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Integrated Bio-Refinery and Forest Products Supply Chain Network Design Using Mathematical Programming Approach

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Abstract. This study presents a mathematical programming approach to design an integrated bio-refinery and forest product supply chain network. In the text, the basic concepts of supply chain, supply chain management, and supply chain design are introduced. The mathematical programming and its applications on various supply chain design problems are reviewed. Earlier works in the supply chain design problems have focused on the supply chains serving the primary product flows. The flows of energies, fuels, as well as the process biomass residues are generally ignored. Since forest and process biomass residues play a significant role in the bio-energy and bio-refining operations, which could subsequently reduce the non-renewable energy and fuel consumptions, these flows must be considered in the design of the bio-refinery supply chain. In this study, we present a mixed integer programming model for the integrated bio-refinery and forest product supply chain. A general market-driven supply chain network structure is proposed allowing the optimal investment decisions to be made in choosing the right facilities, technologies, capacities, and their locations, that strategically maximize the supply chain value. In the model development, the biomass and energy supply decisions are also considered as decision variables. The model is validated using an experimental case.

Keywords. Supply chain management, supply chain design, optimization, integration, bio-refinery, forest products.

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1. Introduction

Driven by the energy crisis, soaring oil prices, environmental concerns caused by green house gas emissions, bio-energy and bio-technology have experienced significant advancements over the last few years to convert biomass into value-added products such as energy (heat and power), bio-fuels (pellet, bio-ethanol, and bio-diesel), and chemical products. As various bio-technologies emerge, the concept of bio-refinery is developed. Based on the concept of petroleum refinery, bio-refinery can be defined as a facility that integrates biomass conversion processes and equipments to produce power, heat, fuels, and value-added chemical products from biomass (National Renewable Energy Laboratory 2009). By converting various components of the biomass and their intermediates to produce multiple value added product mix, bio-refining technology can potentially generate values from the traditional biomass residues, reduce non-renewable fossil fuel consumptions, reduce energy costs, and greenhouse gas emissions.

In recent years, many individual enabling technologies have been developed to support the bio-energy and bio-refining process, including pelletization, combustion, co-combustion, gasification, pyrolysis, digestion, and fermentation (Frombo et al. 2009). All these technologies can be broadly classified into three conversion platforms: mechanical, thermo-chemical, and bio-chemical. Previous works have investigated different converting platforms and technologies to effectively and efficiently convert bio-mass to various bio-products. As organizations eager to set strategies and make investment decisions in this emerging business direction, they are facing many challenging decisions to find the best investment strategy that will maximize the net profit of the organizations. Biomass can be derived from several sources, among which forest biomass will play a significant role in the bio-refining industry. Consequently, the impact of bio-refinery development on the existing forest product industry must be examined. It is therefore desirable to design a sustainable supply chain from biomass supply through various manufacturing transformation processes and distribution networks to deliver the products to the market that strategically maximize the supply chain value.

In this Chapter, the potential opportunities of integrating bio-refinery with forest product manufacturing systems will be investigated to optimize the biomass flows and utilizations. We will present a mathematical programming model for the integrated bio-refinery and forest product (IBRF) supply chain network design. The emphasis is to demonstrate how the optimization modeling techniques can be applied in the design of this integrated supply chain and how the solutions can be used to help the organizations in their investment decisions. Specifically, we will address the following strategic questions:

i. *Should woody biomass and process residues be used for bio-products or forest products manufacturing, what are the best trade-offs and optimal mix, and which demand market should one serve?*
ii. *What manufacturing facilities (e.g. power, pellet, biochemical/thermochemical plant) and how many of them should an organization use to satisfy its target market demand, and where should they be located?*
iii. *Should different manufacturing facilities be built separately or partially/fully integrated?*
iv. *Should these manufacturing facilities be built at green field or at an existing mill site to integrate with the existing manufacturing activities, such as pulp and paper mill, sawmill or wood composite mill to produce a new product mix using mill residues without additional transportation cost?*
v. *What technologies and at what capacities should be installed?*
vi. *What products and at what quantity should each manufacturing facilities be capable of producing?*
vii. *Which raw material sources (or suppliers) to use and what are the raw material allocations?*

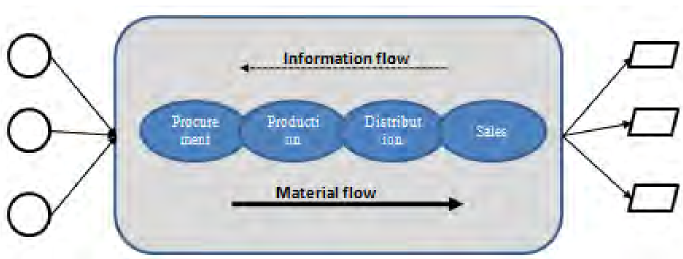
This Chapter is organized as follows. In the next Section, the basic concepts of supply chain management and supply chain design are provided. An introduction of the modeling approach for supply chain design is presented in Section 3, followed by literature reviews of the research that has been carried on the various supply chain design problems to date. The bio-refinery supply chain design, model development and numerical illustrations are presented in Section 4, with concluding remarks and future research opportunities being given in Section 5.

2 The concept of supply chain management and supply chain design

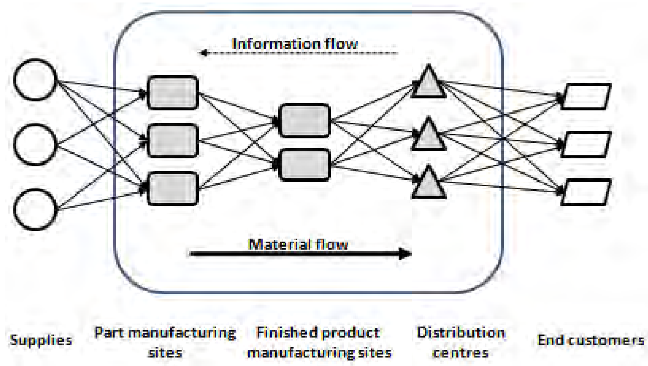
2.1 The basics of supply chain

Supply chain can be broadly classified in four stages: procurement, production, distribution, and sales. Procurement stage describes the activities, functions and relationships at the supply end of the business including the purchasing decisions, transactions, supply capabilities, inbound transportations of primary raw material, parts, components, and services. Suppliers are the organizations who provide goods and services. Production stage describes the activities and functions associated to the manufacturing of goods using the raw materials, parts and/or components. Manufacturer is the organization who performs the production activities. In a supply chain, manufacturer may be regarded as a customer from the supplier point of view and a supplier from its down-stream manufacturer or its customer point of view. Distribution represents the activities and functions related to the product shipments and/or transhipment using different transportation means and intermediate distribution facilities to effectively transport the products from production locations to the customer locations. Distribution centre is a facility that provides temporary storage as well as transhipment services to separate large load into smaller ones or combine smaller loads to a large one to improve transportation efficiencies and reduce costs. Distribution services may be owned by the manufacturer or sub-contracted to the third logistic companies. The manufacturer may have its own transportation services or may use public transportation system or sub-contract to private companies. Lastly but not least, sales stage refers to the general activities, functions and relationships with the customers, to identify and forecast the demand, determine the price as well as promotion strategies, developing contract and collaboration relationships.

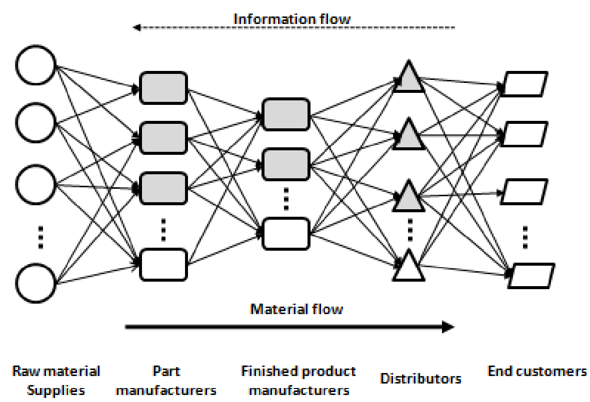
In this regard, there exist three different views of supply chain. First of all, there is a single mill intra-organizational supply chain consisting of different functional units linked by the flows of goods, information and finance fulfilling the supply chain functions of procurement, production, distribution and sales. This supply chain represents the simplest linear structural supply chain as shown in figure 1(a) with a single superior organisational level management. Many studies have been carried out addressing the importance and benefits of supply chain management in this supply chain context. The second is the multi-site intra-organizational supply chain. The supply chain is also formed within a single organization however it may have several supplying, manufacturing and distribution sites scattered in different locations with material, information and financial flows between each site forming intra-organizational supply chain network as shown in Figure 1(b). Despite the complexities of the supply chain network, supply chain management and centralized decision making mechanism are still feasible which has been the focus of many researches. The last is the inter-organizational supply chain consisting of several suppliers, manufacturers, warehouses, distributors, and customers belonging to different organizations. These organizations are linked by material, information and financial flows to transform raw material into value added parts, components, and end products for the customers (Stadtler 2002), as shown in Figure 1(c). This large complex supply chain network presents the complete view of multi-organizational general supply chain network and intra-organizational supply chain is only a subsection of this large supply chain. Due to the complexity of the business context, private information, and often conflict interests of different organizations, integrated supply chain management, despite its significant underlying benefits, is difficult to reach and game theory approach is often adopted in order to reach at least Pareto optimal decisions.



(a) Single-site intra-organizational supply chain



(b) Multi-site intra-organizational supply chain



(c) Inter-organizational supply chain

Figure 1. Supply chain structures

2.2 Supply chain management

Supply chain management (SCM) is the tasks of integrating organizational units along a supply chain, managing, and coordinating the flows of goods, services, information, and finance in order to improve the competitiveness of the organization. The term of SCM was first developed in the 1980s to express the need for integrating the key business processes from the suppliers to end users (Oliver and Webber 1982). The benefits of supply chain management have been well established and documented. Through coordinated and integrated supply chain planning, the supply chain operations may be synchronized, inventories may be reduced, manufacturing efficiencies may be improved, and customer satisfactions may be achieved resulting in cost reductions and high profitability. In an intra-organizational system, since different supplying, manufacturing, and distribution sites and functions are part of one large organization, optimal multi-site capacity allocations and resource utilizations including manufacturing, distribution, inventory, and labour can be reached to timely satisfy the customer demand at the lowest supply chain cost.

2.3 Supply chain design

Supply chain design is also known as strategic supply chain network planning which is a long-term planning typically covering a planning horizon from three to ten years. In strategic supply chain design, organizations set strategies and directions to make right investment decisions for resource acquisitions and allocations to satisfy the defined market requirements. Typical decisions involve the definition of product program and demand market locations, the establishment or closure of manufacturing and distribution facilities, and the installation of major production lines. The objectives are most often financially oriented being either profit maximization or cost minimization, subject to customer service and budget constraints (Goetschalckx 2002). The strategic decisions are linked in a hierarchical manner to the tactical and operational planning decisions within the supply chain. One well known framework for illustrating how the decisions are interrelated is the one presented by Fleischmann et al. (2002) as shown in Figure 2. This two-dimensional supply chain framework illustrated the relationship of the different supply chain planning levels and the linkage across the four supply chain stages. In strategic supply chain design, it is particularly important that the investment decisions are made jointly for the manufacturing and distribution facilities taking into account the product demand and market dynamics as well as long term raw material availabilities. It is equally important that the product development and market selection decisions are made taking into consideration the manufacturing and distribution facility configurations, capabilities, costs, and efficiencies. Once the manufacturing and distribution facilities are built, this supply chain configuration will have long-term impact on the supply chain performances and will set constraints for the supply chain operations and their performances.

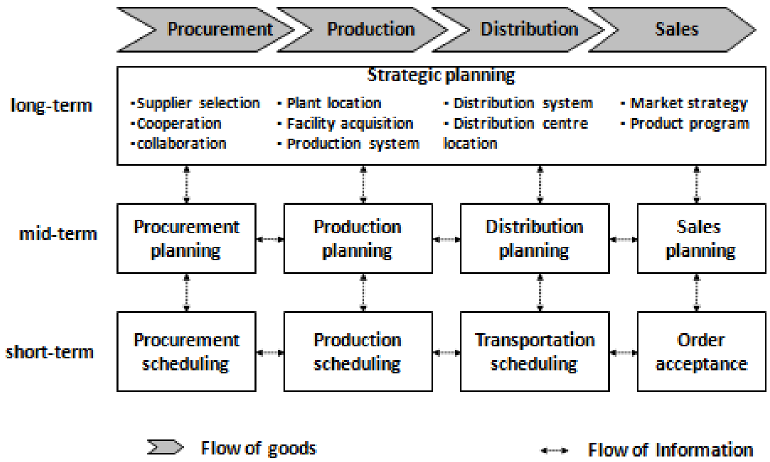


Figure 2. Supply chain planning matrix (adapted from Fleischmann et al. 2002)

Designing supply chain network is a complex task which requires comprehensive evaluations covering both engineering and financial aspects, that are often company or industry specific. Decision support models have thus been developed to support various supply chain design problems. These models usually involve the use of mathematical programs and dominantly the mixed integer linear programs. In the next section, we introduce the linear and mixed integer linear programming techniques and provide literature studies on how these techniques have been applied in various supply chain network design problems. The development of bio-refinery supply chain model will be presented thereafter.

3 Modeling approach in supply chain design

3.1 Introduction to linear and mixed integer programming

Using linear inequalities to solve problems in order to maximize or minimize a linear objective function subject to linear constraints can be found as early as the 1940s. The early model developed by Dantzig was originally focused on finding rapid solutions for military deployment, training, and logistical supply problems (Martin 1999). In 1947, Dantzig formalized the concept of linear program, as we know it today. In the linear program, a planning problem was formulated with a linear objective function subject to solving a system of linear equations and inequalities. The term program does not refer to a computer program, rather it is a term used by the military to describe the plan or proposed solution to the deployment and logistical problems. The terms of linear programming and linear optimization are used synonymously in many publications. The linear programming problem (*LP*) is generally formulated in the following form:

(*LP*) $$\min c^T x \qquad (3.1)$$

$$\text{s.t. } Ax \geq b \tag{3.2}$$
$$x \geq 0 \tag{3.3}$$

where A is an m x n matrix of rational numbers, c is an n component rational column vector and b an m component rational column vector. Equation (3.1) is the objective function. This objective function is minimized subject to, abbreviated by s.t. in (3.2), the constraint set (3.2) and the non-negativity constraints (3.3). The unknowns, or variables x in the problem, are called decision variables. The vector b in (3.2) is known as the right hand side. The canonical structure (*LP*) is a linear program in standard form.

In *LP*, all decision variables x are continuous variables which may take any positive values satisfying the constraints (3.2) and (3.3). In many cases, however, decision variable may involve “yes/no” or “0/1” decisions, such as, installing a facility or not, funding a project or not, etc. and integer variables are therefore required. Using rounding fractional values for these decisions can result in infeasibility or significant profit loss. In this case, some of the variables need to be restricted to integer values. An *LP* where some decision variables are restricted to be integer values is known as mixed integer linear program (*MILP*), or simply mixed integer program. The mixed integer programming (*MIP*) can be formulated as:

(*MIP*)

$$\min c^T x \tag{3.4}$$
$$\text{s.t. } Ax \geq b \tag{3.5}$$
$$x \geq 0 \tag{3.6}$$
$$x_i \in Z, i \in I \tag{3.7}$$

where Z is a sub-set of integer values and some decision variables $x_i \left(i \in I\right)$ can only take values within this sub-set. When all of the variables in *MIP* are restricted to be integers, it is an integer linear programming problem, or often called integer programming (*IP*) problem. When all of the integer variables in *IP* are restricted to be binary variables, it is a binary integer programming (*BIP*) problem. Sometimes we use just the term “integer program” to loosely mean a linear program with some or all of the variables required to be integers.

In this Chapter, we focus on *MIP* problems and specifically the strategic supply chain design problems. In the following sections, we review the different supply chain design models developed to date.

3.2 Single echelon single period capacitated network design models

Earlier network design problem has focused on sub-section of single functions of the supply chain, such as manufacturing or distribution facility location-allocation problems. Models for such problems can be found as early as the 1970s. The problems involve the selection of locations of the manufacturing or distribution facilities from finite set of candidate facility locations that are used as potential sources to satisfy customer demand at various destinations. Examples of manufacturing facility location models can be found in Ellwein and Gray (1971), Geoffrion and McBride (1973), and Soland (1973) in which the distribution centres are regarded as demand locations with deterministic demand. Associated with each potential facility location is a capacitated facility with fixed establishment cost, capacity, as well as variable operational cost and distribution cost. The objective is to determine the facility location that minimizes the total fixed establishment and operational cost.

Geoffrion and Graves (1974) addressed the distribution facility location problem, to determine the optimal locations of the intermediate distribution facilities between plants and customers. In this problem, the manufacturing plant locations are pre-determined with known capacities that produce several commodity products. The demand is known for each commodity at each of the demand zones. This demand is satisfied by shipping via regional distribution centres (DCs), with each demand zone being assigned exclusively to a single DC. The candidate locations of the DCs are given and the maximum and minimum annual allowable throughputs of each DC are known. If a DC site is selected, it will incur a DC fixed costs as well as a linear variable cost. Transportation costs between the selected DCs and demand zones are assumed to be known. The objective is to determine which DC sites are to use with what DC size, serving which demand zones, and using what transportation patterns that can satisfy the demands at lowest total distribution cost.

Subsequent to these facility location-allocation models, several extensions were made to the model development. Brown et al. (1987) presented a *MIP* multi-commodity single period model to determine plant open-closure with facility to plant assignment decisions where each plant may have several facilities. The objective is to minimize total fixed investment and variable operational cost. A goal decomposition approach is introduced yielding pure network sub-problems for each commodity, which can be solved efficiently for large scale problems. Paquet et al. (2004) developed single period manufacturing network design model for manufacturing facilities producing multi-products based on non-trivial product structure and bills of material under deterministic demands. In this model, the notion of capacity options is introduced and facility technology and capacity selection decisions are taken into account in the modeling. Bender's decomposition solution method is proposed. Gebennini et al. (2009) developed a mixed-integer programming model for the distribution centre location problem determining the number of facilities, the choice of their locations and the assignment to customer demand taking into account the anticipated tactical decisions on inventory control, production rates, and service-level in a stochastic environment.

3.3 Production-distribution network design model

Despite the valuable supports the single stage manufacturing or distribution facility location-allocation models provided, the weakness of the decoupled planning approach has been well recognized. One of the limitations of this approach is that since the design of the individual stage, manufacturing or distribution, seeks for decisions that minimizing their local fixed and operational cost, it may increase the cost of the other stage and consequently yield solutions with higher total supply chain cost. In many business environments, the manufacturing-distribution facility location-allocation decisions are internal organization decisions which have significant impact on company performance and competitiveness. Integrated production-distribution network design approach, hence, presents promising opportunities for further supply chain cost reductions.

The integrated production-distribution design models were mostly developed in the 1990 by several authors. Cole (1995) developed a multi-commodity single period strategic production-distribution design model where the plants as well as depots closing decisions are included. The key contribution of this study is the consideration of stochastic customer service, which is defined as the fraction of customer demand satisfied from warehouse stock and delivery time / distance to serve each customer. It is addressed by carrying safety stock, together with warehouse location, customer allocation, and channel selection. Non-linear customer service constraints are linearized and a tractable model is obtained which is solved using CPLEX. This model is important when safety stock costs are significant. Vidal and Goetschalckx (1996) presented a production-distribution in which supplier reliability is incorporated. The supplier reliability is formulated by a set of linearized constraints which assume that the probability of all supplier deliveries to each plant being on time must reach at least a specified target value. Martel and Vankatadri (1999) addressed the single period multi-products production-warehouse location allocation problems under economies of scale. Capacity expansion or contraction possibilities by technology types at the facilities are also considered. A non-linear mixed integer programming model is developed which is solved using scenario improvement approach with successive *MIP* algorithm. Thanh et al. (2008) developed a multi-echelon and multi-commodity multi-period deterministic model for the design and planning of a production-distribution system to determine facility opening, closing, enlargement, supplier selection, as well as flow decisions along the supply chain. The best period of opening or closing facilities and dynamic inventory decisions are included.

3.4 Global supply chain network design model

As companies increasingly extending their business towards other countries to increase their market share while benefit from lower labour cost, favourable currency exchange rate, and tax benefits of the foreign countries, global supply chain issues and network design problems have attracted considerable attentions. As discussed earlier, supply chain design problem generally comprises the decisions regarding the supply chain network configurations, the number and location of production and /or distribution facilities, the amount of capacity at each facility, the technology to be selected, the allocation of each market to one or several facilities, and the supplier selections. Global supply chain design extends this definition to include the selection of facilities at international locations. Due to the international factors, the problem becomes significantly complicated (Meixell and Gargeya 2005).

One of the important international factors that is critical to the global supply chain design is the transfer price. A transfer price is the price at which goods and services are traded across international borders between subsidiaries of a multinational company (Martel et al. 2005). It is one of the most important international tax issue faced in multinational company. In operations management field, transfer price has been regarded as an accounting problem rather than an important decision opportunity in a global supply chain design (Goetschalckx et al. 2002). Many publications have assumed transfer price to be deterministic (Arntzen et al. 1995, Canel and Khumawala, 1996, Bhutta et al. 2003, Martel 2005, Vila et al. 2007). One of the reasons is that, in most of supply chain design problems, product price is generally considered to be predetermined. Another possible reason is that setting transfer price as decision variable will result in non-linear models making them much harder to solve. Nevertheless, according to Nieckels (1976), the impact of transfer price on taxable income, duties, and management performance is significant. Small changes in transfer prices may lead to significant differences in the after tax profit of a company. Nieckels (1976) presented a non-linear mathematical model in which transfer price was regarded as decisional variable with objective function being to maximize the global after-tax profit. Systematic heuristic procedure is proposed that assigns specific values to the transfer prices, allowing model to be simplified and solved iteratively until no further improvement in the objective function is possible. Following the work of Nieckels (1976), several authors have investigated the global supply chain problems having transfer price being formulated as decision variables (Cohen et al. 1989, Vidal and Goetschalckx 2001, Gierdrum et al. 2002, Martel et al. 2005). Cohen et al.(1989) presented a non-linear multi-period production-distribution supply chain design model with transfer price as decision variables. Fixed cost structure allowing economies of scale, bill of material, international tariffs, currency exchange rates, and corporate tax rates, are also considered. Vidal and Goetschalckx (2001) developed a non-convex optimization model for the global supply chain. Gjerdrum et al. (2002) proposed a non-linear mixed integer programming model for a two-enterprise network to examine the transfer price policy and determine optimal transfer prices that maximize the profits of each partner. The model is solved using linearization technique coupled with Nash-equilibrium based algorithm. Martel et al. (2005) developed a single period production-distribution supply chain design model in which a simple formulation was proposed to find optimal transfer price decisions. This formulation is based on the observations that transfer prices are comparatively small in practice, hence, a finite set of varying mark-up percentage multipliers may be introduced. Binary variables can then be defined corresponding to the transfer price multipliers allowing optimal transfer prices to be determined while preserving the linearity of the model.

Another important factor that has significant influence on the global supply chain network design as well as supply chain operational performance is the exchange rate. Since many global supply chain network design models developed to date are single period models, static mean exchange rate values have been used in these models (Cohen and Lee 1989, Canel and Khumawala 1996, Vidal and Goetschalckx 2001, Goetschalckx et al. 2002, Martel et al. 2005). In today’s global economic environment, exchange rate may change considerably over time. A network designed under current exchange rate and market assumptions may not achieve the expected financial returns and may experience losses in the worst case scenario when the exchange rate becoming unfavourable. Therefore, in strategic global supply chain network design, it is important that the dynamics and stochastic characteristics of exchange rate are considered. This raises the necessity to incorporate an adequate exchange rate forecasting model and taking into account the forecast errors in the supply chain design (Martel et al. 2005). However, forecasting exchange rates is a complex task which can be influenced by many factors including random events, institutional frictions and market distortions. Haug (1992) developed a multi-period international location model in which dynamic exchange rate and inflation variability are considered. Mohamed (1999) and Bhutta et al. (2003) proposed a simple linear function to estimate the exchange rate in their supply chain network design model. Other approach, such as generalized linear auto-regressive model may also be applicable (Yu et al. 2005).

Other international factors that have been widely addressed include import and export tarrifs, duties, and corporate tax rates (Haug 1992, Arntzen et al.1995, Canel and Khumawala 1996, Munson and Rosenblatt 1997, Martel et al. 2005, Martel 2005). Since these factors are typically associated with government policies of each country, they are relatively stable. Hence, these factors are generally assumed to be known parameters. In addition to the above factors, Haug (1992) addressed worker skill issues in foreign countries in the development of the international facility location model. Arntzen et al.(1995) discussed the timing aspect of the production and distribution network that is required to product and ship the products to the customer locations. In this regard, the time measurements were introduced in the objective function through weight factor so that both cost and time are used as criteria to derive recommended supply chain design. Customer satisfaction, balance of materials, offset trade, local content, as well as duty drawback restrictions are also considered. Munson and Rosenblatt (1997) investigated a global supply chain problem with local country content rules for supplier sourcing. These rules require that a firm opening a manufacturing plant within the country must purchase a specified quantity of components from suppliers of the country. Martel et al. (2005) examined trade barriers, national labour, infrastructure, resource supply, and competitions in the multinational supply chain design context.

3.5 Supply chain network design under uncertainties

Classical method in supply chain network design modelling, as presented in the previous sections, generally assumes that all the input parameters are deterministic, hence, *MIP* modeling approach has been used predominantly. In real world problems, it is almost invariably that not all parameters are known with certainty. For instance, customer demand, market price, exchange rate, may change un-predictably from time to time. Consider that a decision maker makes the decisions on the facility investment and installation based on the information known to date. After these strategic decisions have been made, random events may occur which will affect the actual performance of the supply chain resulting in unfavourable financial outcomes. One way to mitigate the impact of these uncertainties is to anticipate their occurrences at the design stage to develop robust supply chain network design solutions. There are different approaches to solve optimization problems with uncertainties. One approach is stochastic programming. Stochastic programming (*SP*) can be regarded as an extension of *LP* or *MIP*, where some of the parameters are replaced by random variables whose probability distribution are known or can be estimated. The objective is to find some policies that are feasible for all the possible data instances while maximizes (minimizes) the expectation of the objective function. The concept of stochastic programming, its theoretical development, and solution methodologies can be found in Shapiro (2003) and Higle (2005). Another approach is called robust optimization where the parameters are known only within certain bounds. The objective is to optimize the worst case performance of a system under uncertainties (Kouvelis and Yu 1997, Snyder 2006, Klibi et al. 2010) or the performance at some known degree to the worst case according to the risk aversion of the decision makers (Bertsimas and Sim 2004). Mulvey et al. (1995) developed a scenario based robust optimization framework in which the probability distributions of the random parameters are assumed to be known and plausible realizations of these random variables are realized through scenario generations. The model formulation is characterized by combining the goal programming with the stochastic programming where recourse cost variability and model infeasibility are penalized using goal programming weight to simultaneously trade-off between solution and model robustness.

Kogut and Kulatilaka (1994) developed a stochastic dynamic programming model for production switching decisions under exchange rate uncertainties. The flexibility decisions of a manufacturing system to switch locations as currency exchange rates fluctuate to benefit from the favourable exchange rates were examined taking into account the cost of switching, shutting down, starting up, as well as labour related costs and managerial time commitments. Malcolm and Zenois (1994) presented a scenario based robust optimization model for energy capacity expansion decisions under power demand uncertainties. Lowe et al. (2002) developed a scenario based two-phase multi-screening approach to incorporate exchange rate uncertainties and risks in an international production and sourcing model. Santoso et al. (2005) proposed a two-stage stochastic programming model for a supply chain network design problem taking into account the uncertainties of demand, supply, capacity, and processing/transportation costs. Vila et al. (2007) extended the supply chain network design problem taking into account the market opportunities using two-stage stochastic programming approach. Azaron et al. (2008) presented a multi-objective stochastic programming model for supply chain design taking into account various uncertainties in demand, supply, processing, and transportations. The multi-objective functions of minimizing the total investment costs and future capacity expansion cost, as well as minimizing the variance of the total cost and financial risk of not meeting a certain budget are proposed. A goal attainment technique is used to solve the model in order to find Pareto-optimal solutions. Franca et al. (2009) addressed the multinational supply chain design in which the strategic trade-off decisions of supply chain profitability and quality of raw material supply are modeled. Pan and Nagi (2010) presented a robust optimization model for an integrated production and logistics supply chain design problem.

3.6 The supply chain design in bio-energy and bio-refinery system

With the rapid development of bio-energy and bio-refinery systems, we have seen increasing number of publications in the area of bio-energy and bio-refinery supply chain design. In bio-energy supply chain design, most of the contributions are focused on biomass supply chain optimization from harvesting area to bio-energy plants with or without intermediate terminals while determining the plant location, allocation, and capacity. In this direction, Kumar et al. (2003) analysed the optimum plant size and power cost for power plants using three biomass fuels, agricultural residues (grain straw), whole boreal forest (logs, tops and limbs) and forest harvest residues (tops and limbs), respectively, in western (Alberta) Canada. Freppaz et al. (2004) developed a decision-support system (DSS) for forest biomass in an effort to find suitable plant locations and sizes as well as optimal supply areas within a region. Gunnarsson et al. (2004) presented an *MIP* model studing biomass supply chain problem determining the optimum sourcing, transportation, and allocation of forest and sawmill residues to satisfy the demand at various known heating plant locations in Sweden. Gronalt and Rauch (2007) proposed a simple stepwise heuristic approach for a regional wood biomass supply network design problem that supply biomass from several forest areas to a number of energy plants in Austria. Kanzian et al. (2009) developed a deterministic *MIP* model for the regional woody biomass supply network from forest to the heating plants including the optional use of intermediate terminals in Austria. Frombo et al. (2009) presented an *LP* based strategic planning model determining the annual harvesting quantities and suitable power plant capacities with different thermo-chemical conversion technologies at the pre-determined plant location. In the area of bio-refinery supply chain design, two contributions have been found to date. Eksioglu et al. (2009) presented an *MIP* model in designing the bio-refinery supply chain determining the number, size and location of bio-refineries needed to produce cellulosic ethanol using corn stover and woody biomass. Parker et al. (2009) evaluated the infrastructure requirements of hydrogen production from agricultural residues. A mixed-integer non-linear programming model was developed to find the most efficient and economical configuration of the supply chain pathway.

4 Integrated bio-refinery and forest product supply chain design

In the earlier studies, supply chain design problems have focused on the design of facility and distribution networks serving primary products within a single industrial environment. Take bio-refinery supply chain design, for instance, the bio-refineries are generally designed as stand alone facilities with potential biomass supply sources and product markets (Eksioglu et al. 2009, Parker et al. 2009). Similar approach was taken for the bio-energy supply chain design problems (Kumar et al. 2003, Freppaz et al. 2004, Gunnarsson et al. 2004, Gronalt and Rauch 2007, Kanzian et al. 2009, Frombo et al 2009). These supply chain design problems can be represented by the supply chain illustrated on the left hand side of Figure 3. Since in bio-refinery supply chain systems, the supply chain performance depends strongly on the cost, consistency, and efficiency of the biomass supply, coordinated biomass supply and bio-refinery manufacturing can have significant opportunity for effective biomass utilization, cost reduction, and value chain optimization. In this section, we will discuss the opportunities for the IBRF supply chain design as illustrated on the right hand side of the Figure 3. The flows of energies and forest product manufacturing residues will be examined. The potentials of re-allocations of the manufacturing residues for bio-energy and bio-fuel productions will be investigated. The challenges faced in forest product manufacturing due to increased competitions for raw material supply will be discussed.

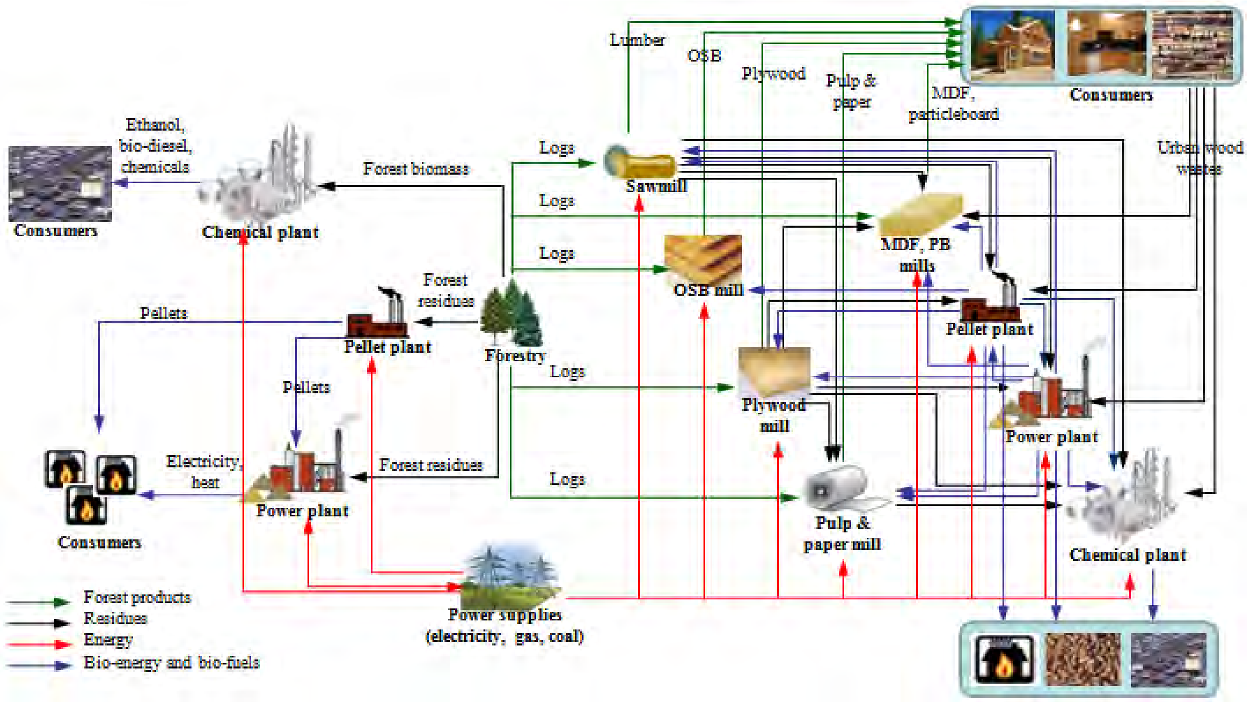


Figure 3. Integrated bio-refinery and forest product supply chain framework

4.1 General descriptions of integrated bio-refinery and forest products supply chain

The IBRF supply chain network can be broadly defined as a network consisting of many suppliers, manufacturers, distribution centres, and customers. Having realized the opportunities of coordinated biomass supply and bio-refinery manufacturing systems, the bio-refineries may be built stand alone at green field site(s) purchasing biomass from forest suppliers and forest product manufacturers while selling bio-energy and bio-fuels back to the forest product manufacturers or to the consumer markets as shown on the right hand side of Figure 3. Alternatively, the bio-refineries may be established within an existing forest product manufacturing site. The existing forest biomass supply system may thus be used to serve both bio-refinery and forest product manufacturing allowing optimal biomass allocations to maximize the value of the supply chain. The traditionally unused biomass, such as forest residues, as well as low value intermediate products, such as barks, sawdust, shavings, chips, pulp liquor may be used to produce value added bio-products including bio-energy, bio-fuels, and chemical products to satisfy the internal and external demands.

4.2 Candidate facilities and their characteristics

At each manufacturing site, existing or green field, one or several facilities may be established, as shown in Figure 4. Within each facility, a production activity can be carried out producing specific set of products using the defined technology under the given capacity. For example, a pulp and paper mill may have chipping, pulping, paper-making, and energy facilities. An energy facility may have a recovery boiler of given capacity producing steam and heat to meet the production requirements. New facilities may be installed, such as a CHP, and/or pellet, and/or bio-ethanol facilities, depending on the economic evaluations. In this section, we analyse different candidate facilities and their characteristics which are potentially important for the IBRF supply chain design.

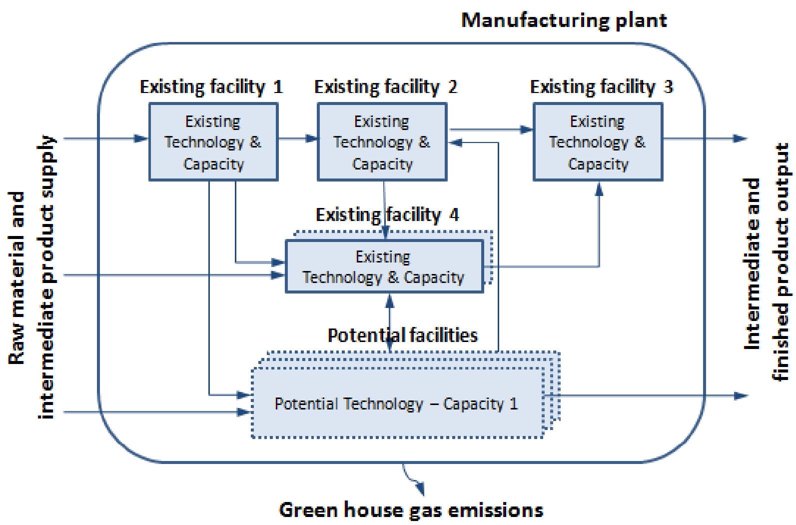


Figure 4. Facility establishments of a manufacturing site.

4.2.1 Sawmill facility

Lumber industry is at the heart of the forest industry and a significant contributor to the social and economical development in Canada. It is the driving mechanism for the forest operations and a primarily dominant consumer of forest biomass. Wood chips produced by the lumber industry support several other sectors of the forest products industry including pulp and paper as well as wood composite sectors, which in turn generate significant values to the Canadian economy. Lumber industry is also a significant producer of process residues. As logs are processed to produce lumbers, considerable quantities of by-products, in addition to chips, are produced simultaneously, such as, barks, sawdust, and shavings. These by-products are currently used either as feed stock for the local boilers to generate heat or sold to secondary processing mills to produce wood panels. For the development of IBRF supply chain, existing sawmills can be one of the important biomass sources, thus, should be included as candidate mill locations for bio-refinery. Existing sawmill technologies and capacities can be considered as the candidate technologies and capacities, respectively. Unlike previous studies of supply chain design and planning problems where emphases have been placed on lumber productions, this study will focus on the co-production of both lumber as well as its by-products to investigate the best investment opportunities to maximize the biomass values. While sawmill can produce different lumber products, we will focus on the product type level, assuming the expected quantities of the by-products are proportionally correlated with the aggregated lumber production.

4.2.2 Pulp and paper facilities

In the pulp and paper production, wood chips are processed first at the pulp facility through either a mechanical or a chemical method to produce pulp. The pulp, either bleached or non-bleached, in the diluted form is then passed through the paper facility where the randomly interwoven mat of fibres is pressed and dried to produce paper. Despite the struggles many pulp and paper companies faced due to the decreased market prices, increased wood costs, and competitions from low cost countries, pulp and paper manufacturing system, particularly the kraft pulping process, has a significant role to play in the development of bio-refining technology. Traditionally, pulping process has been regarded as low-yield process in which only celullose fibres of wood are collected for paper production. Most hemicellulose and lignin components of the wood are dissolved forming spent pulp liquor which are concentrated and burned in recovery boiler to produce process steam and recover the inorganic cooking chemicals for reuse. Because the heating value of hemicellulose is considerably lower than that of lignin, significant loss has been realized by burning hemicellulose. Recent technology has proposed to extract hemicellulose from wood chips before pulping stage to generate higher value products without adverse impact on the pulp production, yield, and properties (Wafa Al-Dajani and Tschirner 2008). Due to the unique characteristic of the kraft pulping process, the integration of bio-refining technology with pulping production has been investigated to seamlessly produce bio-fuel and bio-chemicals, such as ethanol and acetic acid. It has been reported that this process is economically promising if it is integrated in an existing kraft mill and an extraction facility is available (van Heiningen 2006). Since cellulose is an important source of fibre for pulp and paper production which continue to be a value recovery activity, the pulping facility will remain as a candidate facility for the existing pulp and paper mill with existing technology and capacity option.

Black liquor is currently used as feed stock for recovery boiler. This technology will remain in the technology set, however, it may be upgraded with a CHP technology. We assume the black liquor yield follows a known function of total pulp produced (Biermann 1993). The recipes of making hemicellulose, black liquor, and pulp as well as the efficiencies of their yield are known in advance.

4.2.3 Wood panel facilities

There are different wood panel facilities and technologies available to produce different panel products, including particleboard (PB), medium density fibreboard (MDF), plywood, and oriented strand board (OSB). PB and MDF are products used widely for non-structural applications, such as furniture, shelves, and kitchen cabinets. PB is made of low grade wood logs and sawmill residues, such as, chips, sawdust, and shavings. These raw materials are processed into small wood particles which are bonded using synthetic resin under high temperature and pressure. MDF is also made of low grade wood logs and sawmill residues. However, instead of processing these raw materials into small particles, mechanical refining process is used which convert the chips, sawdust, and shavings into wood fibres which are then bonded using urea formaldehyde resin under high temperature and pressure. Since both PB and MDF require sawmill residues as their dominant raw material supplies, the general bio-technology development will undoubtedly have significant impact on their raw material availability and cost. The sustainability of these two sectors will eventually depend to the market demand and profitability comparing with the emerging bio-products.

Plywood and OSB are structural wood panels used mainly for building constructions, as wall, roof and floor sheathings in North America. Plywood is made of wood logs where the logs are first debarked, steam treated, and peeled into veneers. The veneers are then processed through series of drying, grading, gluing, forming, and pressing to produce plywood. In plywood production, peeler cores of 3 to 4 inch in diameter are generally rejected which are used to make wood chips forming another important process biomass source. Lastly, but not least, OSB is made of wood logs which are processed into thin wood strands that are bonded using phenol formaldehyde resin under high temperature and pressure. Since wood strands are physically ideal for the hemicellulose extractions, it presents significant opportunity for an integrated bio-chemical facility. Despite the current economic down turn, the projected demand for the OSB products are expected to remain strong and, hence the yield and economic return for hemicellulose, and consequently, ethanol and acetic acid productions from OSB process will be promissing (Paredes et al. 2008).

From these analyses, to develop comprehensive and sustainable IBRF supply chain, wood panel facilities should be included as the candidate facilities, with existing technologies and capacity options.

4.2.4 Biochemical facility

Economical conversion of woody biomass into value added bio-products and chemicals require efficient use of its components: hemicellulose, cellulose, and lignin. Among these biopolymers, hemicellulose is the easiest one that can be extracted under moderate conditions. With the rapid advancement of bio-refining technology, various methodologies of extracting hemicellulose have been studied.

To extract hemicellulose and converting it into bio-ethanol and acetic acid, biochemical facility is required for pre-treatment, hydrolysis, and fermentation. Depending on the types of biomass used, the conditions of pre-treatment and hydrolysis, the acid and enzyme used, the cost and efficiency can be different. Despite the numerous publications found to date, the technology is yet under development at laboratory scale. For demonstration purposes, we have included a biochemical facility using fermentation technology as a candidate technology to convert hemicellulose to bio-ethanol. We assume the hemicellulose, and subsequently the bio-ethanol productions, are known functions of the oven-dry chip quantities used (Boussaid et al. 1998, Heller et al. 2007). As an independent facility, it may be established at various forest product plants, such as sawmill, pulp and paper mill, panel mill or green field mill sites with different installation costs. The decisions of weather or not selecting such a facility, its location, and capacity, however, are decision variables to be determined by the optimization model.

4.2.5 Energy facility

The core element of energy facility is the boiler and/or CHP generator. Both technologies are characterized by the thermo-chemical reactions that convert fuel substances into energy through combustion. The difference between the two is that, the boiler generates heat and steam only, whereas the CHP technology by installing a steam turbine can generate heat, steam and electricity simultaneously. After the use in the electricity generation cycle, the steam from the steam turbine can be piped to internal facilities where steam and heat are required, or to demand locations through district heating system to provide heat energy. Traditionally, energy facility is built to produce energy from non-renewable fuels (natural gas, fuel oil, coal). Recently, more and more energy facilities have used biomass, including forest residues, pellets, barks, chips, sawdust, shavings, pulp liquor, to minimize the consumptions of the non-renewable fuels. This facility may be established at one or several existing mill sites or a green field site to serve for internal and external manufacturing or commercial energy needs. Depending on the internal biomass fuel availabilities, various fuel options may be implemented. However, biomass fuel from internal source, if available, presents the most attractive and economically advantageous option to reduce fuel outsourcing and shipping costs.

The latest development in thermo-chemical technologies has gone beyond the conventional combustion process. Advanced gasification and pyrolysis technologies are developed to convert biomass into various fuel gas and pyrolysis oil for either heat and electricity generation or producing high value transportation fuels (Van Loo and Koppejan 2007). Within the scope of this study, we limited the bio-energy technologies to the conventional heat/steam generation and CHP generation. As gasification and pyrolysis technologies become commercially viable, they can be added easily as candidate technologies.

4.2.6 Pellet facility

Lignocellulosic biomass from plants usually have a low bulk density of 30 Kg/m^3 and varying moisture content ranging from 10%, such as shavings, to 70%, such as barks and chips. Pelletization can transform the low density and low heating value biomass into high heating value pellets with increased specific density of more than 1000 Kg/m^3 with consistent low moisture content (Mani et al. 2006). Pellet facility is the establishment that combines the technology and equipments to accomplish this transformation. In pellet production, virtually all woody biomass can be used as input materials, such as wood logs, forest residues, landfill residues, and process residues of barks, chips, sawdust, and shavings. However, due to the process handling and operational cost as well as product quality concerns, process residues have become preferred raw materials. Given the raw material consumptions, if the candidate pellet facility is installed within an existing manufacturing site, for example, in a sawmill site, more effective utilization of process residues will be possible, in addition to energy generations as discussed earlier. This option could potentially reduce the chip supply to the pulp and paper mills as well as sawdust and shavings supplies to the PB and MDF mills. If it is installed in integration with pulp and paper or wood panel facilities, since it will use the same materials currently consumed by the pulp and wood panel productions, optimal allocations of raw materials among different facility options will need to be investigated. Alternatively, it may be installed in a green field site. In all cases, it is a complex strategic decision that can be faced by many organizations to determine the most profitable option. It requires a comprehensive analysis and advanced mathematical tool to support such decisions.

Table 1 provides a summary of different facilities and technologies, including the input raw material they consume and primary outputs as well as by-products they produce, respectively.

Table 1. A summary of facilities, technologies, and their input-, output-, and by-products

Facilities	Technologies	Inputs	Outputs	By-products
Sawmill	Lumber production	logs	lumbers	barks, chips, sawdust, shavings
Pulp mill	Pulp production	logs, chips, chemicals	pulp	pulp liquor
Panel mill	Panel production	logs, chips, sawdust, shavings, chemicals	panels	barks, fines
Biochemical	Fermentation	chips	ethanol	extracted chips
Pellet	Pelletization	forest residues, barks, chips, sawdust, shavings	pellet	
Energy	Heat generation	forest residues, landfill residues, barks, chips, sawdust, shavings, natural gas, fuel oil, electricity	steam	heat
Energy	CHP	forest residues, landfill residues, barks, chips, sawdust, shavings, natural gas, fuel oil, electricity	electricity	steam, heat
Energy	Recovery boiler	Pulp liquor	steam	heat
Energy	Recovery CHP	Pulp liquor	electricity	steam, heat

4.3 Raw materials, intermediate and finished products

In IBRF supply chain modeling, one of the complexities is to analyse different types of flows of materials, products, by-products, as well as energy across different mills in different industries. In addition, due to the nature of the problem, one product from a facility may serve as raw material, intermediate product, or energy for the other. For instance, chips from sawmill are considered as raw materials for pulp facility, or fuel for energy facility. Electricity and heat produced from an energy facility using barks, chips, sawdust, and shavings in a sawmill can be used as energy for internal lumber production and mill energy consumptions. These interactive flows of raw material, intermediates, finished products, and energy between supplier-plant, plant-plant, and plant-customer further complicate the problem. To effectively model this integrated supply chain, it is necessary to classify the biomass and define the concept and scope of raw materials, intermediate, and finished products.

4.3.1 The classification of biomass

As it has been discussed in the previous section, woody biomass can be derived from different sources in different forms. They can be purchased from the publicly and/or privately owned forest land in the forms of forest logs and harvesting residues, from forest product manufacturers in the forms of process residues, and from landfills in the forms of barks and bio-wastes. For the purpose of this study, we classify the woody biomass into the following nine classes:

i. *Forest saw logs*: good quality logs, depending on the diameters and species, that can be used for lumber, LVL, and veneer productions;

ii. *Forest pulp logs and thinning*: logs of poor quality, and/or in smaller diameter that can be used for wood composites and pulp productions;

iii. *Forest residues*: tree tops and branches collected in the harvesting areas that can be used for thermo-chemical productions;

iv. *Barks:* process residues from log debarking process of sawmill, wood composite and pulp and paper mills, that can be used for pellet and thermo-chemical productions;

v. *Chips*: Sawmill process residue, can be used as raw materials for wood composites, pulp and paper, pellet, as well as bio- and thermo-chemical productions;

vi. *Shavings:* Sawmill process residue, can be used as raw materials for wood composites, pellet, and thermo-chemical productions;

vii. *Sawdust:* Sawmill process residue, can be used as raw materials for wood composite, pellet, and thermo-chemical productions;

viii. *Pulp liquor*: Pulp mill process residue where hemicellulose and lignin components may be used for bio- and thermo-chemical productions;

ix. *Landfill residues*: The woody residue deposits containing mainly barks that have been decomposed in various degree over the years which present as potential biomass source for thermo-chemical production.

4.3.2 The definitions of raw materials, intermediate and finished products

Having classified the biomass materials, we define, within the context of this supply chain, raw material as the product that is purchased from the supply sources, such as logs, forest residues, landfill residues, chemicals, coal, electricity, natural gas, and fuel oil. If a product or by-product is manufactured in a production site that can be used to produce subsequent products either within or at an exterior production site, this is called an intermediate product. A product manufactured that cannot be used further for the subsequent product manufacturing within the defined supply chain scope, it is defined as a finished product. It is important to note that the definition of raw material, intermediate, and finished products are relative to the defined supply chain environment. For instance, we classify bio-ethanol as a finished product in our supply chain context, which can be an intermediate product in another. Electricity purchased from electricity suppliers is regarded as raw material but as an intermediate product if it is manufactured in a production site. We make no distinction for its identity as it can be used interchangeably within the production process. Table 2 summarizes the definitions of the raw materials, intermediate, and finished products with example products.

Table 2. Product sets, their definitions and examples.

Product sets	Definitions	Product examples
Raw materials	Products that are purchased from supply sources within the defined supply chain scope	logs, forest residues, landfill residues, coal, chemicals, electricity, natural gas, fuel oil
Intermediate products	Products or by-products manufactured that can be used to produce subsequent products within the defined supply chain scope	barks, chips, sawdust, shavings, pulp, pulp liquor, pellet, electricity, heat
Finished products	Products or by-products manufactured that cannot be used for subsequent production within the defined supply chain scope	lumber, paper, wood panels, bio-ethanol

In a general supply chain structure, each manufacturing site may serve intermediate products to itself, external manufacturing sites, as well as demand markets, such as electricity, heat, pellet, chips. As for the finished products, the manufacturer can only serve them to the demand markets.

4.4 Model development

We are now ready to develop the strategic design model for the IBRF supply chain. We will describe the generic case first and the model formulation thereafter.

4.4.1 Case description

Consider a single organizational case in which the organization has several existing forest product manufacturing mills as shown by the solid round-cornered rectangular symbols in Figure 5. It would like to make an investment on one or several bio-refineries to be installed either within the existing mills or at the selected green field sites. The green filed sites are shown as the dotted round-cornered rectangular symbols in Figure 5. These existing and green field sites form the finite list of candidate manufacturing sites, which is refer by "$\mathcal{M}$". The organization has several candidate supply sources for biomass, chemicals, electricity, and fuel supplies. We denote the set of supply sources as "$\mathcal{S}$". In the down stream of the supply chain, the organization serves several demand markets, denoted by "$\mathcal{C}$". In its generic form, this supply chain network can be expressed by $\mathcal{T} = \{\mathcal{N}, \mathcal{A}\}$, where $\mathcal{N}$ represents the entire set of network nodes $\mathcal{N} = (\mathcal{S}, \mathcal{M}, \mathcal{C})$, and $\mathcal{A}$ is the set of arcs, represents the entire set of inbound, outbound, and internal flows carried out by the transportation activities between the pair of nodes $\mathcal{A} = (\mathcal{S} \times \mathcal{M}, \mathcal{M} \times \mathcal{M}, \mathcal{M} \times \mathcal{C})$. We assume the supply chain network has a general structure so that the products not only flow along the supply chain as illustrated in Figure 1(b), but also within and across different manufacturing sites, as illustrated in Figure 5. Thus, each plant, may have several roles: a manufacturer that produces intermediate and finished products; a supplier that supplies products to internal and external production and demand locations; and a customer that receives products from suppliers and other plants. With this network structure, greater flexibility is possible allowing the optimization model to determine the best network configuration for the supply chain.

Recall that each manufacturing site may have one or several facilities with existing or potential technologies and capacity options, in designing the IBRF supply chain, the facility location-allocation, technology, and capacity selection decisions must also be made simultaneously. A technology can be defined by the products it can produce through the combined establishment of process know-how and production equipments (Martel 2005). Once the technology is determined, the raw materials that the technology requires and the products it produces will be determined. Let $\mathcal{G}$ be the set of technologies and g a particular technology, where $\left(g \in \mathcal{G}\right)$. Also, let $\mathcal{G}_n$ be the sub-set of technologies that can be installed at a manufacturing site $n \in \mathcal{M}$. For each candidate technology g, one or many candidate capacity options are available. A capacity option $k \in \mathcal{K}_g \left(\mathcal{K}_g \subset \mathcal{K}\right)$ may correspond to the capacity that is already existed, or one that is to be added as a new resource. In this latter case, different options can be associated with equipment of different sizes to reflect economies of scale. Since each facility will associate to only certain sub-set of technologies, the establishment decisions of a facility may be determined explicitly by the technology decisions. Thus, in the model development, the facility index will be unnecessary. Once a facility with certain technology and capacity option is chosen, the space constraint of establishing such facility must also be considered. However, the exact facility layout is not included in the model formulation at this stage, since it is a problem requires more detailed product flow analysis which, by itself, could be an optimization problem.

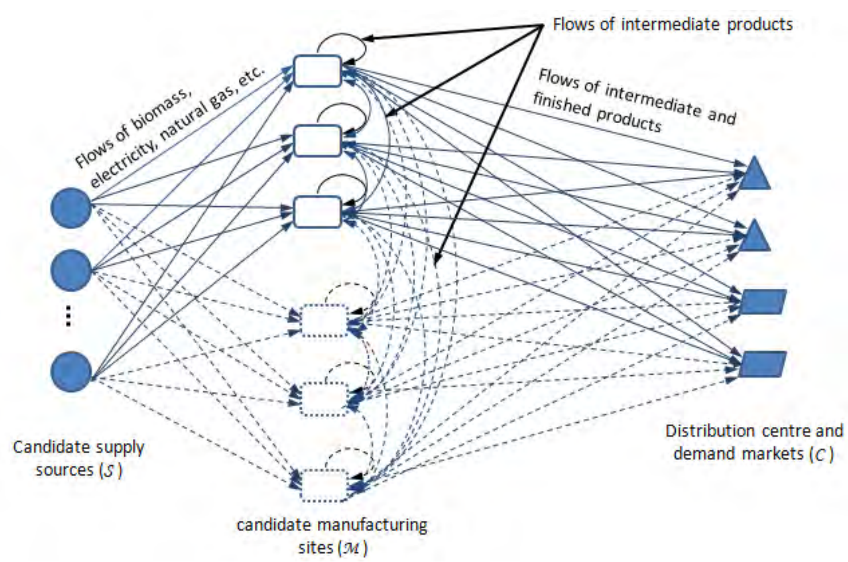


Figure 5. Generic bio-refinery supply chain network

Let I be the set of products including the sub-sets of raw materials $I^{\mathcal{RM}}$, intermediates $I^{\mathcal{INT}}$, finished products $I^{\mathcal{FIN}}$, and energy products $I^{\mathcal{EN}}$, and i be the particular product $i \in I = I^{\mathcal{RM}} \cup I^{\mathcal{INT}} \cup I^{\mathcal{FIN}}$, where $I^{\mathcal{EN}} \subset I$. The conversions of raw materials to intermediate and finished products are accomplished through a set of recipes $\mathcal{R}\left(r \in \mathcal{R}\right)$. We assume, for a given technology, one or several recipes can be developed according to the mixture of raw materials (and/or intermediate products) the technology consumes and the products it can produce. For a standard period of recipe usage, the quantities of raw material and intermediate product consumptions as well as the quantities of intermediate and finished product productions, including by-product productions, are assumed to be known. For a given product, its production efficiency may vary depending on the recipe used which is also assumed to be known.

This Chapter focuses on a demand-driven supply chain network design. The objectives are to provide investment decision support for the organizations on the selection of manufacturing sites, facility technologies, capacity options, and material supply sources that optimize the biomass utilization and maximize the supply chain net present value (NPV). As we develop the model, the following assumptions are necessary:

i. The existing mills proposed have potential spaces to build new facilities;
ii. For both existing and green field sites, if a mill site is selected (opened), it will incur an annual fixed cost. The fixed closure cost, however, would only apply to the existing mill sites.
iii. If a facility is used (installed) at a mill site, it will incur an annual fixed facility cost. The fixed facility closing cost would only apply to the existing facility;
iv. Products are aggregated to product types requiring the same technology;
v. Demand markets are sufficiently large to absorb all productions. The decisions of whether or not serving a particular product to that market is governed by the profitability of that product at the market.

In the model development, the organization's budget constraint is also built-in so that the investment decisions can be made within the budget limit. In the next section, we present the *MIP* based IBRF supply chain design model.

4.4.2 Multi-period integrated bio-energy and forest product supply chain design model

To formulate the model, the following indexes, sets, parameters, and decision variables are defined:

Indexes and sets

$t \in \mathcal{T}$ Set of time periods (years)
$i \in I$ Set of product types with $I^{\mathcal{RM}}$, $I^{\mathcal{INT}}$, $I^{\mathcal{FIN}}$, $I^{\mathcal{EN}}$ being the subset of raw materials, intermediate products, finished products, and energy products, where $I^{\mathcal{EN}} \subset I = I^{\mathcal{RM}} \cup I^{\mathcal{INT}} \cup I^{\mathcal{FIN}}$
$n \in \mathcal{N}$ Set of network nodes where $\mathcal{N} = \mathcal{S} \cup \mathcal{M} \cup \mathcal{C}$
$g \in \mathcal{G}$ Set of candidate technologies
$k \in \mathcal{K}$ Set of candidate capacity options
$\mathcal{K}_g$ Set of candidate capacity options of technology g, $k \in \mathcal{K}_g \subset \mathcal{K}$
$r \in \mathcal{R}$ Set of production recipes
$\mathcal{R}_g$ Set of production recipes for technology g, $r \in \mathcal{R}_g \subset \mathcal{R}$

Parameters

d_{int} Demand of product $i \in I^{\mathcal{INT}} \cup I^{\mathcal{FIN}}$ from demand market $n \in \mathcal{C}$ in period t
p_{int} Unit sales revenue for product $i \in I^{\mathcal{INT}} \cup I^{\mathcal{FIN}}$ at demand market $n \in \mathcal{C}$ in period t
c_{int} Unit cost of purchasing raw material $i \in I^{\mathcal{RM}}$ from a supply node $n \in \mathcal{S}$ in period t
$c_{inn't}$ Unit cost for shipping product $i \in I$ from location n to location n' $(n, n' \in \mathcal{N})$ in period t
c_{irn} Unit production cost of producing product $i \in I^{\mathcal{INT}} \cup I^{\mathcal{FIN}}$ using recipe r at plant node $n \in \mathcal{M}$
u_{ir} Consumption quantity of product $i \in I^{\mathcal{RM}} \cup I^{\mathcal{INT}}$ using recipe r during per unit usage of recipe r
q_{ir} Production quantity of product $i \in I^{\mathcal{INT}} \cup I^{\mathcal{FIN}}$ using recipe r during per unit usage of recipe r
ϕ_{ir} Efficiency factor of producing product $i \in I^{\mathcal{INT}} \cup I^{\mathcal{FIN}}$ using recipe r
e_{in} Estimated annual consumption of product $i \in I^{\mathcal{EN}}$ at plant node $n \in \mathcal{M}$, if it is opened
e_{ik} Estimated annual consumption of product $i \in I^{\mathcal{EN}}$ by capacity option k with technology g$\left(k \in \mathcal{K}_g\right)$ if it is installed or used

s_k Space required to install equipment of capacity k with technology g $\left(k \in \mathcal{K}_g\right)$

S_n Total space available at candidate plant node $n \in \mathcal{M}$

K_{int} Capacity availability for product $i \in I^{\mathcal{RM}}$ at supply node $n \in \mathcal{S}$ in period t

K_{ik} Production capacity of producing product $i \in I^{\mathcal{INT}} \cup I^{\mathcal{FIN}}$ using capacity option k with technology g $\left(k \in \mathcal{K}_g\right)$

a_{nt} Annual fixed cost for selecting a candidate supply node $n \in \mathcal{S}$

a_n Annual fixed cost for opening candidate plant at node $n \in \mathcal{M}$

a_{kn} Annual fixed cost of opening (installing) capacity option k with technology g $\left(k \in \mathcal{K}_g\right)$ at plant node $n \in \mathcal{M}$

b_n Fixed cost for closing plant node $n \in \mathcal{M}$

b_{kn} Fixed cost for shutting down capacity option k with technology g $\left(k \in \mathcal{K}_g\right)$ at plant node $n \in \mathcal{M}$

α Discount rate

B Annual budget availability

G Sufficient large number

Decision variables

Y_n Binary variable being "1" if plant $n \in \mathcal{M}$ is open, and "0" otherwise

Y_{kn} Binary variables being "1" if capacity option k $\left(k \in \mathcal{K}_g\right)$ is installed at plant $n \in \mathcal{M}$, "0" otherwise

Y_{nt} Binary variable being "1" if supply source $n \in \mathcal{S}$ is selected for the period t, and "0" otherwise

X_{rnt} The number of usage of recipe r at plant node $n \in \mathcal{M}$ in period t

$X_{inn't}$ Flow quantity of product i from node *n* to n' $\left(n \neq n'\right)$ in period t, where $n, n' \in \mathcal{N} = \left\{\mathcal{S}, \mathcal{M}, \mathcal{C}\right\}$

The objective function is:

Max:
$$\sum_{t\in\mathcal{T}} \frac{1}{(1+\alpha)^{t-1}} \Bigg(\sum_{i\in I^{\mathcal{INT}}\cup I^{\mathcal{FIN}}} \sum_{n\in\mathcal{M}} \sum_{n'\in\mathcal{C}} p_{in't} X_{inn't} - \sum_{n\in\mathcal{M}} a_n Y_n - \sum_{k\in\mathcal{K}} \sum_{n\in\mathcal{M}} a_{kn} Y_{kn} - \sum_{n\in\mathcal{S}} a_{nt} Y_{nt}$$
$$- \sum_{i\in I^{\mathcal{INT}}\cup I^{\mathcal{FIN}}} \sum_{r\in\mathcal{R}} \sum_{n\in\mathcal{M}} c_{irn} q_{ir} X_{rnt} - \sum_{i\in I} \sum_{n\in\mathcal{N}} \sum_{n'\in\mathcal{N}\setminus\{n\}} c_{inn't} X_{inn't} - \sum_{i\in I^{\mathcal{RM}}\cup I^{\mathcal{INT}}} \sum_{n\in\mathcal{S}} \sum_{n'\in\mathcal{M}} c_{int} X_{inn't} \Bigg)$$
$$- \sum_{n\in\mathcal{M}} \left(b_n \left(1 - Y_n\right) + \sum_{k\in\mathcal{K}} b_{kn} \left(1 - Y_{kn}\right) \right) \tag{4.1}$$

Subject to the following constraints:

$$\sum_{n\in\mathcal{M}} X_{inn't} \le d_{in't} \qquad \forall i \in I^{\mathcal{INT}} \cup I^{\mathcal{FIN}}, n' \in \mathcal{C}, t \in \mathcal{T} \tag{4.2}$$

$$\sum_{n\in\mathcal{S}\cup\mathcal{M}\setminus\{n'\}} X_{inn't} + \sum_{r\in\mathcal{R}} q_{ir}\phi_{ir} X_{rn't} - e_{in'} Y_{n'} - \sum_{k\in\mathcal{K}} e_{ik} Y_{kn'} - \sum_{r\in\mathcal{R}} u_{ir} X_{rn't} - \sum_{n''\in\mathcal{M}\cup\mathcal{C}\setminus\{n'\}} X_{in'n''t} = 0 \qquad \forall n' \in \mathcal{M}, i \in I, t \in \mathcal{T} \tag{4.3}$$

$$\sum_{n'\in\mathcal{M}\cup\mathcal{C}} X_{inn't} \le \sum_{r\cup\mathcal{R}} q_{ir}\phi_{ir} X_{rnt} \qquad \forall i \in I^{\mathcal{INT}} \cup I^{\mathcal{FIN}}, n \in \mathcal{M}, t \in \mathcal{T} \tag{4.4}$$

$$\sum_{r\in\mathcal{R}_g} q_{ir} X_{rnt} \le \sum_{k\in\mathcal{K}_g} K_{ki} Y_{kn} \qquad \forall i \in I^{\mathcal{INT}} \cup I^{\mathcal{FIN}}, g \in \mathcal{G}, n \in \mathcal{M}, t \in \mathcal{T} \quad (4.5)$$

$$\sum_{n'\in\mathcal{M}} X_{inn't} \le K_{int} Y_{nt} \qquad \forall i \in I^{\mathcal{RM}}, n \in \mathcal{S}, t \in \mathcal{T} \quad (4.6)$$

$$\sum_{n\in\mathcal{S}\cup\mathcal{M}\setminus\{n'\}} X_{inn't} \le G Y_{n'} \qquad \forall i \in I^{\mathcal{RM}} \cup I^{\mathcal{INT}}, n' \in \mathcal{M}, t \in \mathcal{T} \quad (4.7)$$

$$\sum_{k\in\mathcal{K}} s_k Y_{kn} \le S_n Y_n \qquad \forall n \in \mathcal{M} \quad (4.8)$$

$$\sum_{n\in\mathcal{M}} \left(a_n Y_n + b_n \left(1 - Y_n\right) + \sum_{k\in\mathcal{K}} \left(a_{kn} Y_{kn} + b_{kn} \left(1 - Y_{kn}\right)\right)\right) \le B \quad (4.9)$$

$$X_{rnt}, X_{inn't} \ge 0,\ Y_n, Y_{kn}, Y_{nt} \in \{0,1\} \qquad \forall i, r, k, n, n', t \quad (4.10)$$

The objective function is to maximize the NPV assuming the first period being the present period. The NPV is expressed as the present value of sales revenue from selling the marketable products, minus the annual fixed cost on opening plants, installing (using) facilities, and contracting with suppliers, the total variable cost for production, shipping, and raw material purchasing, as well as the fixed plant and/or facility closing costs. The revenues for the intermediate products that are consumed internally and/or shipped to other manufacturing sites are not included since it is regarded as an organization's multi-site internal flows. However, the shipment cost are included in the objective function which is a function of shipping distance.

Constraints (4.2) define the demand satisfaction constraints stating that for any marketable product and during any period, not all the market demand will be satisfied by the shipments from manufacturing plants. Constraints (4.3) are product flow balance constraints describing the general flow balance rule that for a product *i*, the total inbound shipments and internal productions at plant node $n \in \mathcal{M}$ should be equal to its internal fixed and variable consumptions and outbound shipments. For a raw material $i \in I^{\mathcal{RM}} \setminus I^{\mathcal{EN}}$, the internal production and outbound shipment quantities will be equal to "0" and the constraints indicate that the raw material supplied by the suppliers to mill $n \in \mathcal{M}$ must be sufficient to satisfy its consumptions. For the intermediate products, shipments within and between plants are allowed. The model will determine weather or not should such shipment be economically acceptable. For the finished products, the inbound shipments from external sources and internal consumptions are equal to "zero" and the constraints state that the production quantity must be equal to the outbound shipments. With regard to the energy product $i \in I^{\mathcal{EN}}$, fixed energy consumptions are included in constraints (4.3), in addition to its variable consumptions, to take into account the electricity and heating requirements upon the opening of a plant and installation or utilization of a facility. These fixed requirements generally cover the non production uses of electricity and heat for lighting, space heating, cooling, electrical appliances, as well as other miscellaneous regular uses. Constraints (4.4) define the shipment upper bound of a plant implying that for any intermediate or finished product, the total shipment from a plant $n \in \mathcal{M}$ should not exceed its production of the given period. Constraints (4.5) and (4.6) provide the production and supply capacity constraints. Constraints (4.7) stress that the inbound shipment to a plant $n \in \mathcal{M}$ could only be made if the plant is open. Constraints (4.8) provide the space availability constraints indicating that a facility of technology-capacity k could only be installed at plant $n \in \mathcal{M}$ if the plant has sufficient space. The annual budget constraints are given by constraints (4.9). Constraints (4.10) define domains for the decision variables.

4.5 Experimental case studies

In order to validate the model, a prototype and an experimental case are developed based on forest industry in Saguenay-Lac-St-Jean region, Quebec, Canada. The case includes a single organization having two sawmills and one pulp mill that purchase raw materials from 6 potential suppliers and selling products to two target demand markets. The organization has a budget which allows it to finance for investment on one or several bio-refineries or bio-energy facilities with different technologies to produce value added bio-products. Five candidate mill locations have been identified including the three existing mill locations and two green field locations. Seventeen candidate technology-capacity options are proposed in the potential investment. Given the candidate technology-capacity options and the possible recipe choices, the expected raw material and intermediate product consumptions, as well as the intermediate and finished product productions can be defined, forming 17 products. The planning horizon is 3 years. Table 3 summarizes the scope of the example case.

Table 3. The scope of the example case

Indexes	Size
Candidate plants	5
Technologies	9
Technology-capacity options	17
Candidate suppliers	6
Raw materials	6
Intermediate products	9
Finished products	3
Customer zones	2
Recipes	30
Planning horizon (years)	3

4.5.1 Data Collections

To perform a demand driven supply chain design that maximize the value of the biomass, end to end supply chain data are required. Due to the large scope of the problem covering several sectors of different industries, data collection becomes very challenging. In this case study, exact industrial data were not always available, therefore, the data are collected from various sources, including the literature, professional and industrial magazines, official government and institutional internet sites, periodic market reports, as well as industrial expert advises and estimates.

During the data collection, preparation, and model validation, several challenges are experienced. One of the challenges is that due to the different product types, from forest biomass, process residues, to lumbers, pulp, energy, fuels, different units have to be used. Further more, for the same product type, different units are often used in different publications and data sources. To ensure the model functioning correctly, a standard unit has to be developed for each type of product and convert the different units according to the standard unit of that product throughout the data files. Once the product type has the same unit, cross examination of the data from different data sources must be carried out to ensure the data consistencies. The second challenge is that the product types change after the mechanical, thermo-chemical and bio-chemical conversions and consequently the units also change. Careful formulation and unit transformation through production recipes are made to ensure no mixed unit calculation is performed. The third challenge is the moisture content involved in the forest biomass and process residues, such as barks, chips, sawdust, shavings, solid content of pulp liquor, and the moisture content of the finished products, such as lumber, pulp, and pellet. Since the mass quantities, prices, costs, and heating values of the biomass are affected by their moisture contents, correct moisture conversions are necessary to ensure the consistency of the results.

Having collected all the data, a Microsoft Access database was developed and populated. The *MIP* model is programmed using Optimization Programming Language OPL 6.3 with a Microsoft Access Database connection to read data inputs and write solution outputs. The model is solved using CPLEX 11.2 optimizer. The program was run on an Intel Core 2 Duo workstation with CPU 2.00 GHz, 4.00 GB of RAM, and Window Vista Home Edition Version 2007.

4.5.2 Results and Discussions

Figure 5 presents an example of the IBRF supply chain configuration designed using the *MIP* model. The design illustrated here is based on a single scenario with the proposed candidate plant sites, facility technologies, capacity options, and supply sources, satisfying the defined markets at the deterministic market demand and price (Table 3). According to this scenario, the solutions suggest that all the existing sawmills (S1 and S2) and pulp mill (P1) should continue to open and the existing lumber and pulp making facilities should continue to be used. The existing boilers at S1 and S2 should also be used. However, the existing recovery boiler at P1 should be replaced (upgraded) by a recovery CHP generator of the same capacity to produce both heat and electricity from pulp liquor. Investment should be considered for pellet facility within all the existing mills to produce pellets from forest residues, sawdust, and shavings. A green field plant at location G1 is suggested to open, however, it will only produce chips with residue barks from pulp logs. Three forest supply sources are selected to supply different mills. Only an electricity supplier is selected for energy supply. The supplies of natural gas and heavy fuel oil are not selected. In this scenario, investment for ethanol production is not suggested. Despite the significant cost reduction of using process by-product chips to produce ethanol, it is still comparatively less profitable than pellet and electricity. For ethanol production to become economically attractive, further production cost reduction and possibly favourable policies through tax credit and financial subsidies are required.

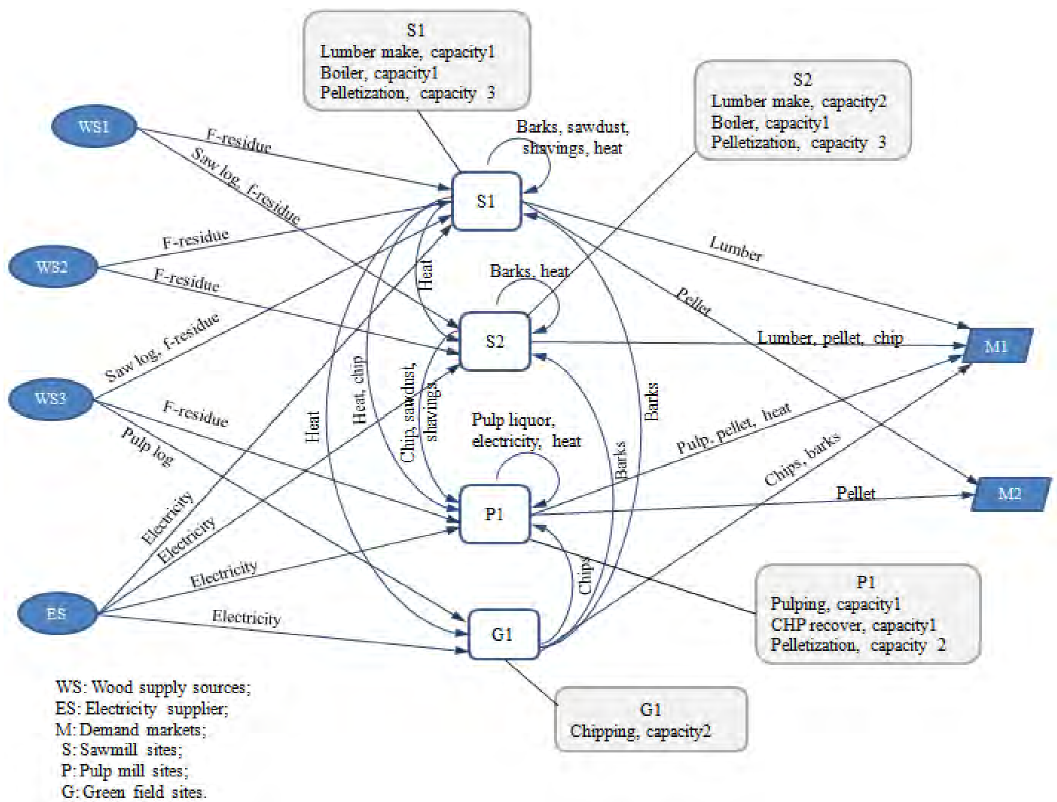


Figure 6. An example of the bio-refinery supply chain configuration design using the MIP model.

In this demonstrative case study, the problem has generated approximately 2000 constraints and 2500 decision variables including 70 binary variables which can be solved in less than 2 seconds with solution gap of 0.3%. Although the testing problem is relatively small, several important aspects, such as the energy flows, as well as the flows of forest and process residues between suppliers and candidate plants in this general supply chain network are modelled. The optimal investment option upon evaluating varying bio-refining technologies and capacity options using biomass is revealed. The methodology provides an important basis upon which various complex models may be developed for more complicated real scaled problems.

It is important to note that while the model is very powerful in evaluating different design options to find the most profitable solutions, the results are case and scenario sensitive. Each business has its own particularities. Therefore, real business data are required and comprehensive scenario studies are essential.

5 Conclusions

With the rapid advancement of bio-energy and bio-refinery technologies, organizations are facing critical moment to transform from traditional manufacturing system towards a bio-technology enabled system to optimize biomass utilizations and maximize the supply chain value. However, making the right investment decisions is a complex task which requires comprehensive analysis and advanced decision supporting tools. This chapter introduced an optimization modeling approach for the IBRF supply chain network design. In the text, the basic concepts of supply chain, supply chain management, and supply chain design are provided. The mathematical programming techniques and their applications in various supply chain design problems are reviewed. Through comprehensive analysis of biomass and energy flows in the various forest product manufacturing sectors, we identified potential opportunities for biomass cost reductions and their effective utilizations through IBRF supply chain optimization. In the supply chain design, a general network structure is proposed, and an *MIP* based supply chain design model is developed allowing optimal biomass allocations to be realized and the right facility investment to be made. The model was validated using an experimental case. An optimal design based on the given market, supply, and budget scenario is provided.

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