A Decision-Support Tool for Evaluating the Technical and Economic Potential of Integrating Bioenergy Production within Pulp and Paper Mills

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Abstract. To overcome declining markets and low-cost competition, Canadian pulp and paper (*P&P*) mills are considering the diversification of their product platform. Investing in bioenergy is emerging as a promising way to boost the sector. In this paper, we present a mathematical programming approach to evaluate the profitability of bioenergy investments, in the case of a *P&P* mill, while assessing technical and economical associated risks. The mill, so called integrated forest biorefinery (*IFBR*), could produce a set of high value bioproducts from biomass generated in the mill or supplied from outside. The *P&P* activity generates residues, such as black liquor and pulp sludge, which could be used to produce bioenergy. The *P&P* activity should, then, be well managed, by considering the possibility to, temporarily, stop producing *P&P*, while assuming the costs associated with the shutdowns. The objective is to develop a decision-support tool for investors and stakeholders, within the forest sector, aiming to optimise the value creation network of the *IFBR* and to maximise the profitability of future investments in bioenergy, while optimising the existing *P&P* activity.

Keywords. Bionergy, integrated forest biorefinery (IFBR), pulp and paper (P&P), roadmap.

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1. Introduction

The rise of Canadian dollar, the US housing crisis and the low-cost competition have led to important losses within the Canadian forest industry. Pulp and paper mills, particularly, are struggling to maintain their competitiveness, due to reduced pulp and paper demand, increased competition from low-costs and emerging countries and continued substitution of online media for paper based products [1]. Integrating new high-added value products is seen as one of the most viable solutions to allow the *P&P* mills to evolve towards a competitive business model, by transforming a conventional mill to an *IFBR* producing, in addition to pulp and paper products, a range of products including electricity, steam and biofuels, from biomass ([2], [3]).

Biomass is considered as an abundant renewable resource that encompasses all organic materials of vegetable or animal origin. It includes forest woody residues (forest harvesting residues and mill residues), agricultural residues and municipal solid waste [4]. **Table 1** shows in details the different usable forms of biomass.

Biomass type	Examples
Forest residues	Top, branches, barks, roadside residues
Mill residues	Sawdust, chips, black liquor, paper sludge
Agricultural residues	Wheat straw, corn stover
Municipal solid waste	Organic solid waste, sewage sludge

Table 1: Different biomass types

P&P mills can take advantage of biomass by diversifying their revenues and reducing fossil energy consumption. In addition, a major part of industrial residues comes from *P&P* industry and forest exploitation [5], such as Black liquor and paper sludge, which present near-zero cost raw materials [6]. So, *P&P* mills have already an available logistical infrastructure and a set of generated residues for processing biomass to produce higher valued products [3]. This predisposition of *P&P* mills to host bioenergy investments makes the integration of such investments more advantageous, in terms of investment costs, than building a bioenergy stand-alone plant [7].

Biomass can be used to produce a set of high-value products including bioenergy, biomaterials and biochemical products [8]. In this work, we are interested in bioenergy pathway. Bioenergy is a source of energy obtained by the decomposition process of organic materials in biomass, and by the combustion of combustible materials released, which encompasses biofuels, power and heat [9]. To produce bioenergy, a set of technologies is already available. In [10], the principal avenues to convert biomass into bioenergy are presented, including all available pathways to produce heat, electricity and biofuels. The maturity degree of these technologies varies between commercial scale status and pilot or demonstration projects [11]. In [12], the maturity degree of different bioenergy technologies has been assessed, in terms of efficiency, investment and operational costs. The authors have shown the enormous potential of the technological development for bioenergy, and substantial cost reduction, enhanced by governmental incentives and bioenergy increasing demand. Even for demonstration scale technologies, their efficiencies have been proved and they would be ready for commercialisation between 2010 and 2025 [9].

As our objective is to assess the viable bioenergy opportunities for investing, we only consider the bioenergy technologies that are already commercialized or ready for commercialization ([13]; [4]).

The Canadian *P&P* mills should evolve into *IFBR*s to thrive within the decline of paper demand and uncertain fossil energy status. An *IFBR*, for the case of *P&P* sector, would integrate bioenergy production to the conventional *P&P* activity, by using supplied and plant-generated biomass and transforming it in high-value bioenergy products. The fossil energy and power needs, as natural gas and electricity, could be supplied from outside, or satisfied, internally, by bioenergy production, allowing the *IFBR* to be energy self-sufficient. In **Figure 1**, we present the value creation network of a standard *IFBR*.

The biomass supplied could be industrial residues from other forest mills like sawmills and other *P&P* mills, including chips that could be used for both *P&P* or bioenergy production, agricultural residues from farms, forest residues generated by harvesting activity, or even urban waste residues from municipalities. The chips are the only biomass source that could be used to produce both *P&P* conventional products and bioenergy products. The other biomass sources would be used to produce only bioenergy products. The technologies considered in the *IFBR* are *Fermentation* to produce *Bioethanol*, *Pelletization* to produce *Pellets, Pyrolysis* to produce *Pyrolysis oil*, *Digestion* to produce *Biogas*, *Cogeneration* to produce *Electricity* and *Steam*, and *Gasification* to produce *Synthetic gas*. The *Synthetic gas* could be further processed to produce *Fischer-Tropsch Diesel* by *Fischer-Tropsch Synthesis* technology, or to produce *Synthetic natural gas* by *Methanation* technology. We also consider that some technologies generate co-products when producing the bioenergy products. Besides *Black Liquor* and *Paper Sludge* generated by *P&P* activity, we consider *Lignin*, a co-product of *Fermentation*, and *Naphtha*, a co-product of *F-T Synthesis* [8]. All these technologies have proven their profitability, once implanted within many bioenergy plants [4]. Therefore, there is already an increasing demand for bioenergy, which is, according to many recent studies, much more than the available bioenergy capacities [14].

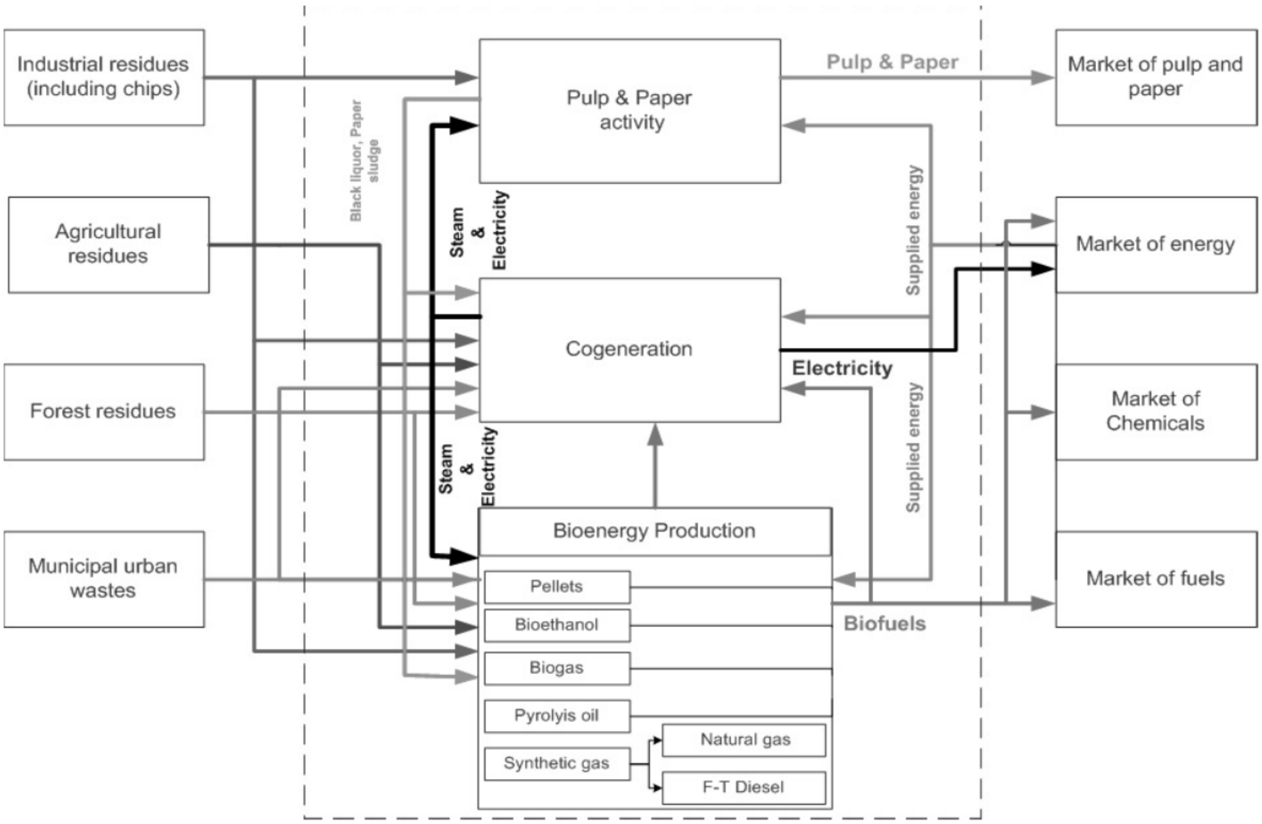

Figure 1: ***IFBR*** **value creation network**

For the *IFBR*, the demand markets are, besides the conventional *P&P* market, oil industry, chemical industry, power generation distributors, etc. The growing demand is mainly driven by technology development and efficiency improvements pushed by supportive policies [15]. The Canadian government has launched a number of bioenergy incentive programs, in order to reduce greenhouse gases and fossil energy dependence, such as carbon tax on fossil fuels, biofuel blending quotas and bioenergy investment subsidies. However, there are still some barriers for bioenergy investments such as lack of bioenergy-related data and the uncertainty about economic profitability and investment scale for bioenergy [14].

The investments in bioenergy have to be, besides being eco-friendly, economically viable to insure its durability. Moreover, financial analyses are essential to support the bioenergy development, since capital costs represent 35% to 50% of total bioenergy costs [15]. Bioenergy investments require the mobilisation of important financial funds. Thus, it would be essential to assess their profitability by considering all the incurred costs over the entire value creation network and throughout long-term planning horizons [16].

As shown above, a set of bioenergy production technologies are available, different biomass sources could be used, some bioenergy products could be processed to produce other bioenergy products, and the *P&P* activity affects directly the bioenergy production by its generated residues that could be used to produce bioenergy products.

Our contribution in this work is to assess and decide on the following: Which technologies should be implanted? What would be the timing of implantation? Which biomass sources should be used in each technology? What would be the production capacity of each technology? And how to manage the *P&P* activity to ensure an optimal synergy with bioenergy production?

To answer these questions, we propose a decision-support tool, which aims to help stakeholders in designing value creation network for forest products integrating bioenergy, particularly in the case of *P&P* mills. The output would be a road map for investments in bioenergy, maximizing the financial value of the *IFBR*, over a long-term planning horizon, while ensuring an optimal operating activity for the conventional *P&P* plant.

The remainder of the paper is organized as follows. In section 2, we present a review of the principal previous works done in biorefinery designing and integrating bioenergy into *P&P* mills. Section 3 is devoted to describe the methodology that we have undertaken to develop our decision-support tool. In section 4, we present the different components of our mathematical model. A summary and discussions of the results are discussed in Section 5. Finally, we conclude our work by discussing the overall results and presenting suggestions for future research.

2. Literature Review

This section is structured as follows. First, we discuss the research works dealing with the biorefining supply chain design. Then, we review the literature focusing on the potential of integrating biomass and producing bioenergy within *P&P* mills.

2.1. The biorefinery design

Since the potential of biorefining has been proven as a promising strategy for forest industry to diversify the revenues sources and remain competitive ([3]; [17]; [18]; [8]), several research projects have studied the problem of integrating biomass in biorefining supply chains. [19] have presented a summary of the supply chains transforming biomass in bioenergy and the different levels of integrating biomass in the supply chains as biomass availability, the harvesting site allocation and the bioenergy plant location. [20] have been interested to the supplying chain of biomass to a bioenergy plant. By considering several options in each of the three supplying stages, harvesting, transport and storage of biomass, the objective is to decide the optimal configuration of the supplying chain, while considering the whole network. [21] have compared three different biomass storage scenarios to assess obtained biomass quality supplying a cogeneration plant. Other papers have proposed decision support systems, for bioenergy supply chains, with different optimization objectives. The decision support tool developed by [22] aims to decide the capacities and locations of a cogeneration plant and the biomass flows supplied in each period, in order to meet the demand of a number of municipalities in electricity and heat, while minimizing the investment and operations costs. [23] have proposed a decision support optimization module to design a value creation network of electricity and heat. By considering four different ways to produce electricity and heat, and three different types of biomass, forest residues, agricultural residues and urban waste residues, the performance of each network configuration is assessed. The objective is to decide the quantity of each type of biomass supplied annually and the installed production capacity, while minimizing the associated logistic costs.

There are several works in the literature that have considered scenario simulation of different biorefinery designs, to assess the profitability of investing in bioenergy ([24]; [25]). Nevertheless, there are few works that have considered mathematical approaches in designing biorefineries, while integrating the strategic and the tactical levels. [26] have proposed a mixed integer-programming model, which optimizes strategic decisions (location, number and capacities of plants and collection sites) as well as tactical decisions (flows of biomass, quantity of bioethanol produced) for a bioethanol logistic network. In a multi-period model, [27] have optimized a set of strategic decisions, such as location and capacity of bioethanol plant, as well as a number of tactical decisions including biomass supplied and flows of final products, while considering the possibility of adding ethanol production capacity over the twenty years planning horizon. The authors consider future changes for several parameters, such an increasing bioethanol demand over the periods, and a capacity-dependent production cost.

During the last years, there has been an increasing awareness of the potential of integrating biomass to the *P&P* mill supply chain, in order to propose new high-value added products and regain their competitiveness. In the following subsection, we review the major works dealing with this issue.

2.2. IFBR potential for P&P mills

Biomass integration within the value creation network of *P&P* mills has gained, recently, the interest of many researchers and forest-industry-strategy experts, in order to detect the causes of the stalemate situation of *P&P* companies, and to assess the economic and environmental potentials of *IFBR*, judged as being one of the viable ways to ensure their competiveness [3]. [28] has discussed the limits of traditional business model of the U.S. *P&P* industry, based on an economy-of-scale production of *P&P* products and selling them as commodities. A new business model embracing the *IFBR* concept would offer to the forest industry companies a unique opportunity to create a competitive advantage. In Canada, there has been a growing interest for transforming the *P&P* mills into IFBRs by exploring the integration of bioenergy products to their core business, aiming to ensure more revenues from higher-value added products, besides conventional *P&P* products [29]. Nevertheless, there are different risks associated with that transformation; such as technical, economic and commercial risks, which should be assessed and mitigated, while evolving to the new business model [6]. Different authors have developed strategies frameworks to involve these risks in the conversion of *P&P* mills into *IFBR*s. A three-phase strategic approach has been developed by [18] in order to allow a step-by-step transition of the business model of the *P&P* mill, while mitigating the risks and maximising the generated margins. In a complementary work, [30] have presented a hierarchical methodology to support the product portfolio definition and technology selection strategies, while building the *IFBR* supply chain design. A margins-based supply chain operating policy has been developed as the core of this methodology. After addressing the challenges facing the global *P&P* mills, [31] have developed a five-step dynamic strategic framework for *P&P* mills to evolve towards a competitive business model. The biorefinery strategy has been identified as one of the main emerging business opportunities, allowing *P&P* mills to gain a sustainable competitive advantage.

While a number of papers have undertaken the assessing of the *IFBR* concept applied to *P&P* mills, by developing strategic frameworks, few works have tackled the transformation of *P&P* mills into *IFBR*s, by using modeling methodologies, in order to obtain optimal supply chain design as an output. [7] have compared three *IFBR* scenarios, by developing process models for a pulp mill-based biorefinery. The only bioenergy technology considered was the bioethanol production by a hemi-cellulose pre-extraction form the wood chips, which would be used to produce pulp after the extraction. [32] have developed a mathematical modeling approach to maximize the net present value of investments in bioenergy, over a planning horizon of three years. The authors consider the whole forest product supply chain network, and the bioenergy investments could be made within *P&P* mills, sawmills or even in stand-alone plants. The considered bioenergy technologies have been pellets production, cogeneration, and bioethanol production. The objective is to optimize the financial value of investments in bioenergy implanted in the first period of the planning horizon.

By evaluating the literature done regarding the *IFBR* design and the assessment of the bioenergy investment potential for *P&P* mills, one should note the lack of works tackling the design of the entire value creation network of *IFBR*s for *P&P* mills, while integrating all biomass types utilizable and the possible avenues of bioenergy investments. There are also no works that aim to optimize the decisions of investing in bioenergy over a long-term and dynamic planning horizon, while deciding the timing and the capacity options to implant through the periods of the Horizon.

Our contribution is to develop a decision-support tool, based on mathematical programming, which optimizes the strategic design of an *IFBR* for the case of a *P&P* mill, while considering different bioenergy technologies, and different biomass sources, to decide the technologies to implant, the capacity options to add, and the timing of investment, over a long-term planning horizon. The other originality of the present work is to build an optimal roadmap of bioenergy investments, over the planning horizon, while managing the *P&P* activity, in order to maximize the financial value of the built *IFBR* in an evolutionary future.

3. Methodology

In the previous section, a number of research works have been only interested in developing mathematical models for designing *IFBR*s, while some other works have developed strategic approaches serving as guidelines to transform *P&P* mills to *IFBR*s. For the reviewed mathematical models, we have noted a lack of detailed analyses assessing the technical feasibility and the adaptability of the products and technologies evaluated in the mathematical model, in the Canadian context, in Quebec particularly.

Our motivation is, then, to build a holistic approach that adapts the mathematical modeling to the particular context of the Quebec *P&P* mills and embraces both the qualitative and the quantitative aspects of the bioenergy supply chain design. The qualitative aspect is covered by defining what we have called “initial pool”, in which we have pre-selected a number of technologies, products, raw materials, as well as other supply chain components that fit to the *P&P* mill sector in Quebec. Then, the construction of a real database has been essential to ensure a viable quantitative analysis through the model solving.

The methodology that we have undertaken, to develop the decision-support tool, encompasses four principal steps: the initial pool definition, the real database construction, the mathematical model, and finally the investments roadmap (**Figure 2**).

3.1. Initial pool definition

As mentioned in the first section, several configurations are available to transform the *P&P* mill into an *IFBR*. There are different types of biomass that could be used, several technologies, with different conversion rates, that could transform each type of biomass into a number of bioenergy products. These different possible configurations make deciding the right configuration an arduous task. Thus, in this first step, our aim is to pre-select a set of feasible configurations, by keeping the ones, which better fit to the Canadian *P&P* mills. To perform this task efficiently, we have referred to the reports and case studies related dealing with the Canadian context (see **Figure 1**). Therefore, we have chosen the biomass types that are available in Quebec and adapted to be used in *P&P* mills. For bioenergy products and technologies, we have selected the technologies, whose viability has been proven in North American context, particularly in the forest industry. For the bioenergy products that we have considered, the conversion rate and the production cost are judged to be economically viable, and there is already an increasing demand for them. The choice of capacity options, for each technology, has been based on real implanted capacities in integrated biorefineries in North America to make sure that the bioenergy capacities added, really fit well with the volume of demand. We have also considered economies of scale for investment costs and production costs based on real case studies [33]. The choice of the planning horizon, the financial horizon, the fiscal lifetime and the economic lifetime, has been carefully calibrated to be appropriate with the design of such value creation network.

3.2. Real database construction

In order to obtain a real decision-support tool, it was essential to feed the optimization model with real-data parameters. Thus, we have collected and assessed real data from governmental reports, multinational organisation researches, specialised biomass magazines, and recent academic works (see Appendix). For several parameters used in our mathematical model, we have found different values or future forecasts. We have constructed intervals based on these values and we have used the average value of these intervals as inputs. The collected data have allowed us to obtain realistic values for the different parameters of the model, such as biomass availability, biomass supplying cost, conversion rate, investment cost, operational cost, plant-gate product prices, the different demand estimations, in the case of a *P&P* mill based in Quebec.

For some parameters, for which we have not found real values, we have used formulas to obtain them, such as estimating some biofuel prices based on their lower heating value [34], or deducing the plant-gate prices from market prices [35].

In order to estimate the future trend for the parameters that evolve over the periods, we have used several reports publishing bioenergy development outlooks over the next decades ([36];[37]; [13]; [9]).

3.3. Mathematical model

Once the real database constructed, based on the best pre-selected configurations, we have developed a mixed integer-programming model, to maximize the financial value of the *IFBR* over the defined planning horizon. Besides the standard costs included in supply chain design, such as cash-flow and annualized investment cost, we have integrated more detailed financial analysis tools, like tax rate, depreciation, debts, and the estimated residual value of the *IFBR* at the end of planning horizon. The objective of the mathematical model is to maximize the objective function, described above, under a number of constraints to ensure feasible solutions. The model developed represents the centerpiece of the methodology, since it connects the qualitative step in which we have chosen the elements and the assumptions to considerate in the design, with the quantitative output, in order to obtain an investment roadmap. The next section is devoted to describe the mathematical model in details.

3.4. The investments roadmap

The roadmap of investments is the principal output of the mathematical model. It prescribes the bioenergy technologies to be implanted and the timing of capacity options added, during the planning horizon. The obtained planning of long-term investments in bioenergy maximizes the financial value of the developed *IFBR*, by optimizing the bioenergy production and the *P&P*

activity. This planning takes into account the evolution of several parameters over the periods of the planning horizon, such as biomass availability, technologies maturity, bioenergy demand and energy market price. The obtained roadmap constitutes a first strategic step to help stakeholders ensure a viable transition of a conventional *P&P* towards a competitive IBFR. Obviously, only the decisions made for the first planning cycle would be implanted. The objective of such decision-support tool is to anticipate the eventual changes in technical and economic environment, over a long planning horizon, which allows decision makers to be proactive in deciding investments in bioenergy.

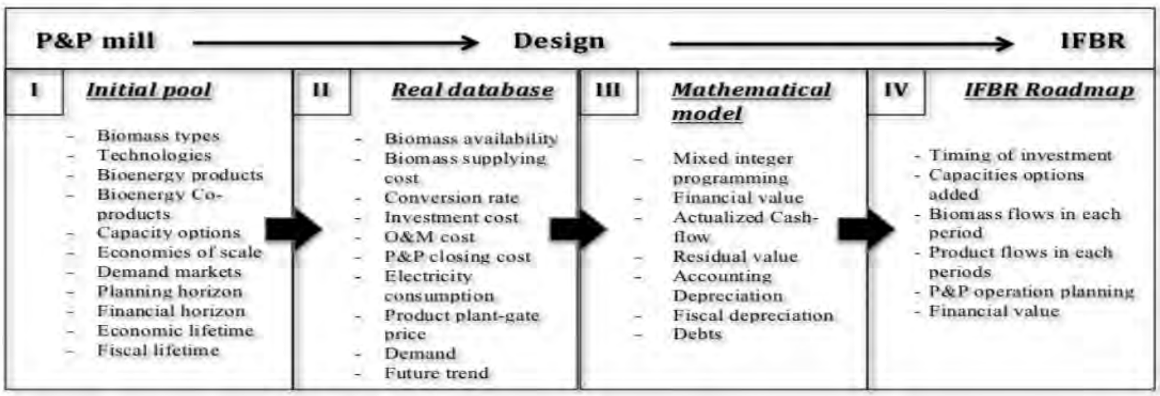

Figure 2: IFBR design methodology

4. Mathematical model

By considering *P&P* mill, producing conventional *P&P* products, our purpose is to optimise the investment timing in bioenergy products over a planning horizon *H*=20 years. The developed model aims to maximise the financial value of the *IFBR* at the end of the planning horizon. Since investments in bioenergy require substantial financial funds, we have performed a detailed financial analysis including accounting and fiscal depreciation, tax rate, discount rate, salvage value and the debts in the end of *H*, besides the traditional analysis, which includes operational and investments costs.

To decide which technology to implant, which capacity option to add, and when to add that option, we have had to optimise anticipated tactical decisions, in each period, including the quantity of biomass supplied, the quantity of bioenergy products produced, the flows of bioenergy products and co-products within the *IFBR* and to the demand markets, and the quantity of *P&P* products produced and shipped to the *P&P* market.

The financial value of the *IFBR* at the end of the horizon is the sum of the actualized financial cash flow and the salvage value actualized at the end of *H*.

In this work, we consider a deterministic model with predetermined parameters, which evolve all over the periods of the planning horizon, to take into account the technical and the economic evolution regarding the bioenergy development, such as conversion rate, investment cost, production cost, and bioenergy demand.

The model aims to optimize the value creation network of forest products, including *P&P* products and bioenergy products. The *P&P* activity and the bioenergy activity are interdependent, in the sense that *P&P* activity generates a number of co-products, such as black liquor and paper sludge, which could be used to generated bioenergy. On the other hand, some bioenergy products generated by the implanted technology, such as electricity, steam and natural gas, could be used to fulfill the mill energy needs. Besides bioenergy products, a number of technologies generate some bioenergy co-products, which could be used in the mill further, to generate bioenergy products or could be sold directly to the market.

Thus, during the planning horizon, we have to decide, jointly, about bioenergy activity and *P&P* activity. There are two types of planning periods: A five-year period in which we decide about strategic investments in bioenergy technologies. The choice of a five-year interval is due to the fact that the five-year period is widely used in international reports to estimate the technical and economic change regarding the bioenergy development ([14]; [13]). A one-year period is used to decide to keep running or not the *P&P* activity, while assuming an operating cost and a closing cost. This one-year period is also used to anticipate a number of tactical decisions regarding the product flows throughout the *IFBR* supply chain.

To well assess profitability of the *IFBR*, we consider strategic costs including investments costs, accounting and fiscal depreciation, debts and salvage value. Besides, we consider a number of operational costs including supplying costs and production costs.

We consider a fixed discount rate to get actualized costs and revenues, in order to discount all future cash flows and obtain their estimated present value.

While developing the model, a number of assumptions are made:

- Economies of scale have been considered for bioenergy investment costs and production costs. The scaling factor has been set at 0,7 [33].
- All the steam produced by cogeneration in the mill is used to fulfill mill steam needs.
- All the space needed to implant potential bioenergy technologies is available
- The accounting depreciation, as well as the fiscal depreciation, are split linearly during the planning periods.
- The biomass supplying costs include transportation costs within 100 kilometres [38].
- The bioenergy investments are irreversible. Once implanted, a technology could not be shut down during the planning horizon.
- The *P&P* activity could be shut down, temporarily, if it is judged unprofitable by the model while considering the estimated closing and restarting costs.

The different parts of the model, including sets, parameters, decision variables, costs and revenues, objective function and constraints, are presented in the following.

4.1. Sets

- T: Number of periods;
- $H = 1 .. T$: Planning horizon expressed in periods;
- C: Number of cycles;
- $Cycle\ Cycles = 1 .. C$: Planning horizon expressed in cycles;
- RM: Set of raw materials (biomass);
- $INTP$: Set of generated co-products;
- $FINP$: Set of bioenergy products;
- $Options$: Set of capacity options;
- PP: Set of *P&P* (pulp and paper) products;
- S: Set of biomass suppliers;
- G: Set of bioenergy technologies;
- M: Set of demand markets.

4.2. Parameters

- FH: Financial horizon (period of repaying debts);
- EL: Economic lifetime (period of accounting depreciation);
- FL: Fiscal lifetime (period of fiscal depreciation);
- LP: Number of periods in a planning cycle;
- BG: A big number;
- TR: Tax rate;
- r: Discount rate (capital rate);

- $CSUP_{i,t,n}$: Supplying cost of biomass $i \in RM$, in period $t \in H$, from supplier $n \in S$;
- $B_{i,t,n}$: Quantity of biomass $i \in RM$, available in period $t \in H$, from a supplier $n \in S$;
- Bd_c: Available budget in cycle $c \in C$;
- $e_{ELEC,n,i}$: Electricity consumption per unit of capacity installed of technology $n \in G \cup "p"$ to produce $i \in FINP \cup PP$;
- FCP: Operating fixed cost of *P&P* activity;
- $\rho_{i,t,j,n}$: Conversion rate of $i \in RM \cup INTP \cup FINP$, in period $t \in H$, to produce $j \in FINP$ by technology $n \in G$;
- $CA_{o,n,c}$: Investment cost of implanting the option $o \in O$ of the technology $n \in G$, in cycle $c \in Cycles$;
- b_p: Closing cost of *P&P* activity $"p"$;
- $K_{o,n}$: Capacity of the option $o \in O$ of the technology $n \in G$;
- $capP_p$: Capacity installed of the *P&P* activity $"p"$;
- $CUP_{i,t}$: Unit production cost of $i \in INTP \cup FINP \cup PP$, in period $t \in H$;
- $\alpha_{i,j}$: Proportion of generating co-product $i \in INTP$ by producing $j \in FINP \cup PP$;
- $P_{i,t}$: Selling price (plant-gate price) of $i \in INTP \cup FINP \cup PP$, in period $t \in H$;
- $d_{i,t,m}$: Expected demand of $i \in INTP \cup FINP \cup PP$, in period $t \in H$, for a demand market $m \in M$.

4.3. Decision variables

Binary variables

$X_{o,n,c}$ =1 if the capacity option $o \in O$ of the technology $n \in G$ is added in cycle $c \in C$, 0 otherwise.

$Z_{p,t}$ =1 if the *P&P* activity is operating in $t \in H$, 0 otherwise.

Integer variables

$FB_{i,t,n,n'}$ Flows of biomass $i \in RM$, in period $t \in H$, which are shipped from supplier $n \in S$ to technology $n' \in G$;

$FC_{i,t,n,n'}$ Flows of co-products $i \in INTP$, in period $t \in H$, generated by the technologies $n \in G \cup "p"$ to other technologies $n' \in G$ or market $n' \in M$;

$FFP_{i,t,n,n'}$ Final product flows $i \in FINP$, in period $t \in H$, from technologies $n \in G$, to other technologies $n \in G \cup "p"$, or to the demand markets $n' \in M$;

$QP_{i,t,p}$ — Produced quantity of *P&P* products $i \in PP$, in period $t \in T$, by *P&P* activity $"p"$;

$QBio_{i,t,n}$ — Produced quantity of bioenergy products $i \in FINP$, in period $t \in T$, by technologies $n \in G$.

In **Figure 3**, we present a graph in which the decision variables are represented spatially over the *IFBR* supply chain, from the suppliers to the markets.

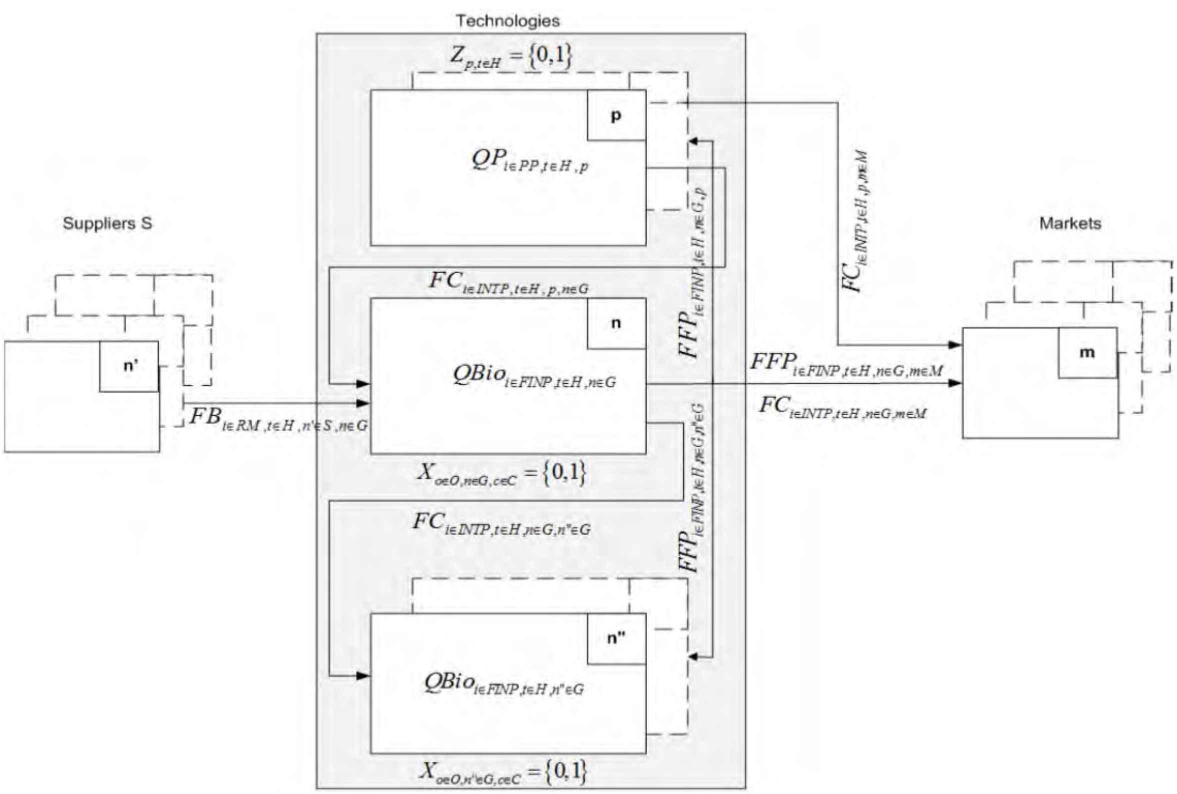

Figure 3: Decision variables over the IFBR supply chain

4.4. Costs and Revenues

In this section, we present the different costs and revenues figuring in the objective function.

4.4.1. Actualized sales of P&P products

The actualized sales of *P&P* products are given by the product of the selling price, $P_{i,t}$, and the quantity produced per period, $QP_{i,t,p}$, discounted using the discount rate r.

$$RevPPAct = \sum_{t \in H, i \in PP} \frac{\left(P_{i,t}.QP_{i,t,p}\right)}{\left(1+r\right)^{t}} \quad \textbf{(1)}$$

4.4.2.Actualized production cost of P&P products

The actualized production cost of *P&P* products is given by the product of the unit production cost, $CUP_{i,t}$, and the quantity produced per period, $QP_{i,t,p}$, discounted using the discount rate r.

$$ProdCostPPAct = \sum_{t \in H, i \in PP} \frac{\left(CUP_{i,t}.QP_{i,t,p}\right)}{\left(1+r\right)^{t}} \quad \textbf{(2)}$$

4.4.3.Actualized operating fixed cost of P&P activity

The actualized operating fixed cost of *P&P* activity is equal to the operating fixed cost of *P&P* activity, *FCP*, if the *P&P* activity is operating in that period ($Z_{p,t}$=1), discounted using the discount rate r.

$$FixCostPPAct = \sum_{t \in H} \frac{FCP.Z_{p,t}}{\left(1+r\right)^{t}} \quad \textbf{(3)}$$

4.4.4.Actualized closing cost of P&P activity

The actualized closing cost of *P&P* activity is equal to the closing cost in that period, b_p, if the *P&P* activity is not operating in that period ($Z_{p,t}$=0), discounted using the discount rate r.

$$ClosCostPPAct = \sum_{t \in H} \frac{b_p.(1 - Z_{p,t})}{(1+r)^t} \quad \textbf{(4)}$$

4.4.5.Actualized bioenergy sales revenues

The actualized bioenergy sales revenues are given by the product of the selling price, $P_{i,t}$, and the sum of bioenergy product flows, from the different technologies to the markets, $\sum_{n \in G, m \in M} FFP_{i,t,n,m}$, discounted using the discount rate r.

$$\mathrm{Re}\,vBioAct = \sum_{t \in H, i \in FINP} \frac{P_{i,t}.\sum_{n \in G, m \in M} FFP_{i,t,n,m}}{(1+r)^t} \quad \textbf{(5)}$$

4.4.6.Actualized co-products sales revenues

The actualized co-products sales revenues are given by the product of the selling price, $P_{i,t}$, and the sum of co-products product flows, from the different technologies including *P&P* activity to the markets, $\sum_{n \in G \cup "p", m \in M} FC_{i,t,n,m}$, discounted using the discount rate r.

$$\mathrm{Re}\,vCoAct = \sum_{t \in H, i \in INTP} \frac{P_{i,t}.\sum_{n \in G \cup "p", m \in M} FC_{i,t,n,m}}{(1+r)^t} \quad \textbf{(6)}$$

4.4.7.Actualized bioenergy production costs

The actualized production cost of bioenergy products is given by the product of the unit production cost, $CUP_{i,t}$, and the sum of quantities produced by all the implanted technologies per period, $\sum_{n \in G} Qbio_{i,t,n}$, discounted using the discount rate r.

$$\mathrm{Pr}\,odCostBioAct = \sum_{t \in H, i \in FINP} \frac{CUP_{i,t}.\sum_{n \in G} Qbio_{i,t,n}}{(1+r)^t} \quad \textbf{(7)}$$

4.4.8. Actualized biomass supplying cost

The actualized supplying cost of biomass is given by the product of the unit supplying cost, $CSUP_{i,t,n}$, and the sum of biomass flows to the different implanted technologies, $\sum_{n'\in G} FB_{i,t,n,n'}$, discounted using the discount rate r.

$$RMCostAct = \sum_{t\in H, n\in S, i\in RM} \frac{CSUP_{i,t,n}.\sum_{n'\in G} FB_{i,t,n,n'}}{(1+r)^t} \quad \textbf{(8)}$$

4.4.9. Actualized fiscal depreciation of bioenergy investments

The actualized fiscal depreciation of bioenergy investments is equal to the sum of bioenergy investment costs, for the technologies already implanted, $\sum_{n\in G, o\in O} CA_{o,n,i+1}.\max\left(X_{o,n,i+1} - X_{o,n,i}, 0\right)$, annualized, over the planning periods, by dividing it by the fiscal lifetime *FL*, over the planning horizon, and discounted using the discount rate r.

$$DepFiscAct = \sum_{i=0}^{C-1} \left(\sum_{t=i.LP+1}^{T} \frac{\sum_{n\in G, o\in O} CA_{o,n,i+1}.\max\left(X_{o,n,i+1} - X_{o,n,i}, 0\right)}{FL.(1+r)^t} \right) \quad \textbf{(9)}$$

4.4.10. Accounting depreciation of bioenergy investments

The accounting depreciation of bioenergy investments is equal to the sum of bioenergy investment costs, for the technologies already implanted, $\sum_{n\in G, o\in O} CA_{o,n,i+1}.\max\left(X_{o,n,i+1} - X_{o,n,i}, 0\right)$, annualized by dividing it by the economic lifetime *EL*, over the planning cycles.

$$DepAcc = \sum_{i=0}^{C-1} \left(\sum_{t=i.LP+1}^{T} \frac{\sum_{n\in G, o\in O} CA_{o,n,i+1}.\max\left(X_{o,n,i+1} - X_{o,n,i}, 0\right)}{EL} \right) \quad \textbf{(10)}$$

Total investment cost for bioenergy

The total investment cost for bioenergy is equal to the sum of bioenergy investment costs, for the technologies already implanted, $\sum_{n\in G,o\in O} CA_{o,n,i+1}.\max\left(X_{o,n,i+1}-X_{o,n,i},0\right)$, over the planning cycles.

$$InvTot=\sum_{n\in G,o\in O,c\in C} CA_{o,n,c}.\max\left(X_{o,n,c}-X_{o,n,c},0\right) \tag{11}$$

4.4.11. Investment cost considered over the periods of the planning horizon

The investment cost for bioenergy, considered for the planning horizon, is equal to the sum of bioenergy investment costs, for the technologies already implanted, $\sum_{n\in G,o\in O} CA_{o,n,i+1}.\max\left(X_{o,n,i+1}-X_{o,n,i},0\right)$, which is annualized, over the planning periods, by dividing it by the financial horizon *FH*, over the planning cycles.

$$InvHorizon=\sum_{i=0}^{C-1}\left(\sum_{t=i.LP+1}^{T}\frac{\sum_{n\in G,o\in O} CA_{o,n,i+1}.\max\left(X_{o,n,i+1}-X_{o,n,i},0\right)}{FH}\right) \tag{12}$$

4.4.12. Actualized investment cost considered over the periods of the planning horizon

The investment cost for bioenergy, considered for the planning horizon, is equal to the sum of bioenergy investment costs, for the technologies already implanted, $\sum_{n\in G,o\in O} CA_{o,n,i+1}.\max\left(X_{o,n,i+1}-X_{o,n,i},0\right)$, which is annualized, over the planning periods, by dividing it by the financial horizon *FH*, over the planning cycles, and discounted using the discount rate .

$$InvHorizonAct=\sum_{i=0}^{C-1}\left(\sum_{t=i.LP+1}^{T}\frac{\sum_{n\in G,o\in O} CA_{o,n,i+1}.\max\left(X_{o,n,i+1}-X_{o,n,i},0\right)}{FH.(1+r)^{t}}\right) \tag{13}$$

4.4.13. IFBR debts in the end of the planning horizon

The debts of the *IFBR* in the end of the planning horizon are equal to the total investment cost for the bioenergy technologies *InvCost*, minus the investment cost for bioenergy incurred by the company over the planning horizon, *InvHorizon*.

$$Debts = InvTot - InvHorizon \tag{14}$$

4.4.14. Actualized net cash flow of the IFBR

The actualized net cash flow of the *IFBR*, is equal to the sum of the actualized net operating profits of bioenergy activity, the actualized net operating profits of the P&P activity, and the proportion of actualized refundable fiscal depreciation $\mathrm{TR}.\left(DepFiscAct\right)$, minus the actualized investment cost over the planning horizon.

$$\begin{aligned} NetCFAct = {} & \left(1 - TR\right).(\mathrm{Re}\,vPPAct - \mathrm{Pr}\,odCostPPAct - FixCostPPAct - ClosCostPPAct) \\ & + \left(1 - TR\right).\left(\mathrm{Re}\,vBioAct + \mathrm{Re}\,vCoAct - \mathrm{Pr}\,odCostBioAct - RMCostAct\right) \\ & + TR.\left(DepFiscAct\right) - InvHorizonAct \end{aligned} \tag{15}$$

4.4.15. Salvage value of the IFBR in the end of the planning horizon

The salvage value of the *IFBR*, in the end of the planning horizon, is equal to the total investment cots for bioenergy, $InvTot$, minus the accounting depreciation, *DepAcc*, minus the debts, *Debts*, actualized at the period *T*, using the discount rate *r*.

$$SVT = \frac{InvTot - DepAcc - Debts}{\left(1 + r\right)^{T}} \tag{16}$$

4.5. Objective function

The objective function is to maximize the sum of the actualized net cash flow of the *IFBR*, *NetCFAct*, and the salvage value of the *IFBR* at the period *T*, *SVT*.

$$Max\ \left(NetCFAct + SVT\right) \tag{17}$$

4.6. Constraints

4.6.1.Availability of supplied biomass

The flows of biomass residues *FMP*, which represent the raw materials *RM* used in the *IFBR*, cannot exceed the quantity of biomass *B* available from suppliers *S*, in each period *t*.

$$\sum_{n \in G} FB_{i,t,m,n} \leq B_{i,t,m} \quad \forall i \in RM, \mathrm{m} \in S, t \in H \tag{18}$$

4.6.2.Logical constraint for non supplied biomass

If the biomass $i \in RM$ is not used in period *t* by technology $n \in G$, the flows of this type of biomass to that technology are equal to zero.

$$\sum_{m \in S} FB_{i,t,m,n} \leq \sum_{j \in FINP} \rho_{i,t,j,n}.BG \quad \forall i \in RM, n \in G, t \in H \tag{19}$$

4.6.3.Receipt production of bioenergy products

The quantity produced of each bioenergy product $i \in FINP$, in each period *t*, depends on the conversion rate of inputs consumed. These inputs could be supplied biomass (*RM)*, co-products generated within the *IFBR* (*INTP)*, or even other bioenergy final products (*FINP)*.

$$\begin{aligned} QBio_{i,t,n} - \sum_{j \in RM, m \in S} \rho_{j,t,i,n}.FB_{j,t,m,n} - \sum_{j \in INTP, m \in G \cup "p"} \rho_{j,t,i,n}.FC_{j,t,m,n} \\ - \sum_{j \in FINP \neq i, m \in G \neq n} \rho_{j,t,i,n}.FFP_{j,t,m,n} = 0 \quad \forall i \in FINP, n \in G, t \in H \end{aligned} \tag{20}$$

4.6.4.Electricity flows equilibrium

The quantity of electricity produced by cogeneration has to ensure the needs of other technologies and the *P&P* activity, in electricity, in each period t, depending on the capacities installed in the cycle associated with that period, $c(t)$.

$$FFP_{'ELEC','t','COG',m} - \sum_{o\in O} e_{ELEC',m,i}.K_{o,m}.X_{o,m,c(t)} \geq 0$$
$$\forall m \in G \neq 'COG', i \in FINP, t \in H \tag{21}$$

$$FFP_{'ELEC','t','COG',p} - e_{ELEC',p,j}.capP_p.Z_{p,t} \geq 0$$
$$\forall m \in G \neq 'COG', j \in PP, t \in H \tag{22}$$

4.6.5. Bioenergy product flow equilibrium

Each bioenergy product $i \in FINP$ produced in each period *t*, is equal to the sum of its flows consumed in other technologies and its flows shipped to the market

$$QBio_{i,t,n} - \sum_{l\in G\neq n\cup "p"} FFP_{i,t,n,l} - \sum_{m\in M} FFP_{i,t,n,m} \geq 0 \quad \forall i \in FINP, n \in G, t \in H \tag{23}$$

4.6.6. Co-product availability from bioenergy and P&P products

The flows of co-products available for selling or for using in other technologies are generated according to a proportion, *α*, of the quantity of some bioenergy or *P&P* products.

$$\sum_{m\in G\cup M} FC_{i,t,n,m} - \sum_{l\in FINP} \alpha_{i,l}.QBio_{l,t,n} \leq 0 \quad \forall i \in INTP, n \in G, t \in H \tag{24}$$

$$\sum_{m\in G\cup M} FC_{i,t,p,m} - \sum_{l\in PP} \alpha_{i,l}.QP_{l,t,p} \leq 0 \quad \forall i \in INTP, t \in H \tag{25}$$

4.6.7. Capacity of production constraint for bioenergy products

The quantity of bioenergy products produced in each period *t*, and its flows to other technologies and the market, should not exceed the capacity of production installed in the cycle including that period, $c(t)$.

$$QBio_{i,t,n} - \left(\sum_{o\in O} K_{o,n}.X_{o,n,c(t)}\right) \leq 0 \quad \forall i \in FINP, n \in G, t \in H \tag{26}$$

$$FFP_{i,t,n,m} - \left(\sum_{o\in O} K_{o,n}.X_{o,n,c(t)}\right).BG \leq 0$$
$$\forall i \in FINP, n \in G, m \in G \cup "p" \cup M, t \in H \tag{27}$$

4.6.8. Capacity of production constraints for P&P products

The quantity of *P&P* products produced each period t should not exceed the capacity installed in that period, if the *P&P* activity is operating

$$QP_{i,t,p} - capP_p.Z_{p,t} \leq 0 \quad \forall i \in PP, t \in H \tag{28}$$

4.6.9. Investment irreversibility constraint

If a technology has been already implanted, it remains implanted all over the planning horizon.

$$X_{o,n,c} - X_{o,n,c-1} \geq 0 \quad \forall n \in G, o \in O, c \in C \tag{29}$$

4.6.10. Budget availability constraint

The investment cost per cycle cannot exceed a predefined budget

$$\left(\sum_{n \in G, o \in O} CA_{o,n,c}.\frac{\left(X_{o,n,c} - X_{o,n,c-1} \right)}{C} \right) - Bd_c \leq 0 \quad \forall c \in C \tag{30}$$

4.6.11. P&P demand constraint

The *P&P* production, in each period, should not exceed the demand for these products in that period.

$$QP_{i,t,p} - \left(\sum_{m \in M} d_{i,t,m} \right).Z_{p,t} \leq 0 \quad \forall i \in PP, m \in M, t \in H \tag{31}$$

4.6.12. Bioenergy product demand constraint

The flows of bioenergy products shipped to the demand markets, in each period, should not exceed the demand for these products in that period.

$$\sum_{n \in G} FFP_{i,t,n,m} \leq d_{i,t,m} \quad \forall i \in FINP, m \in M, t \in H \tag{32}$$

4.6.13. Co-product demand constraint

The flows of co-products shipped to the demand markets, in each period, should not exceed the demand for these products in that period.

$$\sum_{n \in G} FC_{i,t,n,m} \leq d_{i,t,m} \quad \forall i \in INTP, m \in M, t \in H \tag{33}$$

4.6.14. Non-negativity constraint

$$X_{o,n,c} = \{0,1\} \quad \forall o \in O, n \in G, c \in C;$$

$$Z_{p,t} = \{0,1\} \quad \forall t \in H;$$

$$FB_{i,t,n,m} \geq 0 \quad \forall i \in RM, t \in H, n \in S, m \in G;$$

$$FC_{i,t,n,m} \geq 0 \quad \forall i \in INTP, t \in H, n \in G \cup "p", m \in G \cup M;$$

$$FFP_{i,t,n,m} \geq 0 \quad \forall i \in FINP, t \in H, n \in G, m \in "P" \cup G \cup M;$$

$$QP_{i,t,p} \geq 0 \quad \forall i \in PP, t \in H;$$

$$QBio_{i,t,n} \geq 0 \quad \forall i \in FINP, t \in H, n \in G.$$

(34)

5. Results and Discussion

The mathematical model has been implemented in CPLEX Optimisation Studio 12.3, on a 2.4 GHz dual-core Intel Core i5 machine, with 4GB of RAM.

The data was implemented in an ACCESS database, linked to CPLEX. Similarly, the optimisation results have been exported to an ACESS database to simplify the assessing of the output data. In **Figure 4**, we present a graph that illustrates spatially the sets of the different nodes over the *IFBR* supply chain, comprising suppliers, biomass types, bioenergy products, bioenergy co-products, *P&P* products, *P&P* co-products, bioenergy technologies, *P&P* activity, and demand markets).

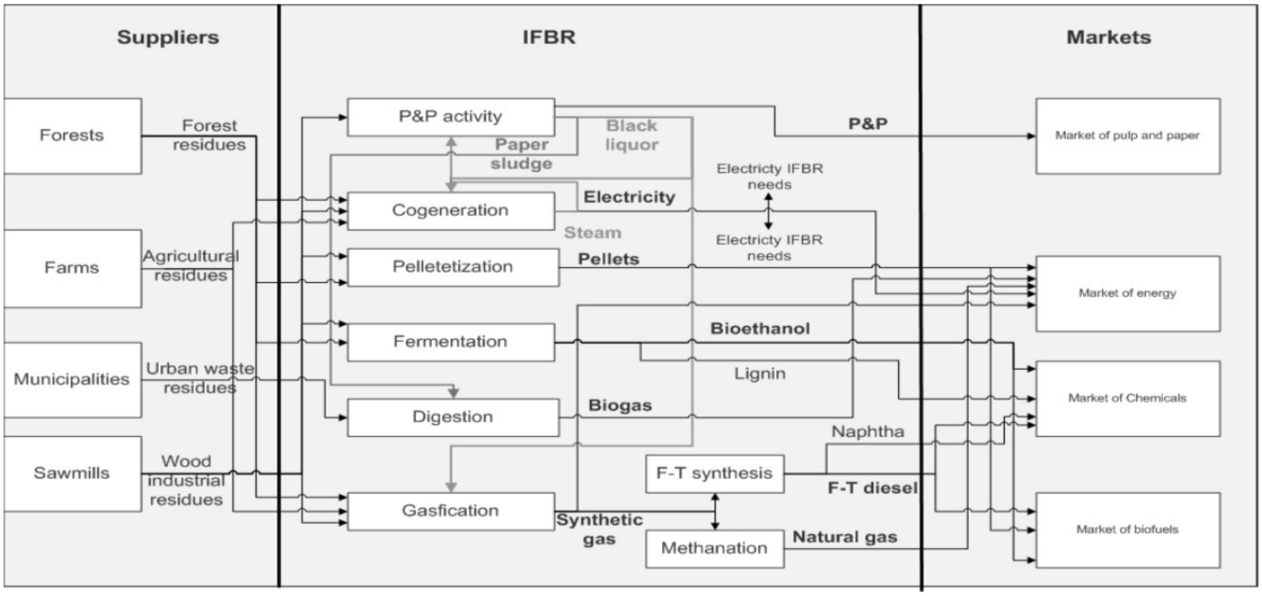

Figure 4: Sets and nodes over the IFBR supply chain

In **Table 2**, we present the time-related parameters values, including the planning horizon, the number of periods, the number of planning cycles, the cycle length, the financial horizon, the fiscal lifetime, and the economic lifetime.

Parameter	Value
Planning horizon	20 years
Number of periods	20
Number of cycles	4
Length of cycle	5 years
Financial horizon	20 years
Fiscal lifetime	20 years
Economic lifetime	30 years

Table 2: time-related parameters values

The optimal solution has been found in less than 30 seconds, under the above configuration.

The obtained *IFBR* financial value reveals the substantial potential of integrating bioenergy production technologies within *P&P* mills. By implanting gradually, over the planning horizon, an integrated forest biorefinery that produces bioenergy products besides *P&P* conventional products, the investors could generate an actualized cash-flow of more than $512 million and an estimated residual value of 79,332 $ million for the *IFBR* at the end of *H*. The investments made over the planning horizon depend on the financial funds available over it. In our case, we assume that the stakeholders have financial funds according to average available budgets found in the literature, which allowed us to invest for about $789 million from which $631,48 million are repaid over the planning horizon. The remaining part, $158,198 million, would be considered as debts of the company. In **Table 3**, we summarize these financial results.

Cost/Revenue	**Value**
Total investment cost ***InvTot***	$789,68 million
Investment cost over *H* ***InvHorizon***	$631,48 million
Accounting depreciation over *H* ***DepAcc***	420,98 million
Debts at the end of *H* **= *InvTot* - *InvHorizon***	158,198 million
Actualized net cash flow ***NetCFAct***	$512,698 million
Salvage value at the end of *H* ***SVT***	$79,332 million
IFBR financial value* = *NetCFAct* + *SVT	**$592,031 million**

Table 3: summary of financial results

Under the different assumptions made and the parameters values chosen in this developed model, the technologies implanted over the planning horizon are: *Digestion* which produces *Synthetic natural gas* (**SNG1**), *Fermentation* which produces *Bioethanol* (**BE**) and generates *Lignin* (**LGN**) as co-product, *Cogeneration* which produces *Electricity* (**ELEC**) and generates hot steam, as co-product which is totally used to fill the *IFBR* needs in steam, and *Pelletisation* which produced *Pellets* (**GRAN**). The *IFBR* continues to produce *P&P* products to meet market demand. The *P&P* activity generates two principal co-products: *Black Liquor* (**BL**) and *Paper Sludge* (**PS**), which will be used as inputs for bioenergy products.

For this case, the optimal road map for bioenergy investments is presented in **Table 4**. A grey cell means that the option $o \in O$ of the technology $n \in G$ is implanted in cycle $c \in C$. For example, the option "*Op*3" of technology "*Fermentation*" is implanted in cycle "1", with 90 million of liters as bioethanol production capacity per year. In cycle "4", the option "*Op*1" is implanted, adding 30 million of liters of bioethanol production capacity for the *IFBR*, which generates a total bioethanol production capacity of 120 million of liters per year. A part of the electricity produced by *Cogeneration*, fills the needs of the *IFBR* in power. The remaining part is sold to the market.

The progressive implantation of bioenergy technologies, by adding capacities during the planning periods, is explained by the increasing demand for bioenergy demand in the next years combined to an improvement in biomass conversion rates and lower bioenergy investments cots. Thus, it would be more profitable for the *IBFR* to adapt progressively its bioenergy capacities to the demand and profit from technological and economic maturity of bioenergy technologies, rather than implement all the bioenergy capacities in the beginning of the planning horizon, which would generate higher investment costs and lower adaptability to the market changes.

Tech	Cycle1			Cycle2			Cycle3			Cycle4		
	Op1	Op2	Op3	Op1	Op2	Op3	Op1	Op2	Op3	Op1	Op2	Op3
Digestion		80.10^6 m^3			80.10^6 m^3		40.10^6 m^3	80.10^6 m^3		40.10^6 m^3	80.10^6 m^3	
Fermentation			$90.\ 10^6$ liters			$90.\ 10^6$ liters			$90.\ 10^6$ liters	$30.\ 10^6$ liters		$90.\ 10^6$
Cogeneration			$480.\ 10^6$			$480.\ 10^6$			$480.\ 10^6$	$160.\ 10^6$		$480.\ 10^6$
Pelletisation		$40.\ 10^3$ tons			$40.\ 10^3$ tons		$20.\ 10^3$ tons	$40.\ 10^3$ tons		$20.\ 10^3$ tons	$40.\ 10^3$ tons	
Gasification												
F-T												
Methanation												

Table 4: roadmap of bioenergy investments

For the *P&P* activity, its optimal operating roadmap would be to shut down the *P&P* production for three periods (1, 7 and 17) and to keep it operational during the other periods of the planning horizon (**Table 5**). For the biorefinery, it would be, financially, more profitable to produce only bioenergy products during the *P&P* shutdown periods.

Period t	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Z=(0,1)	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1

Table 5: operational roadmap for P&P activity over the planning horizon H

This operational roadmap for the *P&P* activity generates $950,964 million of revenues with a total production cost of about $595 million including $20,58 million as shutting-down cost and more than $208 million as operating fixed cost (**Table 6**).

Production cost ($)	Fixed cost ($)	Closing cost ($)	Revenues ($)
367,257 million	208,068 million	20,587 million	950,964 million

Table 6: operational financial summary of P&P activity over the planning horizon H

To decide which bioenergy technology to implant and what capacity option to add, in each cycle, we have also optimised tactical level decisions, made all over the periods of each cycle, by determining the biomass flows supplied (**Table 7**), the quantity of bioenergy and *P&P* products produced (**Table 8**), the flows of final products and co-products within the *IFBR* and to the market (**Table 8** and **Table 9**).

By assessing the biomass used to produce bioenergy (**Table 7**), the quantity used is relatively small, when considering the estimated available biomass over the planning horizon. Only 28,77 of the 71,22 million tons available are used to produce bioenergy. Excepting the urban waste residues (**UWR**), which more than 17 of the 18 million available tons are used, essentially due to its negative supplying cost, the using of other types of biomass represent less than half of the available quantities. Particularly, less than 10% of available waste process residues (**WPR**), as chips and sawdust, are used. Their relatively higher conversion rate has not been enough to cover their higher supplying cost comparing to the other biomass types. The *IFBR* low consumption of available different types of biomass reveals the considerable potential of that resource to be converted in high value bioenergy products. One important fact to notice is that, during most of the planning periods, all types of biomass are used to produce energy. The diversity of the supplying sources allows the *IFBR* managing uncertainty in biomass availability and protecting itself against demand variability.

	Flows of biomass per Technology (tons)				**Total (tonne)**	**Available biomass (tons)**
	COG	**FER**	**DIG**	**PELL**		
AR	0	4.261.198,4	0	0	4.261.198,4	24.855.899
FR	4.105.457,45	885.960,7	0	1.028.627,28	6.020.045,43	16.119.761,3
UWR	0	0	17.486.895,7	0	17.486.895,7	18.029.657,6
WPR	0	1.008.469,6	0	0	1.008.469,6	12.221.169,1
Total (tonne)	4.105.457,45	6.155.628,7	17.486.895,7	1.028.627,28	**28.776.609,13**	**71.226.487**

Table 7: biomass supplied over planning horizon H

For the bioenergy investments made over the planning horizon, the capacities installed allow the *IFBR* to meet a major part of bioenergy estimated market demand (**Table 8** and **Table 9**), especially for *Fermentation*, where the bioethanol (**BE**) production satisfies most of the demand. For the synthetic natural gas (**SNG1**), the gap of 500 million m^3 between the production and the demand can be explained by the additional important funds required to add more production capacity for the technology *Digestion*.

Product	Technology	Total production	Total demand
P&P	***P&P***	2.053.042,8 tons	2.420.835 tons
BE	**FER**	1.776.231.990 Liters	1.796.104.170 Liters
ELEC	**COG**	9.407.411.580 Kwh	9.344.377.900 Kwh
GRAN	**PELL**	613.851,96 tons	858.663,55 tons
SNG1	**DIG**	1.928.240.050 m^3	2.515.893.600 m^3

Table 8: P&P and bioenergy production over the planning horizon H

For *Cogeneration*, the major part of the electricity production, more than 8 billion Kwh, fills the needs of the *IFBR* in electricity. Only 1,16 billion Kwh are sold to the market (**Table 9**).

Product	*IFBR*				Market	Total demand
	DIG	**FER**	**PELL**	***P&P***		
ELEC (Kwh)	755.873.200	752.296.100	468.867,7	6.734.975.000	1.163.798.646	9.344.377.900
BE (Liters)	0				1.776.231.990	1.796.104.170
GRAN (tons)	0				613.851,96	858.663,55
SNG1 (m^3)	0				1.928.240.050	2.515.893.600

Table 9: flows of final products within the IFBR and to the market over the planning horizon H

For the co-products, the *P&P* generated co-products, **BL** and **PS**, are used as inputs to produce bioenergy. Due to their zero production cost, it should be more profitable to convert them in high value bioenergy products rather than sell them directly to the market and use external supplied biomass. For **LGN**, its estimated market demand is totally met by the available generated quantity (**Table 10**).

Product	**Co-product**	***IFBR***	**Market**	**Total demand**
P&P	BL (tons)	COG 3.490.172,6	0	0
P&P	PS (tons)	DIG 221.730,91	0	0
Bioethanol	LGN (kg)	0	724.438,4	724.438,4

Table 10: co-products flows within the IFBR and to the market over the planning horizon H

The operational financial summary of the *IFBR* over the planning horizon shows an important profitability by integrating bioenergy production to the *P&P* activity. The revenues generated from bioenergy products and co-products would be more than $1,472 billion, which covers comfortably the $251,746 million of supplying biomass and the $464,377 million of operations and maintenance (O&M) costs (**Table 11**).

Biomass supplying cost ($)	**O&M cost ($)**	**Revenues ($)**
251.746.800	464.377.400	1.472.040.000

Table 11: operational costs and revenues summary over the planning horizon H

The obtained results clearly show the substantial potential of integrating bioenergy into *P&P* mills, for the used data adapted to the Quebec *P&P* sector. The decision-support tool developed in this paper, has allowed us assessing several bioenergy investment scenarios, while considering their interaction with *P&P* activity through a set of co-products, such as black liquor and paper sludge, that could be used to produce bioenergy products. In the case of Quebec *P&P* mills, the case-study results have shown that the best strategy to transform the mill in an *IFBR* would be to invest in a set of bioenergy products and use diverse biomass sources. Therefore, one of the most important findings of this work is that bioenergy integration within the *P&P* sector should ensure a diversity of bioenergy options, in order to hedge against market changes and demand uncertainty. To get a durable competitive advantage, a number of small niche markets would, then, overtake the mass market for *P&P* products.

From another hand, the estimated 20-years snapshot of the developed *IFBR*, given by the roadmap, confirms the need for optimally managing the *P&P* activity while investing in bioenergy. As shown in the results, it would be more profitable for the *IFBR* to continue to produce conventional *P&P* products in most of the planning periods, while integrating progressively the bioenergy products. The *IFBR* could, then, take profit from the increasing demand for bioenergy while ensuring diverse revenue sources by producing both conventional forest products and bioenergy.

By using this support-tool decision, the forest industry stakeholders, particularly those of the *P&P* sector, would have a clearer vision about the most profitable bioenergy investments to implant in the coming years as well as a better understanding of the best practises of transformation strategies from a *P&P* mill to an *IFBR*, in order to ensure a long-term competitiveness.

6. Conclusions

The “integrated forest biorefinery” concept, *IFBR*, is presented as a promising opportunity for Canadian pulp and paper mills, to overcome their stalemate situation and evolve towards a competitive business model. In this paper, we have developed a mathematical approach aiming to obtain an optimal roadmap for investments in bioenergy, considering a set of possible bioenergy investments, while managing their synergy with the pulp and paper activity. The bioenergy roadmap presents a multi-period investment plan giving a snapshot of the *IFBR* transformation strategy over the planning periods.

To well assess the potential of that transformation, we have presented a four-step methodology; embracing both the qualitative and quantitative aspects of bioenergy supply chain design. The design approach has led to a real decision-support tool, which would help forest industry stakeholders in designing long-term and competitive business models.

The developed decision-support tool has been initiated by a qualitative study adapted to the Canadian forest industry context. A real database has been constructed to feed the model with a set of parameters reflecting the reality of the Canadian pulp and paper sector, which would be useful to assess ulterior bioenergy investments. A detailed financial analysis, mostly ignored in supply chain design optimization, has been integrated to the developed model, which complements the strategic and operational costs traditionally integrated in such analyses.

The results of the study adapted to the Quebec pulp and paper mill sector have shown that it would be financially profitable to invest, over a 20-years planning horizon, in a number of bioenergy technologies including bioethanol, biogas, pellets and cogeneration, while managing the operation of the pulp an paper activity. Still, other bioenergy technologies, such as gasification, F-T synthesis, and methanation have not been considered as profitable to the *IFBR*, essentially due to their high investment costs comparing to their technological maturity. Governmental financial incentives and strategic alliances within forest industry could boost the implementation of these technologies during the coming years.

The obtained solution output has revealed the substantial financial potential of the transformation of a pulp and paper mill into an *IFBR*, considering a dynamic planning horizon, economically, technically and commercially. Nevertheless, the investment roadmap depends on a prefixed scenario of the parameters evolution over the planning horizon. Our next step, is to develop a scenario-tree based model, where each branch represents an evolution scenario for these parameters, in order to explicitly consider technical, economic and commercial uncertainties related to such long-term investments.

7. Appendix

The database has been built using real data from reports and studies as well personal assumptions, in case of unavailable data.

Parameters	Index	Values	References
Fiscal lifetime	FL	20 years	[8]
Financial horizon	FH	20 years	[8]
Economic lifetime	EL	30 years	[39]
Tax rate	TR	30%	[8]
Length of planning horizon	T	20 years	[8]
Number of periods per cycle	LP	5 years	[15]
Capital rate	r	5%	[15]
Operation fixed cost of *P&P* activity	FCP	$20million	[8], personal assumption
Closing cost of *P&P* activity	b	$10million	[8], personal assumption
Co-product rate α	α(Black liquor)	1,7 dts/t of P&P	[17]
	α (Paper sludge)	0,2t/t of P&P (1,7 million of tons for 8 million tons of produced pulp)	[40] [41]
	α (Naphtha)	0,195L/L of F-T diesel	[8]
	α (Lignin)	0,4 kg/L of ethanol	[42]
Supply cost *CSUP*	Forest residues FR	66 to 82$/dt	[8]
	Agricultural residues AR	40 to 90$/dt	[38]

	Wood process residues WPR	70 to 90$/dt		
	Urban waste residues UWR	-30 to 0$/t		
Biomass availability (million dt/y) *B*	FR	From 19,5 to 32,5 in CA	0,64(*)	[43]
		6,4 in Qc		[44]
	AR	5,3 to 14 in CA So, 10 as average	1(*)	[44]
	WPR	4 to 5 in CA	0,5(*)	[43]
	UWR	7 in QC	0,7(*)	[45]
	(*) We assume that: - The biomass available in QC is about 20% of the total biomass available in Canada. - The *IFBR* has access to 10% of the amount of biomass available in QC			Personal assumption
	Future trend	From +1 to +4% annually		[36]
Conversion rate *ρ*	**Technologies Output**	**Inputs**	**Values**	**References**
	CHP Cogeneration (Electricity)	AR, FR	740 kwh to 1100 kwh/t	[8]
		BL	1200 kwh/dts	[17]
		WPR	1020 kwh/t	[46]
		Biogas (SNG1, SNG2)	35%	[47]
	Fermentation (Bioethanol)	WPR	340L/dt	[13]
		FR	280-300L/dt	[8]
		AR	250-290L/dt	[48]
	Digestion (SNG1)	PS	$200m^3$/dt	[49]
		MSW	$100m^3$/dt	[50]
	Gasification	AR, FR	600-650 m^3/dt	[48]

	(Syn. Gas)	BL	480-500 m^3/dt		[48]
	Gasification + Methanation (SNG 2)	AR, FR	245-290 m^3/dt		[37]
	Gasification + F-T synthesis (F-T diesel)	AR, FR	235L/dt		[8]
	Pelletisation (Pellets)	WPR	0,55 tonne/dt		[51]
	Future trend	+15% by 2030 So, +0,75%/year over 20 years			[37]
Investment costs	**Products**	**Values**			**References**
	P&P	$220 million for 264 286 tons produced (To estimate the accounting depreciation)			[8]
	Electricity	3750$/kwe			[8]
	Bioethanol	From 169 to $315 million for 200 millions L/Y			[8]
	F-T diesel (F-T Synthesis)	$403 million for 180 million L/Y (gasification+ F-T synthesis) (*) We assume that the F-T synthesis investment cost is equal to the investment cost for gasification		(*) $200M for 180Ml/Y for F-T synthesis	[8] [48]
	Pellets	$320.000 for 2700t/Y			[52]
	Syn.gas (Gasification)	$200M for 486Mm^3			[48]
	SNG1 (Digestion)	2$/m^3 (approximation)			[53]
	SNG 2 (Methanation)	$230 million for 180 Mm^3/Y (*) (*) We assume that the methanation investment cost is equal to the investment cost for gasification			[37] [48]
	Economies of scale	Scaling factor (R=0,7)			[33]

	Future trend	From 2010 to 2030: -30% So , -7,5% per cycle of 5 years		[13]
Production costs (Operations)	**Products**	**Values**		**References**
	Pulp	318$/ton		[8]
	Electricity	3$C to 6.5$C/kwh		[13]
	Bioethanol	0,15 to 0,3$/L		[8]
	SNG1	0,026$/m^3		[50]
	F-T diesel	$72 million for 180ML/Y (Gasification+F-T synthesis) So, 0,2$/L (*) (*) We assume that the operational costs for gasification and F-T synthesis are equal)		[8]
	Syn.gas	0.07$/m^3		
	SNG2	0,07$/m^3		
	Pellets	65$/t		[52]
	Future trend	From 2010 to 2030: -20 to -30% So, -1 to -1,5 annually		[13]
Electricity consumption per technology (Kwh/unit)	**Technologies**	**Values**		**References**
	Bioenergy technologies	1,14Kwh/m^3 · SNG2 produced (gasification+methanation) Because of lack of data, we have used this data fo all technologies		[37]
	P&P activity	3047,5 Kwh/ton produced		[54]
Capacity options (We assume a set	P&P	2007:an average of 142,6 kt produced 2008: an average of 120,8kt produced	130.000 t/year	[41]

of 3 possible options per technology)	Cogeneration	From 20 to 50 MW (typical capacities in P&P mills in Canada)	20 MW 40 MW 60 MW	[37]
	Pelletisation	From 20 000 to 120 000t/y as typical capacities in Canada	20 kt/y 40kt/y 60kt/y	[51]
	Fermentation	36 ML/Y	30 ML/Y 60 ML/Y 90 ML/Y	[53]
	Gasification +F-T synthesis	30 millions L/Y	30 ML/Y 60 ML/Y 90 ML/Y	[55]
	Gasification	160 M m^3/Y 320 M m^3/Y 480 M m^3/Y		Personal assumptions by referring to real biorefinery capacities
	Methanation	40 M m^3/Y 80 M m^3/Y 120 M m^3/Y		
	Digestion			
Market price $/unit	**Products**	**Values**		**References**
	Ethanol	0.65$/L (plant gate price)		[8]
	F-T diesel	0.8$/L (plant gate price)		[8]
	Kraft Pulp	750$/t (We consider 500 to 1000$/t due to market uncertainty)		[8]
	Lignin	From 168 to 750$/t		[8]
	Pellets	From 160 to 190$/t		[56]

	Electricity	10,6 $C/kwh (Januray 2012 pricing)	[57]
	Naptha	0,55$/L	[8]
	Future trend	+20 to 50% by 2030. So, from +1 to +2,5% annualy	[13]
	Biofuel price estimation from fossil fuel price (for non available biofuel price data)	$RSP_{bio} = \left(\frac{LHV_{bio}}{LHV_{fossil}} \right) .RSP_{fossil}$	[34]
Expected demand (For non available data, we used the option capacities as bounds)	**Products**	**Values**	**References**
	Ethanol	43-130 ML/y (*) (*)We assume that the *IFBR* could have access to 10-30% of bioethanol market in Qc. We have estimated the bioethanol market to about 5% of gasoline demand in Qc (8704 ML as average for the past 5 years)	[8]
	Lignin (0.4kg/L ethanol)	Estimated as 40% of ethanol market:17000-50000t/y	
	F-T diesel	9 -26ML/Y (*) (*)We assume that the *IFBR* could have access to 10-30% of biodiesel market in Qc. We have estimated the F-T diesel market to about 2% of diesel demand in Qc (4422 ML as average for the past 5 years)	

	Naphta (0.195L/L F-T diesel)	Estimated as 20% of F-T market: 1,8M to 5ML/y		Personal assumptions based on capacity options that we have considered
	Syn.gas	Random values from 160 M m^3/y to 480 M m^3/y		
	SNG2	Random values from 40 M m^3/y to 120 M m^3/y		
	SNG1	Random values from 40 M m^3/y to 120 M m^3/y		
	Pellets	Random values from 20 kt/y to 60kt/y		
	Electricity	Random values from 160 Gwh/y to 480 Gwh/y		
	Pulp	130kt/y We assume a -1 to -2% future trend annually due to structural change in pulp demand		
	Future trend	Market share for Biofuels	+30-50% by 2030 So,+1,5 to 2,5% annually	[9]

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