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Sustainability assessment of integrated forest biorefinery implemented in Canadian pulp and paper mills

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ABSTRACT

To overcome declining markets and low-cost competition, the integrated forest biorefinery (IFBR) business model has received a lot of attention from the pulp and paper (P&P) sector. This article deals with sustainability assessment of IFBR implemented in P&P mills for bioenergy production. The objective is to develop a mathematically-based approach, for decision makers within the forest sector, that aims to optimize the sustainability of the IFBR value creation network. A multi-objective optimization model, applied to a Canadian case study and integrating environmental life cycle assessment (LCA), is developed. The life cycle inventory is performed for the whole system. The objective functions consist in minimizing greenhouse gas emissions and maximizing the financial value of the IFBR over a long-term planning horizon, while optimizing the existing P&P activity. Different economic and environmental indicators are introduced to compare Pareto optimal investment roadmaps. The proposed model leads to a decision support tool for the transformation of P&P companies by planning sustainable bioenergy investment implementation. Furthermore, this model may assist decision makers in emissions planning and reporting according to related regulations requirements. The obtained results show that the IFBR allows the P&P industry to diversify its portfolio and generate new revenues, while contributing substantially to emission reduction efforts in Canada and producing clean and renewable energy. However, government support will be needed to perform a successful business plan.

1. Introduction

Canadian pulp and paper (P&P) companies are considering the use of biomass and investment in bioenergy as a promising way to boost the sector, considering that they are facing many difficulties in maintaining their competitiveness (Mansoornejad et al., 2013; Machani et al., 2014). The main reasons for this difficult situation are the P&P demand reduction due to the substitution of electronic media for paper-based products and the fierce competition from low-cost countries. Hosting bioenergy investments in existing P&P mills will be more cost effective than building a bioenergy greenfield stand-alone plant (Huang et al., 2009; Chambost et al., 2008). Thus, by exploiting mill industrial waste and biomass available, P&P mills can reduce the use of fossil-based energy, diversify their product portfolio and become potential suppliers of clean energy (Benjamin et al., 2009; Gregg and Smith, 2010; Mansoornejad et al., 2013). On the other hand, bioenergy production requires the adoption of an industrial model called *biorefinery*. This model is sustainable according to its definition by the International Energy Agency (Publications IEA Bioenergy Task 42 Biorefinery, 2013). Hence, the integrated forest biorefinery (IFBR) business model leads to greater economic viability (You et al., 2011), and has the potential to significantly reduce greenhouse gas (GHG) emissions. In fact, the climate change issue, especially following the Kyoto Protocol, come more into focus during the last years (Finnveden et al., 2009). In order to deal with global warming and reduce GHG emissions, businesses, individuals and public officials need to integrate environmental considerations in their decision making (Nilsson and Eckerberg, 2007, Finnveden et al., 2009).

As a result, the IFBR business model has received much attention from the P&P sector in industrially mature countries, primarily in North America and Western Europe. For the Canadian case, an important step toward a sustainable future is to adopt the Federal Sustainable Development Act of 2008 (Senate and House of Commons of Canada, 2008). Regarding the P&P sector, the federal sustainable development strategy, adopted in 2010, considers that the maintenance and sustainability of this heritage become an urgent issue for its major socio-economic impact. According to (Environment Canada, 2016), the implementation strategies related to the above objectives require the

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creation of new technologies that can reduce GHG emissions and improve energy efficiency, and the assessment of the environmental performance of new and emerging technologies. This require also the integration of new projects for lignocellulosic valorization according to new product and market pathway including biorefinery, and finding a new business model that enhances the diversification of high added value products. To achieve this ambitious strategy, Canadian government has launched a number of bioenergy incentive programs to support the transformation of the P&P companies, and to reduce GHG emissions and fossil energy dependence (Natural Resources Canada, 2012). Nevertheless, the IFBR model is still in the experimental phase, and there is a lack of economic, technological and environmental validations that may increase the confidence of funders, investors and stakeholders in this sustainable model. It is therefore crucial to develop quantitative tools to evaluate and optimize the environmental sustainability of the IFBR implementation.

Many challenging issues arise when dealing with the design problem of value creation network integrating bioenergy. The first challenge lies in the complexity of the supply design problem, considering that several configurations are available to transform P&P mill into an IFBR. There are different types of biomass that could be used, and several technologies that can be adopted, with different ranges of conversion rates, which could transform biomass into a number of bioenergy products. The second challenge is how to quantitatively measure the economic and environmental dimensions of sustainability for the entire value creation network and how to incorporate these measures into the optimization framework. Third, we have to establish the trade-off between the economic and environmental dimensions of sustainability in a multi-objective optimization context.

In this paper, a multi-objective mathematical model is developed providing a road map for sustainable investments in bioenergy, minimizing GHG emissions, and 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 proposed model allows the evaluation of the environmental component considering life cycle thinking context.

The remainder of the paper is organized as follows. Section 2 identifies the research gaps in the existing literature and highlights the paper contribution. Section 3 presents the problem statement and the system description. In Section 4, we detail the methodology including our integrated conceptual model and the mathematical formulation. Computational results obtained for the case study and related recommendations are discussed in Section 5. Finally, Section 6 concludes the paper.

2. Literature review

This review is structured around two main bodies of literature that are related to our research. The first is the literature on green supply chain management using life cycle assessment (LCA) and multi-objective optimization. The second is the literature on sustainability assessment of IFBR implemented in P&P mills for bioenergy production. Next, we discuss each of these research areas. Then, we identify the gaps in both areas and highlight the paper contribution.

2.1. Green supply chain management

Green or environmentally sustainable supply chains have been the object of a large number of studies, as shown in many survey papers such as (Srivastava Samir K., 2007; Sarkis et al., 2011). Green supply chain management (GrSCM) deals with the integration of environmental issues to improve the environment impact of supply chain activities without compromising economic and operational performance (Lee, 2015; Mentzer John T. et al., 2011). For many firms, the focus is shifting from purely economic considerations to a wider scope that includes environmental aspect through the implementation of ISO 14001 environmental management system and the use of certified suppliers (Agi and Nishant, 2017; Ansari and Qureshi, 2015). This shift involves the implementation of several environment-friendly measures aimed at reducing waste, energy efficiency, recycling, remanufacturing, eco-design and reverse logistics (Zhu and Sarkis, 2004).

While LCA is widely recognized as a scientifically reliable tool to evaluate environmental impact, modeling techniques based on mathematical programming have been also widely used to integrate environmental issues for GrSCM. In fact, many studies have identified the integration of multi-objective optimization and LCA as a suitable practice to support sound decision making in supply chain design (Finnveden et al., 2009; Rajeev et al., 2017). Such integration can potentially lead to both improved economic and environmental performance (Cano-Ruiz and McRae, 1998; García and Caballero, 2012; Mota et al., 2015). Government intervention is essential for promoting the industry of bioenergy production, by providing incentives to create favorable economic and market conditions. Through government incentives, many countries developed favorable conditions for biorefineries (Bautista et al., 2016). The technological dimension is also important, especially in the field of bio-based products, due the emergence of new technologies that need to be evaluated (Hofmann et al., 2012).

In spite of a large number of papers on the integration of multi-objective optimization and LCA for GrSCM, only a few studies have considered industrial applications using actual data. Furthermore, in the relatively scarce existing applications, the LCA method is not explicitly used. The impact is vaguely estimated in advance and re-integrated as product, feedstock and transport attribute, without considering realistic inventory by process.

2.2. IFBR sustainability assessment

The emergence of ISO 14001 certification standards has provided companies with a standardized and proven framework, for developing a viable and effective environmental management strategy. Barla (2007) highlighted how adopting the international norm ISO 14001 may impact environmental performance in the P&P industry of Quebec (Canada). Doonan et al. (2005) defined the main determinants of the environmental performance of the P&P sector. The environmental aspect stands out as a label to optimize the sustainability of value creation networks. Mansoornejad et al. (2010) recommended LCA tools for environmental footprint assessment, and multiple criteria decision making framework taking into account different aspects for making a final compromise decision instead of being limited to economic performance.

Regarding the IFBR implemented in P&P, many researchers have presented configurations and integration architectures. The synergy with the incubator activity is generally expressed by the recovery of co-products and waste generated beside energy self-sufficiency. To ensure the economic and environmental viability of the entire value creation network at both the strategic design and the operational planning levels, efficient optimization strategies are needed (Machani et al., 2014; You et al., 2011; Gnansounou and Dauriat, 2010; Chaabane et al., 2011). In (Wang et al., 2013), the authors proposed a multi-objective, mixed-integer nonlinear programming model for the superstructure optimization of hydrocarbon biorefineries, via gasification pathway under economic and environmental criteria, including a number of major processing stages and considering alternatives of technologies and equipment. However, the authors did not consider the strategic long-term planning aspect. The same gap is present in the approach developed by (Andiappan et al., 2015) who used multi-objective optimization to synthesize a sustainable IFBR, which simultaneously considers economic performance and environmental impacts. (Cambero et al., 2016) have developed a multi-objective biorefinery supply chain optimization model, applied for a case study in British Columbia (Canada) for the production of bioenergy and biofuels using forest and wood residues. This work did not consider the management of the technology capacity and the investment depreciation or taxation. The economic and environmental assessments of integrated Lignin-Kraft Pulp biorefinery for the production of lignin and its derivatives were discussed in (Benali et al., 2016). Without using any mathematical programming model, Moshkelani et al. (2013) discussed the concept of IFBR integrated in a Kraft mill, and presented a methodology to perform high-level process integration and intensive energy efficiency. In (Machani et al., 2015) a mathematical model was developed to evaluate the profitability of a set of transformation strategies under different trend-based future scenarios and to identify the most robust strategic options for integrating biorefinery in pulp and paper company. The study carried out by (Machani et al., 2014) allows setting a roadmap for planning the implementation of bioenergy investments in P&P. However, in (Machani et al., 2014) and (Machani et al., 2015), only the economic performance was optimized; the environmental component was not considered.

2.3. Research gaps and paper contribution

The above literature review has shown that only a few studies have considered industrial applications using actual data. In addition, the LCA method is not explicitly used. The impact is vaguely estimated in advance and reintegrated, without considering realistic inventory by process. This review has also revealed the lack of works tackling the sustainable design of the entire value creation networks integrating bioenergy. In particular, there is no existing work on IFBR sustainability based on mathematical programming which considers long-term bioenergy strategic investment for all value creation network components, the synergy with the P&P incubator activity, the management of the technology capacity and the investment depreciation and taxation.

To fill these identified gaps, the present paper deals with sustainability assessment of IFBR implemented in Canadian P&P mills. This work comes in response to the needs of decision makers in the governance of the sector to evaluate emerging technologies with the aim of reducing GHG emissions, and transforming P&P in a sustainable manner into second-generation IFBR having self-sufficiency in clean energy. Considering an industrial application, we develop a mathematical model as a decision support tool for long-term strategic bioenergetics investment planning. This model helps forest stakeholders to optimize the strategic and sustainable design of a P&P company aiming to integrate bioenergy investments, while considering different bioenergy technologies and different biomass sources in deciding on the technologies to embed, the capacity options to add, and the timing of investment, over a long-term planning horizon. We integrate multi-objective optimization and LCA, and we evaluate the environmental and economic aspects of the eco-design of emerging bioenergetics technologies according to contextual and realistic data. The LCA method is explicitly and properly applied. That is, the life cycle inventory is performed for the whole system assessed to integrate the LCA method in multi-objective modeling. This paper uses a multi-criteria analysis to take into account the conflicting aspects evaluated. Furthermore, the paper analyzes the synergy with the P&P incubator activity. Considering government recommendations for the selection of the bioenergetics pathways, the expected role of the P&P industry in the Canadian energy transition strategy is taken into account. The present work also considers the management of the technology capacity and the investment depreciation and taxation.

3. Problem statement

The proposed IFBR design is determined based on the Canadian government recommendations and the expected role of P&P industry in the Canadian energy transition strategy. The problem is to assess the sustainability of the integration of three pathways in IFBR retrofitted in P&P mills. These pathways include bioethanol, waste to energy fuel and energy cogeneration.

Bioethanol pathway: This consists in producing bioethanol from a biodiversity of lignocellulosic biomass using simultaneous saccharification and fermentation (SSF) technology.

Waste to energy pathway: It produces biogas from paper sludge (PS) and municipal solid waste using anaerobic digestion (AD) technology.

Energy cogeneration pathway: This consists in producing electricity and heat from black liquor (BL) and biogas using cogeneration heat and power (CHP) technology.

The main stages of the IFBR supply chain are:

- Supply stage which deals with the procurement and transport to the plant of forest, agriculture, industrial and municipal residues;
- Manufacturing stage which deals with the conversion of various biomasses using appropriate technologies; and
- Distribution stage.

The entire system of IFBR integrated in P&P is presented in Fig. 1. The assessment is done over a twenty (20) year horizon equally divided into four (4) investment cycles of five (5) years each. Two sustainability aspects are considered by this assessment. The economic aspect is evaluated using the Net Present Value (i.e. Actual Net Cash Flow) added to Salvage Value indicator, and the environmental aspect related to climate change is evaluated using GHG emissions indicator.

In this study, the following questions are answered:

- Which investment plan optimizes the economic and environmental dimensions considered? More specifically, which pathways will be retained in each investment cycle along with the appropriate technology and production capacity?
- What is the effect of selected investment choices on business plan in terms of production planning and environmental related consequences?
- How could the P&P activity be managed to ensure an optimal synergy with IFBR?

A set of relevant decision variables and input data are required for the mathematical formulation of the problem.

3.1. Decision variables

3.1.1. Binary variables

- For IFBR: These variables indicate whether a capacity option is selected or not, for a technology in a particular pathway, during an investment cycle.
- For P&P: These variables indicate whether the P&P activity is operating in a particular planning horizon period.

3.1.2. Continuous variables

These variables account for:

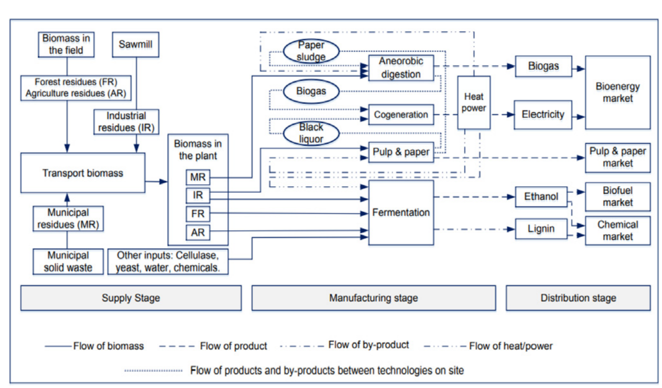


Fig. 1. IFBR implemented in a pulp and paper mill.

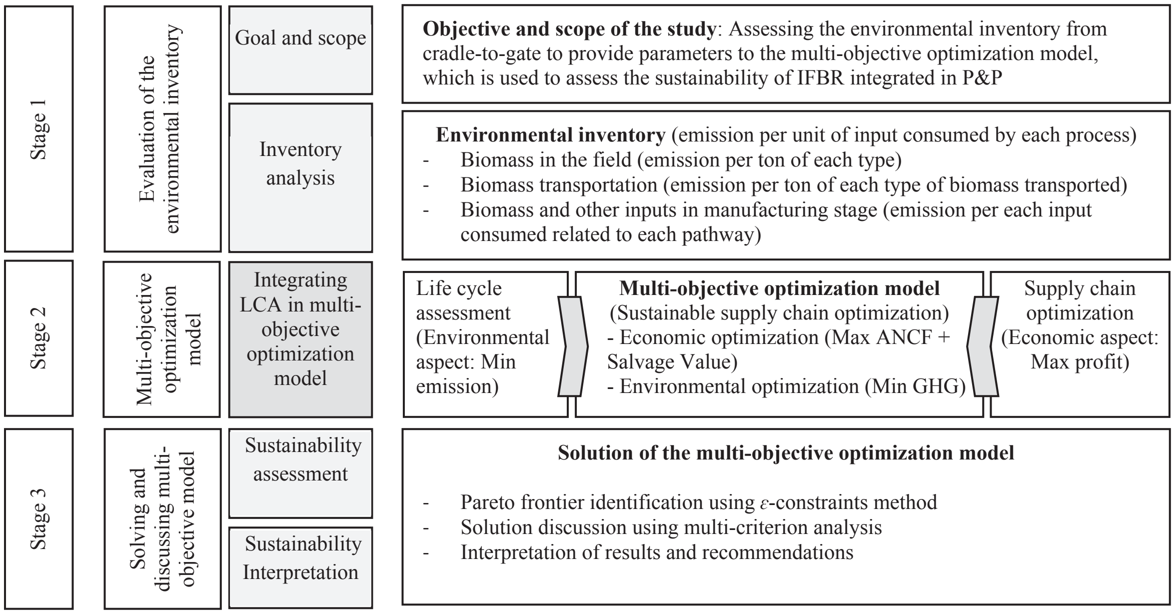


Fig. 2. Conceptual model to assess sustainability of IFBR integrated in P&P.

- The flows of biomass to the different pathways;
- The flows of products and by-products between integrated pathways;
- The flows of products and by-products shipped to the different markets; and
- The emissions generated in the supply and manufacturing stages.

3.2. Input data

3.2.1. In the supply stage

- A set of lignocellulosic biomass composed of forest residues (crop residues), agricultural residues (corn stover and wheat straw), industrial sawmill residues (sawdust, shavings and bark), and municipal solid waste composed by organic residues;
- At the procurement level, the cost of each biomass type and its quantity are known as well as their future trends;
- The emissions per ton of the forest residues and the agricultural residues, at the field stage and at the transportation stage, will be calculated using a life cycle assessment model;
- For industrial sawmill residues, the emission evaluated in the Canadian context in (McKechnie et al., 2014) is used; and
- For municipal residue, the emissions are equal to those generated by collecting and transporting this feedstock to the plant as reported in (Friedrich and Trois, 2016).

3.2.2. In the manufacturing stage

- The conversion rates of different biomass and inputs are known for each technology used in various pathways. In addition, these conversion rates change with the improvement of technological efficiency;
- The production cost for each unit of product is known as well as the fixed cost of the P&P activity; and
- Any interruption of the P&P activity in a given period has a known closing cost.

3.2.3. In the distribution stage

Bioenergy market conditions and demand availability are considered known.

3.2.4. About investment

As indicated before, the assessment covers a planning horizon divided into 4 cycles of 5 years each. For each technology, investment is possible at the beginning of each cycle according to available capacity options. Three options are available for each proposed technology for the various IFBR pathways. A known budget is allocated for the investment over the entire horizon of this study, and the cost per unit of capacity of the embedded technology is known.

4. Methodology

In this section, the integrated conceptual model is first detailed; then the mathematical formulation of the multi-objective optimization model is presented.

4.1. Integrated conceptual model

The conceptual model is developed using a multi-stage approach. Fig. 2 presents the different stages developed below.

4.1.1. Stage 1: Evaluation of the environmental inventory

The environmental inventory phase provides a set of parameters needed to integrate the LCA concept in the optimization of the supply chain. This evaluation is conducted in accordance with the LCA standard method described by the international standards of series ISO 14040 and ISO 14044 (ISO 14040, 2006). The LCA is a useful tool to analyze the environmental implications of a product/process/service during all the stages of its life cycle, through the assessment of resource use and emissions related. According to the ISO standards, an LCA consists of four phases: Definition of the goal and scope, inventory analysis, impact assessment and interpretation.

4.1.1.1. Definition of the goal and scope. The environmental impact is evaluated by the GHG indicator, which is the aggregation of a set of a greenhouse gases emissions (CO_2, N_2O, CH_4 and CF) weighted according to the widely adopted weighting method edited by the Intergovernmental Panel on Climate Change (IPCC, 2014). The goal of the assessment is to provide environmental parameters needed for the multi-objective optimization model. The scope is extended from the extraction of biomass and energy required for its development and production to the gate of the IFBR plant after conversion of biomass (cradle-to-gate). The system boundary includes three parts:

- Feedstock production, harvesting and collection of agricultural, forest, industrial and municipal residues, then storage and transfer to the collection centers;
- Transportation from the field, sawmill or the collection centers to the IFBR plant taking into account the transport logistics used, the type of fuel consumed and the life cycle of these fuels from the extraction of crude oil to its use by the mode of transportation concerned; and
- The conversion process by the different pathways in the IFBR.

4.1.1.2. Inventory analysis and impact assessment. To assess the GHG indicator related to the stage of supply and transportation of forest residue and agricultural residue, GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model is used. In general, the GREET model is structured to systematically examine the life cycle energy use and emissions associated with a wide range of vehicle technologies and feedstock sources for producing alternative fuels (Brinkman and Wang, 2005). In the present context, to evaluate the GHG emissions caused by the supply and transportation of forest and agricultural residues, the GREET model uses the inventory reported in (Han et al., 2011), which presents the LCA of forest and agricultural residues and subsequent upgrading to produce renewable gasoline and diesel fuels. However, the GHG indicator related to the procurement and transport stage of industrial residues is that suggested by Ontario Forest Research Institute (McKechnie et al., 2014). The emission related to municipal residues is that generated by their collection as suggested in (Friedrich and Trois, 2016). The first rows of Table 1 specify the processes of biomass supply (plantation, harvesting and collection) and transport from the field to IFBR plant. It presents the calculated GHG inventory for the supply and transport of agriculture and forest residues. Note that these values are very important because they will be used in the multi-objective optimization model to take into account the environmental impact of the biomass supply and transportation.

The emission related to the manufacturing phase for the inputs of the different pathways is determined from different studies existing in the literature. In this manufacturing phase, the LCA method takes into account the evolution of the biomass conversion rate estimated at 0.75% each year in (Hacatoglu et al., 2010). Table 1 presents the GHG inventory related to each pathway including pulp and paper activity. It summarizes the evaluation methods of the mass and GHG inventories for each process input, while indicating the reference and/or the model used for each GHG inventory evaluation of the processes included in the system boundary. The assessment of the environmental impact is integrated into the multi-objective optimization model through the GHG inventory values estimated for the processes shown in Table 1. These values are defined according to the different processes covered by the scope of this study. Note that some of them are provided by the optimization model.

4.1.2. Stage 2: Multi-objective optimization model

This stage integrates the environmental aspect of the first stage to the optimization of the value creation network based on the economic dimension. All data related to the economic inventory can be found in (Machani et al., 2013). These data were also used in (Machani et al., 2014) to evaluate the economic potential of integrating IFBR in Canadian P&P mills.

Strategic long-term bioenergy investment planning is the main goal through the maximization of the economic objective resulting from IFBR over the horizon period. Anticipated tactical planning of production is determined accordingly, taking into account several parameters during the planning horizon considered, such as the availability of raw materials, changes in technological efficiency, bioenergy market conditions, the effect of fiscal policy on direct taxes, etc.

In order to integrate the environmental impact into the optimization of the supply chain, the following steps are adopted:

- *In the procurement phase*

The emission for each biomass is obtained by multiplying the value of procurement flow with the environmental load per unit of biomass including transportation burden. The total emission is the aggregation of the emissions of all types of biomass used.

- *In the manufacturing phase including flows between different pathways*

The emission related to this phase is obtained using the life cycle inventory performed in the first stage, in order to assess the environmental impact of each product and co-product produced by the several pathways according to the scope of the study.

The multi-objective optimization mathematical model calculating this emission is further detailed in Subsection 4.2.

4.1.3. Stage 3: Solving the multi-objective model

First, the Pareto frontier is identified as a set of optimal solutions where the trade-off is possible between the two objectives considered. Then, the most interesting solutions are identified and analyzed according to criteria chosen based on the study context.

- *Definition of Pareto frontier and evaluation of the optimum solution*

Multi-objective optimization is able to provide a set of optimal solutions, known as Pareto optimal solutions (Collette and Siarry, 2003). Each Pareto optimal solution is a compromise between the objectives covered by the study. In the present case study, the Pareto frontier is generated making use of the ε-constraints method (Mavrotas, 2009). This method involves transforming one objective to a constraint target, and optimizing the other one while varying the constraint between the extreme values. It is at the Pareto frontier that a trade-off can be performed between the two objectives, in order to define optimality that remains subjective or dependent on decision makers' choices.

- *Criteria adopted to select good solutions*

The model provides a set of information that allows analysis according to several criteria and related indicators. From these criteria, the impact of the optimality on the various pathways of the IFBR is analyzed. For instance, the investment is analyzed using the cash return on capital invested (CROIC) and the internal return rate (IRR). However, the emission is analyzed using the global emission rate (ER). A combined indicator expressing the ratio of the internal return rate of the investment over the emission rate (IRR/ER) is used to reflect the relative value of the two indicators mentioned above. The internal integration rate (IIR) and the waste recycling rate (WRR) are also used. According to these indicators, the rankings of different Pareto frontier solutions are made, in order to distinguish the more advantageous ones.

4.2. Formulation of the mathematical model

The following assumptions are considered:

- Raw materials are completely consumed at the end of each planning period;
- Heat production is sufficient for all the activities studied;
- Co-products of pulp and papers that are unused in other processes will be accounted for in the global emission;
- At the digestion stage, the emission is determined considering the biogenic emission of carbon dioxide, the total recovery of methane (CH_4), and the emission of nitrous oxide (N_2O) which is considered here to be insignificant;
- Any investment planned in a particular cycle is final and irreversible.

Table 1
GHG emission inventory.

Process	Input	Input item	GHG inventory	Mass inventory balance
Biomass plantation, harvesting, and collection	Energy, water, and fertilizers	Agriculture residues (AR)	88 kg CO_2-eq.ton^{-1} (GREET model)	
		Forest residues (FR)	18 kg CO_2-eq.ton^{-1} (GREET model)	
Transport from the field to IFBR plant	Energy, and means of transport	Transport of AR	22 kg CO_2-eq.ton^{-1} (GREET model)	
		Transport of FR	47 kg CO_2-eq.ton^{-1} (GREET model)	
Fermentation (Bioethanol pathway)	Biomass	Agriculture residues	110 kg CO_2-eq/ton (GREET model)	3.70 kg/L of ethanol (Machani et al., 2014)
		Forest residues	65 kg CO_2-eq/ton (GREET model)	3.45 kg/L of ethanol (Machani et al., 2014)
		Industrial residues	105 kg CO_2-eq/ton (McKechnie et al., 2014)	2.94 kg/L of ethanol (Machani et al., 2014)
	Energy	Electricity	Decision variable	220 kwh/ton biom. (Lythcke-Jorgensen and Haglind, 2015)
		Heat	Decision variable	3.8 GJ/ton biom. (Lythcke-Jorgensen and Haglind, 2015)
	Cellulase and yeast	Cellulase	10.3 kg CO2-eq/kg (Karlsson, 2014)	0.32 g/MJ of ethanol (Budsberg et al., 2015)
		Yeast	3.2 kg CO_2-eq/kg (Soam et al., 2016)	1.3 g/MJ of ethanol (Soam et al., 2016)
Cogeneration (Energy cogeneration pathway)	Black liquor	Black liquor (BL)	79 kg CO_2-eq/ton (Economic allocation)	0.83 kg/KWh of electricity (Machani et al., 2014)
		BL to Cogeneration	0.0078 kg CO_2-eq/KWh (NCASI, 2005)	
	Biogas	Biogas	Decision variable	0.5 m3/KWh of electricity (Machani et al., 2014)
		Biogas to Cogeneration	0 kg CO_2-eq/KWh (Hahn et al., 2015)	
Anaerobic digestion (Waste to energy fuel pathway)	Municipal residue	Municipal residues	11.3 kg CO_2-eq/ton (Friedrich & Trois, 2016)	10 kg /m3 of biogas (Machani et al., 2014)
		Municipal residues to Anaerobic digestion	0 kg CO_2-eq/m^3 (NCASI, 2005)	
	Paper sludge	Paper sludge	30 kg CO_2-eq/ton (Economic allocation)	5 kg/m3 of biogas (Machani et al., 2014)
		Paper sludge to Anaerobic digestion	0 kg CO_2-eq/m^3 (NCASI, 2005)	
	Energy	Electricity	Decision variable	75 kwh/ton of biomass (Stephen and Peter, 2012)
		Heat	Decision variable	32 kwh/ton of biomass (Stephen and Peter, 2012)
Pulp and paper	Biomass	Industrial residues	105 kg CO_2-eq/ton (McKechnie et al., 2014)	2 ton/ ton of dry pulp (Machani et al., 2014)
	Energy	Electricity	Decision variable	638 kwh/ ton of dry pulp (NCASI, 2011)
		Heat	Decision variable	22.7 GJ/ ton of dry pulp (NCASI, 2011)
	Chemicals	Na2CO3	415 kg CO_2-eq/ton (NCASI, 2005)	10 kg/ton of dry pulp (added to recovered chemicals) (NCASI, 2005)
		CaCO3	440 kg CO_2-eq/ton (NCASI, 2005)	10 kg/ton of dry pulp (added to recoered chemicals) (NCASI, 2005)

Using the notations presented in Appendix 1, environmental and economic objective functions and all relevant constraints are explained.

4.2.1. Environmental objective function

The environmental objective function minimizes the impact on climate change of the IFBR integrated in P&P over the planning horizon T. GHG emission is the indicator to measure this impact. The total emission of the system assessed includes the emission of ethanol pathway ($GHGP_1$), the emission of lignin ($GHGC_1$), the emission of biogas for the market ($GHG2M$), the emission of electricity for the market ($GHG3M$), the emission of the pulp and paper pathway ($GHGP_4$), and the emission of pulp and paper co-product (Black Liquor and Paper Sludge) non recovered. Each term involved in the total emission calculation is explained below.

Total emission of ethanol pathway ($GHGP_1$): This emission is generated by bioethanol pathway at supply and manufacturing stages over the planning horizon T:

- In the supply stage, emission is calculated by multiplying the flow of biomass b consumed by fermentation technology e in each period t, $FB_{b,e,t}$, by the emission related to the procurement including transport of each type of biomass b, GHG_b.
- In the manufacturing stage, the emission takes into account the Flows of Other Inputs l consumed by the technology e in each period t, $FOI_{l,e,t}$ associated with the pretreatment and fermentation phases such as the cellulase (enzymes to convert biomass in sugars), yeast for fermenting sugars as well as internal flows of final product i (electricity and heat) produced by technology e (cogeneration) and consumed by technology e' at this stage in period t, $IFFP_{i,e,e',t}$. The previous flows are affected respectively by the unit emission burden related to those inputs, $GHGOI_l$, $GHG3MWh_t$ and $GHG5MWh_t$. The total emission generated by bioethanol pathway is,

$$GHGP_1 = \sum_{t=1}^{T} \sum_{b\,\varepsilon\,\{1,3,4\}} GHG_b \cdot FB_{b,1,t} + \sum_{t=1}^{T} (IFFP_{3,3,1,t} \cdot GHG3MWh_t + IFFP_{5,3,1,t} \cdot GHG5MWh_t) + \sum_{t=1}^{T} \sum_{l\,\varepsilon\,\{1,2\}} GHGOI_l \cdot FOI_{l,1,t} \sum_{b\,\varepsilon\,\{1,3,4\}} FB_{\,b,1,t} \cdot CR_{b,1} \tag{1}$$

Total emission of P&P: The total emission of P&P is calculated by the aggregation of the emission related to the supply flows of biomass b consumed by the technology e (Kraft Pulp) in the period t, $FB_{b,e,t}$, added to the emission generated in the conversion stage using craft pulp process. In this stage the emission takes into account other input flows l, $FOI_{l,e,t}$, associated with the pretreatment and conversion phases as the sodium hydroxide, the sodium sulfide known as white liquor as well as heat and electricity flows consumed, $IFFP_{l,e,e',t}$. The emission was determined by multiplying the previous flows by the emission burden related, $GHGOI_l$ (other inputs), $GHG3MWh_t$ (electricity) and $GHG5MWh_t$ (heat). An allocation method was adopted to assign the emission among the co-products BL and PS recovered under the IFBR. The resulting emission is,

$$GHGP_4 = \sum_{t=1}^{T} GHG_1 \cdot FB_{\,1,4,t} + \sum_{t=1}^{T} (IFFP_{3,3,4,t} \cdot GHG3MWh_t + IFFP_{5,3,4,t} \cdot GHG5MWh_t) + \sum_{t=1}^{T} \sum_{l\,\varepsilon\,\{3,4\}} GHGOI_l \cdot FOI_{l,1,t} \cdot FB_{\,1,4,t} \cdot CR_{1,4} \tag{2}$$

Total emission of AD pathway (GHGP2): This emission includes the feedstock emission burden calculated by multiplying the flow of feedstock consumed, $FB_{b,e,t}$(biomass flow) and $IFCP_{j,e,e',t}$ (co-product internal flow), by the emission burden related to each feedstock, GHG_b and $GHGC_j$, in addition to the emission generated at the digestion stage over the planning horizon. The latter emission includes energetic inputs emission associated with the digestion process such as electricity and heat consumed to save the ambient temperature in the digester. Then, total emission related to AD is,

$$GHGP_2 = \sum_{t=1}^{T} GHG_2 \cdot FB_{2,2,t} + \sum_{t=1}^{T} (IFFP_{3,3,2,t} \cdot GHG3MWh_t + IFFP_{5,3,2,t} \cdot GHG5MWh_t) + \sum_{t=1}^{T} GHGC_2 \cdot IFCP_{2,4,2,t} + \sum_{t=1}^{T} GHG_{2,2} \cdot FB_{2,2,t} \cdot CR_{2,2} + \sum_{t=1}^{T} GHGC_{2,2} \cdot IFCP_{2,4,2,t} \cdot CRC_{2,2} \tag{3}$$

The emission of biogas sold is equal to emission related to one unit of biogas, $GHG2M3$, multiplied by the flow of biogas shipped to the market, $MFFP_{i,t}$, during the horizon period. That is,

$$GHG2M = GHG2M3 \sum_{t=1}^{T} MFFP_{2,t} \tag{4}$$

Total emission of cogeneration $GHGP_3$: The emission concerns the flow of black liquor, $IFCP_{j,e,e',t}$, and biogas feedstock, $IFFP_{i,e,e',t}$, according to the flow converted by cogeneration unit to produce electricity and heat added to the emission produced in the stage of cogeneration process. Each flow is multiplied by the emission burden related. Total emission related to cogeneration is,

$$GHGP_3 = \sum_{t=1}^{T} GHGC_3 \cdot IFCP_{3,4,3,t} + \sum_{t=1}^{T} GHG2M3_t \cdot IFFP_{2,2,3,t} + \sum_{t=1}^{T} GHGP_{2,3} \cdot IFFP_{2,2,3,t} \cdot CRP_{2,3} + \sum_{t=1}^{T} GHGC_{3,3} \cdot IFCP_{3,4,3,t} \cdot CRC_{3,3} \tag{5}$$

The emission of electricity sold is equal to the emission generated by one unit of electricity, $GHG3MWh$, multiplied by the flow of electricity shipped to the market during the horizon period, $MFFP_{3,t}$:

$$GHG3M = GHG3KWh \sum_{t=1}^{T} MFFP_{3,t} \tag{6}$$

Total emission of lignin $GHGC_1$: This emission is calculated by multiplying the emission of ethanol by the allocation rate, AR, determined according to energy method based on Low Heat Value (LHV) related to ethanol and lignin:

$$GHGC_1 = GHGP_1 \cdot AR_{1,1} \tag{7}$$

The total emissions generated in the IFBR is calculated by the aggregation of the emission generated in the entire system, as explained above, added to those generated by the emission of pulp and paper co-product (Black Liquor and Paper Sludge) non recovered. Hence, the total emission is:

$$GHGtotal = GHGP_1 + GHGP_4 + GHG2M + GHG3M + \sum_{t=1}^{T} \sum_{j\in\{2,3\}} GHGC_{j,t} \cdot (QCP_{j,t} - IFCP_{j,t}) + GHGC_1 \tag{8}$$

Total emission of biomass from the field to the plant: The total emission related to biomass in supply stage, GHG_FTP (Eq. (11)), is composed by emission of biomass in the field, GHG_BIF (Eq. (9)), added to emission generated by transportation stage, GHG_TR (Eq. (10)). These equations are:

$$GHGBIF = \sum_{t=1}^{T} \sum_{b=1}^{4} GHGIF_b \sum_{e=1}^{4} FB_{b,e,t} \tag{9}$$

$$GHGTR = \sum_{t=1}^{T} \sum_{b=1}^{4} GHGTR_b \sum_{e=1}^{4} FB_{b,e,t} \tag{10}$$

$$GHGFTP = GHGBIF + GHGTR \tag{11}$$

4.2.2. Economic objective function

Following (Machani et al., 2014), the economic objective function is about maximizing the sum of the Actualized Net Cash Flow (ANCF) and the Salvage Value (SV) of the IFBR at the end of the horizon period. The economic objective function is:

$$EOBJ = (ANCF + SV) \tag{12}$$

The Actualized Net Cash Flow: It is the actualized operating profit of bioenergy and P&P activity added to present value of tax saving derived from fiscal depreciation, *TR.AFD*, minus tax, *TR.ACF*, and present value of investment cost, *A_INV_H*, over the planning horizon *T*. That is,

$$ANCF = (1 - TR)\cdot ACF + TR\cdot AFD - AINVH \tag{13}$$

The Net Cash Flow (NCF) is:

$$NCF = (1 - TR)\cdot CF + TR\cdot FD - INVH \tag{14}$$

The term *ACF* in Eq. (13) includes the present value of all the market products revenue, *ARMP*, added to the present value of the market co-product revenue, *ACPR*, minus the present value of operating fixed cost of P&P activity, *AFCPP*, the present value of closing cost of P&P activity, *ACCPP*, the present value of production cost of all products, *APC*, and the present value of biomass supplying cost, *ABC*:

$$ACF = ARMP + ACPR - APC - AFCPP - ACCPP - ABC \tag{15}$$

Hence, the present value of the cash flow at each period *t* is:

$$ACF_t = ARMP_t + ACPR_t - APC_t - AFCPP_t - ACCPP_t - ABC_t;\ t = 1,\ 2,\ \ldots, T \tag{16}$$

The cash flow is given by:

$$CF = \sum_{t=1}^{T} ACF_t\cdot(1 + r)^t \tag{17}$$

$$CF_t = ACF_t\cdot(1 + r)^t \tag{18}$$

Each term in Eq. (15) can be calculated from its aggregate form: see Eq. (20) to Eq. (25) below.

The salvage value of the IFBR at the end of the planning horizon: It is equal to the total investment costs for bioenergy minus accounting depreciation and debts discounted at the period *T*, using annual interest rate *r*:

$$SV = \frac{TINV - ADBI - D}{(1 + r)^T} \tag{19}$$

The present value of revenue generated by all market products: It is given by the product of selling price of each product *i*, SP_i, and the flow of products, $MFFP_{i,t}$, shipped to the market in each period *t* actualized using annual interest rate *r*:

$$ARMP = \sum_{t=1}^{T}\sum_{i=1}^{4} \frac{(SP_i\cdot MFFP_{i,\,t})}{(1 + r)^t} \tag{20}$$

The present value of production cost of all products: It is given by the product of the production unit cost, PUC_i,of each product *i* and the quantity produced in each period *t*, $QFP_{i,t}$, actualized using annual interest rate *r*:

$$APC = \sum_{t=1}^{T}\sum_{i=1}^{4} \frac{(PUC_i\cdot QFP_{i,\,t})}{(1 + r)^t} \tag{21}$$

The present value of operating fixed cost of P&P activity: It is equal to fixed cost of P&P products, *FCPP*, multiplied by P&P activity state in each period *t*, W_t,actualized using annual interest rate *r*:

$$AFCPP = \sum_{t=1}^{T} \frac{(FCPP\cdot W_t)}{(1 + r)^t} \tag{22}$$

The present value of closing cost of P&P activity: It is equal to the closing cost, *CC*, if the P&P activity is not operating in that period ($W_t = 0$), actualized using annual interest rate *r*:

$$ACCPP = \sum_{t=1}^{T} \frac{CC\cdot(1 - W_t)}{(1 + r)^t} \tag{23}$$

The present value of co-products sales revenue: It is given by multiplying the selling price, SC_j, and the co-products market flows, $MFCP_{j,t}$, in each period *t* actualized using annual interest rate *r*. Since only Lignin co-products are sold, we have:

$$ACPR = \sum_{t=1}^{T} \frac{SC_1\cdot MFCP_{1,t}}{(1 + r)^t} \tag{24}$$

The present value of biomass supplying cost: It is given by the product of the unit supplying cost of biomass *b*, BUC_b, by the sum of biomass flowed to the different technologies, $FB_{b,e,t}$, in each period *t* actualized using annual interest rate *r*:

$$ABC = \sum_{t=1}^{T}\sum_{b=1}^{4} \frac{BUC_b \sum_{e=1}^{4} FB_{b,e,t}}{(1 + r)^t} \tag{25}$$

The present value of fiscal depreciation of bioenergy investments: It is the bioenergy investment cost for the technologies *e* already added with capacity option *o* over the planning periods *c*, $IC_{o,e,c}$, divided by the fiscal lifetime, *FLT,* over the planning cycles, actualized using annual interest rate *r*:

$$AFD = \sum_{c=0}^{C-1}\sum_{t=(c\cdot PC+1)}^{T} \frac{\sum_{e=1}^{3}\sum_{o=1}^{3} IC_{o,e,c+1}\cdot(Y_{o,e,c+1} - Y_{o,e,c})}{FLT\cdot(1 + r)^t} \tag{26}$$

Thus, the fiscal depreciation (FD) is:

$$FD = \sum_{c=0}^{C-1}\sum_{t=(c\cdot PC+1)}^{T} \frac{\sum_{e=1}^{3}\sum_{o=1}^{3} IC_{o,e,c+1}\cdot(Y_{o,e,c+1} - Y_{o,e,c})}{FLT} \tag{27}$$

The accounting depreciation of bioenergy investments: It is equal to the sum of bioenergy investment costs for the technologies already added with capacity option *o* over the planning period *c*, $IC_{o,e,c+1}$,annualized by dividing it by the economic lifetime, *ELT,* over the planning cycles:

$$ADBI = \sum_{c=0}^{C-1}\left(\sum_{t=(c\cdot PC+1)}^{T} \frac{\sum_{e=1}^{3}\sum_{o=1}^{3} IC_{o,e,c+1}\cdot(Y_{o,e,c+1} - Y_{o,e,c})}{ELT}\right) \tag{28}$$

The total investment cost for bioenergy: It is equal to the bioenergy investment costs for the technologies already added over the planning cycles:

$$TINV = \sum_{c=1}^{C}\sum_{e=1}^{3}\sum_{o=1}^{3} IC_{o,e,c}\cdot(Y_{o,e,c} - Y_{o,e,c-1}) \tag{29}$$

The horizon investment cost for bioenergy: It is equal to the bioenergy investment costs for the technologies already added annualized over the planning periods by dividing it by the financial horizon *T*, over the planning cycles:

$$HINV = \sum_{i=0}^{C-1}\left(\sum_{t=(c\cdot PC+1)}^{T} \frac{\sum_{e=1}^{3}\sum_{o=1}^{3} IC_{o,e,i+1}\cdot(Y_{o,e,i+1} - Y_{o,e,i})}{T}\right) \tag{30}$$

The present value of the horizon investment cost: It is equal to the bioenergy investment costs, for the technologies already added annualized, over the planning periods, by dividing it by the financial horizon *T*, over the planning cycles, and actualized using annual interest rate *r*:

$$AINVH = \sum_{i=0}^{C-1}\left(\left(\sum_{t=i\,PC+1}^{T} \frac{\sum_{e=1}^{3}\sum_{o=1}^{3} IC_{o,e,i+1}\cdot(Y_{o,e,i+1} - Y_{o,e,i})}{T}\right)(1 + r)^{-(i\cdot PC+1)}\right) \tag{31}$$

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

$$D = TINV - HINV \tag{32}$$

4.2.3. Constraints

Availability of supplied biomass: The flow of biomass b representing the raw materials used in the *IFBR* cannot exceed the quantity of biomass supply available, BS_b, in each period t. The evolution trend of the biomass supply, BST, has been taken into account:

$$\sum_{e=1}^{4} FB_{b,e,t} \leq BS_b\cdot(1 + BST\cdot(t-1))\ \forall\ b = 1,\ 2,\ ...,4;\ t = 1,\ 2,\ ...,T \tag{33}$$

Mass balance of bioenergy production: The quantity produced of each bioenergy product i, in each period t, depends on the conversion rate of inputs consumed. These inputs could be supplied by biomass flow, FB, in site flow of co-products, $IFCP$, or internal flow of final products, $IFFP$:

$$\begin{aligned} &QFP_{i,e,t} - \textstyle\sum_{b=1}^{4} CR_{b,e}\cdot(1 + CT\cdot(t-1))\cdot FB_{b,e,t} \\ &- \textstyle\sum_{j=2}^{3} CRC_{j,e}\cdot(1 + CT\cdot(t-1))\cdot IFCP_{j,4,e,t} - \\ &CRP_{2,e}\cdot(1 + CT\cdot(t-1))\cdot IFFP_{2,2,e,t} = 0\ \forall\ i = 1,2,3;\ t = 1,2,...,T \end{aligned} \tag{34}$$

Electricity flows balance: The quantity of electricity produced by cogeneration for each period t must satisfy the internal demand according to the production capacity installed for each cycle:

$$IFFP_{3,3,e,t} - \sum_{o=1}^{3} CE_e\cdot CO_{o,e}\cdot Y_{o,e,c(t)} \geq 0\ \forall\ e = 1,2;\ t = 1,\ 2,\ ...,T \tag{35}$$

$$IFFP_{3,3,4,t} - CE_4\cdot CA_p\cdot W_t \geq 0\ \forall\ t = 1,\ 2,\ ...,T \tag{36}$$

Bioenergy product flow balance: Any bioenergy product i produced in each period t is greater than or equal to the sum of its flows consumed in site by other technologies and the quantity sold to the market:

$$QFP_{i,t} - \sum_{e'\in\{1,2,3,4\}\setminus\{i\}} IFFP_{i,i,e',t} - MFFP_{i,t} \geq 0\ \forall\ i = 1,\ 2,3,4;\ t = 1,\ 2,\ ...,T \tag{37}$$

Co-product availability: In each period t, the flows of co-products j valid for sale or for internal consumption are generated according to a proportion, $\alpha_{j,i}$, of the product i:

$$QCP_{j,t} - \sum_{i=1}^{4} \alpha_{j,i}\cdot QFP_{i,t} \leq 0\ \forall j = 1,\ 2,\ 3;\ t = 1,\ 2,\ ...,T \tag{38}$$

Capacity of production constraint for bioenergy and P&P products: The quantity of each product i produced in each period t, its flows to the market and to the internal use must not exceed the production capacity in the cycle $c(t)$:

$$QFP_{i,e,t} - \sum_{0=1}^{3} CO_{o,e}\cdot Y_{o,e,c(t)} \leq 0\ \forall\ i,\ e = 1,2,3;\ \ t = 1,2,\ ...,T \tag{39}$$

$$\begin{aligned} &IFFP_{i,e,e',t} - \left(\sum_{0=1}^{3} CO_{o,e}\cdot Y_{o,e,c(t)}\right)\cdot BN \leq 0\ \forall\ i = 1,2,3;\ e = 1,2,3,4; \\ &e' \in \{1,2,3,4\}\setminus\{e\};\ t = 1,\ 2,\ ...,T \end{aligned} \tag{40}$$

$$QFP_{1,4,t} - CA_p\cdot W_t \leq 0\ \forall\ t = 1,2,\ ...,T \tag{41}$$

Investment irreversibility over the entire planning horizon: Any installed technology is irreversible throughout the planning horizon:

$$Y_{o,e,c} - Y_{o,e,c-1} \geq 0\ \forall\ e,\ o = 1,\ 2,\ 3;\ c = 1,2,\ ...,4 \tag{42}$$

Budget availability constraint: The investment cost in each cycle cannot exceed an allowed budget:

$$\sum_{e=1}^{3}\sum_{0=1}^{3} (Y_{o,e,c} - Y_{o,e,c-1})\cdot IC_{o,e,c} - BD_c \leq 0\ \forall\ c = 1,2,\ ...,4 \tag{43}$$

P&P product, bioenergy products and co-products demand constraint: The flows of P&P product, bioenergy products and co-products sold in the markets, in each period t, should not exceed the demand for these products in that period:

$$QFP_{4,4,t} \leq DP_4\cdot W_t\ \ \forall\ t = 1,\ 2,\ ...,T \tag{44}$$

$$MFFP_{i,t} \leq DP_i\cdot(1 + DT\cdot(t-1))\ \ \forall\ i = 1,2,3;\ t = 1,2,\ ...,T \tag{45}$$

$$MFCP_{1,t} \leq DC_1\cdot(1 + DT\cdot(t-1))\ \ \forall\ t = 1,2,\ ...,T \tag{46}$$

Non-negativity constraints

$$\begin{aligned} Y_{o,e,c} &= \{0,1\} \quad \forall\ o,\ e,\ c \\ W_t &= \{0,1\} \quad \forall\ t \\ FB_{b,e,t} &\geq 0 \quad \forall\ b,\ e,\ t \\ FOI_{l,e,t} &\geq 0 \quad \forall\ l,\ e,\ t \\ IFCP_{j,e,e',t} &\geq 0 \quad \forall\ j,\ e,\ e',\ t \\ IFFP_{i,e,e',t} &\geq 0 \quad \forall\ i,\ e,\ e',\ t \\ MFFP_{i,t} &\geq 0 \quad \forall\ i,\ t; \\ MFCP_{i,t} &\geq 0 \quad \forall\ j,\ t \\ QFP_{i,t} &\geq 0 \quad \forall\ i,\ t \\ QC_{j,t} &\geq 0 \quad \forall\ j,\ t \end{aligned} \tag{47}$$

5. Results and discussion

IBM ILOG CPLEX Optimization Studio involving OPL programming language and CPLEX solver is the environment adopted for programming and solving the model. This environment has been interfaced with Access MS-Office 2013 through SQL language. The Pareto frontier was programmed in VBA under Microsoft Excel interfaced with the model in CPLEX Optimization Studio and with Access MS-Office 2013. The mathematical model runs have been executed on a 3.40 GHz Intel Core (TM) i7-2600 CPU server machine with 16 GB of RAM and 64 bits operating system.

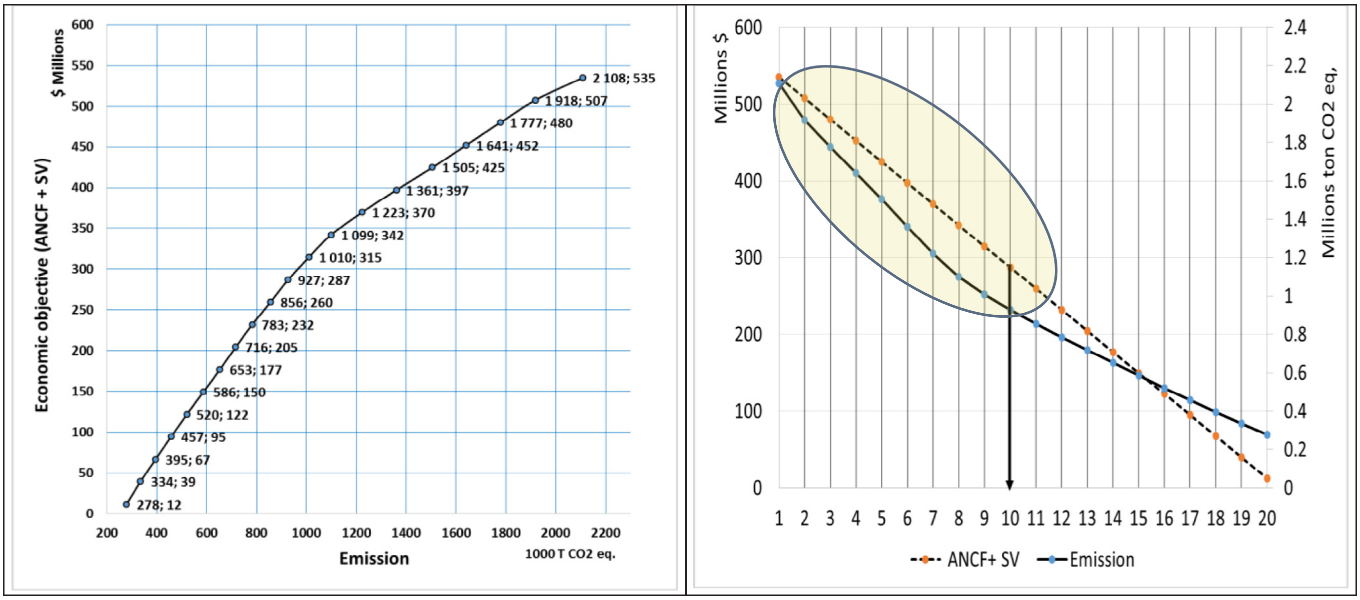
This section discusses the model results including a sensitivity analysis, and presents recommendations for a successful implementation of the bioenergy production in Canadian P&P mills.

5.1. Pareto frontier generation

The Pareto frontier was generated making use of the ε-constraint method. According to this method, the model was first executed under the economic objective and then under the environmental objective. The results generated constitute the two extreme solutions of the Pareto frontier. The other solutions are obtained by dividing the range between the two economic objectives into nineteen (19) equal intervals generating twenty (20) solutions. The Pareto frontier at each of these solutions is obtained by optimizing the environmental objective function subject to the economic constraint. This resulted in the Pareto frontier shown in Fig. 3(a). The environmental and the economic objectives are presented in Fig. 3(b) for each Pareto frontier solution. Each solution is a compromise between the two aspects concerned. The analysis will be restricted to the ten first solutions where the trade-off is more significant. In fact, by solution ten the economic objective is reduced by 50% and the ethanol pathway is no longer viable. It is considered that decision makers would not tolerate further degradation of the economic objective in order to reduce emissions.

5.2. Pareto optimal investment roadmaps

The primary goal of the mathematical model is to provide an optimal roadmap of bioenergy investments, aiming to optimize both the financial and the environmental values of the developed IFBR. The proposed multi-objective model prescribes the bioenergy technologies to be embedded, the production capacity, the timing of capacity options added, and the capital invested. Table 2 presents the optimal investment roadmap for each Pareto frontier solution. The results in this table show that the production capacity for the energy cogeneration pathway selected is steady at 40 MWh, *i.e.* such production capacity is embedded in Cycle 1 and remains unchanged for the rest of the planning horizon.



a. Pareto frontier. **b.** Emission and economic objective behavior.

Fig. 3. Multi-objective solutions.

This energy is principally used to fill the needs of the IFBR in power and the remaining part is sold to the market. The corresponding optimal capacity of 40 MWh is reasonable, and in line with Goortani et al. (2010) who suggested that 44.5 MWh of electricity can be attributed to cogeneration units in Canadian Kraft pulping mill. On the other hand, waste to energy pathway using anaerobic digestion (AD) technology is embedded in Cycle 2, with 80 million cubic meters (Mm^3) per year as biogas production capacity. Then, an additional capacity of 40 Mm^3 is embedded in Cycle 4. We remark that, for the cogeneration and the AD technologies, the capacity options are the same for all Pareto optimal solutions; the resulting capital invested are indeed the same: $150.4 million (M$) and 240 M$, respectively.

However, for the bioethanol pathway (fermentation technology), the implemented production capacity (and the corresponding investment capitals) change from one Pareto solution to another. We remark that the total bioethanol production capacity decreases as the solution index increases. This change ranges from 120 million liters (ML) per year for Solution 1 to 30 ML for Solution 7, whilst the ethanol production is no longer viable for Solutions 8–10. In line with the selected capacity, the total capitals invested change from 145.2 M$ for Solution 1 to 36.3 M$ for Solution 7.

The above results suggest that the deterioration in the economic objective from one solution to another is caused by the reductions in the ethanol production and its corresponding investment capital. At the same time, the environmental objective is enhanced as the ethanol production makes use of forest residue as a cleaner biomass. This is justified by the fact that the proportion of ethanol in the economic objective degrades to benefit the pulp production, since they share the same raw material (industrial residue). Competition at the supply level favors the pathway that presents a better relationship between emissions and economic performance. Here, the ethanol production 'migrates' towards the use of a cleaner biomass (forest residue) and reduces its production capacity at the same time.

5.3. Selection of the optimal solution

The selected Pareto optimal solution may depend on the transactions that can be established between environmental and economic aspects, according to the constraints of management and governance of the incubator P&P industry (integrating bioenergetics production). In our context, the used indicators are the cash return on capital invested, the internal return rate, the emission rate, the internal integration rate, and the waste recycling rate. In what follows, we explain how these economic and environmental indicators are used to compare the Pareto optimal solutions. In Fig. 4, we evaluate these indicators for each solution.

5.3.1. Cash return on invested capital

To evaluate how much cash flow per dollar the IFBR generates from invested capital, we calculate the Cash Return On Invested Capital (CROIC) ratio:

$$CROIC = ANCF/AINVH \tag{48}$$

where *ANCF* and *A_INV_H* are the actualized net cash flow and the actualized invested capital defined in Equations (13) and (31), respectively.

Fig. 4(a) presents this ratio for each Pareto optimal solution. The higher the CROIC, the more cash the IFBR is generating from the invested capital. Remark the CROIC variations do not follow that of the economic objective function. For example, Solution 1 (which has the highest economic objective function) provides lower CROIC than Solutions 2 and 3. According to the CROIC ratio, Solutions 2 and 3 are good candidate with 1.38 and 1.37 (respectively).

5.3.2. Internal return rate

To further analyze the investment component, the internal return rate (IRR) indicator is used to measure the economic performance of the selected investment. The IRR is the interest rate at which the net present value of the cash flow is equal to zero. Using Microsoft Excel, the IRR is evaluated by solving the following equation which takes into account the fiscal taxation and the salvage value:

$$\sum_{t=1}^{T} \frac{NCF_t}{(1+IRR)^t} - HINV + \frac{SV}{(1+IRR)^T} = 0 \tag{49}$$

According to this indicator, Solutions 1–4 and 6 of the Pareto frontier are all remarkable targets for potential transactions (their corresponding internal return rates are higher than 16%). Solution 4 has the highest IRR (16.57%) and is preferred for all bioenergy production pathways.

Table 2
Pareto optimal roadmaps for bioenergy investments.

Cycle	1		2		3		4		Total	
Technology	Cogeneration (C: Capacity in MWh; K : Capital in Million$)									
Pareto frontier solutions	C MWh	K M$	C MWh	K M$	C MWh	K M$	C MWh	K M$	C MWh	K M$
1	40	150.4	–	–	–	–	–	–	40	150.4
2	40	150.4	–	–	–	–	–	–	40	150.4
3	40	150.4	–	–	–	–	–	–	40	150.4
4	40	150.4	–	–	–	–	–	–	40	150.4
5	40	150.4	–	–	–	–	–	–	40	150.4
6	40	150.4	–	–	–	–	–	–	40	150.4
7	40	150.4	–	–	–	–	–	–	40	150.4
8	40	150.4	–	–	–	–	–	–	40	150.4
9	40	150.4	–	–	–	–	–	–	40	150.4
10	40	150.4	–	–	–	–	–	–	40	150.4
Technology	Anaerobic Digestion (C: Capacity in Million m^3; K : Capital in Million$)									
Pareto frontier solutions	C Mm^3	K M$	C Mm^3	K M$	C Mm^3	K M$	C Mm^3	K M$	C Mm^3	K M$
1	–	–	80	160	–	–	40	80	120	240
2	–	–	80	160	–	–	40	80	120	240
3	–	–	80	160	–	–	40	80	120	240
4	–	–	80	160	–	–	40	80	120	240
5	–	–	80	160	–	–	40	80	120	240
6	–	–	80	160	–	–	40	80	120	240
7	–	–	80	160	–	–	40	80	120	240
8	–	–	80	160	–	–	40	80	120	240
9	–	–	80	160	–	–	40	80	120	240
10	–	–	80	160	–	–	40	80	120	240
Technology	Fermentation (C: Capacity in Million L; K : Capital in Million$)									
Pareto frontier solutions	C ML	K M$	C ML	K M$	C ML	K M$	C ML	K M$	C ML	K M$
1	90	108.9	–	–	30	36.3	–	–	120	145.2
2	60	72.6	30	36.3	–	–	–	–	90	108.9
3	60	72.6	–	–	–	–	30	36.3	90	108.9
4	60	72.6	–	–	–	–	–	–	60	72.6
5	–	–	60	72.6	–	–	–	–	60	72.6
6	30	36.3	–	–	–	–	–	–	30	36.3
7	–	–	–	–	30	36.3	–	–	30	36.3

5.3.3. Emission rate

The emission rate (ER) per $1000 of cash flow for the whole activity indicates the environmental content of cash flow involved in each Pareto solution analyzed. That is,

$$ER = GHGtotal/CF \tag{50}$$

where *GHG_total* and *CF* are the total emission and the cash flow defined in Equations (8) and (17), respectively.

Fig. 4(c) shows that the emission rate is higher for a better economic solution. The slope at which the emission rate decreases is not the same. Economic and environmental performance indicators may diverge about identifying target solutions for transactions. To settle the conflict between the evolution of investment performance and related emissions, a relative performance indicator is introduced.

5.3.4. The relative performance ratio

The ratio IRR/ER combines two conflicting indicators (IRR and ER). According to this ratio, as shown in Fig. 4(d), Solutions 4 and 6 dominate the other solutions with a preference for Solution 6. Note that although Solution 8, 9 and 10 have higher ratios, they are not considered because it has been already observed that the ethanol production is no longer viable for these solutions.

5.3.5. Other indicators analyzed

To guide decision maker selecting a compromise solution in Pareto frontier, the analysis is further strengthened with two additional indicators. On the one hand, the P&P waste recycling rate (WRR) is defined as:

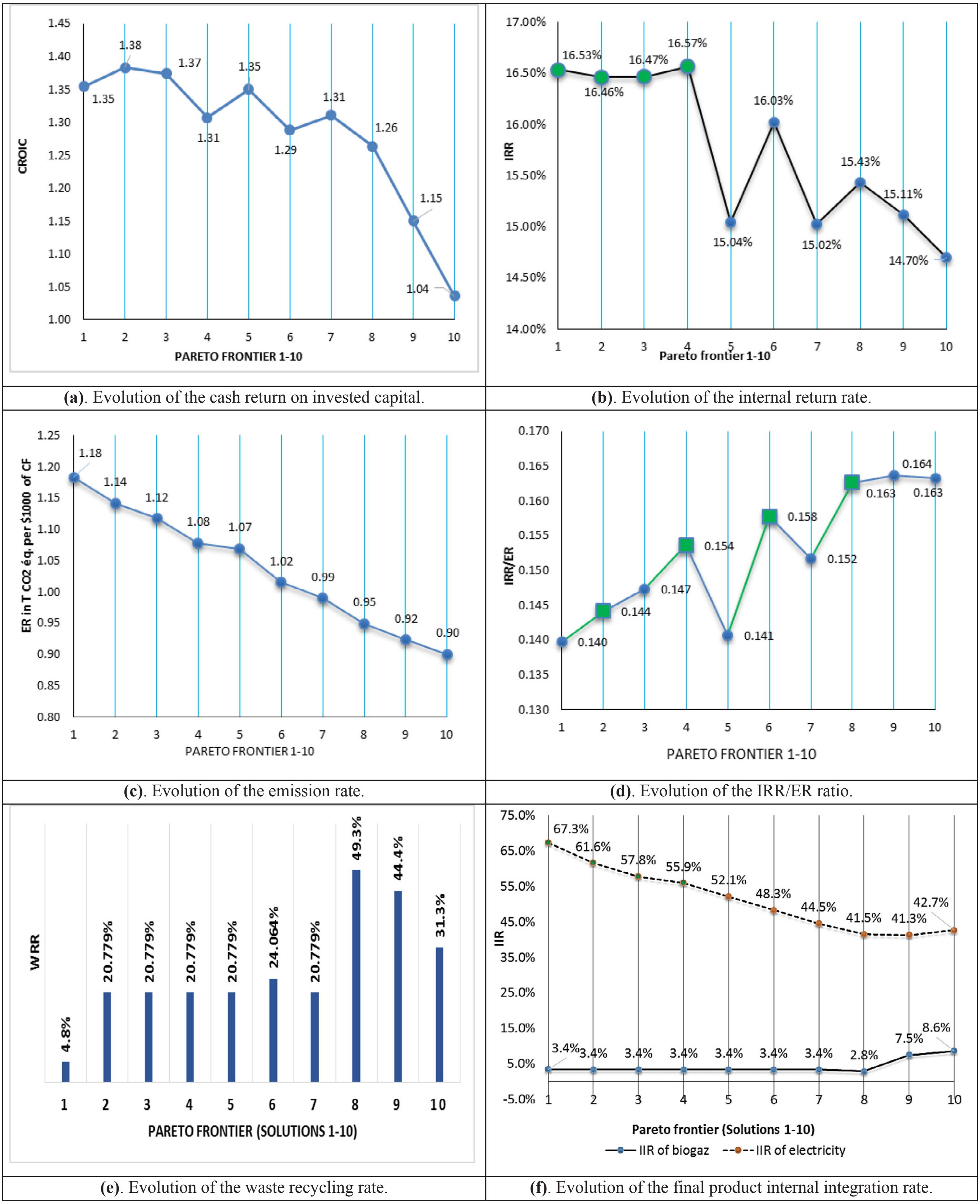
$$WRR = \sum_{t=1}^{T} IFCP_{2,4,3,t} / \sum_{t=1}^{T} \alpha_{2,4} \cdot QFP_{4,t} \tag{51}$$

where $IFCP_{2,4,3,t}$ is the flow of co-product 2 (Paper Sludge) generated by technology 4 (Kraft Pulp) and used by technology 3 (Cogeneration Heat and Power) in period t; $QFP_{4,t}$ is the quantity of final product 4 (Pulp and Paper) produced in period t; and $\alpha_{2,4}$ is the fraction of co-product 2 (Paper Sludge) for product 4 (Pulp and Paper). A higher WRR means that more Paper Sludge is recycled by anaerobic digestion unit to produce biogas. Fig. 4(e) shows that the WRR indicator favors the transaction with Solution 6, and disadvantages Solution 1 for which the waste recycling rate does not exceed 5%.

On the other hand, the internal integration rate (IIR) of the final products (biogas or electricity) is defined as the ratio of the flow of final products integrated in other conversion process on site, over the quantity of final products produced. That is, we have for biogas ($i = 2$) and electricity ($i = 3$):

$$IIR_i = 1 - \sum_{t=1}^{T} MFFP_{i,t} / \sum_{t=1}^{T} QFP_{i,t} \tag{52}$$

A higher IIR means that the IFBR is well integrated. For biogas, Fig. 4(f) shows a low IIR for all Pareto solutions: 3.4% for Solutions 1–7. This means that 96.6% of final products are sold, while 3.4% are



(a). Evolution of the cash return on invested capital.

(b). Evolution of the internal return rate.

(c). Evolution of the emission rate.

(d). Evolution of the IRR/ER ratio.

(e). Evolution of the waste recycling rate.

(f). Evolution of the final product internal integration rate.

Fig. 4. Solutions analysis in Pareto frontier.

internally consumed by the cogeneration. The electricity IIR decreases from 67.3% for Solution 1 to 44.5% for Solution 7. For Solutions 1–4, less than 45% of electricity is sold. The rest of electricity (more than 55%) is internally integrated, ensuring internal satisfaction with clean energy.

5.3.6. Ranking

Table 3 summarizes the ranking of solutions taking into account all the indicators analyzed. According to this ranking, Solutions 4 and 3 are potential compromise targets. However, it is up to the investor to choose the optimal solution depending on the context and the concerns of the P&P companies. Incentives granted to the bioenergy production sector, environmental and market-related regulatory constraints may be other reasons for investment choice.

After discussing the choice of the potential optimal solution based on a set of criteria, the interpretation of the impact will concern biorefinery integration and synergy with the incubator activity under Solution 4, which is considered as a highly recommended compromise solution.

5.3.7. Integration features and synergy with the incubator activity

Internal economic integration is an intrinsic attribute of biorefineries. In our case, the internal integration rate of electricity production is 100% upstream (inputs) and 61.6% downstream (outputs), thus ensuring internal satisfaction with clean energy. The waste rate is well reduced and the system operates in complete independence from fossil fuels. The cogeneration is supplied with 98.27% in black liquor, consumed in full; the rest (1.73%) is provided by the biogas representing 3.4% of the anaerobic digestion unit total product. The latter unit is supplied with paper sludge at a rate of 1.7% and with municipal waste at a rate of 98.3%. Paper sludge is recovered at 20.8%.

From the foregoing, it is noted that incubator activity is essential for the supply of the cogeneration unit, while the anaerobic digestion pathway acts as a safety support for cogeneration supply. The optimal configuration of the system studied confirms that energy production supply depends on the incubation activity, and that fermentation is the pathway affected the most by the transactional mechanism from one solution to the other. It is therefore natural to analyze the robustness of the system with regard to energy security, in the context of the deterioration of the incubator activity, and to study the impact of the government incentives to encourage ethanol production. To validate the results obtained, a robustness analysis is performed and a comparison will be made with other research work about GHG emission per product.

5.4. Sensitivity analysis

After estimating key parameters' changes, we analyze their impact on the Pareto optimal solution and on the performance indicators adopted to select good solutions. This analysis allows us to test the model robustness by assessing the quality of the proposed solutions. It also validates and increases our understanding of some relationships between the model variables and parameters. The uncertain parameters considered are P&P demand and price, ethanol price, and fiscal depreciation.

5.4.1. Estimation of parameters' changes

5.4.1.1. P&P demand. We consider two cases of demand degradation: **20%** and **-30%**. This choice is based on observed trends. Over the past decade the Canadian P&P industry has experienced major crises and changes impacting the structure of its supply and demand (McCarthy and Lei, 2010). Its market share has declined significantly. In (Karikallio et al., 2011), the authors reported that the market share of the world's largest companies in the P&P industry has declined considerably and demand for paper exports is price elastic, implying that an increase in export reduces the value of the product unit price. According to Food and Agriculture Organization (FAO) statistics, the market share of North American companies has decreased from 41% to 35% between 2002 and 2006. Furthermore, wood pulp exports decreased by 10%, between 1995 and 2014, for the Canadian case. During the same period, the quantity of wood pulp produced decreased by 32% in Canada.

5.4.1.2. P&P price. We consider two cases of price degradation: **10%** and **-15%**. Given the elasticity of export prices (Karikallio et al., 2011), this is an estimated price to maintain the level of exports.

5.4.1.3. Ethanol price. Federal and provincial governments are supporting ethanol industry through a number of overlapping programs that subsidize production, investment and distribution infrastructures (Laan et al., 2009). Taking into account the subsidies allocated for the production of lignocellulosic ethanol, the ethanol price is estimated to increase and we consider two cases: **+10¢** and **+15¢** (per liter).

5.4.1.4. Fiscal depreciation. In addition to market incentives, a proactive engagement of public partnership through several investment measures is undertaken to create favorable conditions for sustainability. Hence, the conversion of wood residues into bioenergy is part of the processing and manufacturing activities that can claim declining balance depreciation ranging from 30% to 100% according to the Canadian tax depreciation regulation. An accelerated depreciation using a rate of **50%** is proposed for analysis.

5.4.2. Analysis and interpretation of results

For each scenario, the new Pareto optimal solutions are evaluated using our solution methodology. Each case is called scenario (SC), and is identified by a number (SC1 to SC7). For all the scenarios, we have observed small deviations from the initial Pareto curves. To further analyze the impact of these deviations, we evaluate their impact on the criteria and indicators adopted to select good solutions of the Pareto frontier. By adopting the same criteria and indicators indicated in

Table 3
Ranks of the different Pareto frontier solutions according to different indicators.

Pareto frontier	Solutions ranking (Pareto frontier)												Total score	Final rank
	CROIC		IRR		ER		IRR/ER		WRR		IIR			
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank		
1	1.354	3	16.53%	2	1.18	7	0.140	7	4.8%	7	67.3%	1	27	7
2	1.383	1	16.46%	4	1.14	6	0.144	5	20.8%	2	61.6%	2	20	3
3	1.374	2	16.47%	3	1.12	5	0.147	4	20.8%	2	57.8%	3	19	1
4	1.307	6	16.57%	1	1.08	4	0.154	2	20.8%	2	55.9%	4	19	1
5	1.350	4	15.04%	6	1.07	3	0.141	6	20.8%	2	52.1%	5	26	6
6	1.288	7	16.03%	5	1.02	2	0.158	1	24.1%	1	48.3%	6	22	4
7	1.310	5	15.02%	7	0.99	1	0.152	3	20.8%	2	44.5%	7	25	5

Table 4
Sensitivity analysis results for Solution 3.

Scenarios	Emission rate variation	Internal return rate variation	Internal integration rate variation		Waste recycling rate variation	Variation in cash flow composition			Variation of invested capital and related pathway	
			Electricity	Biogas		Ethanol	Pulp	Biogas	Capital invested variation (M$)	Pathway
SC1: − 20% of P&P demand	0.098	− 1.89%	15.60%	1.77%	1.36%	5.7%	− 10.5%	4.8%	9	Fermentation
SC2: − 30% of P&P demand	0.108	− 3.35%	37.01%	1.59%	21.70%	1.6%	− 20.6%	18.7%	49	Fermentation & Anaerobic digestion
SC3: − 10% of P&P Price	0.149	− 0.14%	1.89%	0.00%	0.00%	4.4%	− 8.5%	4.1%	9	Fermentation
SC4: − 15% of P&P Price	0.245	− 2.40%	1.89%	0.00%	0.00%	7.4%	− 13.9%	6.5%	9	Fermentation
SC5: + 10c of ethanol price	− 0.067	2.13%	6.40%	3.44%	0.27%	12.1%	− 8.6%	− 3.6%	27	Fermentation
SC6: + 15c of ethanol price	− 0.113	3.15%	7.17%	6.87%	− 4.11%	17.5%	− 12.5%	− 5.0%	27	Fermentation
SC7: Accelerated fiscal depreciation	− 0.015	1.91%	0.00%	0.00%	25.00%	0.0%	0.0%	0.0%	76	Cogeneration & Anaerobic digestion

subsection 5.3, our analysis will focus on Solution 3 which represents the best solution for all scenarios. Table 4 presents for each scenario the variations observed in the considered criteria, in cash flow (CF) composition, and in capital investments and pathways.

In what follows, the impacts are analyzed in terms of sustainability, investment choice and energy security. This analysis allows checking the relevance of technology and production capacity choices, energy security, proper trade-offs between conflicting sustainability objectives, and synergy with the incubator activity. The analysis includes also the impact of government incentives related to the administration of ethanol prices and the application of accelerated depreciation.

5.4.2.1. Relevance of investment choice. The following observations interpret the model results in terms of investment choices.

- ***Economic incentives increase the capital invested and reduces emissions***

Under Scenarios 5 and 6, the increase in the market price of ethanol (as a result of economic incentives) lead to an increase in the capital invested and in the ethanol cash flow composition. We remark that this increase in investment and in 'clean' production capacity is accompanied with an improvement in emissions. Here, the model is behaving as expected in terms of the trade-offs between the two aspects of sustainability. Thus, economic incentives represent sustainability levers.

- ***Under unfavorable P&P market conditions, the bioenergy investment increases***

Scenario 2 considers the degradation of commercial P&P demand by 30%. It leads to a fall in P&P production, reducing its share in actualized cash flow by 20.6%. Under this scenario, the capital invested in bioenergy increases by 13.2% (49 M$), shared between ethanol production (+11% relative to ethanol investment in the reference scenario) and anaerobic digestion (+28.6% compared to the investment in anaerobic digestion in the reference scenario). This behavior proves that investment planning supports synergy with the incubator activity. Thus, the increase in ethanol production offset the decline of P&P activity. Furthermore, the additional production of biogas secures cogeneration by partially replacing the lack of black liquor.

5.4.2.2. Security of cogeneration unit supply. The behavior of the model proves its robustness in terms of energy security. The following explains the elements ensuring the stability of the evaluated system.

- ***An increase in internal energy demand leads to an increase in biogas internal integration rate to secure the supply of cogeneration***

Under Scenarios 5 and 6, the increase in ethanol production capacity leads to the need of internal energy production (increase of electricity internal integration rate by 6.40% and 7.17%), to meet the additional demand of the fermentation pathway. This, in turn, leads to the increase of biogas internal integration rate (3.44% and 6.87%) to ensure energy security.

- ***A degradation in P&P demand increases the electricity internal integration rate to satisfy the energy balance***

Under Scenarios 1 and 2, the electricity internal integration rate increases by 15.60% and 37.01% (respectively). In fact, when the incubator activity market is deteriorated, the energy balance is satisfied. Note also that in case of an increase of the ethanol production, following investment incentives, the integration rate increased by 6.4% (SC5) and 7.17% (SC6). This occurs either in response to an additional demand for energy or because of a lack of black liquor supply in the case of incubator activity difficulty.

- ***Improvement of waste recycling rate***

The recycling rate of waste has improved by 21.7% under SC6 to increase biogas production and to remedy the lack of black liquor used for cogeneration.

From the above discussion, it can be seen that energy security is well preserved by the model. The system exhibits a robust behavior by adapting to different contexts through the integration rate of finished products and through the regulation of production capacity to achieve energy balance.

5.4.2.3. Impacts of governmental support incentives. Concerning incentives granted to the production of ethanol in SC5 and SC6, the results prove increased investment in the bioethanol pathway, and overall improvement of all the performance indicators as illustrated in Table 4. However, the application of accelerated fiscal depreciation positively influences investment in bioenergy production other than ethanol pathway. The application of this fiscal mode improves the environmental performance (-15 kg CO_2 eq. per \$1000 of CF) and economic performance ($+1.9\%$ of the IRR), improves the recycling of waste by 25% and increases the invested capital by 15.8%. Thus, the system transforms the financial advantage allowed in SC5, SC6 and SC7 into environmental impacts, which validates the trade-off between the conflicting aspects of sustainability. These scenarios highlight the importance of government support to make the business model transformation more successful. This may encourage decision-makers to build a positive public-private partnership to achieve a sustainable business plan.

The internal integration of the end products is weakly sensitive to the decrease in the price of pulp under scenarios 3 (-10%) and 4 (-15%), whereas the recycling rate of waste is insensitive for the scenarios concerned. However, these scenarios increase, on the one hand, the emission respectively of 149 and 245 kg CO2 by 1000 \$ of CF and impacting, on the other hand, the upward investment in the fermentation pathway.

5.5. Emission per pathway compared with other research references

To strengthen the robustness of the model, a comparison of emission impacts has been made with some research work. Thus, at the area of solution analyzed, average emissions per product are summarized as follows:

- For ethanol, the result found was 16.1 g CO_2 eq.MJ^{-1} ethanol taking into account LHV for 21.2 MJL^{-1} ethanol (Thomas, 2000). This result, in line with that reported by (Karlsson, 2014), amounts to 13.2 g CO_2 eq.MJ^{-1} and 14.9 g CO_2 eq.MJ^{-1} ethanol resourced by forest residues respectively for ISO method (which applied the international standard for life cycle assessment) and RED method (which applied the EU Renewable Energy Directive methodology). GREET model for cellulosic ethanol from forest residues pathway reports 21.4 g CO_2 eq.MJ^{-1} (C. E. P. A. - Air Resources Board, 2009). (Spatari et al., 2010) reports, according to (Brinkman and Wang, 2005), an emission of 17 g CO_2 eq.MJ^{-1} ethanol.
- The emission found for one ton of pulp was 314.4 kg CO_2 eq in line with (CEPI, 2011) that found 340 kg CO_2 eq. However (McKechnie et al., 2014) found 491 kg CO_2 eq (Electricity is assumed to be sourced by a mix of grid electricity, and on-site cogeneration).
- The emission of 1 m^3 of biogas found was 0.130 kg CO_2 eq (5.9 g CO_2 eq.MJ^{-1}). (Edwards et al., 2011) cited 10–25 g CO_2 eq.MJ^{-1}.
- The emission of one MW of electricity and heat found was respectively 38 kg and 16.7 kg CO_2 eq using the energy allocation method (NCASI, 2005). This emission is in line with (WNA et al., 2011) reporting 45 kg CO2 eq.MW^{-1} electricity from biomass.

5.6. General recommendations

Low emissions level and economic performance are possible for IFBR integrated in Canadian P&P. However, some improvements and recommendations can enhance the sustainability and reduce the risks of implementing IFBR.

- *About energy self-sufficiency:* The results show a proportion of sold electricity ranging from 32.7% to 58.7% of the electricity produced. This constitutes a potential guarantee for the internal clean energy supply. Hence, it is recommended to export the electricity according to flexible contracts in terms of quantity supplied in order to reinforce the internal self-sufficiency.
- *About the risks inherent to the anaerobic digestion unit:* The dependence of AD unit on municipal waste inputs is risky due to competition with methanation projects. Furthermore, the average rate of unused PS is 74% for which the AD pathway does not ensure an integral recovery. To avoid rejection of organic and chemicals wastes it is recommended that other avenues be explored.
- *Viability of ethanol pathway*: According to the optimum solutions presented in Pareto frontier, ethanol pathway becomes non-viable from solution 8. The improvement in economic performance may strengthen the consistency of this pathway as was shown when analyzing robustness (Subsection 5.2*)*. To ensure the long-term sustainability of ethanol production, policy makers should develop a framework to promote the production and use of ethanol and sustain the ethanol supply chain. A financial or fiscal government support is recommended to relax the trade-off for strengthening the choice of a successful business plan.

6. Conclusion and research perspectives

To provide a road map for sustainable investment in bioenergy, a multi-objective mixed integer model has been developed. The obtained results show that the redesign of the business plan integrating investment in bioenergy production according to the sustainability paradigms has become possible using a systemic and decision support tool. The IFBR allows the pulp and paper industry to diversify its portfolio and generate new revenues while contributing substantially to emission reduction efforts in Canada and producing clean and renewable energy. The robustness analysis of the model, in the case of incubator activity market difficulty, proves that the investment technology architecture preserves the integrity of the IFBR, particularly in terms of energy self-sufficiency.

Furthermore, the model provides the basis for implementing a dedicated environmental-economic accounting. Thus, the management of the environmental component enriches the information system allowing the calculation of the carbon stock, the transfer of the carbon attribute to resellers and the compliance with the environmental reporting requirements. In addition, the model allows the manipulation of the allowances and the trade related, while measuring progress towards sustainable development goals.

Finally, it should be pointed out that ethanol pathway implementation needs economic incentives to reinforce its viability. It is proved that market incentives improve the overall sustainability performance of the biorefinery. In particular, government support will be needed to perform a successful business plan when integrating ethanol pathway.

We are currently investigating the use of scenario trees and multistage stochastic programming to take into account more uncertainties in the proposed mathematical model. Other research perspectives include the integration of social dimensions taking into account the social acceptability of large-scale biorefinery projects by the social community, based on potential impacts on regional development.

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Appendix 1. Notations

Set and indices	
B	Set of biomass types, B = {IR, MR, FR, AR} where IR is Industrial Residues, MR is Municipal Residues, FR is Forest Residues, and AR is Agriculture Residues
b	Biomass index, $b = 1, 2, \ldots, 4$ where b is equal to 1 for IR, 2 for MR, 3 for FR, and 4 for AR
OI	Set of other inputs, OI = {Cellulase, Yeast, Chemical 1, Chemical 2} where Chemical 1 is NaOH, and Chemical 2 is Na_2S
l	Other input indices, $l = 1, 2, \ldots, 4$ where l is equal to 1 for Cellulase, 2 for Yeast, 3 for NaOH, and 4 for Na_2S
PW	Set of pathways, PW = {ETH, WTF, EC, P&P} where ETH is Ethanol, WTF is Waste To Fuel, EC is Energy Cogeneration, and P&P is Pulp and Paper
p	Pathway index, $p = 1, 2, \ldots, 4$ where p is equal to 1 for ETH, 2 for WTF, 3 for EC, and 4 for P&P
$TECH$	Set of technologies, $TECH$ = {FERM, AD, CHP, KP} where FERM is SSF (Simultaneous Saccharification and Fermentation), AD is Anaerobic Digestion, CHP is Cogeneration Heat and Power, and KP is Kraft Pulp
e	Technology index, $e = 1, 2, \ldots, 4$ where e is equal to 1 for FERM, 2 for AD, 3 for CHP, and 4 for KP
e'	Destination technology index, $e' = 1, 2, \ldots, 4$ where e' is equal to 1 for FERM, 2 for AD, 3 for CHP, and 4 for KP
PD	Set of products, PD = {ETH, SNG, ELECT, PP, HEAT} where ETH is Ethanol, ELECT is Electricity, SNG is Biogas, PP is Pulp and Paper, and HEAT is Heat
i	Product index, $i = 1, 2, \ldots, 5$ where i is equal to 1 for ETH, 2 for SNG, 3 for ELECT, 4 for PP, and 5 for HEAT
CP	Set of co-products, CP = {LGN, PS, BL} where LGN is Lignin, PS is Paper Sludge, and BL is Black Liquor
j	Co-product index, $j = 1, \ldots, 3$ where j is equal to 1 for LGN, 2 for PS and 3 for BL
OP	Set of capacity options OP = {op1, op2, op3} where op1 is option 1, op2 is option 2, and op3 is option 3
o	Option index, $o = 1, \ldots, 3$ where o is equal to 1for op1, 2 for op2, and 3 for op3
T	Number of periods
t	Period index, $t = 1, 2, \ldots, T$
C	Number of cycles
c	Cycle index, $c = 1, 2, \ldots, C$
Parameters	
ELT	Economic lifetime for accounting depreciation
FLT	Fiscal lifetime for accounting fiscal depreciation
PC	Number of periods in the planning cycle
BN	Big Number
CC	Closing cost of P&P
$FCPP$	Operation fixed cost of P&P
r	Annual interest rate
$CR_{b,e}$	Conversion rate of biomass b using technology e
$CRP_{i,e}$	Conversion rate of product i using technology e
$CRC_{j,e}$	Conversion rate of co-product j using technology e
CT	Conversion rate trend
$\alpha_{j,i}$	Fraction of co-product j for product i
BST	Biomass supply trend
TR	Tax rate
$AR_{j,i}$	Allocation rate of emission between product i and co-product j
BUC_b	Unit cost of biomass b
PUC_i	Unit production cost of product i
$IC_{o,e,c}$	Investment cost of implementing option o of technology e in cycle c
$CO_{o,e}$	Capacity of option o of technology e
CA_p	Capacity installed for P&P activity
CE_e	Consumption of electricity per unit of capacity installed for technology e
SP_i	Selling price (plant gate price) of product i
SC_j	Selling price (plant gate price) of co-product j
DP_i	Expected demand of product i
DC_j	Expected demand of co-product j
BS_b	Supply of biomass b
BD_c	Budget available in cycle c
DT	Demand trend of products and co-products
$C(t)$	Returning the planning cycle related to the period t of the horizon
$GHG_{b,e}$	Emission generated in the manufacturing stage by one unit of product using biomass b and technology e
$GHGOI_l$	Emission of one unit of other input l
$GHGP_{i,e}$	Emission generated in the manufacturing stage by one unit of product using product i and technology e
$GHGC_{j,e}$	Emission generated in the conversion stage by one unit of product using co-product j and technology e
GHG_IF_b	Emission of one ton of biomass b in the field

GHG_TR_b	Emission generated by the transportation of one ton of biomass b
GHG_b	Sum of GHG_IF_b and GHG_TR_b
Other environmental notations	
GHG_TOTAL	Total emission over the planning horizon
GHG_BIF	Total emission of biomass in field over the planning horizon
GHG_TR	Total emission of supply stage transportation over the planning horizon
GHG_FTP	Total emission in supply stage (field to plant) over the planning horizon
$GHGP_i$	Emission related to product i over the planning horizon
$GHGC_j$	Emission related to co-product j over the planning horizon
$GHGC_{j,t}$	Emission related to co-product j in period t
$GHG3M$	Emission of ELECT product sold to the market over the planning horizon
$GHG3KWh_t$	Emission related to one KWh of electricity produced in period t
$GHG5KWh_t$	Emission related to one KWh of heat produced in period t
$GHG2M$	Emission generated by SNG sold to the market over the planning horizon
$GHG2M3_t$	Emission related to one m^3 of biogas produced in period t
Other economic notations	
$EOBJ$	Economic objective
CF	Cash flow
CF_t	Cash flow in period t
ACF	Present value of cash flow
ACF_t	Present value of cash flow in period t
$ANCF$	Net present value of the cash flow
NCF	Net cash flow
NCF_t	Net cash flow in period t
SV	Salvage value of the IFBR at the end of the planning horizon
D	Debts of the IFBR at the end of the planning horizon
$ADBI$	Accounting depreciation of bioenergy investments in the planning horizon
AFD	Present value of fiscal depreciation of investments in the planning horizon
T_INV	Total investment cost for all pathways except P&P in the planning horizon
$ACPR$	Present value of co-products revenues in the planning horizon
APC	Present value of production cost of all products in the planning horizon
$ARMP$	Present value of revenues of all market products in the planning horizon
$AFCPP$	Present value of operating fixed cost of P&P activity in the planning horizon
$ACCPP$	Present value of closing cost of P&P activity in the planning horizon
ABC	Present value of biomass supplying cost in the planning horizon
INV_H	Investment cost considered over the periods of the planning horizon
A_INV_H	Present value of the investment cost over the period of the planning horizon
Decision variables	
$Y_{o,e,c}$	= 1 if the capacity option o using technology e is added in cycle c and 0 otherwise
W_t	= 1 if the pathway $p = P\&P$ is used in period t and 0 otherwise
$FB_{b,e,t}$	Flow of biomass b used by technology e in period t
$FOI_{l,e,t}$	Flow, per product unit, of other input l used by technology e in period t
$IFCP_{j,e,e',t}$	Flow of co-product j generated by technology e and used by a different destination technology e' in period t
$IFFP_{i,e,e',t}$	Flow of product i generated by technology e and used by a different destination technology e' in period t
$MFFP_{i,t}$	Flow of final product i shipped to the market in period t
$MFCP_{j,t}$	Flow of co-product j shipped to the market in period t
$QFP_{i,t}$	Quantity of final product i produced in period t
$QC_{j,t}$	Quantity of co-products j produced in period t

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