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Integrated strategic and tactical optimization of forest-based biomass supply chains to consider medium-term supply and demand variations

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HIGHLIGHTS

- Analyzed feasibility of strategic plans considering medium term biomass variations.
- Showed that prescribed plans from strategic model were infeasible at tactical level.
- Developed an integrated model to address long and medium term decisions simultaneously.
- Showed that the integrated optimization model prevents the infeasibility issues.

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ABSTRACT

Using forest-based biomass to produce bio-energy and bio-fuels could provide economic, environmental, and social benefits for communities. However, variability in biomass availability and high cost of delivered feedstock impact the profitability of the supply chain. Therefore, optimization models were developed in previous studies to design cost effective and profitable biomass-based supply chains at strategic level. Medium term variations in biomass supply and demand are not usually accounted for in strategic models. This may affect the feasibility of strategic plans prescribed by the optimization model at tactical level. To solve this issue, an integrated model is developed in this paper that includes strategic and tactical decisions simultaneously in order to optimize forest-based biomass supply chains. In addition to yearly variations in biomass supply, which can occur due to changes in harvest level, monthly variations in biomass availability, bioenergy/biofuels demand, and losses during preprocessing and storage of biomass are incorporated in the model. Other unique features of this model compared to the few integrated models developed in previous studies are as follows. (1) Decision regarding opening a new conversion facility is made yearly, not just at the beginning of the planning horizon. (2) A multi-product (heat, electricity, bio-oil and pellets) supply chain is considered. (3) The impact of fossil-based energy prices on bio-conversion investment decisions are accounted for in the model. (4) The optimization problem is modeled in a way that the global optimum solution is obtained within a reasonable time. Using a case study in Interior British Columbia, it is shown in the paper that the capacity of conversion technologies and the amount of procured biomass prescribed by the strategic model would not be sufficient to meet the monthly demand of bioenergy. Moreover, the net present value of the strategic model is overestimated due to underestimating the demand and procurement cost, and ignoring storage costs. It is shown that these issues are resolved using the integrated model.

1. Introduction

Bio-energy production has the potential to increase economic growth, energy security and resource sustainability [1,2]. Despite these advantages, several economic barriers impede achieving an increased uptake of biomass for bio-energy production [3]. These economic barriers include: (1) higher capital cost of bio-energy plants, and (2) higher delivery cost of biomass compared with those of fossil fuels [3]. For instance, the average levelized cost of electricity (LCOE) (includes both capital and delivered costs) is reported to be 97.7 USD.MWh^{-1} for biomass and 58.6 USD.MWh^{-1} for natural gas-fired power plants [4].The physical characteristics of biomass (low bulk density, high

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moisture content, low energy value, and seasonal and dispersed availability) increase the preprocessing, handling and transportation costs and make the supply chain planning complex [5]. Similar to other industries, supply chain planning, which is concerned with the integration and coordination of various activities from procurement of raw materials to distribution of final products to customers, is imperative in enhancing the productivity and profitability of bio-energy and bio-fuel production [6].

Supply chain planning can be carried out at strategic, tactical, and operational levels. The strategic plan determines the resource requirements such as number, location and capacity of facilities and warehouses as well as the flow of material through the strategic network, whereas tactical and operational level plans are concerned with efficient utilization of resources. In the literature, often separate optimization models have been developed for strategic, tactical, and operational plans. Numerous optimization models were developed for the strategic planning of bio-energy and bio-fuel supply chains to determine the optimal location, size, and type of bio-conversion plants and storage facilities (e.g. in [7–25]). These models considered long term planning horizon, usually for the service life of the plants. For a given supply chain design, tactical models were developed to address decisions related to medium-term production planning, inventory control and logistics management [26–31], while operational level models were developed for short-term planning such as vehicle routing and scheduling [32–34].

When planning is divided into different levels, using solutions from one level may result in infeasible solutions at another planning level. This is the issue observed when using the results of a strategic optimization model for tactical level planning in this research. The results of a strategic optimization model for a forest-based biomass supply chain in British Columbia, Canada is investigated at tactical level. The strategic model optimized the design of the supply chain to produce heat, electricity, bio-oil, and pellets through alternative conversion technologies. The location and capacity of conversion plants as well as flow of biomass and bioenergy/biofuels were the decisions in the model. When the results of the strategic model were analyzed at tactical level considering the monthly variations in supply and demand, two issues were observed. (1) The biomass quantity to be transported to the plants as prescribed by the strategic model were not enough to meet the monthly biomass demand of the conversion plants. (2) Prescribed production capacities were not enough to meet the monthly bioenergy demand. Therefore, the focus of this paper is to solve the mentioned issues and to ensure that the strategic level supply chain decisions prescribed by the optimization model are feasible and implementable at the tactical level. Two different approaches, hierarchical planning and integrated planning, have been used in the literature for this purpose [35].

Table 1
Decisions to be determined by the integrated model and the strategic model and their planning period.

	Integrated model		Strategic model	
	Planning period		Planning period	
Decisions to be determined	Annual	Monthly	Annual	Monthly
The location, type, size and establishment period	✓		✓	
Transportation quantities of each type of biomass from each supply source to each conversion facility		✓	✓	
Storage quantities of each type of biomass and biofuel products at facilities		✓		
Internal utilization of bio-energy and distribution of bio-fuels and bio-energy to markets		✓	✓	

In hierarchical planning, the problem is divided into sub-problems that are solved sequentially in one or more iterations. The top-level model includes long term and aggregated (strategic or tactical) decisions [36]. Decisions from the top-level model impose the framework for more detailed decisions at the operational level. The quality of aggregated decisions are then evaluated based on the feedback received

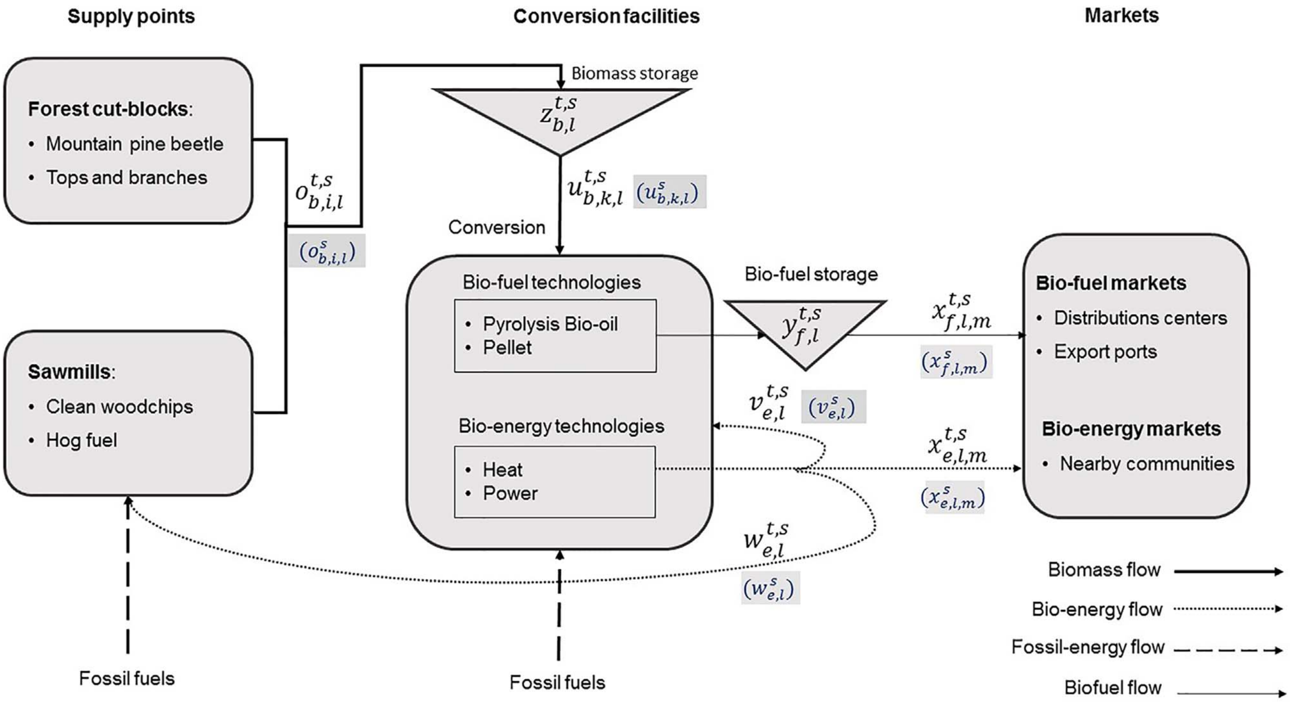

Fig. 1. The schematic view of the integrated strategic and tactical optimization model (the highlighted variables shown in the parenthesis are the decision variables of the strategic model).