8	44.7	50.8	-11.9%	0.0%	
Chips for External Sales	1.06	7.10	24.0	570%	2,163%	
Total Output including Chips Exported	51.8	51.8	74.8	0.04%	44.2%	
Material Utilization Efficiency (%)	72.2%	72.3%	83.0%	0.04%	14.9%	

Table 6-7: Comparisons of Material Utilization Efficiency amongst Three Scenarios

The total forest products output was increased slightly by 0.04% compared to the base scenario, caused by the 6.02 Mm³ GSWE decrease in total final products output and the 6.04 Mm³ GSWE increase in external

sales of chips. This small increase in the total products output and a consistent industrial roundwood supply resulted in a 0.10% increase in the material utilization efficiency in the optimized scenario 1 compared to the base scenario (Table 6-7). In scenario 2, the greater pulpwood input resulted in the total industrial roundwood supply increasing by 25.6%, and consequently, the total merchantable outputs increased by 44.2%. The material utilization efficiency in scenario 2 increased to 83.0%, the highest value observed in any of the scenarios.

6.5.3 Economic Benefits

6.5.3.1 Value Added

Value added is quantified in the various wood products processes within the value chain boundary defined in Figure 6-2 (Section 5.2.2.2). Comparisons of value added from each mill category, subsector and value added per unit fibre input in the three scenarios are presented in Tables 6-8 and 6-9.

The total input to each mill category was quantified by the combination of industrial roundwood and wood by-products consumed in Mm³ GSWE. After material flows were reallocated under the constraints presented in Sections 6.4.1.3 and 6.4.2, the total provincial manufacturing sector earning from scenarios 1 and 2 increased by 229% and 65.9%, respectively, (Table 6-8). In the adjusted scenarios 1 and 2, total manufacturing subsector value added obtained a 14.8% and 26.6% increases, respectively, compared to the base scenario (Table 6-8). These earnings are prior to any considerations of the additional costs that may occur when the additional existing manufacturing capacity is utilized or current operation lines are closed.

Wood pulping was the manufacturing process that added the greatest value followed by sawmilling. Wood pulp and lumber were therefore the two predominant products arising from the wood products manufacturing and pulp and paper manufacturing subsectors. The value added obtained from the pulp and paper manufacturing subsector increased from 55.3% of the total value added in the base scenario to 67.0% in optimized scenario 1. In contrast, the value added obtained from the wood products manufacturing subsector decreased from 44.7% of the total in the base scenario to 33.0% in optimized scenario 1. The substantial increase of chips exports in Scenario 2 resulted in a smaller pulp and paper manufacturing value added and smaller pulp and paper manufacturing subsector value added the opposite trend with greater wood products manufacturing value added and smaller pulp and paper manufacturing subsector value add than that in the base scenario (Table 6-8). These changes were caused by diverting more material to the manufacturing options that have the greatest earnings potential given capacity, supply and price constraints.

From the perspective of value added per unit fibre input, in the base scenario, the other panel mill category created the greatest value added per unit of fibre input at 135 C\$/Mm³GSWE, with the pulp and paper mills ranking second and third at 81.9 and 80.3 C\$/Mm³GSWE, respectively. In contrast, despite the absolute size

of its value added, lumber's value added from each cubic metre of log input was relatively low at 25.8 C/Mm³ GSWE, approximately one third of the value achieved by pulp. All mills, with the exception of chip mills, created value. OSB mills created the lowest values in accordance with 2007's market conditions and (Table 6-8).

]	Base Scena	ario	Optimiz	ed Scenari	o 1	Optimi	zed Scena	rio 2
	Value	Cumulative	Value	Value	Cumulative	Value	Value	Cumulative	Value
Gross value Added	Added	Fibre Input	Added/AII4	Added	Fibre Input	Added/AII4	Added	Fibre Input	Added/AII4
Irom Willis	(Million	(Mm ³	(C\$/m ³	(Million	(Mm ³	(C\$/m ³	(Million	(Mm ³	(C\$/m ³
	C\$)	GSWE)	GSWE)	C\$)	GSWE)	GSWE)	C\$)	GSWE)	GSWE)
Lumber	1,458	56.6	25.8	1,019	39.7	25.7	1,455	56.7	25.7
OSB	49.3	2.53	19.5	34.5	1.77	19.5	49.3	2.53	19.5
Veneer	73.7	2.24	32.9	51.9	1.56	33.2	74.1	2.23	33.2
Plywood	103.1	2.83	36.4	72.4	1.98	36.7	103	2.82	36.7
Other Mills	60.7	1.97	30.8	42.8	1.37	31.2	61.2	1.96	31.2
Other Panel	135.0	1.00	135	156	1.30	120	130	1.00	130
Chip	-14.3	2.78	-5.15						
Pellet	77.6	2.58	30.1	21.5	1.80	11.9	54.9	2.58	21.3
Pulp	1,632	19.9	81.9	2,261	25.6	88.3	1,792	19.7	91.0
Paper	824	10.3	80.3	1,158	13.3	87.1	944	10.2	92.3
Extra By-Product Sales	42.5			284			961		
Total Value Added	4,442			5,101			5,624		
Delivered Logs Cost	-5,038			-4,365			-5,755		
Transportation Cost	-155			-83.0			-48.2		

Table 6-8: Comparisons of Value Added from Mill Categories amongst Three Scenarios

Notes: Negative values means the finished product has less value that the input materials. A blank field infers that the value is 0.

The value added per unit of fibre input for the entire manufacturing subsector increased from $62.9 \text{ C}/\text{m}^3$ GSWE in the base scenario to 78.9 and 85.1 C/m³ GSWE in scenarios 1 and 2, respectively (Table 6-8). This showed that reallocation of fibre flows in response to prevailing market conditions was one means of increasing the value added per unit of fibre input. It should also be highlighted that the demand, supply and prices of products are dynamic and therefore ongoing adjustments for fibre flows will be required to continue to provide the greatest value addition. These changes in fibre flow will need to occur at the enterprise level because this is the point at which manufacturing decisions are made. The benefits of

developing a more responsive fibre flow framework therefore needs to be explored at the scale of an integrated forest products company and this concept is investigated in Chapter 7.

Value Added & Value	Conventional	Optimized	Optimized	Changes in Optimized	Changes in Optimized
Added per Input	Scenario	Scenario 1	Scenario 2	Scenario 1 (%)	Scenario 2 (%)
EBITDA (Million C\$)	500	1,648	830	229%	65.9%
WPM GVA (Million C\$)	1,986	1,682	2,889	-15.3%	45.5%
PM GVA (Million C\$)	2,457	3,419	2,735	39.2%	11.3%
Total AVA4 (Million C\$)	4,442	5,101	5,624	14.8%	26.6%
Total AII4	70.7	64.6	66.1	-8.63%	-6.51%
WPM GVA%	44.7%	33.0%	51.4%	-26.2%	14.9%
PM GVA%	55.3%	67.0%	48.6%	21.2%	-12.1%
WPM Return of Log_4 (C $^{m^3}$					
GSWE)	27.4	34.0	41.4	24.1%	51.1%
PM Return of Log_4 (C $^{m^3}$					
GSWE)	81.3	87.9	91.4	8.10%	12.4%
MS Return of Log_4 (C\$/m ³	62.9	78.9	85.1	25.6%	35.4%
GSWE)					

Table 6-9: Comparisons of Subsector Value Added and Value Added per Unit of Fibre Input amongstThree Scenarios

6.5.3.2 Value Creation along the Value Chain

The value added throughout the wood fibre flow network in the base scenario and the optimized scenarios 1 and 2 are depicted in Figures 6-6 to 6-8, respectively. Value added flows started with the negative values representing the costs of delivered logs and value added is created in the manufacturing processes. Values of by-products created from the wood products manufacturing mills were presented in positive numbers as the sale revenue and negative numbers as the raw material costs before they were consumed within the network (Figures 6-6 to 6-8).

Table 6-9 shows that the pulp and paper manufacturing subsector achieved a higher value added and a greater value added per unit of input than wood product manufacturing in the base scenarios. Therefore, in order to obtain the greatest value added from the provincial forest products industry in 2007, individual forest products companies should have maximized pulp and paper manufacturing by ensuring that the pulp and paper manufacturing subsector operated at full capacity. It is feasible to assume that instead of harvesting high grade sawlogs and veneer logs, more low-value pulpwood can be harvested to meet the

market demand of pulp and paper products at the time when this study was taken. Accordingly, in optimized scenarios 1 and 2, the supply of pulpwood to the pulp and paper manufacturing subsector was increased from 3.7% in the base scenario to 34.1% and 25.1%, respectively, to support increased pulp and paper productions (Figures 6-6 to 6-8). Because chip mills created negative value added in 2007, no industrial roundwood was allocated to produce chips at chip mills in both of the optimized scenarios to avoid the potential value losses (Table 6-8).

In addition, besides the manufacturing costs, which were considered in the mill earnings calculations, delivered logs (industrial roundwood) purchases and internally utilized by-products transportation were two important net costs. Despite the same industrial roundwood input, a greater proportion of pulpwood in optimized scenario 1 made the total delivered log costs 13.3 % lower than for the base scenario. In optimized scenario 2, the total industrial roundwood input was 25.6% greater than the base scenario. However, benefiting from the higher ratio of low-cost pulpwood input, the total delivered log costs were 14.2% more than the base scenario (Tables 6-4 and 6-8). In optimized scenarios 1 and 2, fewer by-products were transported and utilized intra-provincially due to the increased use of low-cost, directly chipped pulpwood. Consequently, the by-products transportation costs in the optimized scenarios 1 and 2 were respectively one half and one third those of base scenario (Figures 6-6 to 6-8 and Table 6-8).

In summary, fibre flow reallocation could increase value added per unit raw material input under certain supply and demand constraints and market conditions. It is therefore one means of improving the economic contributions from primary forestry manufacturing sector. Despite the improvement in economic outcomes obtained from the material flow adjustments in both optimized scenarios, the total value added per unit of input for BC's forestry manufacturing subsector remained consistently below that of Canada and the other forestry nations studied in Chapters 3 and 4 (Figure 3-5). This observation suggests that factors other than material flow reallocation should also be considered in order to enhance BC's forestry sector's economic outcomes.



* This key applies to Figures 6-3 to 6-5.

** By-products transportation costs, manufacturing costs and labor costs are not labelled in the figure

Figure 6-6: Value Creation along the Material Flow in the Base Scenario, 2007 (Unit: Million C\$)



* By-products transportation costs, manufacturing costs and labor costs are not labelled in the figure

Figure 6-7: Value Creation along the Material Flow in the Optimized Scenario 1, 2007 (Unit: Million C\$)



* By-products transportation costs, manufacturing costs and labor costs are not labelled in the figure

Figure 6-8: Value Creation along the Material Flow in the Optimized Scenario 2, 2007 (Unit: Million C\$)

6.5.4 Social Benefits

The number of employees and the employees per unit of cumulative fibre input were the two social benefit indicators used in this study and the data for these variables for each of the three scenarios are presented in Table 6-10.

In contrast to the approach used for the value added calculations, it was assumed that the employee per unit of input volume ratios (FTE/Mm³ GSWE) for each mill category obtained from the base scenario could be applied to estimate the employees needed by total cumulative fibre input in both scenarios 1 and 2. While it might be assumed that larger mills employ fewer people per unit of input volume input, data for the BC industry was insufficient to enable more precise analysis.

The total cumulative fibre inputs (obtained by aggregating the flows of industrial roundwood and by-products and adjusting for trade) to BC's forest products manufacturing subsector were 103 Mm³ GSWE, 88.4 Mm³ GSWE, and 99.7 Mm³ GSWE in the base scenario, the optimized scenarios 1 and 2, respectively. The industry provided 36,293 jobs in the base scenario, with 51% of the total employees working in lumber

mills. This was further confirmation lumber manufacturing was the predominant component of BC's forest products industry. Pulp mills were the second largest employer, accounting for 24% of the total employees (Tables 6-7 and 6-10). The other mills and the veneer and plywood mills had the highest employment per net fibre input, inferring that these mill categories were the most labor intensive. The pellet and paper mill categories employed the fewest people for each unit of material input.

For each million cubic metres of cumulative fibre input (both industrial roundwood and reused by-products) to the primary forest products manufacturing subsector, 506 workers were employed on average in the base scenario (Table 6-10).

	Base Scenario			Optimal S	cenario 1	Optimal Scenario 2	
	Cumulative	Employee	Employee/	Cumulative	Employee*	Cumulative	Employee*
WIIII	Fibre Input		Cumulated AII	Fibre Input		Fibre Input	
	(Mm ³ GRWE)	(Capita)	(Capita/ Mm ³ GRWE)	(Mm ³ GRWE)	(Capita)	(Mm ³ GRWE)	(Capita)
Lumber	56.6	18,518	327	39.7	12,988	56.7	18,555
OSB	2.53	653	258	1.77	457	2.53	652
Veneer	2.24	1,525	681	1.56	1,064	2.23	1,519
Plywood	2.83	2,213	782	1.98	1,544	2.82	2,206
Other Mills	1.97	2,977	1,511	1.37	2,077	1.96	2,967
Other Panel	1.00	399	399	1.30	519	1.00	399
Chip	2.78	449	162	0	0	0	0
Pellet	2.58	116	45.0	1.80	81	2.58	116
Pulp	19.9	8,682	435	25.6	11,148	19.7	8,575
Paper	10.3	761	74.1	13.3	985	10.2	758
Total	103	36,293	353	88.4	30,862	99.7	35,748
Employee/							
Cumulative AII		506		43	60	498	3

Table 6-10: Employment/Input and Employment Comparisons in Three Scenarios

*: The number of employees in optimized scenarios was calculated by multiplying the employee/input obtained from the base scenario to the volume of total wood fibre input.

In scenarios 1 and 2 (Table 6-10), the total employment and the employment per unit of cumulative fibre input decreased due to the reallocation of fibre away from the more labor intensive wood products manufacturing subsector to the less labor intensive pulp and paper manufacturing subsector. Total employment opportunities in the optimized scenarios 1 and 2 declined by 15.0% and 1.50%, respectively. This analysis indicated that although the total value added per unit fibre input was 1.26 and 1.35 times of that

the base scenario achieved (Table 6-10), 5,430 and 545 full time equivalent job positions would be lost in scenarios 1 and 2, respectively (Table 6-10). Consequently, compared to the base scenario, each unit of fibre input into BC's forest products industry required 76 and eight fewer employees in scenarios 1 and 2, respectively.

6.6 Conclusions and Recommendations for Future Studies

6.6.1 Conclusions

This chapter examined the optimization of material flows through BC's forest products value chain by using the actual material flows and market conditions in 2007 as the base scenario. Two alternate scenarios were evaluated. Scenario 1 was optimized using a constant supply with flexible demand situation, whereas scenario 2 was optimized under the circumstance of flexible supply with fixed demand. Changes of material distribution, value creation, material utilization efficiency and social benefits were then assessed.

Fibre inputs were reallocated to generate higher value creation and therefore, greater economic earnings could be obtained. Improved value added, value added per unit of input and material utilization efficiency were obtained in both of the optimized scenarios. The earnings for optimized scenarios 1 and 2 increased by 229% and 65.9% respectively compared to the base case and the total value added were 14.8% and 26.6% greater than in the base scenario, respectively.

Both scenarios sought to maximize production in the pulp and paper manufacturing subsector, increase the chips external sales and minimize inputs to wood products manufacturing subsector within the constraints set for each scenario. This circumstance was driven by the higher value creation of the pulp and paper manufacturing subsector and high earnings of chips production and export under the market conditions that prevailed during 2007. However, assuming the same levels of employment per unit cumulative fibre input in both optimized scenarios as in the base scenario, the major trade-off for the increased value creation was a decrease in total employment of 15.0% and 1.50%, for scenarios 1 and 2, respectively. This was driven by the reduction in the total volume of material input to the value chain.

This study confirmed that adjusting material flows though BC's forestry products value structure could improve the primary forest products industry's economic outcomes. Under the market conditions that prevailed during 2007, it was beneficial to maximize production within the pulp and paper manufacturing subsector. However, market conditions are dynamic and circumstances that favour the wood products manufacturing subsector more than the pulp and paper manufacturing component are also likely to occur. It would therefore be useful for the BC government to develop a more interactive and responsive provincial material flow model that incorporates up-to-date information on market conditions. However, the improved economic outcomes attained by the material flow adjustments did not increase BC's value added per unit of

input to the levels observed for Canada and several other forestry nations studied in Chapters 3 and 4. Hence, while material flow reallocation modelling provides useful insights with which to inform policy development other factors should also be considered in order to enhance the economic outcomes from BC's primary forestry sector.

6.6.2 Challenges and Recommendations

Developing optimization models could help the industry, government and academic researchers gain a better understanding of whether the current industry management was state-in-art and how improved socio-economic benefits could be obtained. However, there are many challenges and limitations for developing an optimization model to assist with decision makers in promoting the economic contributions from the forest products industry.

• Scenarios Representing Market Conditions

Economic benefits could be improved by reallocating the material flows in both scenarios discussed in this chapter. The function of the optimization model was either to increase the final outputs by using the constant quantity of total industrial roundwood supply or maintain the same outputs by reducing the supply. In the future, more scenarios could be discussed and chosen to assist with analyzing the vulnerability of current material flow system in response with the fluctuating market conditions. Price relations established by using historical lumber, pulp and paper and wood by-products price data covering several market cycles can be used to investigate how price fluctuations affect material flow through the value chain. The models could be made more responsive by incorporating shorter term changes in both material flows and market conditions.

• Price and Cost Assumptions

The prices and costs used in the model were average values for the industry in 2007. However, prices of delivered logs and final products varied with their grades and correlated applications. The uses of the average prices and the manufacturing costs for forest products affected the accuracy of the optimization outcomes.

• Mill Number and Capacity Assumptions

The scenarios discussed in this chapter were based on the mills running in the year 2007. The scenarios could be made more responsive by including changes to the numbers of mills during the study period. Furthermore, this model assumed that all mills could operate at their maximum capacities. In addition, no additional capital cost was specially considered to account for the expenditures of increasing or reducing production capacity. More detailed capacity cost study could be done by noting that mills could operate at

reduced capacities or, run over capacities by adding more shifts, hiring more employees, adding more equipment, or extending the shifts.

• Supply and Demand Balancing Assumptions

In order to better differentiate the industrial roundwood input grades and the associated the purchase prices, this study broke down industrial roundwood into 'sawlogs and veneer logs' and 'pulpwood' as harvested log inputs for BC's primary forest products industry. Both scenarios in this study indicated that based on 2007's market situation, it was more favorable to harvest more low-value pulpwood to produce more pulp and paper products and fewer large diameter sawlogs and veneer logs to produce less structural wood products. If such a scenario is maintained for the longer term, a concern about over-harvesting pulpwood and under-harvesting sawlogs and veneer logs may arise. However, this study focused only on a snapshot of the log supply and forest products demand in 2007. As discussed previously in Section 6.4, lumber and pulp and paper markets may move counter-cyclically over the long term. Demand for structural wood products for housing construction and consumer grade pulp and paper products vary with time and capacity constraints and these short-term counter-cyclical demand variations are likely to even out over the relatively long harvesting cycles practiced in BC. Therefore, a flexible supply chain that takes total industrial roundwood harvest to the most economic uses over a short period of time will likely provide useful benefits for the provincial forestry products industry.

A consideration of the challenges and limitations listed above could make the optimization results more accurate and responsive to the needs of decision makers.

CHAPTER 7 OPTIMIZATION OF WOOD FIBRE FLOWS: CASE STUDY IN A BRITISH COLUMBIAN FOREST PRODUCTS COMPANY

7.1 Introduction

Large companies that utilize several manufacturing sites may operate in an integrated or non-integrated mode (Clemente, 1998; Walter, 2008). An integrated company is the one that either functions at several points within a supply chain (termed a vertically integrated company) or at several locations linked by material flow at one point within a supply chain (termed a horizontally integrated company) (Afuah, 2001).

Several of BC's largest forest products companies are integrated. These companies have operations in either the wood products manufacturing subsector producing sawnwood and panel products or the pulp and paper manufacturing subsector with pulp and paper as their products, or both (MoFR, 2008b). Companies with integrated mills allocate their roundwood harvest across their manufacturing sites and wood by-products are transported among mills to maximize production efficiencies (Natural Resources Canada, 2008). Wood by-products including chips, bark, trim ends, sawdust and shavings are produced by sawmills during the lumber manufacturing process. They are utilized in other types of downstream mills, such as pulp mills, finger-joint mills, pellet plants and bioenergy plants. An historical evaluation of material flows in BC's forest products industry indicated that wood by-products utilization has become increasingly important (Chapter 5). In addition, this study revealed the importance of wood by-products in linking the predominant wood products manufacturing and pulp and paper manufacturing subsectors in the value chain. The complexity of by-products flows creates a range of utilization opportunities for integrated forest product companies and the optimized financial solution to this problem will vary with changes in feedstock costs, manufacturing expenses and market conditions.

Several previous studies have focused on optimizing lumber production to maximize the yield of salable timber (Martin, 2004; Steele, 1984; Stirling, 1998). During the North American lumber market downturn commencing in 2006 (Shepard and Sitar, 2010; Sianchuck et al., 2012), improved economic outcomes may have been possible by focusing more on pulp and paper manufacturing and wood by-products utilizations (Chapters 5 and 6). Prior to lumber manufacturing, bark is removed from the roundwood. Chips, sawdust and a small quantity of trim ends are by-products arising from the sawing process. Additionally, shavings and the major proportion of the trim ends are produced by the planing process. Generally, by-products typically account for about 50% - 60% of the industrial roundwood input by

volume in sawmills (FAO, 1990). In BC, chips and sawdust and shavings produced as by-products amounted to approximately 53% of the total industrial roundwood input to sawmills in 2009 (MoFR, 2011). Given the significant volumes of these materials, it is important to evaluate the optimal economic contributions that might be achieved from these by-products.

Previous studies revealed that the economic outcomes created per unit of input by Canada and its major forestry provinces have been relatively low historically (Chapters 3 and 4). Despite the similarities of the forest products industries in the two North American countries, the USA's AVA/AII values were 1.10 to 2.62 times greater than Canada's (Figure 3-5). Because the value creation process within a jurisdiction is operated by the enterprises rather than by the forest products manufacturing plants, the economic contributions achieved at national or provincial levels can only be increased if the operating enterprises increase their value added per unit material input. There are several tools which could potentially increase an enterprise's economic benefits, such as increasing value creation, improving material utilization efficiency, or both. Because the focus of this dissertation is the impact of material flows structure on socio-economic outcomes, and the wood by-products flow plays a significant role in the forestry sector structure, the objective of this chapter was to investigate the benefits of optimizing material flows within one integrated forest products company under specific market conditions to demonstrate the magnitude of the improvements that may be achieved by changing by-product flows.

7.2 Methodologies and Data Sources

In order to maintain confidentiality, the organization studied in this chapter is termed Company X. The conceptual material flow framework, indicating wood by-product sources and utilizations, for Company X's regional operations in the 2006 fiscal year is presented in Figure 7-1. Company X's mills are located within the box highlighted in light green and mills owned by other companies that consume some of company X's by-products are located outside this boundary (Figure 7-1).

There were six forest product mills located in the broad regional area that company X operated within, namely, two sawmills (sawmill 1 and sawmill 2), one finger joint (FJ) panel mill, one bleached softwood kraft pulp mill, one medium density fibreboard (MDF) mill and one pellet mill. The first four mills (excluding the pellet mill and the MDF mill) were owned by Company X. In this conceptual framework, the finger joint plant was considered to be two mills due to its dual functions: 1) a FJ_Lumber mill that produced lumber as the final product in the lumber production sector and 2) A FJ_Panel plant that manufactured finger joint panels as the final product in the wood by-products utilization sector. Therefore, in this conceptual framework, five mills were owned by company X and they manufactured the final products within the study region and they consisted of three lumber mills (two sawmills and one FJ_Lumber mill), one FJ_Panel plant, and one pulp mill (Figure 7-1).



Notes: FJ: Finger joint; MDF: Medium density fibreboard

Figure 7-1: Company X Fibre Flow Conceptual Framework

Lumber was the final product from the three lumber production mills and the FJ_Lumber mill provided some drying and planing facilities for rough lumber from sawmills 1 and 2 due to the limited capacities at these latter mills. Wood by-products were produced from all lumber mills.

An overview of Company X's typical sawmill manufacturing processes is presented in Figure 7-1. Lumber is the most important final product from the sawmills and it was manufactured after several processes. Chips, the most valuable wood by-product, were generated during the sawing process. In addition to the debarking process, bark could also be obtained from the unloading and sorting process when logs arrived at the log yard. Green sawdust and dry shavings were produced from the sawing and planing operations, respectively. Both the sawing and planing processes produced trim ends (Figure 7-2).

This case study aimed to analyze the current material flow web of wood fibre for Company X's five forest product mills in BC. It was hypothesised that an optimization model could be developed and applied to wood by-products utilization within this enterprise to maximize the total profit by reallocating wood fibre within the value chain.



Notes: BP= By-products; P:GR= Green rough lumber; P:KR= Kiln dried rough lumber; P:GD= Green dressed lumber; P:KD= Kiln dried dressed lumber

Figure 7-2: Generalized Production Flow Chart for a Company X's Sawmill

7.2.1 Methodologies

In this chapter, a material flow model was constructed for the regional operations of Company X in 2006. An optimization model was developed to simulate the fibre flow in the study region and to maximize the company's total economic benefits. Material flow calculations in the model were made on m³ GSWE basis.

7.2.1.1 Scenarios

Two scenarios were established to study the material flows for Company X, namely, the "base scenario" and the "optimized scenario". The base scenario described the original fibre flow for Company X's mills that existed in 2006 and calculated the economic benefit for Company X in that year. This scenario was used as the baseline for comparing the results obtained in the optimized scenario. The optimization model was developed assuming sale prices and costs that prevailed for BC companies on average in 2006.

7.2.1.2 Material Flow Boundary

The regional area used to develop the material flow network was established as the boundary for the wood fibre flows and trading for Company X's regional operations. The region considered included all five mills operated by Company X (FJ_lumber and FJ_Panel operations are located at the same mill) and two external mills which purchased the by-products from Company X.

7.2.1.3 Time Scale

The optimization model was developed to simulate the forest products manufacturing in all the mills within the study region for Company X in the 2006 fiscal year.

7.2.1.4 Conversion Factors

In order to facilitate material flow balancing, conversion factors (m³ GSWE /units of final forest products) were applied to convert all the volumetric and mass data to m³ GSWE for all material flow components. The detailed conversion factors used are presented in Chapter 5 and Appendix G.

7.2.2 Data Sources

Material inputs, product outputs, capacities of all the mills and all other data required were collected from Company X's confidential database. Manufacturing costs and sale prices data were obtained from various published sources, personal communication with the company employees and research professionals (CIBC, 2010; MoFR, 2007b, c; Wood Markets, 2009; 2005). Estimations were applied to get the average prices for the forest products and manufacturing costs when data were unavailable (Appendix M). The forest products sale prices, manufacturing costs and labor costs used (including delivered wood fibre input cost in 2006) are presented in Appendix M. All values were converted into a consistent unit of Canadian dollars per cubic metre of wood fibre output (C\$/m³ GSWE).

This study utilized commercially sensitive information. It was conducted on a confidential basis and all data obtained were kept in secure databases. Details of the company and individual mill operations were not published.

7.3 Base Scenario Description

The base scenario was set up based on the communication with company representatives during field trips. Data that was publicly available for 2006 fiscal year were also used.

Due to the limited kiln drying capacities at the sawmills and the availability of kiln drying capacity at the FJ_Lumber mill, 10% and 49% of the green rough lumber produced by sawmill 1 and sawmill 2, respectively, were delivered to the FJ_Lumber mill to be dried. In addition to its limited drying capacities, sawmill 1 had insufficient planing capacity and a quarter of the dried rough lumber from this sawmill was delivered to the FJ_Lumber mill to be planed. In addition, 39% of kiln dried rough lumber in the FJ_Lumber mill was transported back to sawmill 2 to be planed. The wood flows of the drying and planing processes amongst two sawmills (sawmill 1 and sawmill 2) and the FJ_Lumber mill were therefore relatively complex and they are illustrated in the lumber production section in Figure 7-3. Drying and planing volume losses arising from the rough green lumber transported amongst sawmill 1, sawmill 2 and the FJ_Lumber mill were not considered in this study.

Chips from the sawmills and the FJ_Panel plant were delivered to the pulp mill as a raw material for pulp production. Bark from both sawmills was transported to the pulp mill to be combusted in a cogeneration plant. MDF and pellet mills owned by different enterprises consumed sawdust and shavings from the two sawmills. Additionally, all the trim ends produced by the sawmills were utilized to produce finger joint panels. Final products manufactured in Company X mills in the base scenario are summarized in Table 7-1. In 2006, 735,000, 583,000 and 7,540 m³ GSWE of lumber, pulp and finger joint panels were produced, respectively. The total wood by-products generated by lumber manufacturing amounted to 953,000 m³ GSWE (Table 7-2). Chips were the main by-product accounting for 62.8% of the total by-products volume, arising from three lumber mills, whereas, trim ends had the smallest volume accounting for 3.98% of the total by-produced.



Note: The volumes of wood fibre the along material flow path were omitted from this diagram due to confidentiality requirements.

Figure 7-3: Schematic Diagram Wood Fibre Flow in the Base Scenario

Final Product	Mill	Base Scenario (000 m ³ GSWE)
Lumber	Sawmill 1	281
Lumber	Sawmill 2	238
Lumber	FJ_Lumber	216
Total Lumber	Three Lumber Mills	735
FJ Panel	FJ_fj	7.54
Pulp	Pulp Mill	583
Total	All Mills	1,326

Table 7-1: Final Products in Company X Mills in the Base Scenario, 2006

By-Products Produced	G '11 1	G		T ()
(000 m ³ GSWE)	Sawmill 1	Sawmill 2	FJ_Lumber Mill	Total
1_Chips	340	257	1.93	599
2_Bark	40.1	29.4	0	69.5
3_Sawdust	66.6	55.2	0	122
4_Shavings	57.9	54.7	13.1	126
5_Trim Ends	15.0	18.7	4.28	38.0
Total	519	415	19.3	953

 Table 7-2: Wood By-Products Production in the Base Scenarios, 2006

7.4 Optimization Modeling

In this section, a model was developed to describe the material flow within the company's regional area, to search for the best flow in the lumber production mills and to optimize by-product utilization to obtain the greatest economic outcome for Company X. Comparisons between the optimized scenario and the base scenario were undertaken to assess the changes in the economic benefits and material utilization efficiency that were achieved.

7.4.1 Objective Function

In this section, the model was focussed on maximizing economic earnings (EBITDA) obtained by Company X. The conceptual material model for the Company X material flow optimization study is presented in Figure 7-4.



Figure 7-4: Conceptual Material Flow Options for Company X

This study assumed that in a capitalist economy, wood and wood by-products would flow to their most beneficial long-term uses. Economic optimization was therefore the critical method that determined wood material flows. A computer-based mathematical model was developed using a linear programming approach to analyze the total EBITDA from all Company X's mills in the study area excluding interest, taxes, depreciation and amortization.

The objective function of this economic LP model was to maximize the total EBITDA (for simplicity, EBITDA is referred to 'earnings' in the text) for Company X as shown below:

Maximize EBITDA = Revenue from Final Lumber, FJ Panel and Pulp Products + Revenue from Wood By-Products Sales to External Mills – Final Lumber, FJ Panels and Pulp Manufacturing Costs (with delivered raw material cost) – Internal Rough Lumber Transportation Cost – Internally Used Wood By-Products Transportation Costs

Revenues for Company X were gained from sales of the final products (lumber, FJ panels and pulp) and from by-products sold to other companies. Costs consisted of the manufacturing costs of the final products and transportation costs of lumber transported amongst three lumber production mills and by-products consumed in internal mills. In this objective function, the manufacturing cost consisted of delivered wood material input, labor (direct operations and maintenance), energy, supplies (operations and maintenance) and other non-wood material costs (CIBC, 2010). The FJ panel plant and the pulp mill fully and partly utilized Company X's by-products. Therefore, the internal by-product costs and their transportation costs were already accounted for in the manufacturing costs. In contrast with the by-products purchased from other mills, by-products produced by the company's lumber production sector as the fibre input to the FJ panel plant and the pulp mill were considered to be cost free. It was assumed that the transportation costs and the prices of by-products purchased from other non-Company X mills and supplied by Company X's mills were the same. Additionally, with the assumption that lumber mill by-products were either used by Company X's mills or sold to external mills, the objective function was transformed to:

Maximize EBITDA = Revenue from Final Lumber, FJ Panel and Pulp Products + Revenue from Wood By-Products Produced (Both Sold to External Mills and Utilized in Internal Mills) – Final Lumber, FJ Panels and Pulp Manufacturing Costs (with Delivered Raw Material Cost) – Internal Rough Lumber Transportation Costs

7.4.2 Indices, Variables and Parameters

• Indices

The model indices are presented in Table 7-3. The indices are listed in supplier, product, by-products and by-products consumer categories.

Supplier Category		Product Category		By-products Category		By-products Consumer	
<i>i</i> =1	Sawmill 1	<i>i'</i> =1	Sawmill 1	<i>n</i> =1	Chips	<i>j</i> =1	MDF Mill
<i>i</i> =2	Sawmill 2	<i>i'</i> =2	Sawmill 2	<i>n</i> =2	Bark	<i>j</i> =2	Pellet Mill
<i>i</i> =3	FJ_Lumber	<i>i′</i> =3	FJ_Lumber	<i>n</i> =3	Sawdust	<i>j</i> =3	FJ_Panel
FJP	FJ_fj			<i>n</i> =4	Shavings	<i>j</i> =4	Pulp Mill
Pulp	Pulp Mill			<i>n</i> =5	Trim Ends		

Table 7-3: Indices in the Model

• Variables

The variables set up in this optimization model are listed in Table 7-4:

Variable	Definition
$\mathbf{X}_{i}^{\mathrm{Lumber}}$	Amount of lumber produced from supplier i to external consumers
X^{Pulp}	Amount of pulp produced from pulp mill to external consumers
\mathbf{X}^{FJP}	Amount of FJ panels produced from FJ_Panel plant to external consumers
$\mathbf{X}_{ijn}^{ ext{BP}}$	Amount of by-products number n produced from mill i to consumer j
$\mathbf{Y}^{\text{Lumber}}_{ii'}$	Amount of lumber from supplier i to supplier i' to be further processed rather than sold to the external customers

Table 7-4: Variables in the Model

• Parameters

The parameters included in the models are listed in Table 7-5. Since the FJ_Panel plant consumed trim ends, the index j = 3 was used for FJ_Panel as the by-products end user in the by-products utilization sector.

Parameter	Definition
$\mathbf{P}_i^{\mathrm{Lumber}}$	Selling price of lumber from supplier <i>i</i>
$\mathbf{P}^{\mathrm{FJP}}$	Selling price of FJ panels
$\mathbf{P}^{\mathrm{Pulp}}$	Selling price of wood pulp
$\mathbf{P}^{\mathbf{BP}}_{ijn}$	Selling price of by-product n from supplier i to consumer j
$\mathbf{P}_{i3n}^{\mathrm{BP}} = \mathbf{P}_{i4n}^{\mathrm{BP}} = 0,$	Revenues from selling by-products to the consumer FJ_Panel plant ($j=3$) and pulp
<i>i</i> =1, 2, 3; <i>n</i> =1, 2, 3, 4, 5	mill (<i>j</i> =4) were excluded when the total revenue from Company X was considered
$T^{Lumber}_{ii'}$	Cost of the transporting rough lumber from supplier i to supplier i'
$\mathbf{C}_i^{\mathrm{Lumber}}$	Cost of manufacturing lumber at supplier <i>i</i>
$\mathbf{C}_i^{ extsf{FJP}}$	Cost of manufacturing FJ panels at supplier <i>i</i>
$\mathbf{C}^{\mathrm{Pulp}}_i$	Cost of manufacturing pulp at supplier <i>i</i>
$\mathbf{S}^{ ext{Lumber}}_i$	Lumber production capacity at supplier <i>i</i>
$\mathbf{S}^{\mathrm{Pulp}}$	Pulp production capacity at supplier <i>i</i>
D ^{Lumber}	Total demand for lumber from external consumers
$\mathbf{D}^{\mathrm{Pulp}}$	Total demand for pulp from external consumers
D^{FJP}	Total demand for FJ panels from external consumers
$\mathbf{D}_5^{\mathrm{FJ}}$	Demand of FJ mill for trim ends $n = 5$
$D^{\text{LBP@Pulp Mill}}$	Demand for all by-products at the pulp mill
α_i	Yield of by-products from total lumber produced at mill i

Table 7-5: Parameters in the Model

Company X's mills produced three final products (lumber, pulp, finger joint panels) and five wood by-products (chips, bark, sawdust, shavings and trim ends). There were four end users of wood by-products from lumber production section, including the FJ_fj plant and pulp, pellet and MDF mills (Figure 7-3). FJ_Panel plant and pulp mill were owned by Company X. The pellet and MDF mills were owned by other companies and they purchased wood by-products from Company X. Wood by-products consumption in both the FJ_Panel plant and the pulp mill was considered to be internal consumption.

Each of the above terms in the objective function equation is defined below:

• Revenue

Revenue from final lumber, FJ panel and pulp sales = $\sum_{i=1}^{5} P_i^{\text{Lumber}} X_i^{\text{Lumber}} + P^{\text{FJP}} X^{\text{FJP}} + P^{\text{Pulp}} X^{\text{Pulp}}$

The revenue of the company was obtained by multiplying the selling price of each final product by the quantity of each final product sold to external customers.

Revenue from all by-products yielded from lumber manufacturing = $\sum_{i=1}^{3} \sum_{j=1}^{4} \sum_{n=1}^{5} P_{ijn}^{BP} X_{ijn}^{BP}$

The revenue from all by-products consisted of two parts: 1) Revenue from by-products sales to external mills and 2) The raw material costs saved by replacing a part of by-products purchased from external mills by Company X self-produced by-products from three lumber mills.

• Cost

Final lumber, FJ panels and pulp products manufacturing costs = $\sum_{i=1}^{3} C_{i}^{\text{Lumber}} X_{i}^{\text{Lumber}} + C^{\text{FJP}} X^{\text{FJP}} + C^{\text{Pulp}} X^{\text{Pulp}}$

Several assumptions were applied to determine the total manufacturing cost for the lumber mill, pulp mills and FJ panel plant as individual mill costs could not be published.

Rough Lumber transportation cost =
$$\sum_{i=1}^{3} \sum_{i'=1}^{3} T_{ii'}^{\text{Lumber}} Y_{ii'}^{\text{Lumber}}$$

In the base scenario, due to the limited capacities in sawmills 1 and 2, a part of the rough green lumber from both sawmills was transported to the FJ_Lumber mill to be dried and planed. Furthermore, a part of the dried lumber in FJ_Lumber mill was sent back to sawmill 2 to be further planed due to the insufficient planing capacity at the FJ_Lumber mill. Transportation amongst sawmill 1, sawmill 2 and the FJ_Lumber mill was an important component of the total cost for Company X.

In summary, the objective function is presented in Equation 7-1.

Maximize:

$$\sum_{i=1}^{5} P_{i}^{\text{Lumber}} X_{i}^{\text{Lumber}} + P^{\text{FJP}} X^{\text{FJP}} + P^{\text{Pulp}} X^{\text{Pulp}} + \sum_{i=1}^{3} \sum_{j=1}^{4} \sum_{n=1}^{5} P_{ijn}^{\text{BP}} X_{ijn}^{\text{BP}}$$
$$-\sum_{i=1}^{3} C_{i}^{\text{Lumber}} X_{i}^{\text{Lumber}} - C^{\text{FJP}} X^{\text{FJP}} - C^{\text{Pulp}} X^{\text{Pulp}} - \sum_{i=1}^{3} \sum_{i'=1}^{3} T_{ii'}^{\text{Lumber}} Y_{ii'}^{\text{Lumber}}$$
Equation 7-1

7.4.3 Constraints

The model was subjected to supply and demand constraints, manufacturing limitations, and quality constraints.

• Supply Constraints

The production of the final products could not exceed the capacities of all mills:

1) The volumes of lumber produced from sawmill 1, sawmill 2 and FJ_Lumber mill were less than their capacities, respectively: $X_i^{\text{Lumber}} \leq S_i = 1, 2, 3;$

2) The volume of pulp produced from pulp mill was less than its capacity: $X^{Pulp} \leq S^{Pulp}$;

3) The volume of finger joint panels produced from the FJ_Panel plant was less than its capacity:

$$X^{\text{FJP}} \leq S^{\text{FJP}}$$

• Demand Constraints

In this model, the demand of lumber, pulp and FJ panel products was the same as in the base scenario and the demand of each final product was always met by the supply.

1) Total lumber produced in sawmill 1, sawmill 2 and FJ_Lumber should satisfy the lumber market demand in 2006: $\sum_{i=1}^{5} X_{i}^{\text{Lumber}} = D^{\text{Lumber}}$ i = 1, 2, 3;

2) Total pulp product produced in pulp mill should satisfy the 2006's pulp market demand: $X^{Pulp} = D^{Pulp}$;

3) Total finger joint panels produced in FJ_Panel plant should satisfy the 2006's finger joint panels market demand: $X^{FJP} = D^{FJP}$.

• Manufacturing Limitations

In order to maximize the economic earnings for Company X, by-products played an important role in the value chain. The following limitations were set on by-products flows to satisfy the internal manufacturing demands and to reduce the cost of purchasing additional by-products from external mills.

1) The FJ_Lumber mill took only the rough green lumber from sawmills 1 and 2 for drying and planing after the roundwood was debarked and sawn in both sawmills. Therefore, FJ_Lumber produced neither bark (*n* =2) nor sawdust (*n* = 3): $X_{3j2}^{BP} = X_{3j3}^{BP} = 0$ *j*=1, 2, 3, 4, 5; 2) Based on the wood by-product characteristics, the FJ_Panel plant only consumed trim ends (n = 5) as its raw material input: $X_{i3n}^{BP} = 0$ i=1, 2, 3; n=1, 2, 3, 4;

3) The FJ_Panel plant was the priority end user of trim ends (n = 5) before considering other trim end consumers: $\sum_{i=1}^{3} X_{i35}^{BP} = D_5^{FJ}$;

4) Bark (*n* = 2), the least economic by-product, was prioritized to be initially consumed by the cogeneration plant located at the pulp mill (*j* = 4): $X_{ij2}^{BP} = 0$ *i*=1, 2, 3; *j*= 1, 2, 3;

5) In addition to bark, chips and other by-products were allocated to satisfy the demand of the pulp mill prior to considering other mills: $\sum_{i=1}^{5} X_{i4n}^{BP} = D^{BP@Pulp Mill}$ i=1, 2, 3.

• Quantity Constraints

1) In the optimization model, the volumes of by-products from sawmill 1, sawmill 2 and the FJ_Lumber mill were assumed to be proportional to the volumes of final lumber produced in each mill. The by-products yield ratio α (by-products (m³ GSWE) volume/lumber output volume (m³ GSWE)) obtained from the base scenario was used to determine the output of five by-products from each lumber mill. Furthermore, the final lumber volume produced by each mill was determined after taking account of the rough lumber transported within the lumber production sector (Figure 7-3). The ratio α of the five by-product volumes to the final lumber production from each lumber mill obtained from the base scenario's material flow in 2006 are presented in Table 7-6.

Table 7-6: Yield Ratio α for Wood By-Products in Three Lumber Mills for the Base Scenario (m³ GSWE/m³ GSWE)

			· · · · ·		
By-product	Chins	Bark	Sowdust	Shavings	Trim Ends
Category	Cinps	Dark	Sawdust	Shavings	TTIII Enus
Sawmill 1	1.21	0.14	0.24	0.21	0.05
Sawmill 2	1.08	0.23	0.23	0.12	0.08
FJ_Lumber Mill	0.01	0	0	0.06	0.02
Therefore the by	products' vi	ald constraints y	were set as: $\sqrt[4]{\sum} \sqrt[5]{\sum} x$	$X^{BP} = \alpha (X^{Lumber} + X^{Lumber})$	$\sum^{3} \mathbf{V}^{\text{Lumber}}$).

Therefore, the by-products' yield constraints were set as: $\sum_{j=1}^{n} \sum_{n=1}^{n} X_{ijn}^{BP} = \alpha_i (X_i^{Lumber} + \sum_{i'} Y_{ii'}^{Lumber});$

In addition, 0.46, 0.65, 0.45 and 0.95 m³ GSWE/m³ GSWE were the yields used in the optimization model for lumber, finger joint panel, softwood kraft pulp manufacturing and chipping process, respectively.

2) In order to ensure a good quality of pulp product, the maximum proportion of sawdust (n = 3) and shavings (n = 4) as a percentage of the total raw wood material to pulp manufacturing was set at 20%:

$$\sum_{i=1}^{3} (X_{i43}^{BP} + X_{i44}^{BP}) \le 0.2 \sum_{i=1}^{3} \sum_{n=1}^{5} X_{i4n}^{BP} ;$$

3) Additionally, no lumber could be transported to and from the same supplier: Y^{Lumber}_{ii} = 0 :=1, 2, 3;
4) Non-negativity constraints were set for all the variables and parameters:

 $X_{i}^{\text{Lumber}} \ge 0$ $X^{\text{Pulp}} \ge 0$ $X^{\text{FJP}} \ge 0$ $X_{ijn}^{\text{BP}} \ge 0$ $Y_{iji}^{\text{Lumber}} \ge 0$

In addition to the assumptions previously discussed, several other important assumptions were incorporated into the model. First, the manufacturing capacities in the region were considered to be constant during 2006. Second, rough lumber production and sales in both sawmills were excluded from the model due to lack of data. Third, the model assumed that the MDF mill and the pellet mill used all the excess wood by-products from Company X. Manufacturing cost at each mill with different yields were not disclosed for confidentiality reasons. In this study, each lumber manufacturing facility was assumed to have the same manufacturing cost despite the different mill capacities and lumber recovery factors.

7.5 Results and Discussions

7.5.1 Optimal Solution

This section describes maximization of the total earning under the optimized scenario. The variable X_{ijn}^{BP} in the model quantified five categories of by-products from sawmills and FJ_Lumber mill to the end users. The lumber transportation cost T_{ii}^{Lumber} was assumed to be proportional to the quantity of the products transported in the network. Consequently, this optimization model reallocated the wood fibre flows in the study region to find the best X_{ijn}^{BP} values in order to maximize the total earning from wood by-products utilization for Company X.

7.5.1.1 Optimized Material Flow

The Company X's optimized conceptual material flow of by-products utilization solution is depicted in Figure 7-5.

To simulate the market conditions in 2006, total lumber, FJ panels and pulp productions and sale prices for all the products were unchanged under optimized scenario. In the optimized scenario, the industrial roundwood supply into both sawmills and FJ_Lumber mill was redistributed in the lumber production sector. Compared to the base scenario presented, the utilization of by-products was more diversified and complex compared with the base scenario (Figures 7-3 and 7-5).



Notes: The optimized volumes of wood fibre along material flow were left out due to confidentiality requirements.

The thickness of the arrows in the wood by-products utilization sector represented the volumes of by-products.

Figure 7-5: Schematic Diagram of Company X's Optimized Conceptual By-Product Flow

7.5.1.2 Result Comparisons

A comparison of Company X's forest products outputs from all the mills in the base and optimized scenarios is presented in Table 7-7.

In the optimized scenario, the total lumber production from sawmill 1, sawmill 2 and the FJ_Lumber mill was unchanged despite the 157, 000 m³ GRWE (or 9.90%) increase in industrial roundwood input to Company X's three lumber mills. In addition, the quantities of pulp and FJ panels produced were identical in both scenarios. However, in the optimized scenario, the proportion of lumber produced at each mill

changed substantially. Lumber produced in sawmill 1 and sawmill 2 increased 4.80% and 34.1% by volume, respectively, whereas, the output at the FJ_Lumber mill decreased by 43.7% (Table 7-7).

Final Product	M:11	Base Scenario	Optimized Scenario	Change
	141111	(000 m ³ GSWE)	(000 m ³ GSWE)	(%)
Lumber	Sawmill 1	281	294	4.8%
Lumber	Sawmill 2	238	319	34.1%
Lumber	FJ_Lumber	216	122	-43.7%
Total Lumber	3 Lumber Mills	735	735	0.0%
FJ Panel	FJ_fj	7.54	7.54	0.0%
Pulp	Pulp Mill	583	583	0.0%
Total	All Mills	1,326	1,326	0.0%

Table 7-7: A Comparison of the Product Outputs for the Base and Optimized Scenarios

By adjusting the lumber production amongst the three lumber mills within their capacity constraints, the same lumber output was achieved, while the total production of by-products was increased by 16.5% in the optimized scenario. With the exception of shavings, which decreased by 14.5%, all other by-products increased by between 12.3% and 64.8% in the optimized scenario (Table 7-8).

The relatively low lumber and high pulp prices in the fibre products market during 2006 (Appendix M) provided an incentive for integrated companies to boost the production of by-products and pulp. This result highlighted the economic importance of the intermediate forest products. This study concluded that the maximum economic benefits would be achieved by directing as much wood fibre as possible to pulp, the highest value added product manufactured by Company X under the market conditions that existed at that time. In order to maximize the quantity of wood by-products used for pulp production, industrial roundwood inputs to the lumber production sector were prioritized to the sawmill with the lowest lumber and highest by-product yields. Under the assumption applied in the optimized scenario that other external mills consumed the extra by-products produce from three lumber mills, 84.2% of by-products generated from the Company X's mills were consumed to produce pulp and 15.8% were sold to other mills (Table 7-8).

				Base ScenarioOptimized Scen(000 m³ GSWE)(000 m³ GSWE)		Optimized S	cenario
By-Products	Base Scenario	Optimized Scenario	Change			SWE)	
Produced	(000 m ³ GSWE)	(000 m ³ GSWE)	(%)	Internal Internal			
				Consumed	Sold	Consumed	Sold
1_Chips	599	702	17.2%	599	0	702	0
2_Bark	69.5	115	64.8%	69.5	0	115	0
3_Sawdust	122	144	18.3%	0	122	56.1	87.9
4_Shavings	126	107	-14.5%	0	126	40.6	66.8
5_Trim Ends	38.0	42.7	12.3%	38.0	0	22.4	20.3
Total	953	1,110	16.5%	707	248	935	175

Table 7-8: A Comparison of Wood By-Products Outputs for the Base and Optimized Scenarios

Under the market conditions used for this case study, kraft pulp was the most profitable forest product in 2006 (Appendix M). In addition to the sale price of pulp and its manufacturing costs, the expense of purchasing chips from external mills significantly affected the total earnings and changed the material flow within the value chain. Comparisons of material input for pulp production in the two scenarios are presented in Table 7-9. In Company X, about 1.30 Mm³ GSWE wood by-products were required as the material input to produce approximately 583,000 m³ GSWE wood pulp. Chips were the predominant wood material input for pulp manufacturing.

There were two significant changes to pulp production in the optimized scenario compared with the base scenario. Firstly, a more diverse range of raw materials was used for pulp production in the optimized scenario. Chips, sawdust, shavings and trim ends were all used as feedstocks. Sawdust and shavings amounted to 7.46% of the total raw material input to the pulp mill. As this value was less than the 20% threshold set by the pulp mill, the impact on pulp quality was assumed to be negligible. Secondly, the proportion of by-products consumed from internal mills was raised from 46.2% in the base scenario to 62.3% in the optimized scenario. Therefore, the quantity of chips purchased from external mills declined by 30.0% (Table 7-9).

Sources for	Base Scenario		Optimized Scenario		
Pulp	Pulp Production, By-Products Input Excluding		Pulp Production, By-Products Input Excluding		
Production	Bark (000 m ³ GSWE)		Bark (000 m ³ GSWE)		
	Chips 599		Chips	702	
			Sawdust and Shavings	96.7	
Internal Mills			Trim Ends	9.62	
	Total By-Products Input From	7 00	Total By-Products Input From	808	
	Internal Mills	599	Internal Mills		
	Pulp Produced Using Chips from	0.60	Pulp Produced Using By-Products	364	
	Internal Mills	269	from Internal Mills		
External Mills	Chips	698	Chips	488	
	Pulp Produced Using By-Products		Pulp Produced Using By-Products	220	
	Purchased from External Mills	314	Purchased from External Mills		
Total	Total By-Products Needed	1,296	Total By-Products Needed	1,296	
	Total Pulp Produced	583	Total Pulp Produced	583	

Table 7-9: A Comparison of Pulp Production Sources for the Base and Optimized Scenarios

In conclusion, the reduction of chips purchased from external mills enabled the pulp mill to source approximately two thirds of its feedstock requirements from the company's own lumber mills.

As a consequence of adjusting the lumber production amongst the three lumber mills and reallocating by-product flows, the total earnings for the company from the optimized solution was increased by C\$3.82 million, which was a 4.21% increase over the base scenario (Table 7-10). After considering labor costs, the total value added for Company X increased by 2.37% from C\$161 million in the base scenario to C\$ 165 million in the optimized scenario. The increased earnings and value added was mostly due to the reduced cost of purchasing additional chips from external mills as the raw material input for the pulp mill (Table 7-10). Therefore, instead of purchasing 698,000 m³ GSWE chips from external companies, Company X only needed to purchase 488,000 m³ GSWE chips in total. The earnings from pulp production increased by 45.6% in the optimized scenario and the pulp mill delivered 84.2% of the total earnings for the regional operations of this company (Table 7-10).

The earnings from the three lumber mills were reduced slightly. Given the assumption that the same delivered logs price and manufacturing cost were applied to all three lumber mills (sawmill 1, sawmill 2 and FJ_Lumber), more logs were sawn at the sawmill 1, which had the higher yield of chips. Due to the insufficient drying and planing capacity at sawmill 1, and the increased volume of rough lumber produced at this sawmill, more rough lumber had to be transported to the company's drying and planing facilities at sawmill 2 and the FJ_Lumber facility. Thus, a 23.5% increased transportation cost was incurred for moving
the rough lumber among the three lumber mills lowered the company's economic earnings (Table 7-10). The transportation ratio of lumber transported to the total lumber production by volume increased from 0.74 in the base scenario to 0.81 in the optimized scenario.

The raw material cost, is an essential factor influencing the fibre allocation and the total earnings generated based on the market conditions in 2006. Therefore, increasing the utilization of by-products produced by the three internal lumber mills and reducing the chips purchased from external mills further reduced the raw material cost for pulp manufacturing.

		1			
Profit Source		Base Scenario (Million C\$)	Optimized Scenario (Million C\$)	Change (Million C\$)	Change (%)
Revenue	Lumber Sales	142	142	0	0.00%
	FJ Panel Sales	1.02	1.02	0	0.00%
	Pulp Sales	195	195	0	0.00%
	All By-products Value	28.2	32.6	4.37	15.48%
Manufacturing Cost	Lumber	129	129	0	0.00%
	FJ Panel	0.77	0.77	0	0.00%
	Pulp	143	143	0	0.00%
Labor Cost	Lumber	47.8	47.8	0.00	0.00%
	FJ Panel	0.33	0.33	0.00	0.00%
	Pulp	22.2	22.2	0.00	0.00%
Transportation Cost	Rough Lumber	2.35	2.90	552	23.5%
Total Earnings		90.7	94.5	3.82	4.21%
Total Value Added		161	165	3.82	2.37%

 Table 7-10: A Comparison of the Source of EBITDA and Value Added between the Base and

 Optimized Scenarios

In the optimized scenario, constant lumber, pulp and FJ panels productions and reduced by-products sales to external mills resulted in a 4.6% decrease in the total forest products outputs. Furthermore, the total wood fibre input into Company X's forest products manufacturing, including industrial roundwood and purchased chips, was 2.30% less than in the base scenario. Despite a 9.90% increase in the industrial roundwood input, the total fibre input to the Company's operations was reduced as the consequence of replacing a part of the chips purchased from other external mills by increased quantity of by-products produced by Company X's internal mills. Therefore, the material utilization efficiency for the Company X decreased from 68.9% to 67.3% in response to optimizing economic outcomes under the market conditions that prevailed in 2006

(Table 7-11). As demonstrated by the base scenario, Company X's value added per unit of input in 2006 of 70.5 C\$/m³ GSWE (Table 7-11) was 12.2% above BC's provincial primary forestry manufacturing subsector's average value added per unit of input in 2007 of 62.9 C\$/m³ GSWE (Table 6-9). Furthermore, the optimized scenario revealed that Company X's value added per unit fibre input could have increased by 4.80% to 73.9 \$/m³ GSWE, after optimizing the fibre flow among all the company's facilities.

Duafit Source	Base	Optimized	Change
r ront Source	Scenario	Scenario	(%)
Total Pulp, Lumber and FJ Panel Output (000 m ³ GSWE)	1,326	1,326	0.00%
Total By-Products Sold (Bark Excluded) (000 m ³ GSWE)	247	175	-29.3%
Total Output Including By-products Sold (000 m ³ GSWE)	1,573	1,501	-4.60%
Industrial Roundwood Input (000 m ³ GSWE)	1,585	1,742	9.90%
External Purchase Chips (000 m ³ GSWE)	698	488	-30.0%
Total Input Including Chips Purchased (000 m ³ GSWE)	2,283	2,230	-2.30%
Total Earnings for Company X (Million C\$)	90.7	94.5	4.21%
Earnings Per Input (C\$/m ³ GSWE)	39.7	42.4	6.67%
Total Value Added for Company X (Million C\$)	161	165	2.37%
Value Added/Input (C\$/m ³ GSWE)	70.5	73.9	4.80%
Material Utilization Efficiency (%)	68.9%	67.3%	-2.35%

 Table 7-11: Comparisons of Material Utilization Efficiency and Earnings from Each Unit of Input

 between Base and Optimized Scenarios

In conclusion, prevailing market conditions affected the material flow pattern for an integrated forest products company in BC to achieve optimal economic outcomes. The material flow pattern for the optimized scenario revealed that the wood fibre tended to flow to pulp production, whereas, the volume flowing to lumber mills was reduced, as pulp was five times more profitable (on a C\$/m³ GSWE basis) than lumber in 2006. Under the constraint of constant lumber and pulp outputs in the model, the system created more by-products for the company's internal utilization in the pulp mill by supplying more industrial roundwood and slightly lowering the material utilization efficiency. However, regardless of the decline of material utilization efficiency, in the optimized scenario, the earnings generated per unit of material input (C\$/m³ GSWE) was 6.67% greater than that of the base scenario. Furthermore, the company's value added from each unit of fibre input was consistently greater than BC's provincial average and this value could have been increased by 4.8% under optimal material flow conditions.

7.5.2 Analysis of Challenges and Limitations

The linear programming optimization model developed in this chapter was intended to demonstrate the benefits of material flow optimization and to assist decision makers with planning wood material flows and making strategic decisions for an integrated forest products company. However, there are some limitations and challenges with this approach. Data availability and accuracy were the first concern. The production data used were the average values of 2006 fiscal year. Some sale prices, manufacturing costs and labor costs were estimated due to company's confidentiality requirements. For example, in some cases average provincial or national prices and costs were used in place of company data. These limitations made the results of the study illustrative rather than specific to any individual company.

Secondly, this study was limited to the existing manufacturing plants owned by Company X and the study was constrained to adjusting and reallocating the industrial roundwood supply, rough lumber within three mills together with wood chips purchased from other jurisdictions. In the future, scenarios which consider adding new plants and closing poor performing mills or adopting innovative technologies may also be assessed when developing more sophisticated and complex optimization modeling procedures.

In addition, pulp production was five times more profitable than lumber production in 2006 (Appendix M). Therefore if the market demands for lumber and pulp could be relaxed, it would be interesting to study how roundwood flows would be adjusted to maximize the pulp production needs and minimize the lumber production needs. This study was undertaken based on one market condition prevailing in 2006. However, investigating material flows under a range of market conditions and assessing how robust they are in response to a diverse set of conditions would provide an improved understanding of the relationship between material flow reallocation and the maximization of economic benefits in forest products companies.

7.6 Conclusions

In this chapter a material flow balance was completed for an integrated forest products company in British Columbia for the 2006 fiscal year. This material flow was used as the base scenario for further comparisons. A linear programming model was developed to optimize fibre flows amongst all the company's forest product mills. Comparisons between the base scenario and the optimized scenario were completed by evaluating the wood fibre flows, revenues, costs, value added and material utilization efficiencies.

In the optimized scenario, the industrial roundwood input to two sawmills and the FJ_Lumber mill was redistributed to maximize the output of by-products. The distribution of by-products to all consumers was altered in order to obtain the best economic outcome for the company, under the constraints imposed on the model. In 2006, market kraft pulp was the most profitable product and therefore under the optimized

scenario, the maximum pulp production was achieved with a minimum of fibre purchased externally. With the same lumber output, the model increased and redistributed the industrial roundwood inputs into the three lumber mills to maximize wood by-products production.

This optimization model was used to demonstrate that the material flows through the value chain could be adjusted to achieve a better economic outcome at an enterprise level. Some generic cost and price data were used to prevent the disclosure of confidential company information. By adjusting the industrial roundwood distribution to the three lumber mills, by-products produced were increased by 16.5% while maintaining the same lumber production as in the base scenario. The pulp mill utilized all of the by-products created by the three internal lumber mills and thus the quantity of chips purchased from other companies was reduced. Consequently, the total volume of wood fibre input to Company X decreased by 2.30% compared to that for the base scenario. The modelling demonstrated that Company X could achieve a 4.21% increase in its total earnings and a 4.80% greater value added per unit fibre input while reducing its material utilization efficiency by 2.35%. Although these changes were relatively small in percentage terms, they resulted in increased earnings of C\$ 3.8 million for 2016. This exercise has demonstrated that reallocating the material flowing through a value chain could affect an enterprise's profitability and value added per unit of input. If all companies were able to more effectively allocate their wood fibre flows to the highest value outcomes, these benefits would accrue at the provincial and national levels and thereby improve Canada's national value added per unit of input and consequently improve Canada's ranking amongst the important forestry countries studied in Chapters 3 and 4.

In summary, this study searched for alternative material flow options to gain higher earnings for Company X under the market conditions that prevailed in 2006. It was shown that integrated forest products companies could adjust material flow patterns in response to market changes and achieve improved economic outcomes. By-products flows played a crucial role in linking lumber and pulp productions and complex material flow webs were created in a reasonably large integrated forest products companies. Strategic material allocation and manufacturing planning activities that were responsive to changing market conditions were shown to be important if integrated companies are to maximize their earnings.

CHAPTER 8 SUMMARY OF DISSERTATION, LIMITATIONS AND FUTURE RESEARCH

8.1 Conclusions

The competitiveness of the primary forest products industry has consistently declined compared with many other industrial sectors. In addition, the economic contribution per unit of fibre input in Canada has historically been low. The overall goal of this dissertation was to apply the concept of material flow analysis to evaluate the performance of primary forest products industry with various forest products value structures and to assess their socio-economic contributions at national, provincial and enterprise levels. This objective was achieved through the use of material flow analysis to develop and apply a series of unit input value added indicators to characterize the value chain and quantify socio-economic contributions on a volumetric input basis. The research has provided forest owners, forest product manufacturers and governments with international benchmarks of socio-economic outcomes from the primary forest products industries. The case studies of BC's primary forestry sector and a BC's integrated forest products company investigated wood fibre allocation readjustment as a potential means to increase the economic benefits at provincial and enterprise levels.

Chapter 2 presented an overview of the primary forestry sector in Canada and BC. The historical sub-optimal socio-economic benefits from Canada's primary forest products industries provided an opportunity to assess the suitability and flexibility of the existing primary forestry sector in a given socio-economic system and interpret the impacts of material allocations on the socio-economic outcomes from the primary forestry sector in BC.

The review of literature showed that none of the previous studies focused on understanding the value structure in Canada or BC and its potential for increased socio-economic benefits by adjusting the material flow through the value structure. Material flow analysis was shown to be a useful means of studying the primary forestry sector value structure and it provided a fundamental model for further evaluating socio-economic outcomes. The literature review showed that material flows could be developed on either a volumetric or a mass input basis and the former approach, which required fewer conversions was concluded to be more precise for application in BC. The use of conversion factors to convert various output units to a unified input basis (e.g. m³ GSWE) was identified as the most straightforward way to solve the numerous challenges created by the diversity of output units used by the sector. In addition, the review also revealed the most frequently quantified economic and social indicators within the primary forestry sector were value added, GDP, employment and apparent productivity.

Chapter 3 decomposed gross value added and wood fibre input at stages along the value chain and gained a more thorough understanding of socio-economic benefits created by national primary forestry sectors. Due to the substantial increase in the international trade of intermediate forest products, the domestic harvest was inadequate to quantify the wood fibre entering many nations' forest products value chains. In Chapter 3, a series of input indicators (apparent industrial input (AII)), which account for international trade of industrial roundwood and intermediate forest products (consisting of veneer sheets, chips and particulates, wood residues, and wood pulp) were developed and used to more accurately measure the apparent volumes of wood flowing from forest harvests into the four main stages of the primary forest products value chain. The various AIIs facilitated the detailed comparisons of different national and provincial forestry sector value chains on a common volumetric input basis. In association with the four AIIs, five apparent value added (AVA) indicators were developed to evaluate the return of logs at different stages of the primary forestry sector value chain.

Five return of logs (apparent value added per unit of input) indicators were further evaluated in Chapters 3 to assess where and how much value addition per net input occurred along national forestry sector value chains. The absolute values of these indicators in forestry nations presented economic benefits obtained from each unit of net fibre input throughout the stages of the value chain. The differences between forestry return of log and manufacturing return of log were substantial in most of the developed countries. Forestry return of log ranged from a high of 448 US\$/m³ GRWE in Japan to a low of 10.9 US\$/m³ GRWE in New Zealand. In contrast, manufacturing return of logs varied from a high of 1,690 US\$/m³ GRWE in Japan to a low of 0.22 US\$/m³ GRWE in Chile. Japan displayed the most significant differences between the various return of logs investigated and thus displayed the most significant influence of international wood fibre trade of any nation. It was concluded that return of logs not only revealed the importance of the international trade of forest products, but also enabled value added comparisons to be made irrespective of the size of the industry at the national level.

The fibre input based methodology used to evaluate economic outcomes could not be applied to the analysis of social benefits due to a lack of input-related employment data. Chapter 3 used employment and apparent productivity by both the forestry and logging and the manufacturing subsectors in relation to their correlated unit input value added as alternative social indicators. The trend of employment and apparent productivity versus unit value added in two subsectors revealed clear differences between developing and developed countries. In the forestry and logging subsector, most developing nations displayed higher employment and lower apparent productivity and they achieved higher return of log from this subsector than the developed nations. In contrast, the opposite relationships were observed in most developed nations, which exhibited high forestry and logging productivity and reduced return of log compared to the developing countries. In the manufacturing subsector, the return of log was shown to depend more on the apparent maturity of the primary forestry sector in a commercial sense and a wide range of return of logs.

were observed. The largest value was 677 US\$/m³ GRWE for Japan and the lowest was 139 US\$/m³ GRWE for Malaysia. The majority of the developed nations were less labor intensive than developing nations and their manufacturing subsectors consistently attained higher return of logs than the less developed countries. All the developing nations, together with Canada, which had comparatively low manufacturing subsector productivity, achieved lower return of logs than developed nations. In contrast, the majority of the developed nations studied consistently achieved higher productivity per unit of input than developing nations reflecting the extensive mechanization of the forest products manufacturing in these nations and the observation that many developed countries had substituted capital for labour.

Chapter 4 proposed that the value structure, denoted by the proportional gross value added (GVA) composition of the three subsectors, impacted the national manufacturing subsector value added per unit of input (return of log_4). In all nations studied, manufacturing processes added the greatest value per unit of fibre input. A forestry sector maturation pattern for commercially based primary forest industries was proposed based on the observation that nations with smaller proportionate forestry and logging GVAs and larger proportionate manufacturing GVAs attained greater value added per unit of input and vice versa. This pattern indicated that nations with less advanced forestry sectors tended to have proportionately dominant forestry and logging subsectors and relatively small manufacturing subsectors. As the commercial forestry sector matured, there was a tendency for developing countries with dominant forestry and logging GVAs. In contrast, developed nations had predominant manufacturing subsectors that tended to evolve less quickly as their industries were closer to state-of- the-art and appeared to have less room for further improvement.

The proposed pattern was discussed in a comparison case study between Canada and the USA. Despite some similarities, the forestry sector value structures have been different in both nations, with Canada historically having 9.13% larger proportional forestry and logging GVA and consequently, 9.13% smaller proportional manufacturing subsector GVA than the USA. It was inferred that Canada would achieve lower economic outcomes per unit of input.

In order to improve economic outcomes at national and provincial levels from the perspective of material flow, a good understanding of how wood fibre is presently utilized and how it can be optimally re-allocated is required. This involves actions from the agencies and enterprises involved in forest management and manufacturing.

In Chapter 5, detailed material flow analyses were undertaken for BC's primary forest products industry to elucidate how wood flows at a provincial level affect socio-economic outcomes. Sufficiently accurate balances of BC's wood fibre flows were developed for five different years between 1991 and 2007. These

analyses revealed that the wood products manufacturing subsector received more than 90% of the roundwood inputs and it served as the keystone subsector within the provincial value chain. Wood by-products from the wood products manufacturing subsector, equivalent to about 30% of the industrial roundwood harvest, provided the major fibre source for the pulp and paper manufacturing subsector and played a crucial role in linking these two subsectors. This analysis also revealed that the material utilization efficiency of the value chain increased from 58.6% in 1991 to 73.3% in 2007.

Market conditions are dynamic and the balance between supply and demand for the diverse range of forest products manufactured varies significantly with time. In order to achieve economic outcomes that are close to the optimum, forest products manufacturers that sell products into different markets need to adjust the fibre flows through the value chain in response to these market dynamics. This market responsiveness is especially important for integrated companies with lumber and pulp and paper mills. Quantifying fibre flows on an input basis facilitates the economic analysis of the benefits of reallocating industrial roundwood inputs to a variety of manufacturing options. This analysis was completed at the provincial level for BC in Chapter 6 and for a forest products enterprise in BC in Chapter 7.

In Chapter 6, material flows through BC's forest products value chain in 2007 was concluded to be sub-optimal. A linear optimization model was developed to recommend the optimal design of provincial material flows under the market conditions prevailing in 2007. Two optimized scenarios 1 and 2 showed that by reallocating fibre flows, value added per unit of input for BC's primary forestry sector could be increased by 25.6% and 35.4%, and the earnings could be 229% and 65.9% greater than in the 2007 base case scenario, respectively. However, in both situations the achievements of increased value added and earnings were associated with decreased employment.

Both scenarios sought to maximize production in the pulp and paper manufacturing subsector and minimize the fibre uses in the wood products manufacturing subsector within capacity constraints set for each scenario, and meanwhile, increase the external sales of chips. The optimization result was driven by the higher earnings from the pulp, paper and chips productions under the 2007's market conditions. However, driven by the reduction in the total cumulative volume of material input (the sum of industrial roundwood and by-products from wood products manufacturing subsector) to the value chain, the major trade-off for the increased value creation was a decrease in total employment of 15.0% and 1.50%, for scenarios 1 and 2, respectively.

Chapter 7's enterprise-level investigation concluded that, under the market conditions prevailing in 2006, market kraft pulp was the most profitable product and therefore it was financially beneficial to maximize pulp production with a minimum of externally purchased fibre. With the same lumber output, the industrial roundwood input to the three lumber mills was reallocated to maximize wood by-products production. The total value added and earnings per unit of input increased by 4.80% and 6.67%, respectively, but the

material utilization efficiency decreased by 2.35%. This research demonstrated that adjusting material flows in response to changing market conditions enabled improved economic outcomes to be achieved. Accurate material flow analyses using an input basis were an important prerequisite for these fibre reallocations assessments.

8.2 Limitations

The quantitative results of this research are subject to several limitations. Two main challenges were methodological assumptions and data acquisitions.

8.2.1 Methodological Assumptions

A number of assumptions were made in the development of the research methodologies to accomplish the socio-economic contribution evaluations in the forestry sector.

First, the lack of data on volumes of by-product flowing from primary mills to be reused within the value chain was a serious constraint for developing material flows at the national and provincial levels. Due to this limitation, four AIIs were proposed to quantify the net wood fibre input to four main manufacturing stages and further determine the input based socio-economic benefits at stages of the value chain.

Second, this study employed a volumetric input approach to quantify the material flow through the value chain. However, mass and carbon content based approaches may also be used to balance material flows and provide information from the ecological and environmental perspectives. Instead of mass based units, a volumetric unit is utilized in this dissertation. The reasoning behind this assumption has been delineated in Section 2.3.1.

Third, to facilitate the calculation of conversion factors, the volume shrinkage or swelling of wood fibre was assumed to be linear when the moisture content was below the fibre saturation point.

Fourth, due to the unavailability of other various operating expenses for the traded forest products in other forestry countries rather than Canada, Canada's ratios of operating expenses to fibre costs of various traded forest products were applied to fourteen other forestry nations to obtain the apparent value added at different stages of the value chain.

Finally, in BC's and Company X's material flow optimization studies, potential capacity change costs for various mills were not accounted for separately.

8.2.2 Data Acquisitions

Data acquisition was an important part of this study. However, data obtained from the sources below should be treated with caution.

First, some national forest products' values from FAOSTAT included estimates and some parameters were not provided in a sufficient detail. Therefore, the quality of production and trade data was not equivalent across all the nations studied.

Second, the gross value added and employment data by subsector obtained from the FAO finance report incorporated a number of limitations. Most importantly, employment and value added data underestimated the true levels as they only represented activities in the "formal" or "visible" forestry sector (Lebedys, 2008). This constraint resulted in an underestimation of total forestry sector activities which was greatest for those countries with substantial "invisible" or "informal" forest activities. For this reason, these data are likely to provide a more accurate assessment of forestry sector activities in developed countries rather than developing nations.

Third, national conversion factors provided by UNECE/FAO reports often lacked sufficient detail and they are associated with many production yield assumptions.

Furthermore, this research incorporated several assumptions caused by a lack of data availability and the need to protect confidential data sources for BC's and Company X's material flow development and optimization studies. Several assumptions were made due to insufficient data and the need to protect the intermediate products' prices, manufacturing cost and labor cost data for both BC and Company X.

8.3 Future Work

Future research seeking to evaluate and improve the forestry sector's socio-economic contributions may pursue several directions. The following section proposes four topics for further research based on the results presented in this dissertation.

8.3.1 National and Provincial Level Material and Energy Flow Analyses

Material flow analysis provides a detailed assessment of the wood material input allocation amongst the forestry and logging, wood products manufacturing and pulp and paper manufacturing subsectors. However, a lack of jurisdictional input, output and trade data, in particular, the quantity of wood by-products created by the wood products manufacturing subsector to be used as the additional raw material in the pulp and paper manufacturing subsector greatly increased the difficulties of developing national and provincial material flows. This constraint needs to be addressed if this approach is to be further developed. Therefore, it would be interesting to use statistics to balance wood fibre flow for forest

product industries in future studies to assess the net wood fibre inputs in three subsectors for important forestry jurisdictions. Consequently, a detailed assessment of socio-economic benefits could be undertaken based on the jurisdictional MFA information.

In addition, energy consumption was not addressed in this study. With the additional consideration of energy recovery and consumption, the decision of fibre distribution may alter. Therefore, it would be more insightful if further study can explore energy flows together with material flow studies.

8.3.2 Material Flow Boundary Extension

The material flow studies in this dissertation were constrained by a boundary condition that operated from industrial roundwood harvests in the forests to the production of various primary forest products. A more complete material flow analysis for the forestry sector could be developed by including secondary manufacturing and post-consumer wood and paper waste management.

8.3.3 Material Flow Optimization Study

The optimization modelling of material reallocation in the provincial and enterprise level material flow studies was an initial effort to show the potential gains that may be achieved. If adequate data were available, it would be useful to incorporate more complexity by analyzing the fibre flow when capacity cost variations are more precisely accounted for and including the grades of industrial roundwood inputs and final primary forest product outputs in the models.

8.3.4 Studies of Employment and Productivity per Unit Fibre Input

The limited availability of full time equivalent employment data constrained the quantification of social contributions per unit of input in this dissertation. Subsequently, the same approach used to evaluate economic contributions could be applied to social benefits if more extensive manufacturing and international trade-related employment data were available. To align with return of log indicators, multiple employment/AII and AVA/employment indicators could be used to improve the understandings of each subsector's social contributions and correlated labour efficiencies per unit of fibre input.

8.3.5 Impacts of the Value Structure on Unit Input Value Added Evaluation

This dissertation examined the influence of the value structure, as measured by the GVA composition of the three subsectors, on unit input value added (return of log_4). However, the extent to which variables other than the value structure might impact return of log_4 was not investigated in this research. Many other factors including land prices, tenure structures, harvest volumes and sale prices may also influence the economic benefits produced from each unit of material input. These factors could be evaluated as independent variables in multiple regression formulas in further research.

8.3.6 Environmental Contribution Study

Forestry's contributions to the economy, environment and society are three important aspects of sustainable forest management. Chapters 3 and 4 have evaluated the socio-economic contributions of the forest products industry, and it would be useful to extend this analytical framework to include an assessment of environmental impacts created by the various stages of the primary forestry value chain. If suitable environmental indicators could be developed, optimization studies may be used to maximize a nation's socio-economic benefits from its forest products industry while minimizing its environmental impacts.

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APPENDICES

Appendix A: Factors Considered and Assumptions in AIIs Calculations

Three main factors are considered when converting wood products quantified in various units to m^3 GRWE, including MC, volumetric changes, wood yield (Table A-1).

A wana ga Valuaa		Volumetrie	Conversion	Wood Yield	I-O Factors (m ³
Assumed	Original MC	Change (v/v)	Factors (m ³	(m ³ GSWE/m ³	GRWE /original
			GSWE/original unit)	GRWE)	unit)
Industrial Roundwood	Green (>30%)	0%	1	100%	1
Chips and Particles	Green (>30%)	0%	1	90%	1.11
Wood Residues	10%	8.0%	1	97%	1.12
Veneer Sheets	12%	7.2%	1	54%	2.00
Wood Pulp (weighted		N T 4	2.387	55.8%	4.29
average by pulp category)	ADI (10%)	NA		(ODT/ODT)	4.28

Table A-1: Factors and Assumptions for AIIs Calculations

1 MC

Moisture contents (MC) also varied with the forest product category. Wood by-products arising from forest products manufacturing comprise a wide range of fibre forms with different moisture contents. They are usually dried to reduce the water content prior to trading.

The MC of industrial roundwood and chips and particulates were provided on a green basis (FAO, 2015, 2011). The MC of wood residues was assumed to be 10%. Veneer sheets may be used to make plywood by applying adhesives, pressing and trimming. The MC of the veneer sheets was assumed to be 12%, the same value as that of plywood (APA, 2002; CDGS, 2006; Table A-1).

2 Volumetric Changes

Volumetric changes from oven dry (0% MC) volume to green (30% MC) volume are averaged as 12% based on a study for British Columbia species (Nielson et al., 1985). MC greater than 30% is considered to be green. To simply the calculation, the volume various for moisture content less than 30% is considered linear and the volumetric changes for green wood are negligible in this study.

Using this method, the volumetric change for wood residues (10% MC) to green wood residues is calculated to be 8% and the volume of veneer sheet with 12% MC will have 7.2% increase to reach green size (Table A-1).

3 Wood Yield and Input-Output Factors

In this study, the wood yield (in %) was defined as the ratio of the green volume of the fibre content in a wood product (in m^3 GSWE) to the equivalent volume of green roundwood utilized to manufacture this product (in m^3 GRWE) as shown in Equation 5-1 (Chapter 5).

Wood Yield (m³ GSWE/m³ GRWE) = Product Output (m³ GSWE) / Industrial Roundwood Input (m³ GRWE)

Equation 5-1

With the output products quantified in m³ GSWE excluding wood pulp, wood yield is important to back calculate the raw material input in m³ GRWE. Chapter 5 and Appendix F showed that the yields of chips and particulates ranged 82% to 93% (m³ GSWE/m³ GRWE). In this study, wood yield of 90% was used for chips and particulates for all the countries studied. Different with industrial roundwood and chips and particulates, which are considered as green, yield of wood residues and veneer sheets need to take into account of volumetric variations due to moisture changes. The higher wood yield 97% v/v (m³ GSWE/m³ GRWE) was assumed for wood residues to consider the material loses during the handling process. An average input and output factor (I-O factor) of 1.12 (m³ GRWE/m³ at moisture of 10%) was used for wood residues' unit conversion calculation. Similarly, a wood yield of 54% (m³ GSWE/m³ GRWE) was assumed for veneer sheets production (APA, 2002; CDGS, 2006; MoFR, 2010; Schuler, 2002). After considering the veneer 7.2% volume change from MC 12% to green (Appendix F), an average I-O factor of 2.00 (m³ GRWE/m³ moisture of 12%) was applied for veneer sheets (Table A-1).

Wood pulp input and output factors (I-O factors) (in m³ GRWE/ADT) were calculated and applied to convert the mass of wood pulp production to the green volume of industrial roundwood equivalent input required (m³ GRWE) (UNECE/FAO, 2010a, b). Weighted average wood pulp I-O factors, representing the metric volume of green industrial roundwood required to produce one air dry tonne of wood pulp were calculated based on I-O factors of four wood pulp categories, including chemical pulp, mechanical pulp, semi-chemical pulp and dissolving pulp, gathered from UNECE/FAO from 1961 to 2011 (UNECE/FAO, 2010a, b) and the production of these four pulp categories (FAO, 2015). Wood pulp I-O factors count in both pulpwood (in m³ GRWE) and wood chips (in m³ GSWE) as the input material to produce various types of wood pulp (in ADT).

Appendix B: Ratios of Operating Expenses to Forest Products Traded Values

Forest Products	Ratio Operating Expenses	Traded Fibre Form	Sources	
Forest Froducts	to Fibre Value (%)	as Input	Sources	
Chomical Puln	60.8%	C&P WR	(Canfor, 2008; FPI, 2012; MacDonald, 2006; MoFR, 2007b,	
Chemical Fulp		car, wk	c); Estimated, 4/5 of pulping cost without chipping process	
Mashariaal Dala	112.00/		(Canfor, 2008; FPI, 2012; MoFR, 2007b, c); Estimated, 9/10	
Mechanical Pulp	112.9%	Car, wr	of pulping cost without chipping process	
Average pulp	Varies with country		(Canfor, 2008; FAO, 2015; FPI, 2012; MoFR, 2007b, c;	
		Car, wr	2008c; MacDonald, 2006)	
Paper	73.4%	Wood pulp	(CIBC, 2010; FPI, 2012; MoFR, 2008c Wood Markets, 2009)	
Plywood	35.2%	Veneer to Plywood	(CIBC, 2010; FPI, 2012; MoFR, 2008c; Wood Markets, 2009)	
Logs	17.1%	Trees	(CIBC, 2010; FPI, 2012; MoFR, 2008c; Wood Markets, 2009)	

Table B-1: Ratio Operating Expenses to Fibre Cost for Traded Forest Products

Table B-2: Average Pulping Operating Expenses/Fibre Value in Fifteen Nations, 1990-2011 (%)

Country	Average Chemical/Mechanical	Average Operation Expenses/Fibre Value (%)		
Country	Pulp Production			
Australia	1.38	83.0%		
Austria	3.07	74.0%		
Brazil	17.1	64.0%		
Canada	1.13	85.0%		
Chile	7.40	67.0%		
China	3.97	71.0%		
Finland	1.70	80.0%		
France	2.26	77.0%		
Germany	0.78	78.0%		
Indonesia	19.2	63.0%		
Japan	7.16	67.0%		
Malaysia	0.61	61.0%		
New Zealand	0.94	88.0%		
Sweden	2.43	76.0%		
USA	9.97	66.0%		
Australia	3.49	72.0%		

	FL Subsector Return of Log		MS Subsector Return of Log			Changes between
Country	(2011 US\$/m ³ GRWE)		(2011 US\$/m ³ GRWE)			Return of Log_2-2
	Return of Log_1	Return of Log_2-1	Return of Log_2-2	Return of Log_3	Return of Log_4	and 2-1 (2011 US\$/m ³ GRWE)
Chile	29.8	37.7	0.22	32.2	375	-37.5
Canada	46.7	45.9	53.8	57.5	177	7.89
New Zealand	10.9	76.6	84.2	100	219	7.57
Sweden	84.2	69.5	88.2	82.7	164	18.8
Brazil	65.8	66.5	126	131	219	59.6
Finland	93.6	67.7	115	111	161	47.6
Malaysia	103	199	127	151	139	-72.6
Indonesia	118	119	161	165	180	41.7
USA	41.7	49.1	253	258	262	204
China	202	147	249	247	168	102
Australia	39.9	46.6	312	727	647	265
Austria	173	83.3	319	308	266	235
France	140	151	587	595	424	436
Germany	81.9	90.5	799	857	518	709
Japan	448	91.3	1,690	894	673	1,598

Appendix C: Return of Log Values in 15 Countries Ranked by Return of Log_2-2, Average 1990-2011

Appendix D Forestry Sector Employment and Apparent Productivity

1 Forestry Sector Employment

Employment statistics provide insights on the social contributions from a nation's forestry sector. Trends in total employment in the forestry sector (termed forestry sector employment) over the period 1990 to 2011 for the fifteen countries are presented in Figure D-1.



Note: China's employment in the forestry sector relates to the right axis.

Figure D-1: Forestry Sector's Employment in 15 Countries, 1990-2011 (Lebedys and Li, 2014)

From 1990 to 2011, China had the largest forestry sector employment with a range of 3.00 to 4.57 million FTE being reported (Figure D-1). The USA had the second largest FS employment, ranging from 0.83 to 1.41 million FTE, followed by Brazil with a range of 0.57 to 0.80 million FTE (Figure D-1). The average FS employment in China was three times that of the USA, which employed the second largest forestry workers, and 117 times of that New Zealand, which exhibited the smallest FS employment amongst the nations studied (Figure D-1).

In general, FS employment declined between 1990 and 2011 in most countries studied. For example, employment in the primary forestry sector declined by between 43.9% in Japan and 0.06% in China over the study period. Only three developing nations reported increased FS employment data, namely, Brazil, Malaysia and Chile. The increase ranged from 16.4% in Brazil to 25.1% in Chile between 1990 and 2011.
2 Trends in Employment by Subsector

The average employment from 1990 to 2011 in three forestry subsectors of the fifteen forestry countries studied is presented in Figure D-2. The total forestry sector employment varied widely in countries. The nations with the greatest absolute levels of employment were China, the USA, Brazil, Indonesia, and Japan, whereas, New Zealand, Austria, Australia and Chile exhibited the smallest average FS employment over the same period (Figure D-2). Many factors might contribute to determine the number of jobs in a nation's forestry sector, such as the size of the forest product industry, manufacturing technologies used, labour force supply, wage rates, labour productivity and international forest products market conditions. In general, the data show that developing countries with large populations and large forest product industries offer numerous forestry sector job positions, whereas industrialized countries with small populations, low harvest volumes and advanced machinery and management tend to have smaller forestry sector job markets.



Figure D-2: Employment by Subsector in Fifteen Countries, Average 1990-2011

Over the study period, China's forestry sector had the largest labor market and the trend in China's forestry sector employment has a large influence on global FS employment as, globally, one in every four employees working in the primary forest products industry was employed in China (Figure D-2).

The employment in all three subsectors displayed similar trends. Each subsector (forestry and logging, wood products manufacturing and pulp and paper manufacturing)'s employment is discussed in sequence below. China's forestry and logging subsector employed the largest labour forces of the fifteen countries studied, averaging 1.49 million FTE

over the period. In contrast, despite having a similar AVA2-1 (Figure D-2), the average forestry and logging employment in the USA was only one tenth of that China (Figure D-2). Forestry and logging employment in countries with high AVA2-1 values, such as Canada, Brazil and Indonesia were respectively 4.76%, 5.89% and 5.79% of that China (Figure D-2). Compared with forestry and logging subsector, manufacturing subsector has been more labor intensive in most of nations as greater than 70% of the forestry labors were hired for forest products manufacturing with the exception of China and Chile. China's large manufacturing employment accounted less than 60% of the total forestry sector employment. Chile was the only country where the employment in the forestry and logging subsector was larger than its manufacturing subsector. Therefore, it may be inferred that in nations with low forestry and logging employment, labour in the forestry and logging subsector has been substituted with advanced harvesting technologies (Berg, 2003; Acemoglu and Autor, 2011). Over the study period, the wood products manufacturing subsector in most countries created more employment than the pulp and paper manufacturing subsector, with the exceptions of China, Japan, the USA, France, Finland and Sweden. In particular, China's pulp and paper manufacturing subsector employed about one and half times of its labour force of the wood products manufacturing subsector. The five nations with the largest labour forces in the wood products manufacturing subsector over the study period were China, the USA, Brazil, Indonesia and Japan. In the pulp and paper manufacturing subsector, Germany replaced Indonesia and became one of five countries with the highest employment (Figure D-2).

2 Apparent Productivity by Subsector

Apparent productivity has been used as an indicator of social contribution as it denotes the level of salaries and wages in an industry and reflects the general level of benefits and conditions of employment in an industrial subsector (Lebdeys and Li, 2014; Lebdeys, 2008).

The average apparent productivities from 1990 to 2011 for the forestry sector and each subsector (termed forestry sector apparent productivity, forestry and logging apparent productivity, wood products manufacturing apparent productivity and pulp and paper manufacturing apparent productivity) of the fifteen forestry countries studied are depicted in Figure D-3.

The gross value added per employee in the forestry sector in industrialized countries was generally higher than in developing countries. Finland, Sweden, Australia and Canada had the highest average apparent productivity from 1990 to 2011 ranging between about 100 to 130,000 US\$/FTE. In contrast, China, Indonesia, Malaysia, and Brazil exhibited the lowest sector productivities, varying from 13,000 to 34,100 US\$/FTE (Figure D-3). A nation's apparent productivity may be impacted by many factors including the value added generated, employment numbers, the extent of automation, value added per output, and the level of innovation (Lebdeys, 2008).

Overall, there was no consistent pattern in the subsector productivities across the countries studied. On average, pulp and paper manufacturing was the most productive subsector at 115,000 US\$/FTE followed by the forestry and

logging subsector at 87, 100 US\$/FTE. The wood products manufacturing subsector was the least productive by a significant margin, and it generated 54, 900 US\$/FTE (Figure D-3).

In all the nations investigated, the forestry and logging subsector had the highest average productivity in comparison with other two subsectors' productivities in four nations, including Australia, Austria, Chile, Japan, Finland, Sweden and France had the highest average forestry and logging apparent productivity ranging from 123,000 to 162,000 US\$/FTE. In contrast, China, Chile and Japan had the lowest forestry and logging apparent productivity amongst the fifteen countries studied, ranging between 14,200, and 42,400 US\$/FTE (Figure D-3). Finland achieved the highest average forestry and logging apparent productivity of 162,000 US\$/FTE which was eleven times that of China, the nation with lowest forestry and logging apparent productivity (Figure D-3).

In eleven countries, the wood products manufacturing subsector had the lowest apparent productivity amongst three subsector productivities, although it was the second most productive subsector in Australia, Austria, Chile, and Japan (Figure D-3). In all of these four nations, the pulp and paper manufacturing subsector had the highest productivity and the forestry and logging subsector had the lowest productivity. Australia had the highest wood products manufacturing apparent productivity at 98, 700 US\$/FTE, reflecting the high degree of automation used in this subsector in Australia. Developing countries consistently fell towards the bottom in terms of wood products manufacturing apparent productivity with China's value being the lowest at 10,300 US\$/FTE which was one tenth of that Australia.



Figure D-3: Apparent Productivity in Three Subsectors, Average 1990-2011

In nine of the countries studied, the pulp and paper manufacturing subsector displayed the highest apparent productivities (Figure D-3). The highest apparent productivities in the pulp and paper manufacturing subsector were observed in Chile, Australia and Finland, ranging from 214,000 to 165,000 US\$/FTE, reflecting the high degree of

technology and automation applied in these countries. The nations with the lowest pulp and paper manufacturing apparent productivities were China, Malaysia and Indonesia which attained between 13,200 and 36,200 US\$/FTE,. Chile had the highest average pulp and paper manufacturing productivity of all the nation's studies which is a substantial achievement for a developing country.

In summary, the differences in apparent productivities reflect the level of automation in the industry, the extent to which capital has been substituted for labor, the level of salaries and wages and market conditions. There were three consistent patterns across the nations studied. Firstly, either the forestry and logging or pulp and paper manufacturing subsector attained the highest subsector productivity. Secondly, the wood products manufacturing subsector had the lowest average productivity. Thirdly, forestry sector productivities were consistently lower in the developing nations (33, 900 US\$/FTE on average) than the developed nations (102, 000 US\$/FTE) with the gap between two country groups being substantial. Chile, which had the highest forestry sector productivity of the developing countries, was only 90.3% of Germany's value, the lowest amongst the developed nations (Figure D-3).

Appendix E: Conversions between Units

1 Conversion between Units

It is important to quantify forest products manufacturing inputs and outputs using a common unit to enable any further comparisons. The importance of international trade for the forestry sector is clearly demonstrated by considering exported and imported as industrial roundwood or intermediate forest products as the proportions of global industrial roundwood production. Data provided by FAOSTAT on the trade and production were presented in a wide range of mass and volume units. For example, wood pulp was measured in air dry tonnes (ADT), industrial roundwood were given in m³ green roundwood equivalent (GRWE) and chips and particulates were quantified in m³ green solid wood equivalent (GSWE). Therefore, conversions among these units are required to enable any quantitative studies.

The relationships among units and their conversions used in this dissertation are depicted in Figure E-1. Input/Output Factor can be applied to directly convert final product units to m³ GRWE, the absolute fibre content of the product denoted by m³ GSWE can be calculated by multiplying conversion factors to final products quantified in various units. It is important to note that the unit GSWE describes the green volume of wood prior to any shrinkage. It quantifies the wood fibre contained in the product and is the roundwood equivalent volume needed to produce the product when there are no losses or wood by-products created. GRWE volume is a measure of the green volume of logs (industrial roundwood) used in the manufacture of wood-based products (including wood pulp, paper, wooden furniture, joinery and plywood). It is the sum of GSWE and manufacturing losses or wood by-products (Global Timber, 2010; UNECE/FAO, 2010a). Therefore, fibre in m³ GSWE can be obtained by multiplying yield to the product united in m³ GREW.



Figure E-1: Diagram of Unit Conversions

Appendix F: Material Balances at Sub-Levels

To facilitate the material flow balancing, material flow in BC's forest products industry is the aggregation of four sub-levels, namely, primary sawmilling (PS), structural panels (SP), pulp and paper (PP), and other mills (OM). Primary sawmilling sub-level material balance is presented in Section 5.2.2.5 of Chapter 5. Material balances at structural panels, other mill and pulp and paper sub-levels are discussed below:

1 Structural Panel Material Balance

The structural panel (SP) sub-level material flow consisted of the following three mill categories used by the MFLNRO: the veneer and plywood (VNR & PLY), the oriented strand board (OSB), and the other panels (PNL) mills.

The SP sub-level is an important user of industrial roundwood and it consumed approximately 10% of BC's wood fibre input over the study period. This fibre consumption was distributed among the three mill sub-categories as follows: 6% into VNR & PLY mills, less than 3% into OSB mills and less than 2% into the other PNL mills.

1.1 Material Balance

The final products of VNR & PLY and OSB consumed raw material input in various fibre forms. Some non-wood materials were also added in the manufacturing process, e.g. resins. Therefore, some final forest products in the SP sub-level consist of wood fibre and resins. However, only wood fibre has been quantified in the material flow balancing process. Wood fibre's MC variations and the shrinkage effects have been taken account of in conversion factor calculations to enable the fibre balance.

In addition, some lab work has been done to gather other information that was required to better define on OSB's characteristics (Petit-Etienne, 2009).

1.1.1 VNR & PLY Mills

The schematic material flow for VNR & PLY mills are presented in Figure F-1. The veneer mill in the figure represents the aggregated veneer mills in BC to simplify the material balancing. In this simplified flow, green industrial roundwood utilized as the input for veneer manufacturing. Veneers were either further transformed into plywood or directly sold to the veneer market.

By-products from VNR & PLY mills include chips, sawdust and shavings, trimmings and peeler cores from rotary cutting. Resin was considered as a non-wood component in plywood manufacturing (Figure F-1). The yield of plywood manufactured from veneer was assumed to be 100% in the study.



Figure F-1: Material Flow Schematic for the VNR & PLY mills in the SP Sub-Level

1.1.2 OSB Mills

The schematic material flow of aggregated OSB mills is presented in the Figure F-2. Green industrial roundwood was used as the raw material input to OSB manufacturing. OSB panels as the final product consisted of two components: wood fibre and non-wood was and resin.



Figure F-2: Schematic Material Flow for the OSB mills in the SP Sub-Level

Wax and resin were added during the OSB manufacturing process. Wood by-products from manufacturing comprised sawdust and shaving and trimmings (Figure F-2). The non-wood part including in the trimmings was considered to be negligible.

1.1.3 Other Panel Mills

The other PNL mills category included various composite panel mills, such as medium density fibreboard (MDF), high density fibreboard (HDF) and particle board (PB) mills. Wood fibre in forms of green industrial roundwood, sawdust and shaving and trimmings were used as raw material inputs for other PNL productions. Wax and resin were added during manufacturing to improve the panel's physical properties. Therefore, the final products from other PNL

mills comprise two components: wood fibre and the non-wood wax and resin. Wood by-products produced by Other PNL mills included sawdust and shavings, and trimmings (Figure F-3). The non-wood component in wood by-products was assumed to be negligible for this study.



Figure F-3: Schematic Material Flow for Other PNL Mills in the SP Sub-Level

1.2 Conversion Factors Development

Original data for SP sub-level material balancing were obtained from the MFLNRO confidential report. The green industrial roundwood inputs for both OSB and VNR were measured in thousand cubic metres under bark. In other PNL mills, sawdust and shavings as raw material input were in thousand Bdu. The capacity and the production were reported in millions of square feet (Msf) for all the structural panel mills. Additionally, chips produced as by-products from the veneer manufacturing united in thousand Bdu. Other related volumes included in the structural panels material flow were obtained by the balance calculation. A series of conversion factors were concluded and assessed after taking into account of panel's thickness, non-wood components from all three types of panel productions, volume variations resulted from fibre compression and MC changes.

1.2.1 Panels

The output of panels from the SP sub-level were most frequently given in square feet measured on a 3/8 inch basis and conversion factors and I-O factors were necessary to quantify wood fibre in the form of panels in m³ GSWE and estimate the wood fibre input required in m³ GSWE. Conversion factors were summarized and non-wood component, MC changes, final panel product density, compression and shrinkage were taken into the consideration.

1.2.1.1 Non-Wood Component

Adhesive, wax and other additives were added into panel manufacturing in order to form or stabilize the panel shape and enhance the product properties. Veneer products do not contain non-wood products. In the North America, solid adhesive accounted 2% by mass of plywood panel or 3.5% by volume (Spelter et al., 2006). Meanwhile, additives in forms of wax and resin solids accounted a range of 3% to 5% by volume in OSB products (Chris, 2009). In this study, an average of 4.0% by dry volume or 4.8% by oven dry mass was assumed for solid adhesive content for panels.

The profile of structural panels in the USA and Canada revealed that the liquid phenol formaldehyde (PF) resin became more popular in the forest products industry. PF resin in panels was assumed to account an average of 11% of by oven dry mass. Additives consist of resin and wax accounted an average of 13% by volume (Irle, 2009).

1.2.1.2 Moisture Content

Construction and industrial plywood in North America is required to have a MC not exceeding 18% at the time of shipment (APA, 2002). Measurements showed that the average moisture content of panels at shipment were much lower than this limit (CDGS, 2006). A final moisture content of 9% (oven dry basis) was assumed for panels according to American Panel Association (APA, 2002). In contrast, a final moisture content of 4% (oven dry basis) was assumed for the OSB panels given in the Forintek report (Nielson et al. 1985). Laboratory work on measuring OSB's moisture content has undertaken to crosscheck the moisture contents of OSB. The results indicated that MC of OSB panels collected from BC's OSB mills averaged at 3.70% (Petit-Etienne, 2009). Thus, 4% given in Forintek report (Nielson et al. 1985) was assumed to be the average MC for OSB panels (Petit-Etienne, 2009). For the other panels, e.g. particleboards, the final moisture content of 7% (oven dry basis) was assumed (Carll, 1986).

1.2.1.3 Panel Density

The density of softwood plywood ranged from 450 to 500 kg/m³ (Canadian Forest Industries, 2006). In this study, 475 kg/m³, the average value was assumed as the density for plywood products. Meanwhile, the density of OSB ranged from 580 to 700 kg/m³ (Canadian Forest Industries, 2006), and the average value of 640 kg/m³ was assumed for the density of OSB in this study. In addition, an average density of 720 kg/m³ was assumed for the other panels (e.g. particleboards, MDF), as the density of other panels ranged from 640 to 800 kg/m³ (Canadian Forest Industries, 2006).

1.2.1.4 Panel Compression

With the exception of veneer, compression is an important manufacturing process for all panels to gain better physical properties. However, in order to quantify the green wood fibre input volume, final panel volume should be converted to a non-compressed volume. Volume loss varies significantly for other PNL products. Conversely, volume loss as the result of compressing process was assumed to be negligible for the VNR&PLY products.

1.2.1.5 Shrinkage

Volume shrinkage occurs when MC decreases. With the assumption that wood species and proportions of all wood species to panel production were the same as inputs to BC's lumber production, the average partial volume shrinkages from green to final product MCs were determined for each panel mill category (Table F-1).

Product	MC Change	Shrinkage (%)
Panels	Average shrinkage Green to 0% MC	11.5
OSB	Average shrinkage Green to 4% MC	9.99
PLY/VNR	Average shrinkage Green to 9% MC	8.07
Other PNL	Average shrinkage Green to 7% MC	8.84

Table F-1: Estimated Average Volumetric Shrinkage for Panels, BC (Suchland, 2004)

Year	Product	Original Unit	Volumetric Factor	Non-wood and Compression Correction Factors	Shrinkage Correction Factor	Conversion Factor
			(m ³ of Panel)		(Dry to Green)	(m ³ GSWE/Bdu)
	OSB	/	/	/	/	/
1991	Veneer	Msf (3/8 " basis)	x 0.885	/	x 1.081	0.957
	Plywood	Msf (3/8 " basis)	x 0.885	x 0.999	x 1.081	0.956
	Other panels	Msf (3/8 " basis)	x 0.885	x 1.075	x 1.088	1.035
	OSB	Msf (3/8 " basis)	x 0.885	x 1.155	x 1.099	1.123
1000	Veneer	Msf (3/8 " basis)	x 0.885	/	x 1.081	0.957
1999	Plywood	Msf (3/8 " basis)	x 0.885	x 0.999	x 1.081	0.956
	Other panels	Msf (3/8 " basis)	x 0.885	x 1.099	x 1.088	1.058
2005	OSB	Msf (3/8 " basis)	x 0.885	x 1.350	x 1.099	1.313
2005	Veneer	Msf (3/8 " basis)	x 0.885	/	x 1.081	0.957
to	Plywood	Msf (3/8 " basis)	x 0.885	x 0.999	x 1.081	0.956
2007	Other panels	Msf (3/8 " basis)	x 0.885	x 1.285	x 1.088	1.237

Table F-2: Final Conversion Factors Used for Structural Panels, BC

The final conversion factors for each structural panel mill category are summarized in Table F-2 by taking into account of all the factors considered above. Based on these conversion factors, the outputs of structural panels from MFLNRO data (actual ft³, dry) could be converted into volume of primary products wood fibre in m³ GSWE

1.2.2 Wood By-Products

There are two parts of wood by-products in the structural panel sub-level material flow, including wood by-products from three types of panel manufacturing listed above as the intermediate products and wood by-products as the input material for the other PNL mills.

As mentioned previously, the wood by-products as an input material includes chips and sawdust and shavings. They were available in thousand Bdu. These data were directly converted into m³ GSWE with the same annual conversion factions listed in Table F-3 and Table F-4.

The volume of sawdust and shavings (excluding chips) as the output from panel mills can be directly found from the mass conservation equation: mass in = mass out. The same density (green volume/oven dry mass) was assumed for both inputs and outputs.

2 Other Mill Material Balance

In addition to the PS and SP sub-levels, the other mill sub-level was the third component of the wood products manufacturing subsector. This sub-level consists other types of primary mills do not produce any of the previously mentioned products. In total, these mills consumed less than 2% of the BC green volume of wood fibre input (MoFR, 2009b; 2007a; 2006). This sub-level includes mills producing the following primary products: chips (CHP), pellets (PLT), shake and shingle blocks (SSB), fence posts (PST), utility poles (UTI), other poles (PLE), log homes (LGH), laminated veneer lumber (LVL) and guitars (GTR). Only CHP and PLT mills were included in the material flow analysis due to the negligible volumes produced from other mills in terms of overall industrial roundwood consumption. All the individual chip mills and pellet mills were aggregated and considered as two individual mills. Furthermore, the special linkage function of chips in the material flow made the output from chip mills an addition resource input for pulp mills.

2.1 Material balance

In other mill sub-level, material balance was undertaken for the aggregated chip mill and the aggregated pellet mill. Chips from chip mills were directly consumed by pulp mills as an additional raw material besides industrial roundwood and wood by-products from both PS and PS mills. Some wood by-products from PS and SP sub-level mills were used as raw material for pellet mills in this sub-level. Similar to the other sub-level mills, input and output data for each individual chip and pellet mills were provided from the MFLNRO confidential database. Other mill sub-level models representing the years of 1991, 1999, 2005, 2006 and 2007 were developed and compared in this study.

2.1.1 Chip mills

In the aggregated chip mill, green industrial roundwood (pulpwood) was the input for the chip mills, chips and sawdust and shavings were produced after chipping process (Figure F-4). Wood fibre was measured in various units for chips manufacturing in chip mills. Green industrial roundwood input was united in thousand cubic metres. The mill capacity and the chips production were given in thousand Bdu. The other wood by-products (sawdust and shavings) were determined by the balance calculation.



Figure F-4: Schematic Material Flow of Chip Mills in the Other Mill Sub-Level

2.1.2 Pellet Mills

Pellet mills had more diversified raw material inputs than chip mills. In this study, all the wood fibre inputs, outputs quantified were under bark volumes, therefore, bark and hog fuel have been excluded for the material balance study. Most of the inputs were wood by-products from the PS and SP manufacturing, including sawdust and shavings, and chips (Figure F-5). However, similar with the precedent parts, an average proportion of wood species and an average yield have been applied for the pellet mills.

In pellet mills, units given vary with products. Sawdust and shavings input was united in thousand Bdu. The production capacity and the pellets output were given in thousand tonnes. Other wood wastes which were not available from all the references were quantified by balance calculations.



Figure F-5: Schematic Material Flow in Pellet Mills for Other Mill Sub-Level

2.2 Conversion Factors Development

2.2.1 Chip Conversion Factors

Chips, one of the intermediate products from the chipping process, were measured in the same unit as the by-products from the lumber and veneer manufacturing.

Year	Input	Output	Conversion Factor	Output	Yield
	(000 m ³ GSWE)	(000 Bdu)	(m ³ GSWE/Bdu)	(000 m ³ GSWE)	
2005	3,483	1,170	2.78	3,254	0.93
2006	2,987	878	2.78	2,440	0.82
2007	2,782	916	2.78	2,545	0.92
Average					0.89

Table F-3: Chip Mill Yield in BC, 2005 to 2007

Over a three-year period, the chip yield (m³ GSWE/m³ GSWE) ranged 0.82-0.93 with 0.89 as the average yield (Table F-3). Additionally, the yield of 0.90 was suggested for the years of 1991 and 1999 with the assumption that the chipping process and technologies applied were similar with that in 2005, 2006 and 2007. Based on this assumption, approximate chips output in m³ GSWE were calculated by multiplying the provided input data in m³ GSWE to the estimated yield for both years. Consequently, conversion factors of m³ GSWE/Bdu for chips were obtained by dividing the calculated input in the format of green wood fibre by the provided volumetric output data in Bdu (Table F-4). Other wood wastes including sawdust and shaving as the output from the chip mills could be directly found from mass conservation equation.

Table F-4: Chips Conv	version Factors from the	Estimated Yield	, 1991	and 1999
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Year	Input	Output	Conversion Factor	Output	Yield Assumed
	(000 m ³ GSWE)	(000 Bdu)	(m ³ GSWE/Bdu)	(000 m ³ GSWE)	
1991	2,237	865	2.33	2,013	0.90
1999	4,387	1,657	2.38	3,948	0.90

2.2.2 Pellet Conversion Factors

Pellets are high compressed wood products with a real density of 1,169 kg/m³ (Tumuluru et al., 2008) and ash content of 0.25% to 0.40% by mass (John, 2006). Therefore, the average wood basic density could be applied to the pellet mass to find the GSWE volume of pellets after the moisture content effect adjustment. Based on published MC range of 2.5-4.5%, an average of 3.5% MC is assumed for the pellets as final products (John, 2006). Conversion factors used for pellet products over the years of 1991-2007 are presented in Table F-5. The conversion factors (Table F-5) were assumed to be consistent from 2005 to 2007.

Year	Convers	Conversion Factor				
	m ³ GSWE/Bdu	m ³ GSWE Fibre/ADT				
1991	—	_				
1999	_	_				
2005	2.78	2.47				
2006	2.78	2.47				
2007	2.78	2.47				

Table F-5: Final Conversion Factors for Pellets, BC

2.2.3 Wood By-Products Conversion Factors

Wood by-products (sawdust and shavings) contributed to the pellet mill flows in two ways: as inputs to the pellets production and as wood wastes generated by the pellet manufacturing process. The wood by-products inputs were available in thousand Bdu. They could be directly converted into m³ GSWE using the annual conversion factors in Table F-5. The wood wastes outputs from pellet manufacturing were directly found using the mass conservation equation in the pellet mills fibre balance.

3 Pulp and Paper Material Balance

Pulp and paper manufacturing plays an important role in the material flow balancing as a large quantity of wood by-products from the wood products manufacturing subsector are further processed into pulp and paper products in the pulp and paper manufacturing subsector. The role of wood by-products in linking the wood products manufacturing and pulp and paper manufacturing subsectors adds greatly to the complexity of the material web in BC. It is therefore important to accurately quantify wood by-products along the supply chain to ensure provincial level material flow development. Therefore, a detailed PP sub-level material flow model is an essential component of the wood fibre balance.

3.1 Material Balance

The schematic material flow diagram for the PP sub-level is presented in Figure F-6. The pulp mill in this diagram represents the aggregated pulp mills in BC to simplify the material balancing. In this simplified pulp and paper flow, chips, sawdust and industrial roundwood were used as the raw materials to be pulped in the aggregated pulp mill (Figure F-6). The outputs consisted of wood pulp as the intermediate product to be further processed in paper mills, both market pulp and paper as the final products and other residues (including lignin, extractives and a part of hemicellulose and cellulose) from pulping process. Pulp mills included in this assessment statistics were those used virgin wood fibre as the input material. Pulp mills using either non-virgin wood fibre or non-wood materials as the input, such as waste paper fibre were beyond the scope of this study.



Figure F-6: Schematic Material Flow for the Pulp and Paper Sub-Level

3.2 Conversion Factors Development

Forest products in the pulp and paper material flow consist of market pulp and paper as final products, pulp as a intermediate product and industrial roundwood and wood by-products (chips and sawdust and shavings) as raw material inputs.

Units used to quantify the green industrial roundwood and wood by-products (chips and sawdust and shavings) as inputs were m³ GSWE and Bdu, representitvely. Pulp and paper outputs were measured in air dry tonne (ADT). To convert the wood by-products unit from Bdu to m³ GSWE, conversion factors discussed for the PS sub-level were also used in pulp and paper sub-level 1991, 1999, 2006 and 2007.

However, different with other forest products, the chemical components of pulp and paper products changed after various pulping process. In general, almost all the lignin and a part of hemicelluloses and cellulous were lost in the pulping process. Therefore, the average density of solid wood fibre of pulp and paper was different with that of industrial roundwood. The uncertainties of pulp and paper wood fibre average densities significantly increased the difficulties in developing conversion factors to convert pulp and paper volumes to green solid wood volumes.

The provincial data sources available (MoFR, 2009b, 2007a, 2006) were insufficient to construct the PP sub-level material flow. The MFLNRO data consisted of the volume of total wood fibre (chips, sawdust and shavings and industrial roundwood) utilized in pulp mills for the years 2003 to 2007 in thousand cubic metre, the estimations of the annual mill capacities and output in tonnes. In this sub-level, by applying "top down" approach, a draft material flow was established based on the MFLNRO data. It was further confirmed and validated by the second balance based on MFLNRO's output data in "bottom up" approach. In this second balance, inputs were back calculated by multiplying average pulp yield which represent various processing types to output values of various pulp products. Pulp yield varied by mill type depending on the processing types (Table F-6). Principally, there were two main categories of pulp mills in BC including chemical pulp mills (bleached kraft pulp mills and unbleached kraft pulp mills) and mechanical pulp mills.

		Yield Range	Average Yield		
Pulp Type		% (Bdu Output/Bdu	% (Bdu Output/Bdu	Bdu(Input)/	
		Input)	Input)	ADT(Output)**	
	Bleached Kraft	35(Cedar Western red) –	20	2.14	
Chemical	Pulp* (NBSK)	42 (Spruce Western)	39	2.14	
Pulp	Unbleached Kraft	41(Cedar Western red) –	45	1.96	
	Pulp	48 (Spruce Western)	45	1.80	
	BCTMP-CMP	88-93	93	0.88	
Mechanical	TMP	92-94	94	0.89	
Pulp***	Mechanical SGW	95	95	0.90	

Table F-6: Pulp Yield from Western Species, BC (Nielson et al. 1985)

Notes: NBSK: Northern bleached softwood kraft; SGW: Stone groundwood; BCTMP: Bleached chemi-thermomechanical pulp; CMP: chemimechanical pulp; TMP: Thermomechanical pulp;

*6% loss in bleaching process was assumed;

** Air dry MC was assumed to be 10% and one Bdu contains 2,400 lb of oven dried wood;

***Maximum values were applied.

The changes of the average yields for the pulp production based on the confidential report as well as the percentage of production by processing types in BC over a 17-year period is presented in Table F-7 and Figure F-7. Chemical pulp accounted more than 67% of the annual pulp output in BC by mass, whereas, mechanical pulp shared less than 35% of the total production every year (Figure F-7). The average pulp yield varied with the processing methods and the proportionate productions of different pulp categories in BC. Overall, kraft pulp has the lowest yield, while mechanical pulp has the highest (Table F-7). Over the study period, average pulp yield exhibited an increase trend this might be contributed by the pulping technology improvements (Figure F-7).

Sources	1991	1999	2005	2006	2007
Bleached Kraft Pulp	36%	38%	39%	39%	39%
Unbleached Kraft Pulp	42%	44%	45%	45%	45%
All Kraft Pulp	37%	38%	40%	40%	40%
Mechanical Pulp	91%	93%	94%	94%	94%
Average Yield	45%	47%	49%	49%	49%

Table F-7: Temporal Changes of Pulp Yield Associated with Pulp Processing Types, 1991-2007

Note: Some estimations were made to calculate the pulp yield due to the insufficient data provided in the MFLNRO confidential report.



Figure F-7: Percentage of Pulp Production by Process Types in BC, 1991-2007

After pulp was produced, a portion of the pulp product was directly sent to paper mills to further transform to paper products. This study assumed that the yield of paper from pulp was 100%.

Basic densities of wood fibre in forms of industrial roundwood, lumber, panels and by-products are consistent along the supply chain, whereas, pulp and paper's chemical compositions were different with the raw material inputs after the pulping process. Especially, most of lignin and extractives, together with a part of hemicelluloses and cellulose are removed during kraft pulping process. Consequently, basic density of wood fibre in forms of pulp and paper varies with the pulp process types. Theoretically, wood pulp conversion factors calculation was based on the mass and volume of net fibre content in wood. Since there are a lot of uncertainties in the proportions of lignin, hemicelluloses and cellulose stay in pulp products, and the average density of non-cellulous components. Therefore, the consistency of basic density of wood fibre in pulp was assumed regardless of chemical components changes to

simply the conversion factors development. Material input (mix of industrial roundwood and by-products) was pulped and the output consists of two components, namely, the pulp products and the waste losses. Based on pup yield and the assumption of same density of lignin and wood fibre, conversion factors for pulp and paper products in BC over the 17-year period were presented in Table F-8. Those conversion factors enabled the conversion of the final pulp and paper products in Bdu and ADT to solid cellulose equivalent volume in m³ GSWE.

Year	Primary Fibre Conversion Factor				
	(m ³ GSWE)/Bdu	(m ³ GSWE)/ADT			
1991	2.33	1.95			
1999	2.38	1.99			
2005	2.78	2.32			
2006	2.78	2.32			
2007	2.78	2.32			

Table F-8: Pulp and Paper Conversion Factors Used in Balancing Material Flows in BC

Note: Yield of paper from pulp was assumed to be 100%

3.2.2 By-products

Data indicating annual by-product losses from pulp mills were insufficient. This increased the difficulties in the material flow balancing. Therefore, conversion factors were found and assessed in "top down" approach by cross checking volumes of by-products back calculated based on the output data in "bottom up" approach. Calculations were based on mass conservation.

Appendix G: Summary of Selected Conversion Factors and Input/Output Factors Used in Balancing BC's Material Flows, 1991-2007

Year	Product	Original Unit	Conversion to Dry Volume	Shrinkage Correction Factor	Final Conversion Factors	Yield	Input/Output Factors
			(m ³ RSWE) (Without Adhesive and Uncompressed)	(Dry to Green)	(m ³ GSWE/Final Product Original Unit)	(m ³ GSWE/m ³ GRWE)	(m ³ GRWE/Final Product Original Unit)
1991	Lumber	Thousand Board Feet	1.72	1.042	1.79	0.41	4.40
1999	Lumber	Thousand Board Feet	1.72	1.042	1.79	0.45	3.97
2005	Lumber	Thousand Board Feet	1.752	1.042	1.83	0.49	3.71
2006	Lumber	Thousand Board Feet	1.752	1.042	1.83	0.50	3.69
2007	Lumber	Thousand Board Feet	1.67	1.042	1.74	0.47	3.69
1991	OSB Panel	/	/	/	/	/	/
1999	OSB Panel	Thousand Square Feet (3/8" basis)	0.885 x 1.155 = 1.022	1.099	1.12	0.72	1.56
2005	OSB Panel	Thousand Square Feet (3/8" basis)	0.885 x 1.350 = 1.195	1.099	1.31	0.90	1.46
2006	OSB Panel	Thousand Square Feet (3/8" basis)	0.885 x 1.350 = 1.195	1.099	1.31	0.94	1.39
2007	OSB Panel	Thousand Square Feet (3/8" basis)	0.885 x 1.350 = 1.195	1.099	1.31	0.93	1.41
1991	Veneer	Thousand Square Feet (3/8" basis)	0.885	1.081	0.96	0.52	1.85
1999	Veneer	Thousand Square Feet (3/8" basis)	0.885	1.081	0.96	0.57	1.68
2005	Veneer	Thousand Square Feet (3/8" basis)	0.885	1.081	0.96	0.56	1.71
2006	Veneer	Thousand Square Feet (3/8" basis)	0.885	1.081	0.96	0.59	1.63
2007	Veneer	Thousand Square Feet (3/8" basis)	0.885	1.081	0.96	0.56	1.71
1991	Plywood	Thousand Square Feet (3/8" basis)	0.885 x 0.999 = 0.884	1.081	0.96	0.52	1.85
1999	Plywood	Thousand Square Feet (3/8" basis)	0.885 x 0.999 = 0.884	1.081	0.96	0.57	1.68

Year	Product	Original Unit	Conversion to Dry Volume	Shrinkage Correction Factor	Final Conversion Factors	Yield	Input/Output Factors
			(m ³ RSWE) (Without Adhesive and Uncompressed)	(Dry to Green)	(m ³ GSWE/Final Product Original Unit)	(m ³ GSWE/m ³ GRWE)	(m ³ GRWE/Final Product Original Unit)
2005	Plywood	Thousand Square Feet (3/8" basis)	0.885 x 0.999 = 0.884	1.081	0.96	0.56	1.71
2006	Plywood	Thousand Square Feet (3/8" basis)	0.885 x 0.999 = 0.884	1.081	0.96	0.59	1.63
2007	Plywood	Thousand Square Feet (3/8" basis)	0.885 x 0.999 = 0.884	1.081	0.96	0.56	1.71
1991	Other Panels	Thousand Square Feet (3/8" basis)	0.885 x 1.075 = 0.951	1.088	1.04	0.31	3.35
1999	Other Panels	Thousand Square Feet (3/8" basis)	0.885 x 1.099 = 0.973	1.088	1.06	0.69	1.54
2005	Other Panels	Thousand Square Feet (3/8" basis)	0.885 x 1.285 = 1.137	1.088	1.24	0.73	1.70
2006	Other Panels	Thousand Square Feet (3/8" basis)	0.885 x 1.285 = 1.137	1.088	1.24	0.64	1.94
2007	Other Panels	Thousand Square Feet (3/8" basis)	0.885 x 1.285 = 1.137	1.088	1.24	0.70	1.77
1991	Pellet	/	/	/	/	/	/
1999	Pellet	/	/	/	/	/	/
2005	Pellet	Tonnes	/	/	2.78 x (100/(103.5 x 1.0886)) = 2.467	0.97	2.54
2006	Pellet	Tonnes	/	/	2.78 x (100/(103.5 x 1.0886)) = 2.467	0.97	2.54
2007	Pellet	Tonnes	/	/	2.78 x (100/(103.5 x 1.0886)) = 2.467	0.97	2.54
1991	Chips	Bdu	/	/	2.33	0.90	2.59
1999	Chips	Bdu	/	/	2.38	0.92	2.59
2005	Chips	Bdu	/	/	2.78	0.93	2.98
2006	Chips	Bdu	/	/	2.78	0.82	3.36
2007	Chips	Bdu	/	/	2.78	0.92	3.04
1991	Pulp & Paper	Tonnes (ADT)	/	/	2.33 x (100/(110 x 1.0886)) = 1.946	0.45	4.32

Year	Product	Original Unit	Conversion to Dry Volume	Shrinkage Correction Factor	Final Conversion Factors	Yield	Input/Output Factors
			(m ³ RSWE) (Without Adhesive and Uncompressed)	(Dry to Green)	(m ³ GSWE/Final Product Original Unit)	(m ³ GSWE/m ³ GRWE)	(m ³ GRWE/Final Product Original Unit)
1999	Pulp & Paper	Tonnes (ADT)	/	/	2.38 x (100/(110 x 1.0886)) = 1.988	0.47	4.23
2005	Pulp & Paper	Tonnes (ADT)	/	/	2.78 x (100/(110 x 1.0886)) = 2.322	0.49	4.74
2006	Pulp & Paper	Tonnes (ADT)	/	/	2.78 x (100/(110 x 1.0886)) = 2.322	0.49	4.74
2007	Pulp & Paper	Tonnes (ADT)	/	/	2.78 x (100/(110 x 1.0886)) = 2.322	0.49	4.74

Appendix H: Summary of Prices and Costs for BC's Forestry Sector, 2007

		8 ,				
Decelucita	Price per Output (C\$/m ³	Sources				
Producis	GSWE)					
Lumber	207.5	(CIBC, 2010; MoFR, 2007b, c)				
OSB	131.0	(CIBC, 2010; Wood Markets, 2009)				
Veneer	260.0	Estimated, 2/3 of Plywood price				
Plywood	390.0	(CIBC, 2010; Wood Markets, 2009)				
Other Mills	191.2	(MoFR, 2007b, c)				
Other Panel	315.5	(RISI, 2008; MoFR confidential database)				
Chip	40.10	(Canfor, 2008)				
Pellet	56.66	Personal communication with research specialist				
Pulp	370.8	(CIBC, 2010)				
Paper Lightweight Coated	429.2	(CIBC, 2010)				
Sawdust and Shavings	10.8	(Confidential information, 2008)				
Logs Delivered	74.2	(MoFR, 2007b, c)				
Pulpwood Delivered	38.9	(MoFR, 2007b, c)				

Table H-1: Forest Products Selling Prices in BC, 2007

Products	Cost per Output (C\$/m ³ GSWE)	Sources				
Lumber	125.0	(MoFR, 2007b, c; Wood Markets, 2005)				
OSB	112.9	(RISI, 2008)				
Veneer	152.7	(RISI, 2008)				
Plywood	350.7	(RISI, 2008)				
Other Mills	127.5	Estimated, 2/3 of the sales price				
Other Panel	203.2	(RISI, 2008)				
Chip from Chip mill	8.57	(MacDonald, 2006)				
Pellet	17.65	(Mani et al., 2006; USDA, 2011)				
Pulp	159.5	(Canfor, 2008; Gystafson, 2010)				
Paper	239.2	Estimated, pulp cost was assumed to be 2/3 of paper				
Sawdust and Shavings	0.00	/				
By-Products Transportation Cost	<u> 9</u> 40	(Bradlay 2000)				
(cent/kg* m ³ GSWE)	0.47	(Bradiey, 2009)				
Avg Transportation Distance	59 4	(Magelli et al., 2009; Mani et al., 2006)				
(km)	J7.T					

 Table H-2: Forest Products Manufacturing Costs Excluding Wood Fibre Input Costs in BC, 2007

Products	Cost (C\$/m	per ³ GSW	Output E)	Sources					
Lumber	94.2			(FPAC, 2012; MoFR, 2008c)					
OSB	43.9			(FPAC, 2012; MoFR, 2008c)					
Vanaan	57.2			Estimated, labor cost/manufacturing cost was assumed to					
veneer	57.2			be the same as plywood					
Plywood	131			(FPAC, 2012; MoFR, 2008c)					
Other Mills	102			Estimated, assumed to be 80% of the manufacturing cost					
Other Panel	104.3			(FPAC, 2012; MoFR, 2008c)					
Chip from Chip mill	4.29			Estimated, assumed to be 50% of the manufacturing cost					
Pellet	7.93			(FPAC, 2012; MoFR, 2008c)					
Pulp	44.9			(FPAC, 2012; MoFR, 2008c)					
Paper	61.0			(FPAC, 2012; MoFR, 2008c)					
Sawdust and Shavings	0			/					

Table H-3: Forest Products Labor Costs in BC, 2007

Sub-Level Primary Roundwood Use 74,646(1,000 m ³ G RWE)		Products in Units of Input				Conversion in Manufacturing (000 m ³ G RWE)				Output Proudct in Unit of 000 m ³ Dry RWE (MC, Shrinkage and Compression Adjusted)			Final Products in Units of Output					
		Input/ Output Factor	Input Quantity	Input Product Unit	Yield (m ² G RWE/m ² G RWE)	Primary Product Fiber	Chips Fibre	Shaving s and Sawdust Fibre	Losses	Total Fibre	Final Product Quantity	Chips	Shavings and Sawdust	Final Product Quantity	Output Product Unit	Conversion Factors	Wood Fiber Balance	
Primary Sawmilling		Sawmills S6,592 Roundwood in Sawnwood Chips Sawdust/Shavings Total	3.70	56,592	000 m ³ G RWE	0.47	26,650	21,396	8,546		56,592	25,568	20,491	8,546	15,310 20,491 8,546	Mbfm Mbdu Mbdu	1.74	47% 38% 15% 100%
		5,070 Plywood/Venner Mills Roundwood in Plywood/Veneer Chips Sawdust/Shavings Total	1.72	5,070	000 m ³ G RWE	0.56	2,825	1,832	414		5,070	2,954	1,684	380	2,954	Mft ² (Dry)	0.96	56% 36% 8% 100%
Structural Panel		OSB Mills 2,530 Roundwood in OSB Panels Sawdust/Shavings Total	1.41	2,530	000 m ³ G RWE	0.93	2,351		179		2,530	1,521		179	1,791	Mft²(Dry)	1.31	93% 7% 100%
917		By-Products in By-Products in Roundwood in Other Panels Sawdust/Shavings Total	1.78	330 80	000Bdu 000 m ³ G RWE	0.70	694		302		997	432		302	561	Mft²(Dry)	1.24	70% 30% 100%
		Chip Mills 2,782 Roundwood in Chips Sawdust/Shavings Total	3.04	2,782	000 m ³ G RWE	0.91	2,545	2,545	237		2,782	2,437	2,437	237	916	000Bdu	2.78	91% 9% 100%
Other Mill	2,146	Pellet Mills SawdustäShavings in Pellets Sawdust/Shavings Total	2.54	2,576	000 m ³ G RWE	0.97	2,499		77		2,576	867		77	1,013	000tonnes(Ory)	2.47	97% 3% 100%
		1,970 Roundwood in Chips Sawdust/Shavings Total	2.86	1,970	GGD m ³ G RWE	0.55	1,090	630	250		1,970	NA	NA	250	690	000 m ³ G RWE	1.58	32% 13% 45%
Pulp and Paper	2,429	2,714 Pulp and Paper Mills Chips/Sawdust&Sahavinas in Chips from Chip Mils in Chips from Roundwood in Wood Pulp Lass Total	4.74	2,429 25,070 2,714 30,213	oco m ¹ G RWE oco m ¹ G RWE oco m ¹ G RWE	0.49	14,660			15,553	30,213	8,925		NA	6,158	000 Tonnes	2.32	49% 51% 100%
		Log Export 3,534					Wood Product 52,223	Chips Export 1,060	Sawdust /Shavin gs 5,300	Residues /Lignin/C hemicals 15,553								

Appendix I: Wood Fibre Balance in BC's Forest Product Industry, 2007

Note: The volume difference between "output" and "input" approaches was within 4%.

Appendix J: Historical Prices Selected Forest Products, 2002-2011



(Lethbridge and Forel, 2011; 2009; Roberts et al., 2004)

Appendix K: Mill Categories, Capacity Measurement and Product Measurement Units

1) Lumber Mills

Mills producing lumber are reported in the following 2 sections:

a) Mills that have estimated annual capacity of more than 10 million board feet of lumber.

b) Mills that have estimated annual capacity of less than 10 million board feet of lumber.

Notes:

1. Measurement units are in millions of board feet.

2. Estimated annual capacity is based on a standardized operation of 240 days per year, two 8 hour shifts per day. Actual mill operations may vary from this schedule.

2) Veneer, Plywood, OSB and Other Panel Mills

Mills producing veneer, plywood and other types of panel are listed in this section. For mills that produce both market veneer and plywood, veneer capacity includes market veneer and the veneer that is used within the mill to manufacture plywood. Panel mills that use wood residuals to produce panels or that do not have log-processing capability are also listed in this report.

Notes:

1. Measurement units are in millions of square feet, 3/8" basis (mill. sq. ft., 3/8").

2. Estimated annual capacity for veneer mills is based on a standardized operation of 240 days per year, two 8 hour shifts per day. For plywood mills, estimated annual capacity is based on a standardized operation of 240 days per year, three 8 hour shifts per day. For OSB and other Panel mills, estimated annual capacity is based on a standardized operation of 345 days per year, three 8 hour shifts per day. Actual operations may vary from these schedules.

3) Chip Mills

Only mills that produce wood chips as a primary product are listed in this section.

Notes:

1. Measurement units are in thousands of bone dry units (000 Bdus).

2. Estimated annual capacity is based on a standardized operation of 240 days per year, two 8 hour shifts per day. Actual operations may vary from this schedule.

4) Shake and Shingle Mills

Mills that produce shake and shingles are listed in this section.

Notes:

- 1. Measurement units are in thousands of roofing squares ('000 sq). A roofing square is approximately 100 square feet.
- 2. Estimated annual capacity is based on a standardized operation of 240 days per year, two 8 hour shifts per day. Actual mill operations may vary from this schedule.

5) Log Home Mills

Mills that process logs to manufacture log homes are listed in this section.

A throughput capacity measurement is not as meaningful for log home mills as it is for other types of primary timber processing mills. Therefore, this section does not include estimated annual capacity.

6) Pole and Post Mills

Mills producing poles and posts are listed in this section.

Notes:

1. Measurement units are in thousands of pieces (000 pcs).

2. Estimated annual capacity is based on a standardized operation of 240 days per year, one 8 hour shift per day, although actual mill operations may vary from this schedule.

7) Pellet Mills

Mills producing wood pellets for bio-energy are listed in this section.

Notes:

1. Measurement units are in thousands of tonnes.

2. Estimated annual capacity for pellet mills is based on a standardized operation of 345 days per year, three 8 hour shifts per

day. Actual operations may vary from these schedules.

8) Pulp and Paper Mills

Mills producing pulp and paper are listed in this section. For integrated mills, pulp capacity includes pulp that is used internally to produce paper, and pulp that is shipped from the mill site as market pulp.

Notes:

1. Measurement units are in thousands of tonnes.

2. Estimated annual capacity is based on a standardized operation of 345 operating days per year, 24 hours per day. Actual operations may vary from this schedule.

Appendix L: Summary Objective Function and Constraints in Scenario 2 Optimization

1) Objective Function in Scenario 2:

Maximize Total EBITDA = Revenue from final product sales

- + Revenue from exporting/selling wood by-products (chips and SS)
- Cost of purchasing delivered sawlogs and veneer logs
- Cost of purchasing delivered pulpwood
- Cost of manufacturing final products (excluding wood fibre material)
- Cost of processing chips at the chip mill
- Cost transporting by-products (chips and SS)

2) Terms in the Objective Function

Revenue from selling final products = $\sum_i P_i^{\text{FP}}$. D_i^{FP} .

Revenue from exporting/external selling by-products (chip and SS)

$$= E^{\text{chip}} \cdot \sum_{i} (Z_i^{\text{Chip, out}} - Z_i^{\text{Chip, in}}) + E^{\text{SS}} \cdot \sum_{i} (Z_i^{\text{SS, out}} - Z_i^{\text{SS, in}})$$

Cost of purchasing sawlogs and veneer logs (industrial roundwood excluding pulpwood)

$$=\sum_{i} P_{sv} X_{i}$$

Cost of purchasing pulpwood = $\sum_i P_{pw}$. X_i

Cost of manufacturing final products = $\sum_i C_i^{\text{FP}} D_i^{\text{FP}}$

Cost of processing chips at the chip mill = C^{Chip} . $Z_6^{\text{Chip, out}}$

By-products transportation cost= T. $(Z_i^{\text{Chip, in}} + Z_i^{\text{SS, in}})$.D

3) Constraints

The yields of final products were fixed: $D_i^{\text{FP}} = \alpha_i^{\text{FP}}$.($X_i + Z_i^{\text{Chip, in}} + Z_i^{\text{SS, in}}$)

The yields of chips in wood products manufacturing subsector mills:

$$Z_i^{\text{Chip, out}} = \alpha_i^{\text{Chip}} (X_i + Z_i^{\text{Chip, in}} + Z_i^{\text{SS, in}})$$

The yields of sawdust and shavings in wood products manufacturing subsector mills:

$$Z_i^{\text{SS, out}} = \alpha_i^{\text{SS.}} (X_i + Z_i^{\text{Chip, in}} + Z_i^{\text{SS, in}})$$

The quantity of chips produced by all wood products manufacturing mills could not be greater than the quantity consumed in total: $\sum_{i} (Z_i^{\text{Chip, out}} - Z_i^{\text{Chip, in}}) \ge 0$

The quantity of sawdust and shavings produced by all wood products manufacturing mills could not be greater than the quantity consumed in total: $\sum_{i} (Z_i^{SS, \text{ out}} - Z_i^{SS, \text{ in}}) \ge 0$

Mills 1-6 did not take any chips as input: $Z_i^{\text{Chip, in}} = 0$; i = 1, 2, ..., 6

Mills 1-6 did not take any sawdust and shavings as input: $Z_i^{SS, in} = 0; i = 1, 2, ..., 6$

The input capacity of each mill could not be exceeded: $X_i \leq Cap_i$

The total input for veneer and plywood mill could not exceed the capacity of the veneer mill:

$$X_3 + X_4 \leq Cap_3$$

The total input for pulp and paper mills could not exceed the capacity of the pulp mill:

$$X_9 + X_{10} \leq Cap_9$$

All variables were non-negative: $X_i \ge 0$, $Y_i \ge 0$, $Z_i^{\text{Chip, out}} \ge 0$, $Z_i^{\text{Chip, in}} \ge 0$, $Z_i^{\text{SS, out}} \ge 0$, $Z_i^{\text{SS, in}} \ge 0$

Appendix M: Data for Enterprise Optimization Modeling

			Unit					
Category	Unit	Product	Price or	Sources				
			Cost					
	Non Delivered	Lumber	193.3	(CIBC, 2010)				
		1_Chips	40.1	(Company Information, 2006)				
	Price per Output	2_Bark	0.00	(Company Information, 2006)				
Price	$(C^{s/m^3} GSWE)$	3_Sawdust	10.91	(Company Information, 2006)				
r nee		4_Shavings	10.91	(Company Information, 2006)				
		5_Trim ends	40.1	(Company Information, 2008)				
		Pulp (NBSK)	333.0	(Company Information, 2008)				
		Finger Joint Panel	135.3	Estimated, 70% of lumber price				
Manufacturing		Lumber	175.8	(MoFR, 2007b; c; Wood Markets, 2005)				
Cost	Cost per Output	Ein ann Iaint Dan al	101 5	Estimated, 3/4 of the sales price (with raw				
(Include delivered	(C\$/m ³ GSWE)	Finger Joint Panel	101.5	material cost)				
fibre cost)		Pulp (NBSK)	244.7	(McFarlane, 2011)				
				(FPAC, 2012), estimated by proportional				
Labor Cost		Lumber	65.0	labor cost to manufacturing cost for				
	Cost per Output			western SPF large mill.				
	(C\$/m ³ GSWE)		42.2	Estimated, assumed to be 2/3 of large				
		Finger Joint Panel	43.3	Western SPF sawmill's labor cost				
		Pulp (NBSK)	38.0	(FPAC, 2012)				
Transportation	$(C^{\phi}/m^3 C^{\phi})$	Finger Joint Denal	4 22	(Company Information 2008)				
Cost	(C\$/III (C\$WE)	ringer joint Panel	4.32	(Company Information, 2008)				

Company X, 2006