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Assessing the integration of torrefaction into wood pellet production

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ABSTRACT

In this study a dynamic simulation modeling approach is used to assess the integration of torrefaction into the wood pellet production and distribution supply chain. The developed model combines discrete event and discrete rate simulation approaches and allows considering uncertainties, interdependencies, and resource constraints along the supply chain which are usually simplified or ignored in static and deterministic models. It includes the whole supply chain from sources of raw materials to the distribution of the final products. The model is applied to an existing wood pellet supply chain, located in British Columbia, Canada, to assess the cost of delivered torrefied pellets to different markets, energy demand, and carbon dioxide emissions along the supply chain and compare them with those of regular pellets. In the presented case study, integration of torrefaction leads to lower delivered cost to existing and potential markets due to increased energy density and reduced distribution costs. In comparison with regular pellets, the delivered cost of torrefied pellets ($/GJ) to Northwest Europe is 9% lower. Also, the energy consumption and the emitted carbon dioxide along the supply chain are decreased due to more efficient transportation of torrefied pellets. Integration of torrefaction into the wood pellet production and distribution supply chain could result in less expensive and cleaner biofuel. The feasibility of such integration depends on the trade-off between the higher capital and operating costs and the reduced transportation costs.

1. Introduction

Fast depletion of fossil fuels and environmental concerns related to their extraction and consumption have promoted the use of alternative sources of energy (Panepinto and Genon, 2012; Shirazi et al., 2013). Bioenergy has been regarded as a promising substitute for fossil fuels, mainly due to its renewable and carbon neutral nature (Mizsey and Racz, 2010; Nguyen et al., 2013). As a result, in biomass-rich countries, such as Canada where forests cover around 34% of the entire area of the country (The World Bank, 2013), the bioenergy industry has been growing. Today, forest biomass contribution to Canada's energy supply is 5–6% (NRCan, 2012), while its potential contribution is estimated to be 18% (Paré et al., 2011). The low contribution of forest biomass to energy supply is mostly related to its physical characteristics. Forest biomass is irregular in shape, has low bulk density, low energy density, and high moisture content that contribute to a complex supply chain and high transportation and logistics costs (Demirbas, 2001).

Pelletization is a densification process in which biomass is compressed into cylindrical shape with a diameter of 6–8 mm and a length of 10–12 mm (Mani et al., 2006). Pelletization provides consistent quality, low moisture content, high energy content, and homogenous shape and size that facilitate the logistics of biomass. These properties stimulated rapid expansion of the wood pellet industry around the globe such that wood pellets are recognized as an internationally traded commodity and further expansion of the market for wood pellets is expected (Sikkema et al., 2011; Spelter and Toth, 2009; Beekes, 2014).

Although pellets have desirable characteristics, they are expensive and still cannot compete with fossil fuels in many cases. To further improve the properties of wood pellets, torrefaction of biomass prior to densification has been suggested as a pretreatment step (Gold and Seuring, 2011; Miao et al., 2012). Torrefaction is a thermal treatment that increases bulk and energy densities by removing oxygen and other volatiles (van der Stelt et al., 2011; Peng, 2012). Higher bulk density of torrefied biomass

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improves transportation, storage, and handling processes. Furthermore, torrefied pellets have very low moisture content, are hydrophobic and easily grindable (Pirraglia et al., 2013b). Because of these coal-like characteristics, storage, handling and feeding infrastructure at the coal power plants require minor alternation for co-firing (Schneider et al., 2012). Production of torrefied pellets is, however, more complex and capital intensive than the production of conventional pellets, and the thermal treatment leads to a loss of dry matter.

Torrefaction of different types of biomass and the effect of different processing conditions on biomass properties, such as grindability, energy content, moisture uptake, and particle size were investigated in previous studies. Li et al. (2012) showed that the hardness and moisture adsorption of torrefied pellets are less than that of regular pellets. Peng et al. (2013) studied torrefaction of different softwood species under different temperatures and residence times. Larsson et al. (2013) investigated the effects of die temperature and moisture content in the production of torrefied wood pellets and showed that increasing the die temperature positively affects the pelletization rate and negatively affects the bulk density of the pellets. Economic viability of production and consumption of torrefied wood pellets is addressed in different studies. Chiueh et al. (2012) developed a spreadsheet model integrated with a geographical information system (GIS) to study the production and consumption of regular and torrefied pellets in Taiwan. Pirraglia et al. (2013a) developed a spreadsheet-based model that includes mass balance, energy consumption, and financial analysis of the supply chain. They studied the integration of torrefaction in the U.S. pellet industry using their developed model. Techno-economic analysis of torrefied biomass production was conducted by Shah et al. (2012). They evaluated the sensitivity of the cost and energy consumption of torrefied biomass against changes in biomass type, its moisture content, and the required capital investment. Svanberg et al. (2013) developed a static model representing the supply chain that included sub-models for raw material supply to the torrefaction plant, mass and energy balances for pellet production, capital and operational cost estimations, and distribution system. The model was applied to a case study of supplying torrefied pellets to a Combined Heat and Power (CHP) plant. Beekes (2014) compared the production and consumption of regular and torrefied wood pellets and estimated 15% lower logistics costs for torrefied wood pellets.

Effective management of the supply chains is a critical factor in the success of biofuel and bioenergy applications (Gold and Seuring, 2011; Mafakheri and Nasiri, 2014). Different supply chain modeling approaches have been used to design and plan biomass supply chains including mathematical programming, simulation, queuing theory, and agent based models (Miao et al., 2012). Mathematical programming of the supply chain is usually used in solving strategic and tactical planning of the supply chains (Sharma et al., 2013). Schmidt et al. (2010) developed an optimization model to determine the optimum location and capacity for a bioenergy plant while minimizing the total cost of the supply chain. Strategic planning of biofuel production and distribution was modeled in An et al. (2011). The scope of the model includes feedstock suppliers, preprocessors, refineries, distributors, and customers. The logistics of supplying agricultural biomass to a biorefinery plant was modeled by Ebadian et al. (2013). An optimization model was developed to optimize the inventory planning and the results were validated through simulation of the logistics system. A hierarchical methodology for integrated portfolio design and supply chain network design for forest biorefinery industry was suggested by Mansoornejad et al. (2010). Integrated supply chain design of ethanol and gasoline was studied by Andersen et al. (2013) and Tong et al. (2014). There are many other applications of mathematical programming in the supply chain planning of biomass supply chain. Recent reviews are provided by D'Amours et al. (2008), Shabani et al. (2013), Sharma et al. (2013), and De Meyer et al. (2014).

When dealing with forest biomass, uncertainty in the quality, availability, and accessibility of the material is an inherent feature of the supply chain. The performance of the equipment, their failures, and required repair time in addition to the market fluctuations and policy changes are other sources of uncertainties in this environment. Also, the interdependencies between different stages of the supply chains are an important feature of biomass supply chains. In order to include the effects of the uncertainties and the interdependencies into the analysis, stochastic simulation modeling is used in the literature. Gallis (1996) developed a simulation model of forest biomass to a wood processing facility in Greece to study the effects of changes in the equipment specification, wages, interest rate, and dry material loss on the cost of delivered biomass. Supplying forest biomass to a potential 300 MW power plant in Quesnel, BC was studied using a simulation model developed by Mobini et al. (2010). The uncertainties in availability and moisture content of biomass and their effects on the performance of the logistics system were considered in the model. The delivered cost of biomass to the power plant and possibility of demand fulfillment over the life span of the power plant were evaluated. A simulation model called Integrated Biomass Supply Analysis and Logistics model (IBSAL) was developed by Sokhansanj et al. (2006). The cost of delivered biomass was estimated considering the harvest schedule, climatic factors, and operational constraints in the model. The application of this model in designing new feedstock supply chains is explained in Sokhansanj et al. (2008). The IBSAL model was used to evaluate current and future potential technologies for production, harvest, storage, and transportation of switch grass (Sokhansanj et al., 2009). Also, it was used in Sokhansanj et al. (2010) to analyze the utilization of corn stover as the source of biomass for ethanol production. An and Searcy (2012) used IBSAL to model the biomass logistics system using a conceptual packaging system that increases the density of agricultural biomass to maximize the efficiency of transportation. Logistics planning for a potential biorefinery plant was simulated by Ebadian et al. (2011). This model is capable of including different types of biomass and incorporates the effects of weather conditions and biomass quality on the performance of the supply chain. A GIS-integrated simulation model was developed by Zhang et al. (2012) and was used to find the best option amongst a set of potential locations and capacities for development of a biofuel production facility in Michigan, US. A simulation model, called PSC (Pellet Supply Chain), was developed and used to analyze the wood pellet production and distribution supply chain by Mobini et al. (2013). The scope of the model spans over the entire supply chain from sources of biomass to the customers. The PSC is composed of several modules including suppliers of raw materials, pellet mills, customers, and vehicles. The processes and the flow of biomass inside the pellet mill are also included in the model. Raw material storage, drying, size reduction, pelletization, cooling and pellet storage are the processes included in the pellet mill's module. The PSC model is developed as a decision support tool for design and analysis of the wood pellet production and distribution supply chains.

The evaluation of torrefaction as a pre-treatment approach in a supply chain context has been identified as a research gap in the literature (Ciolkosz and Wallace, 2011; Svanberg and Halldórsson, 2013). In order to address this gap while capturing the uncertainties involved in the biomass supply chains, in the present study, the PSC model is extended by developing the torrefaction process module. The uncertainties in quality measures of biomass, in terms of moisture content, bulk density, heating value, and ash content are considered in the development of the required relationships to model the torrefaction process. PSC has been previously applied to an existing supply chain of wood pellets in BC, Canada and the same case study is considered here to evaluate the production of the torrefied wood pellets in the existing wood pellet supply chain. Delivered costs for regular and torrefied pellets at selected destinations are compared.

2. Wood pellet supply chain

A typical wood pellet supply chain can be divided into three stages of raw material supply, pellet production, and distribution to the customers. Raw material supply includes the procurement and transportation of biomass from suppliers to the pellet mill. The most common forms of biomass used in pellet production are sawdust and shavings that are by-products of wood processing mills. Due to the low bulk density and high moisture content of the raw material, pellet mills are usually located near the sources of raw materials and transportation of raw materials to the pellet mills is carried out by trucks. In some cases, the pellet mills are located adjacent to the suppliers and raw materials are pneumatically conveyed to the pellet mill, which eliminates the need for offsite raw material transportation.

Pellet production includes storage of raw materials, drying, size reduction, pelletization, cooling, and storage of wood pellets. Raw material storage depends on the types of materials. Sawdust and shavings are usually separated in the storage area as the moisture content of shavings is usually low. Shavings do not require drying, while, sawdust should be dried prior to pelletization. After drying, sawdust and shavings are fed to hammer mills for size reduction. Pelletization is the next process followed by cooling and storage of wood pellets.

When integrated into the pellet mill, the torrefaction process usually takes place before the pelletization of biomass. Different torrefaction process designs have been suggested. The basic torrefaction reactor design selected in this paper is the Andritz ACB© Process (Trattner, 2009), the only design that is commercialized, to the best of authors' knowledge. Before being fed to the torrefaction reactor, biomass is dried to a target moisture content of 15%. The biomass is processed in an indirectly heated drum reactor at temperatures of about 280 °C for about 20 min. Part of the biomass is gasified and yields the so called torrefaction gas which is combusted with ambient air to supply the thermal energy for the torrefaction process. The torrefied biomass has a higher specific heating value compared to the dried biomass. Mass and energy balances for the torrefaction process are given in Table 1. Torrefied biomass contains most of the energy content of the dried biomass. The energy content of the torrefaction gas is sufficient to supply the thermal energy for the torrefaction process and also a share of the thermal energy demand in the upstream drying process.

3. Simulation model

The supply chain of wood pellet production was simulated by Mobini et al. (2013). The simulation model, called PSC, is developed in ExtendSim v.8 (Imagine That, 2011), an object oriented simulation environment. Supply chain entities, including the suppliers of raw materials, customers, pellet mills, vehicles, and equipment are developed as modules and stored in libraries that can be used to construct different supply chain configurations. The outputs of this model include estimations of cost, energy input, and carbon dioxide (CO_2) emission along the supply chain.

Table 1
Mass and energy balance for torrefaction of 1 kg biomass (Prins et al., 2006).

	Dried biomass	Torrefaction gas	Torrefied biomass
Dry matter (kg)	0.850	0.159	0.615
Water (kg)	0.150	0.226	0.000
Higher heating value (GJ/dt)	17.70	11.19	21.55
Energy content (%)	100.00	11.83	88.17

In PSC, the discrete event simulation approach is used to model the supply chain entities and their interactions; while flow of materials inside the pellet mill is modeled using the discrete rate approach. In ExtendSim (Imagine That, 2011), the rate based capabilities of continuous simulation technology are combined with discrete event environment to form discrete rate technology (Krahl, 2009). In discrete rate simulation, the state variables of the system components only change at discrete points in time depending on the behavior of the system, as opposed to the continuous models that the whole state of the system is re-calculated at each time step (Damiron and Nastasi, 2008). This type of simulation is especially useful in modeling the systems that deal with flow of material, rates, events, storage capacity, and constraints (Krahl, 2009); such as the pellet mills where flow of biomass between different processing stages is modeled. Using the discrete rate approach enables the simulation model to include the flow of biomass and to simulate the failure and repair times of the equipment and interdependencies between the processing stages inside the pellet mill.

PSC has the capability of incorporating the uncertainties, interdependencies, and resource constraints along the supply chain; which are usually simplified or ignored in static and deterministic models. Sources of uncertainties considered in the model are availability of raw materials at the suppliers' locations, quality of raw materials, processing rates and failure of the equipment, and electricity/fuel consumptions. In PSC, the quality of raw materials and wood pellets are recorded along the supply chain in order to make it possible to incorporate the effects of these parameters on the provided estimations. The biomass quality measures included in the simulation model are moisture content, heating value, ash content, and bulk density. Interdependencies between different stages of the supply chain are taken into account, e.g., where failure of one process might delay the next stages. The resource constraints, e.g., number of available equipment pieces and vehicles are also taken into account in the model. Therefore, PSC provides a more comprehensive perspective of the supply chain than static and deterministic approaches.

3.1. Simulation modules

The PSC simulation model is composed of several simulation modules, each of which represent an entity of the supply chain and takes input parameters that are used in the functions defined based on the roles each entity plays in the supply chain. The modules include suppliers, vehicles, pellet mills, processing stages inside the pellet mill, as well as decision making entities including inventory control, transportation management, and production management modules.

The supplier module is attributed with the variables of location, biomass availability, and quality of biomass that they provide. The availability of biomass at the suppliers' location is calculated based on the biomass production rates that are assigned to each supplier. The availability of biomass at the suppliers' location is used to decide on the raw material procurement and transportation during the simulation run. The data on the quality measures of biomass are also used to calculate the transportation costs (by taking into account the moisture content and bulk density of biomass), and quality of biomass that is available for pelletization at the pellet mill.

The input parameters for the vehicles are number of available vehicles, their working hours, capacity, traveling speed, and loading and unloading rates. The volumetric and weight capacity of the trucks and the bulk density of biomass are used to estimate the payload for each delivery. The transportation scheduling is done based on the transportation orders that are generated by the transportation manager module.

The pellet mill module includes the modules for the processing stages: raw material storage, drying, grinding, torrefaction, pelletization, cooling, and pellet storage. Each process module includes a number of equipment pieces. The number of equipment pieces is defined as an input parameter, e.g., number of grinders or pelletizers. The processing rate of each piece of equipment, failure rates of the equipment in terms of time between failure and time to repair, and power consumption are the other input parameters defined for each piece of equipment. The outputs of each process module include the operating cost, energy input, and utilization rates that are continuously updated during simulation.

The inventory control module defines the time and quantity of raw material procurement from each supplier according to the inventory policy. When raw material procurement is needed, the inventory control module selects the supplier and generates a transportation order. The orders are processed by the transportation management module. Based on the availability of the trucks and the due dates assigned to the transportation orders, the transportation scheduling is performed. The production control module defines the production plans based on the demands for wood pellets and availability of raw materials.

The structure of PSC's modules and components, its inputs and outputs, and the equations that are used in the model are discussed with more detail in Mobini et al. (2013). The PSC model is extended in this study by developing the torrefaction module to be able to simulate the production and distribution of torrefied wood pellets in a supply chain context.

3.2. Torrefaction module

The quality of biomass affects the torrefaction process. The amount of energy contained in the in-feed biomass depends on the heating value and moisture content. Ash content of the material affects the amount of energy required for the torrefaction process. Fig. 1 shows the schematic of the torrefaction module developed in this study. Preconditioned biomass from the dryer is fed to the torrefaction reactor and is heated by the flue gas from the gas burner. Torrefaction gas resulting from the reaction is fed to the gas burner where it is combusted with ambient air. The flue gas from the reactor is used in the drying process. Torrefied biomass is fed to the next process.

The following equations along with the energy and mass balance shown in Table 1 were used in the simulation model to estimate the thermal energy supplied from the combustion of torrefaction gas, the thermal energy demand in the torrefaction reactor, and the excess of thermal energy that can be used in the upstream drying process. The equations take into account moisture content, ash content and heating value as well as process temperature and burner efficiencies.

$$Q_{\text{supply}} = w_{\text{in}}(1-\text{MC})\text{HV}\cdot\partial\cdot\eta \tag{1}$$

$$\begin{aligned} Q_{\text{demand}} = w_{\text{in}}\Big(&\text{MC}\Big(\theta\big(t_{\text{boiling}}-t_{\text{in}}\big)+lh \\ &+\theta'\big(t_{\text{torrefaction}}-t_{\text{boiling}}\big)\Big) \\ &+(1-\text{MC})\Big((1-\text{AC})\sigma\big(t_{\text{torrefaction}}-t_{\text{in}}\big) \\ &+\text{AC}\cdot\varrho\big(t_{\text{torrefaction}}-t_{\text{in}}\big)+\varphi\Big)\Big) \end{aligned} \tag{2}$$

$$Q_{\text{excess}} = \left(w_{\text{in}}(1-\text{MC})\text{HV}\cdot\partial - Q_{\text{demand}}\right)\delta \tag{3}$$

where w_{in} is the total input mass, MC represents the moisture content, HV is the higher heating value per dry tonne, and AC is the ash content per dry tonne. The thermal energy supply (Q_{supply}) is calculated by multiplying the total energy input with the fraction of the heating value contained in the torrefaction gas (∂) and the efficiency of the combination of torrefaction gas burner and heat exchange to the torrefaction reactor (η) which is assumed to be equal to 81% (Trippe et al., 2010).

The thermal energy demand of the torrefaction reactor (Q_{demand}) is calculated based on the thermal energy demand for heating and evaporating the water contained in the feed, heating the biomass including ash, and the actual torrefaction of dry biomass. The heat capacities for water (θ) and steam (θ') as well as the evaporation enthalpy (lh) are taken from Lucas (2006) and equal 4.2 KJ/(kg K), 2 KJ/(kg K), and 2250 kJ/(kg K), respectively. Heat capacities for dry biomass (σ) and ash (ϱ) as well as the heat demand for torrefaction (ϕ) equal 1.7 kJ/(kg K), 1.2 kJ/(kg K), and 530 kJ/kg, respectively (Kornmayer, 2009). Temperatures of the dried biomass input (t_{in}) and the torrefaction reaction temperature ($t_{\text{torrefaction}}$) are assumed to be 70 and 280 °C, respectively (Mani, 2005).

The excess heat of the torrefaction process (Q_{excess}) which can be used in the upstream drying process is estimated as follows. The total energy content of the torrefaction gas is reduced by the thermal energy demand of the torrefaction process and the useable

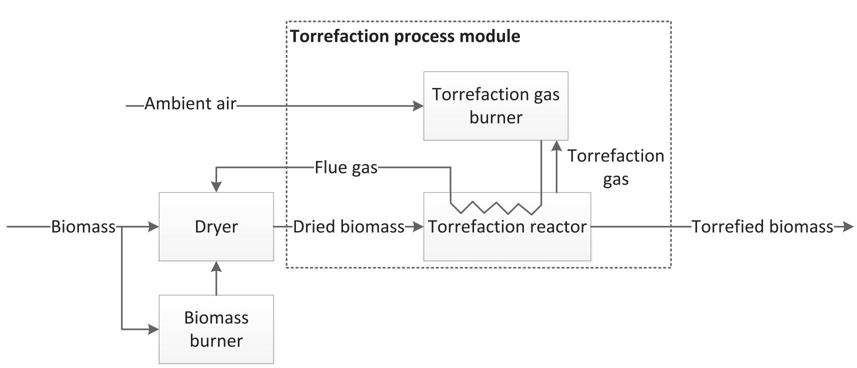

Fig. 1. Drying and torrefaction processes flowchart.

Table 2
Quality measures of sawdust and shavings delivered to the pellet mill.

Stat.	Sawdust			Shavings		
	Moisture content (%)	Bulk density (kg/m^3)	Heating value (GJ/dt)	Moisture content (%)	Bulk density (kg/m^3)	Heating value (GJ/dt)
Mean	29.10	227	18	10.90	131	18
Standard Deviation	2.64	5.5	0.3	1.52	8.38	0.3
Best fitted PDF	Weibull (3.39, 9.02)+21[a]	Loglogistic (18.8, 56.4)+170	Normal (18, 0.3)	Weibull (2.02, 3.32)+8	Pearsonv (15.6, 451)+100	Normal (18, 0.3)

[a] Parameters of the PDFs are shown in the parenthesis before the lower bounds.

fraction for the drying process is δ which is assumed to equal 70%. The required heat energy (R_{heat}) in the drying process is calculated based on the initial wet weight (W_{in}) and dried weight (dW_{in}), target moisture content after drying (MC_t), heat demand of the dryer (HD), and excess heat provided from torrefaction as shown in Eq. (4). The heat demand of the dryer (HD) is expressed as required energy to evaporate one tonne of water and is a specification of the dryer provided by the manufacturer (Obernberger and Thek, 2010). Eq. (5) shows the relationship used in the simulation model to calculate the required weight of fuel (W_{fuel}) to reach the target moisture content. Herein, the heating value and moisture content of fuel are denoted by HV_{fuel} and MC_{fuel}, respectively. γ is the efficiency of the biomass burner.

$$R_{heat} = \left(W_{in} - \frac{dW_{in}}{1 - MC_t}\right)HD - Q_{excess} \tag{4}$$

$$W_{fuel} = \frac{R_{heat}}{HV_{fuel}\left(1 - MC_{fuel}\right)\gamma} \tag{5}$$

Consequently, the developed torrefaction module estimates the dry matter loss due to the torrefaction based on the energy and mass balance while taking into account the quality of biomass as described in Eq. (1)–(5). The processing rate at any given time during the simulation run is defined based on the availability of biomass, upstream drying process, and specification of the equipment while considering the possible failures and required maintenances. The energy demand and cost of the torrefaction are calculated based on the power consumption of process equipment and operating hours.

4. Case study

A wood pellet production and distribution supply chain, located in British Columbia (BC), Canada was considered as a case study in Mobini et al. (2013). The same supply chain is considered here to evaluate the production of torrefied wood pellets. The supply chain includes five suppliers from which sawdust and shavings are transported to the pellet mill, a trucking company that handles the transportation of raw materials, a 20 t/h pellet mill, and an export port that handles incoming rail and outgoing sea transportation. The flow of biomass across the supply chain is shown in Fig. 2. Three stages of the supply chain are explained below.

Suppliers of raw materials are sawmills and shake mills that operate five days a week. Each of the suppliers provides limited amount of sawdust and shavings per operating day. The suppliers are paid based on the dried weight of materials delivered to the pellet mill. Uniform distribution functions, fitted to the obtained data from the industry are used to describe the fluctuations in the daily availability of raw materials from each supplier. The quality of sawdust and shavings, in terms of moisture content (MC), heating value (HV), and bulk density (BD) is estimated based on the samples taken from the truck loads. Probability distribution functions (PDF) listed in Table 2 are fitted to the data provided by the pellet company. Data analysis shows that moisture content of sawdust and shavings delivered to the pellet mill follow Weibull distribution functions with different parameters shown in the table. Bulk density of the delivered loads of raw materials follows Log logistic and Pearson type 5 for sawdust and shavings, respectively; and heating value of sawdust and shavings follows a normal distribution function. These functions are incorporated in the simulation model reflecting the uncertainties in the quality of raw materials.

Two of the suppliers are close to the pellet mill and the raw materials are air conveyed to the storage bins. Transportation of raw material from other suppliers is carried out by an outsourced trucking company. Trucks that transport sawdust and shavings to the pellet mill have a volumetric capacity of 110 m^3. The transportation speed of the trucks follows the Uniform (55, 75) km/h distribution and their fuel consumption follows the Uniform (0.3, 0.35) L/km distribution. The rental charge of the truck is 114 C$/h

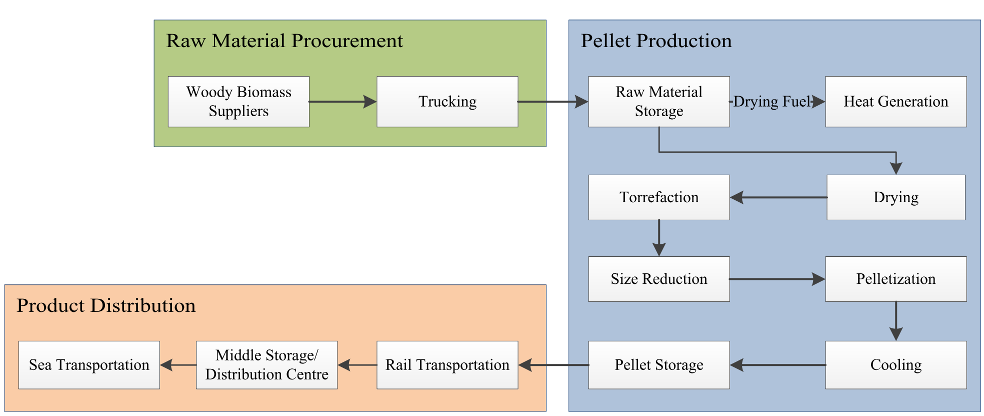

Fig. 2. Schematic of torrefied wood pellet production and distribution supply chain.

and they operate seven days a week from 7 a.m. to 10 p.m. (all the cost figures in this paper are Canadian dollar values).

The pellet mill operates seven days a week and 24 h per day. Sawdust is dried and then mixed with shavings before feeding to the grinders. The required heat for the drying process is provided by a burner fed with sawdust. The fuel consumption in the burner depends on the moisture content and heating value of the fuel and the required heat for the drying process which in turn depends on the in-feed moisture content and target moisture content after drying. Equations describing the performance of the burner and dryer are explained by Mobini et al. (2013). The electricity consumptions are calculated based on the corresponding nominal power of each piece of equipment and the electricity price of 100.00 C$/MWh. Simultaneity factors are considered to reflect the fluctuations in the performance of the equipment due to the processing conditions (Obernberger and Thek, 2010).

The nominal capacity of the existing pellet plant in this case study is 20 t/h of conventional wood pellets; which is equivalent to 15.7 t/h of torrefied wood pellets when considering the higher heating value of 18 GJ/dt and 21.2 GJ/dt for regular and torrefied wood pellets, respectively (regular wood pellets with 10% moisture content and torrefied wood pellets with 3% moisture content). It is assumed that the current demand of the pellet supply chain would be the same in energy terms when torrefaction is added.

Mobini et al. (2013) estimated the total capital investment for a 20 t/h pellet mill at 20.03 M C$. The dimensioning of the required equipment for the torrefaction process is based on mass and energy balances and takes minimum and maximum capacities of equipment into account. Equipment costs and total capital investment for the torrefaction process are estimated using the Total Capital Investment (TCI) method (Peters et al., 2002), shown in Table 3. The electricity consumption of the required torrefaction equipment is estimated at 1100 kW.

Distribution of wood pellets to an international port in North Vancouver is done through rail transportation that costs 28 C$/t. In addition to the current practice of shipping wood pellets from North Vancouver to Northwestern Europe, representative ports in Japan, Korea and China in proximity to coal power plants were selected to estimate delivered costs to potential markets for torrefied wood pellets from BC. Port handling and storage costs as well as costs for ocean transport were obtained from Suurs (2002); Peng et al. (2010) and personal industry contacts. The same unit cost for ocean transportation of pellets to Europe and Asia is assumed in this paper. Shipping route distances to these locations were estimated from (Farnel Soft Inc.) and are shown in Table 4. The energy demand and CO_2 emissions for ocean transportation are calculated based on consumption of 3.7 g diesel / (t km), diesel higher heating value of 45.9 GJ/kg, and 3.6 kg CO_2 / (kg consumed diesel) (Magelli et al., 2009).

5. Results and discussion

The simulation duration covers the operation of one year. To determine the minimum number of required iterations (r), Eq. (6) is used (Banks, 2005), where S_0 is the standard deviation of the initial sample, $z_{\alpha/2}$ is the corresponding Z value of the normal distribution, and ε is the desired half width of the confidence interval. Based on a 95% confidence level and half width of 125 t (8 h of operations), the number of required iterations was calculated at 50. The reported results here are based on the average of 50 simulation iterations.

$$r > \frac{z_{\alpha/2} S_0}{\varepsilon} \tag{6}$$

Table 3
Investment estimation for the torrefaction process with 15.7 t/h capacity.

Equipment	Cost (million C$)
Torrefaction reactor	8.309
Burner	6.036
Heat exchanger	0.700
Turbo blower flue gas	2.578
Turbo blower torrefaction gas	0.154
Precipitator	1.472
Torrefied biomass cooler	0.316
Total	19.565

Table 4
Shipping distances, and transport and logistics costs for different markets.

	Regular pellets (C$/t)	Torrefied pellets (C$/t)
Transport costs from Vancouver to Rotterdam, Europe	50.00	41.00
Handling and storage at Vancouver port	13.00	10.00
Handling and storage at destination port	13.00	10.00
Shipping distance Vancouver to Rotterdam, Europe	16,580 km	
Shipping distance Vancouver to Onahama, Japan	7433 km	
Shipping distance Vancouver to Incheon, Korea	9112 km	
Shipping distance Vancouver to Shanghai, China	9266 km	

While plant productivity was estimated at 89.54% for producing regular pellets, it drops to 84.85% when torrefaction is added to the studied supply chain. Failure of the torrefaction equipment and shortage in the raw material are the reasons for the lower productivity of the plant when torrefaction is added in this case study. The torrefaction process unit becomes the bottleneck and failure of the equipment halts the downstream processes, hence, reducing the productivity. The shortage in the raw material is due to the dry matter loss in the torrefaction process, considering that the availability of raw materials at the suppliers' locations was not increased while higher amount of biomass is required to produce the torrefied pellets with the identical energy content. On average 1.29 t of raw materials were consumed to produce one tonne of regular pellets; while for producing one tonne of torrefied pellets 1.73 t of raw materials was required. Considering the energy content of 18 and 21.2 GJ/t of regular and torrefied pellets, respectively, the additional biomass input on mass basis to achieve the same energy output for torrefied pellets equals about 14%.

5.1. Supply chain costs

The cost structure of the supply chain is estimated using the simulation model. The contribution of each stage of the supply chain is shown in Fig. 3. Raw material procurement and transportation compose 27% of the annual costs and similar to regular wood pellets contribute significantly to the cost structure of the supply chain. The production cost of torrefied pellets, which includes processing, maintenance, personnel and investment costs, represents 53% of the total cost. The break-down of the production cost is shown in the right hand side pie chart. Rail transportation of torrefied pellets to the export port in North Vancouver constitutes about 20% of the total cost.

The cost structure of the supply chain for regular and torrefied pellets are compared in Table 5. The cost estimations associated with each section of the supply chain are provided on the weight basis C$/dt) and the energy terms $/GJ of wood pellets. The delivered cost of torrefied pellets at the North Vancouver port is 142 C$/dt, which

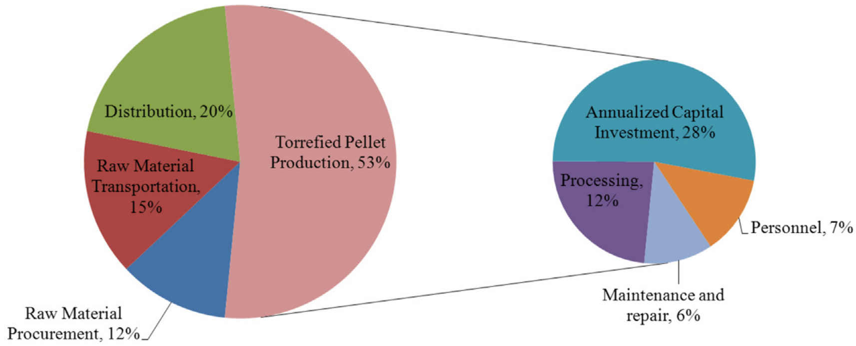

Fig. 3. Estimated cost structure of torrefied wood pellet supply chain.

represents 36% increase in the C$/dt cost of torrefied pellets compared with regular pellets. In energy terms, the estimated cost of delivered torrefied pellets to the North Vancouver port is 7 C$/GJ, while it is 6 C$/GJ for regular pellets, showing about 17% higher cost for torrefied pellets.

5.2. Energy consumption and CO_2 emissions

The energy demand at different stages of the supply chain is estimated and shown in Table 6. The highest input energy was required in the drying process with 395 kWh/t. In the production stage, 162 kWh/t electric energy was consumed for torrefaction, grinding, pelletization, and cooling. For raw material transportation (trucking) 14 kWh/t and for rail transportation of the wood pellets 78 kWh/t was consumed. The energy input along the supply chain was estimated at 648 kWh/t that equals to 11.3% of the energy content of one tonne of torrefied wood pellets. About 137.62 kg CO_2/t was emitted to produce and deliver torrefied pellets to the port, which is equivalent to 0.024 kg CO_2/kWh.

For regular pellets, the estimated input energy along the supply chain is 569 kWh/t which is about 12.7% of the energy content. The amount of emissions along the supply chain for regular pellets was estimated at 136.91 kg CO_2/t (0.027 kg CO_2/kWh). These results indicate that torrefied pellets are superior to regular pellets in terms of consumed energy and emitted CO_2 along the supply chain.

5.3. Effects of uncertainties

The uncertainties in the raw materials availability and quality together with those in the performance of the vehicle and equipment cause fluctuations in the estimated values of the outputs. The histogram and best fitted probability distribution function (PDF) of annual raw material procurement cost, annual raw material transportation cost, annual produced weight of pellets, and total annual costs are shown in Fig. 4. The fluctuations are according to 50 runs of the simulation. The annual raw material procurement and transportation costs vary due to the uncertainties in the moisture content and bulk density of sawdust and shavings. The best fitted PDF for the raw material procurement cost is Normal with 1.84 M C$ average and 0.003 M C$ standard deviation. The raw material transportation cost follows a Normal PDF with 2.44 M C$ average and 0.004 M C$ standard deviation. The uncertainties in the quality measures and availability of raw materials at the pellet mill, plus the uncertainties in the equipment performance leads to the fluctuations in the annual production of the pellet mill. The estimated total annual cost follows a Normal distribution with an average of 16.10 M C$ and a standard deviation of 0.02 M C$. Due to the limited available data on the quality measures of the raw materials and the limited range of changes (Table 2), the uncertainties in the output parameters are relatively small.

Sensitivity analysis of the results with respect to the moisture content of sawdust is performed to further evaluate the effects of biomass quality on the performance of the supply chain. Table 7 includes the effects of changes in sawdust moisture content on the procurement and transportation costs, required fuel in the drying process, the total production of the plant, and the final cost of torrefied pellets. The average moisture content is changed by $\pm$5%.

Sawdust transportation cost and the required drying fuel were positively correlated with the moisture content while raw material procurement cost and production weight were negatively correlated with saw dust moisture content. As moisture content increases, the trucks carry more water which increases the transportation cost per dry tonne and because more water is to be evaporated from the raw material, the drying process becomes more energy intensive and requires more fuel. The raw material procurement cost is based on the dried weight delivered to the pellet mill, therefore, when moisture content is increased less dried material is delivered to the plant and procurement cost decreases (note that the availability of raw materials, i.e. the wet weight of raw materials available at each supplier, was not changed when the moisture content was changed in the sensitivity analysis. It is done

Table 5
Cost structure of the supply chain for regular and torrefied wood pellets.

	Regular pellets		Torrefied pellets	
	Unit cost (C$/dt)	Unit cost (C$/GJ)	Unit cost (C$/dt)	Unit cost (C$/GJ)
Raw material purchase	$13	$1	$16	$1
Raw material transportation	$17	$1	$21	$1
Pellet production				
Processing	$19	$1	$18	$1
Repair and maintenance, Personnel	$17	$1	$18	$1
Annualized capital investment	$16	$1	$40	$2
Transportation to North Vancouver	$31	$2	$29	$1
Total	$104	$6	$142	$7

Table 6
Energy consumption and CO_2 emissions along the supply chain of torrefied wood pellets.

Item	Input energy (kWh/t)	CO_2 emissions (kg CO_2/t)
Raw material transportation (trucking)	14	4
Drying	385 (thermal energy) 10 (electric energy)	116
Torrefaction	66	2
Grinding	37	1
Pelletization	56	1
Cooling	2	0
Rail Transportation of torrefied pellets	78	14
Total	648	138

in order to be able to reflect the effects of the moisture content variations on the production at the pellet mill). Production increases when moisture content decreases because more dried material would be available to be converted to pellets. The total cost decreases when moisture content decreases as a result of reduction in drying fuel requirements, reduced transportation cost, and increased produced weight. When more wood pellets are produced, the specific capital cost decreases.

5.4. Cost comparison for different markets

The increased energy density of torrefied pellets make them more appealing when long transportation distances are involved, such as delivering pellets from BC Canada to the markets in Europe, Japan, Korea, and China. Table 8 shows the estimated cost of regular and torrefied pellets delivered to these locations. It is noted that these cost figures include handling and storage costs at the Vancouver port and destination ports and are presented in C$/t, while the costs in Table 5 do not include handling and storage costs and are in C$/dt. The delivered cost of torrefied pellets on weight basis (C$/t) is higher for all the candidate locations. In energy terms (C$/GJ) the cost of delivered torrefied pellets is similar to that of regular pellets at North Vancouver port after 840 km rail transportation. Including the ocean transportation to Europe makes energy from torrefied pellets about 9% cheaper than regular pellets. For Japan, Korea, and China, delivered cost of torrefied pellets is similar to that of regular pellets on energy basis. The comparison shows that the increased capital investment and increased processing costs are compensated by reduced transportation costs of the products. Furthermore, the higher energy density of the torrefied pellets leads to less energy input and CO_2 emissions along the supply chain when compared to regular pellets on energetic basis. For regular pellets delivered to Northwestern Europe, 17% of their energy content was used along the supply chain while, for torrefied pellets 14% of their energy content was required. The amount of CO_2 emissions per GJ of delivered energy content was estimated at 11 kg and 14 kg for torrefied and regular pellets, respectively.

6. Conclusions

Torrefaction has gained attention as a pre-treatment technology in the solid biofuel industry. In order to provide an integrated perspective of the supply chain, torrefaction and pelletization of forest biomass were simulated using discrete-event and discrete-rate modeling approaches. The simulation model developed in Mobini et al. (2013) was extended by the torrefaction module. The torrefaction module is developed based on Andritz ACB© Process (Trattner, 2009) in which the excess heat from the torrefaction gas is used in the upstream drying process allowing more efficient integration of torrefaction to the existing production. The effects of quality of biomass, in terms of moisture content, heating value, and ash content, were taken into account in the development of the torrefaction module. The simulation model incorporates other sources of uncertainties such as those in availability of raw materials, performance and failure of the equipment, and amount of fuel consumption in the drying process. Moreover, resource constraints along the supply chain and interdependencies between its different

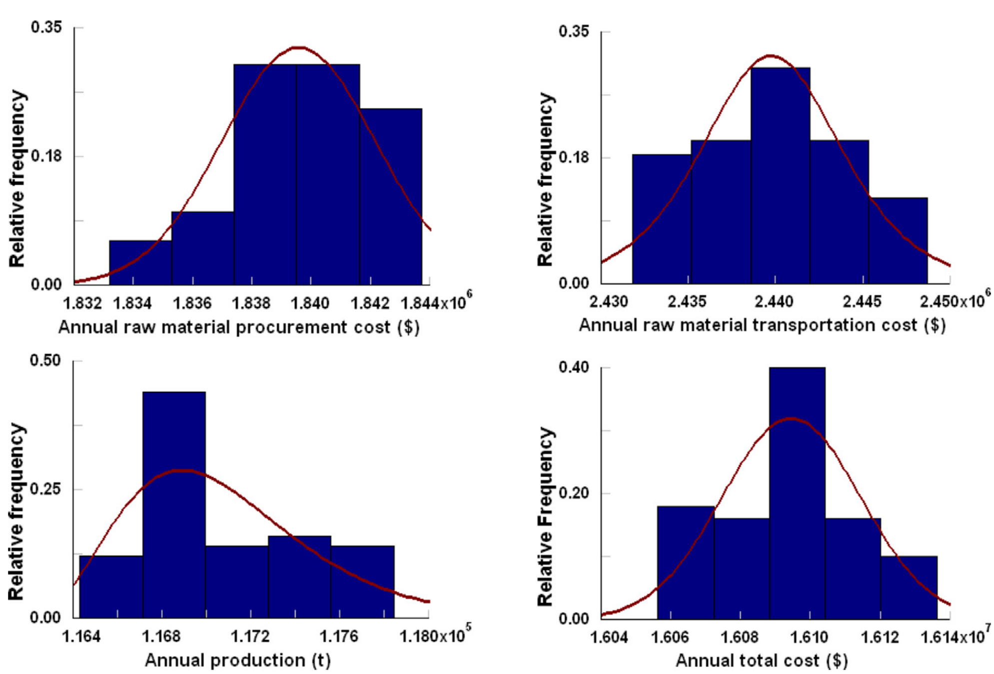

Fig. 4. Histograms and best fitted PDF to the simulation outputs.

Table 7
Effects of variations in sawdust moisture content on the supply chain.

	5% Lower moisture content	Base case	5% Higher moisture content
Procurement Cost (k C$)	1903	1839	1763
Difference	3%	–	−4%
Transportation Cost (C$/dt)	20	21	23
Difference	−5%	–	10%
Required Drying Fuel (t)	1026	6535	12,237
Difference	−84%	–	87%
Produced Weight (t)	122,630	117,082	108,849
Difference	5%	–	−7%
Total Cost (C$/t)	138	142	148
Difference	−3%	–	4%

Table 8
Cost comparison of delivered regular and torrefied pellets to different markets.

Location	Regular pellets		Torrefied pellets	
	C$/GJ	C$/t	C$/GJ	C$/t
Plant's gate	4	66	5	110
North Vancouver	7	107	7	148
Rotterdam, Europe	11	170	10	199
Onahama, Japan	9	144	9	176
Incheon, Korea	9	148	9	180
Shanghai, China	9	148	9	181

stages are considered in the simulation. Including these aspects of the chain into the model assures that more reliable results are obtained in comparison with static models. Furthermore, modular design of the simulation model makes it easy to compare different scenarios for various configurations of the supply chain; which makes the simulation a proper decision support tool for the design and analysis of the supply chains.

Application of the model was demonstrated in a case study. The integration of torrefaction into an existing wood pellet production and distribution supply chain was evaluated. The obtained results were used to compare the torrefied and regular wood pellets in terms of delivered cost, energy consumption, and CO_2 emissions along the supply chain. Estimated cost of torrefied pellets stored at the international port in North Vancouver was 148 C$/t which is 38% more expensive than regular pellets on weight basis. Including the ocean transportation of wood pellets to the existing and potential markets, however, showed that the higher energy density of torrefied pellets along with the lower handling and storage costs make the cost of delivered torrefied pellets comparable or lower than that of regular pellets. This indicates the higher capital investment and processing costs of torrefaction is compensated by lower distribution, storage and handling costs. The results show that torrefied pellets are preferred compared to the regular pellets in terms of the cost of the delivered energy content when long transportation distances are involved. Whether or not this reduction would make economic sense for the pellet manufacturers to add the torrefaction processing unit into their supply chain depends on different factors, such as the associated capital cost, interest rates, market price of torrefied pellets, and requires further investigations.

The effects of the changes in the moisture content, revealed by the sensitivity analysis, indicate the importance of considering the moisture content of the raw materials in the supply chain design as well as the importance of controlling the moisture content along the supply chain.

References

An, H., Searcy, S.W., 2012. Economic and energy evaluation of a logistics system based on biomass modules. Biomass Bioenergy 46 (0), 190–202.

An, H., Wilhelm, W.E., Searcy, S.W., 2011. A mathematical model to design a lignocellulosic biofuel supply chain system with a case study based on a region in Central Texas. Bioresour. Technol. 102 (17), 7860–7870.

Andersen, F.E., Díaz, M.S., Grossmann, I.E., 2013. Multiscale strategic planning model for the design of integrated ethanol and gasoline supply chain. AICHE J. 59 (12), 4655–4672.

Banks, J., 2005. Discrete Event System Simulation, 4/e. Pearson Education India.

Beekes, M., 2014. Advantages and drawbacks for international trade of torrefied products. In: 4th Central European Biomass Conference, January 2014.

Chiueh, P., Lee, K., Syu, F., Lo, S., 2012. Implications of biomass pretreatment to cost and carbon emissions: case study of rice straw and Pennisetum in Taiwan. Bioresour. Technol. 108, 285–294.

Ciolkosz, D., Wallace, R., 2011. A review of torrefaction for bioenergy feedstock production. Biofuels, Bioprod. Biorefining 5 (3), 317–329.

Damiron, C., Nastasi, A., 2008. Discrete rate simulation using linear programming. In: Proceedings of the 40th Conference on Winter Simulation Winter Simulation Conference, p. 740.

D'Amours, S., Ronnqvist, M., Weintraub, A., 2008. Using operational research for supply chain planning in the forest products industry. Infor 46 (4), 265–281.

De Meyer, A., Cattrysse, D., Rasinmäki, J., Van Orshoven, J., 2014. Methods to optimise the design and management of biomass-for-bioenergy supply chains: a review. Renew. Sustain. Energy Rev. 31 (0), 657–670.

Demirbas, A., 2001. Biomass resource facilities and biomass conversion processing for fuels and chemicals. Energy Convers. Manag. 42 (11), 1357–1378.

Ebadian, M., Sowlati, T., Sokhansanj, S., Stumborg, M., Townley-Smith, L., 2011. A new simulation model for multi-agricultural biomass logistics system in bioenergy production. Biosyst. Eng. 110 (3), 280–290.

Ebadian, M., Sowlati, T., Sokhansanj, S., Townley-Smith, L., Stumborg, M., 2013. Modeling and analysing storage systems in agricultural biomass supply chain for cellulosic ethanol production. Appl. Energy 102 (0), 840–849.

Farnel Soft Inc, 2013, September. Port to Port Distances. Available: http://www.searates.com/.

Gallis, C.T., 1996. Activity oriented stochastic computer simulation of forest biomass logistics in Greece. Biomass Bioenergy 10 (5–6), 377–382.

Gold, S., Seuring, S., 2011. Supply chain and logistics issues of bio-energy production. J. Clean. Prod. 19 (1), 32–42.

Imagine That, 2011. ExtendSim Simulation Software, 8.0.2 ed.

Kornmayer, C., 2009. Process Engineering Studies on Flash Pyrolysis of Lignocellulose in a Twin-screw Mixer Reactor (Verfahrenstechnische Untersuchungen zur Schnellpyrolyse von Lignocellulose im Doppelschnecken-Mischreaktor). Karlsruhe Institute of Technology (KIT), Karlsruhe in German.

Krahl, D., 2009. ExtendSim advanced technology: discrete rate simulation. In: Proceedings of the 2009 Winter Simulation Conference.

Larsson, S.H., Rudolfsson, M., Nordwaeger, M., Olofsson, I., Samuelsson, R., 2013. Effects of moisture content, torrefaction temperature, and die temperature in pilot scale pelletizing of torrefied Norway spruce. Appl. Energy 102 (0), 827–832.

Li, H., Liu, X., Legros, R., Bi, X.T., Jim Lim, C., Sokhansanj, S., 2012. Pelletization of torrefied sawdust and properties of torrefied pellets. Appl. Energy 93 (0), 680–685.

Lucas, K., 2006. Thermodynamics: the Basic Laws of Energy and Material Transformations (Thermodynamik : Die Grundgesetze der Energie- und Stoffumwandlungen). Springer, Berlin in German.

Mafakheri, F., Nasiri, F., 2014. Modeling of biomass-to-energy supply chain operations: applications, challenges and research directions. Energy Policy 67 (0), 116–126.

Magelli, F., Boucher, K., Bi, H.T., Melin, S., Bonoli, A., 2009. An environmental impact assessment of exported wood pellets from Canada to Europe. Biomass Bioenergy 33 (3), 434–441.

Mani, S., 2005. A Systems Analysis of Biomass Densification Process. The University of British Columbia.

Mani, S., Sokhansanj, S., Bi, X., Turhollow, A., 2006. Economics of producing fuel pellets from biomass. Appl. Eng. Agric. 22 (3), 421–426.

Mansoornejad, B., Chambost, V., Stuart, P., 2010. Integrating product portfolio design and supply chain design for the forest biorefinery. Comput. Chem. Eng. 34 (9), 1497–1506.

Miao, Z., Shastri, Y., Grift, T.E., Hansen, A.C., Ting, K., 2012. Lignocellulosic biomass feedstock transportation alternatives, logistics, equipment configurations, and modeling. Biofuels, Bioprod. Biorefining 6 (3), 351–362.

Mizsey, P., Racz, L., 2010. Cleaner production alternatives: biomass utilisation options. J. Clean. Prod. 18 (8), 767–770.

Mobini, M., Sowlati, T., Sokhansanj, S., 2010. A discrete-event simulation model on the logistics of forest biomass supply in Quesnel, BC. In: MITACS/CORS 2010 Annual Conference Edmonton AB.

Mobini, M., Sowlati, T., Sokhansanj, S., 2013. A simulation model for the design and analysis of wood pellet supply chains. Appl. Energy 111 (0), 1239–1249.

Nguyen, T.L.T., Hermansen, J.E., Nielsen, R.G., 2013. Environmental assessment of gasification technology for biomass conversion to energy in comparison with other alternatives: the case of wheat straw. J. Clean. Prod. 53 (0), 138–148.

NRCan, 2012. 2012/01/13-last update, Comprehensive Energy Use Database Tables. Homepage of Natural Resources Canada [Online]. Available: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/trends_com_bct.cfm?attr=0, 2012, 04/11.

Obernberger, I., Thek, G., 2010. The Pellet Handbook; the Production and Thermal Utilization of Pellets, first ed. Earthscan, London & Washington, DC.

Panepinto, D., Genon, G., 2012. Biomass thermal treatment: energy recovery, environmental compatibility and determination of external costs. Waste Biomass Valorization 3 (2), 197–206.
Paré, D., Bernier, P., Thiffault, E., Titus, B.D., 2011. The potential of forest biomass as an energy supply for Canada. For. Chron. 87 (1), 71–76.
Peng, J.H., 2012. A Study of Softwood Torrefaction and Densification for the Production of High Quality Wood Pellets. University of British Columbia.
Peng, J.H., Bi, H.T., Sokhansanj, S., Lim, J.C., Melin, S., 2010. An economical and market analysis of Canadian wood pellets. Int. J. Green. Energy 7 (2), 128–142.
Peng, J.H., Bi, X.T., Sokhansanj, S., Lim, C.J., 2013. Torrefaction and densification of different species of softwood residues. Fuel 111 (0), 411–421.
Peters, M., Timmerhaus, K., West, R., 2002. Plant Design and Economics for Chemical Engineers, fifth ed. McGraw-Hill, Boston, MA.
Pirraglia, A., Gonzalez, R., Denig, J., Saloni, D., 2013a. Technical and economic modeling for the production of torrefied lignocellulosic biomass for the U.S. densified fuel industry. Bioenergy Res. 6 (1), 263–275.
Pirraglia, A., Gonzalez, R., Saloni, D., Denig, J., 2013b. Technical and economic assessment for the production of torrefied ligno-cellulosic biomass pellets in the US. Energy Convers. Manag. 66, 153–164.
Prins, M.J., Ptasinski, K.J., Janssen, F.J.J.G., 2006. More efficient biomass gasification via torrefaction. Energy 31 (15), 3458–3470.
Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G., Schmid, E., 2010. Potential of biomass-fired combined heat and power plants considering the spatial distribution of biomass supply and heat demand. Int. J. Energy Res. 34 (11), 970–985.
Schneider, A., Pilz, A., Pollex, A., Zeng, T., 2012. Torrefaction – a method for homogenization of complex biomass fuel for energy use (Torrefizierung – ein Verfahren zur Homogenisierung schwieriger Biomassen für eine energetische Nutzung). In: 12th International BBE-conference for Wood Energy Biomass for Energy Use, Augsburg, Germany in German.
Shabani, N., Akhtari, S., Sowlati, T., 2013. Value chain optimization of forest biomass for bioenergy production: a review. Renew. Sustain. Energy Rev. 23 (0), 299–311.
Shah, A., Darr, M.J., Medic, D., Anex, R.P., Khanal, S., Maski, D., 2012. Techno-economic analysis of a production-scale torrefaction system for cellulosic biomass upgrading. Biofuels Bioprod. Biorefining-Biofpr. 6 (1), 45–57.
Sharma, B., Ingalls, R.G., Jones, C.L., Khanchi, A., 2013. Biomass supply chain design and analysis: basis, overview, modeling, challenges, and future. Renew. Sustain. Energy Rev. 24 (0), 608–627.
Shirazi, M.M.A., Kargari, A., Tabatabaei, M., Mostafaeid, B., Akia, M., Barkhi, M., Shirazi, M.J.A., 2013. Acceleration of biodiesel–glycerol decantation through NaCl-assisted gravitational settling: a strategy to economize biodiesel production. Bioresour. Technol. 134 (0), 401–406.
Sikkema, R., Steiner, M., Junginger, M., Hiegl, W., Hansen, M.T., Faaij, A., 2011. The European wood pellet markets: current status and prospects for 2020. Biofuels Bioprod. Biorefining-Biofpr. 5 (3), 250–278.
Sokhansanj, S., Turhollow, A.F., Wilkerson, E.G., 2008. Integrated biomass supply and logistics: a modeling environment for designing feedstock supply systems for biofuel production. Resour. Eng. Technol. Sustain. World 15 (6), 15–18.
Sokhansanj, S., Mani, S., Tagore, S., Turhollow, A.F., 2010. Techno-economic analysis of using corn stover to supply heat and power to a corn ethanol plant – Part 1: cost of feedstock supply logistics. Biomass Bioenergy 34 (1), 75–81.
Sokhansanj, S., Mani, S., Turhollow, A., Kumar, A., Bransby, D., Lynd, L., Laser, M., 2009. Large-scale production, harvest and logistics of switchgrass (*Panicum virgatum* L.) – current technology and envisioning a mature technology. Biofuels Bioprod. Biorefining-Biofpr. 3 (2), 124–141.
Sokhansanj, S., Kumar, A., Turhollow, A.F., 2006. Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). Biomass Bioenergy 30 (10), 838–847.
Spelter, H., Toth, D., 2009. North American Wood Pellet Sector. United States Department of Agriculture, Madison, WI, USA.
Suurs, R., 2002. Long Distance Bioenergy Logistics: an Assessment of Costs and Energy Consumption for Various Biomass Transport Chains. Utrecht University, Utrecht.
Svanberg, M., Halldórsson, Á., 2013. Supply chain configuration for biomass-to-energy: the case of torrefaction. Int. J. Energy Sect. Manag. 7 (1), 65–83.
Svanberg, M., Olofsson, I., Flodén, J., Nordin, A., 2013. Analysing biomass torrefaction supply chain costs. Bioresour. Technol. 142 (0), 287–296.
The World Bank, 2013. World Developement Indicators: Forest Area (% of Land Area). Available: http://data.worldbank.org/indicator/AG.LND.FRST.ZS, 2013, September.
Tong, K., Gong, J., Yue, D., You, F., 2014. Stochastic programming approach to optimal design and operations of integrated hydrocarbon biofuel and petroleum supply chains. ACS Sustain. Chem. Eng. 2 (1), 49–61.
Trattner, K., 2009. The ACB© Process – a Brief Introduction. ANDRITZ AG, Graz.
Trippe, F., Fröhling, M., Schultmann, F., Stahl, R., Henrich, E., 2010. Techno-economic analysis of fast pyrolysis as a process step within biomass-to-liquid fuel production. Waste Biomass Valorization 1 (4), 415–430.
van der Stelt, M.J.C., Gerhauser, H., Kiel, J.H.A., Ptasinski, K.J., 2011. Biomass upgrading by torrefaction for the production of biofuels: a review. Biomass Bioenergy 35 (9), 3748–3762.
Zhang, F., Johnson, D.M., Johnson, M.A., 2012. Development of a simulation model of biomass supply chain for biofuel production. Renew. Energy 44 (0), 380–391.