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Modeling of biomass-to-energy supply chain operations: Applications, challenges and research directions

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HIGHLIGHTS

- An extensive review of biomass supply chain operations management models presented in the literature is provided.
- The models are classified in line with biomass supply chain activities from harvesting to conversion.
- The issues surrounding biomass supply chains are investigated manifesting the need to novel modeling approaches.
- Our gap analysis has identified a number of existing shortcomings and opportunities for future research.

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ABSTRACT

Reducing dependency on fossil fuels and mitigating their environmental impacts are among the most promising aspects of utilizing renewable energy sources. The availability of various biomass resources has made it an appealing source of renewable energy. Given the variability of supply and sources of biomass, supply chains play an important role in the efficient provisioning of biomass resources for energy production. This paper provides a comprehensive review and classification of the excising literature in modeling of biomass supply chain operations while linking them to the wider strategic challenges and issues with the design, planning and management of biomass supply chains. On that basis, we will present an analysis of the existing gaps and the potential future directions for research in modeling of biomass supply chain operations.

1. Introduction

There is an increasing interest in renewable and environmentally friendly energy sources. Biomass, which entails any organic matter derived from living organisms, is one of the most utilized sources of renewable energy. It is comprised of plant and animal materials, as well as residues such as wood from forests, crops, seaweed, materials left over from agricultural and forestry processes, and organic industrial, human and animal wastes (Saidur et al., 2011). Biomass has been the main source of energy in rural areas for centuries. In the past decade, biomass has been consistently ranked as the fourth greatest source of global energy, accounting for 10–14% of final energy consumption, following coal (12–14%), natural gas (14–15%) and electricity (14–15%) (Kheshgi et al., 2000; Parrika, 2004; Balat and Ayar, 2005; Demirbas, 2005; Oregon, 2010).

Climate change, dependency on foreign oil and the foreseen gap between energy supply and demand are among the main reasons behind a growing attention towards renewable energy sources. The availability of various types of biomass resources and maturity of conversion technologies has made it an attractive source of energy in the European Union (EU) (EBTP, 2006; McCormick and Kaberger, 2007; An et al., 2011). In addition to carbon mitigation and energy security, biomass energy production is associated with the creation of new jobs, the creation of a new source of income for farmers, cheaper heat supply, and reduced landfill disposal (Thornley, 2006; Saidur et al., 2011). Despite all these benefits, in practice, the use of biomass as a source of energy comes with a number of challenges, such as the potential competition with food and feed production, low energy density, high logistic costs, traffic noise and air pollution (Thornley, 2006; Saidur et al., 2011).

The most common biomass conversion-to-energy methods are: direct combustion, pyrolysis, fermentation, gasification, and anaerobic digestion. The choice of the method depends upon a number of factors, such as the type and quantity of biomass, environmental standards, and financial resources (Saidur et al., 2011).

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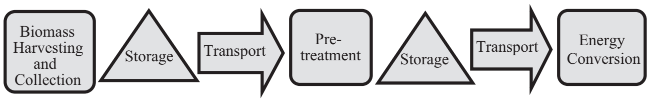

Fig. 1. Operational components of a biomass supply chain.

Supply Chain Management (SCM) plays a critical role in the management of bioenergy production processes (Gold and Seuring, 2011). Biomass Supply Chain Management has been defined as the integrated management of bioenergy production from harvesting biomaterials to energy conversion facilities (Annevelink and de Mol, 2007; Gold and Seuring, 2011). The parties involved in a biomass energy supply chain are: the supplier of biomass, transportation and distribution entities, energy production facility developers and operators, the government and utility firms who provide the incentives, and the end-users (Adams et al., 2011). In this sense, a typical bioenergy supply chain is comprised of five main components of harvesting and collection, pre-treatment, storage, transport, and energy conversion as shown in Fig. 1 (Iakovou et al., 2010).

Biomass energy supply chain differs from traditional supply chains in several ways. Among them are the seasonal availability of agricultural biomass, low energy density, demand variations due to uncertain energy production performance and the variability of biomass materials, which has implications for transport and storage (Iakovou et al., 2010). Thus, the main objectives of biomass supply chain management are to minimize costs, environmental impacts of the supply chain, and ensure continuous feedstock supply (Gold and Seuring, 2011).

This paper reviews the existing literature and research on the use of mathematical models to formulate design, planning and management decisions in biomass supply chain operations. Our review considers the research that has been conducted in relation to different operational stages of a biomass supply chain, including harvesting, storage, transport, and energy conversion. To the best of our knowledge, this paper is a first attempt to provide a comprehensive review of the existing literature in modeling of biomass supply chain operations while linking them to the wider strategic challenges and issues with the design, planning and management of biomass supply chains. A particular novelty of this research is that, based on the provided review, it presents an analysis of the existing gaps and future research opportunities in biomass supply chain operations modeling. It should be mentioned that we conduct a global review, considering the studies from different jurisdictions (USA, Asia, EU, etc.) and accounting for variations (in materials, technologies, regulations, and policies). We account for both solid and liquid biomass supply chains associated with transportation, power generation, and heating. In this sense, the review will provide an opportunity to explore the differences and similarities in challenges and issues related to biomass supply chains given the above mentioned variations.

2. Biomass supply chain modeling

Reviewing the models developed to deal with decision problems endemic in the various states of a biomass supply chain, they could be classified into five categories (according to Fig. 1), as follows.

2.1. Biomass harvesting and collection

In this component of biomass supply chains, the main decisions to deal with are allocation of land, harvest scheduling, and biomass collection planning based on the analysis of biomass soil/moisture contents, climatic conditions, land availability, and bioenergy demand.

Murray (1999) developed biomass harvest scheduling models with consideration of spatial restrictions that are due to land availability and productivity. He proposed two models called 'Unit Restriction Model' (URM) and 'Area Restriction Model' (ARM). In URM, harvest scheduling is performed in such a way that no two adjacent blocks are selected at the same time. In ARM, harvest scheduling is subject to one more constraint. Namely, each block can be harvested no more than once during each planning period. Gunnarsson et al. (2004) adopted an integer programming model to analyze 0–1 decisions regarding the harvest areas. It identified whether or not a specific land should be harvested in line with bioenergy demands downstream the supply chain. Similar cost minimization/yield maximization linear and mixed-integer programming models have been developed for land allocation and scheduling in biomass harvesting subject to various forms of area restrictions (Martins et al., 2005; Gunn and Richards, 2005; Goycoolea et al., 2005; Constantino et al., 2008). Gemtos and Tsiricoglou (1999) proposed a model to determine water and soil contents of collected cotton stalks in various farms located in central Greece over a period of two years, estimating the impact of these parameters on optimization of biomass collection costs.

Furthermore, Eksioglu et al. (2009) proposed a mixed integer programming (MIP) model with the objective of minimizing the total cost of a biomass supply chain, accounting for deterioration, seasonality and availability of biomass materials. The proposed model identifies the optimal number, size and location of collection facilities, bio-refineries, as well as the amount of biomass shipped, processed and held as inventory. In order to account for the effect of weather conditions on biomass availability, Sokhansanj et al. (2006) developed a discrete-event model that predicts the number and size of equipment needed to meet the rate of harvest, while considering the bio-refinery demand and biomass delivery cost.

2.2. Biomass pre-treatment

Pre-treatment is a mechanical or chemical process (or a combination of them) that converts biomass into denser energy carriers not only to increase its energy conversion rate but also to facilitate handling, storage and transportation, and to reduce the associated costs (Kumar and Sokhansanj, 2007; Larson et al., 2010). Processes such as drying and torrefaction (i.e. reducing the moisture content with heating in the absence of oxygen), carbonization, pelletization, chopping, shredding, and grinding are some of pre-treatment approaches adopted by biomass energy industry (Uslu et al., 2008; Stelt et al., 2011). For production of liquid fuels from lignocellulosic biomass, processes such as pyrolysis (heating biomass in the absence of air) and hydrolysis (using water to convert biomass polymers to fermentable sugars) are used for biodiesel and ethanol production, respectively (McKendry, 2002b; IRENA, 2013). It should be mentioned that not all biomass materials need to undergo a pre-treatment. For instance, maintaining a certain amount of moisture content in logs is considered a quality parameter (from a strength point of view), making them a good candidate for pelleting (Lehtikangas, 2001).

The inclusion and choice of pre-treatment processes not only influences the costing profile of storage and transport activities but also impacts the structure of biomass supply chains. Uslu et al. (2008) have compared the impact of alternative pre-treatment processes (pelletization, torrefecation and pyrolysis) on the cost efficiency of a biomass supply chain under various location scenarios for pre-treatment facilities. The findings points to the fact that combined torrefaction and pelletization could be a promising option that not only reduces the logistic costs but also improves the energy efficiency of conversion facilities (Uslu et al., 2008). Further, as Chiueh et al. (2012) advocate, torrefaction requires more demonstrated real-world (and large scale) cases to establish its performance from technical and economic perspectives.

In addition, Chiueh et al. (2012) have proposed a GIS-based model to analyze the cost efficiency and carbon emission performance of various scenarios for location of a pre-treatment facility and transportation alternatives in a biomass supply chain for power generation. The results show that a remarkable share of supply chain costs is associated with the transportation, sorting and storage activities in pre-treatment processes. In this sense, achieving the economy of scale in biomass pre-treatment by establishing large pre-treatment facilities to process a significant quantity of biomass materials is challenging due to increased transportation and storage costs. Alternatively, Carolan et al. (2007) have proposed a biomass supply chain model with a network of several small pre-treatment units. The proposed model achieves the economy of scale while minimizing the transportation and storage costs as a result of decentralization of preprocessing activities.

2.3. Biomass storage

Typical decisions related to storage component of biomass supply chains are analysis of the location of storage facilities and storage capacity planning/scheduling as follows.

Choosing an appropriate location for biomass storage facilities is not only influenced by the type and characteristics of biomass materials, but is also constrained by transportation options. Further, some researches recommended on-field biomass storage to reduce the overall delivery costs (Allen et al., 1998; Huisman et al., 1997). The use of intermediate storage locations between biomass fields and the power plant has been studied (with decisions on distance and capacities) using a dynamic discrete event simulation (Nilsson and Hansson, 2001), as well as by the use of linear programming models (Kanzian et al., 2009; Tatsiopoulos and Tolis, 2003). Impact of incorporating intermodal storage facilities in biomass supply chains has also been captured through a mixed-integer optimization model (Eksioglu et al., 2010). An inter-modal point is the one in which different transportation modes (road, train, etc.) meet, which could serve as an optimally planned point of storage and distribution for biomass materials. The study concludes that in order to minimize the total cost of biomass supply chain, the location of inter-modal storage/distribution center should be as close as possible to bioenergy production facility. The option of locating the storage facility next to the biomass power plant was also considered using a dynamic programming approach, which thereby minimize the total storage cost of biomass residues, subject to their seasonal availability (Papadopoulos and Katsigiannis, 2002). Further, a mixed integer linear programming method was proposed by Zhu et al. (2011) to determine biomass storage and refinery locations, subject to transportation modes and quantities.

In terms of storage capacity planning and scheduling, Cundiff et al. (1997) developed a linear programming model with the objective of minimizing the total farm-to-storage costs, including the costs of expanding and operating storage capacity. In this model, the uncertainties arising from regional weather conditions are incorporated with their impacts on biomass production ratios and supply chain performance. This is of particular importance from storage capacity/scheduling perspective, as the extreme weather conditions such as drought, heavy precipitation, and extreme temperatures not only affect biomass yields but also influence the quality of biomass materials and thus undermine their storage conditions and requirements. Further, in order to integrate the schedule of storage activities and inventories with the whole supply chain operations, Dunnett et al. (2007) have adopted a state-task-network optimization framework, originally developed in process industry for batch production scheduling in process industry. It formulates the storage scheduling on the basis of the upstream (harvesting) and downstream (energy conversion) schedules, showing that an integrated scheduling framework could lead to a 5–20% reduction in total cost of biomass supply chains (depending on the type of biomass materials).

2.4. Biomass transport

Several researchers have used integer linear programming to identify optimal biomass transportation strategies (deciding on types and quantities of biomass delivered) subject to constraints on biomass availability, transportability and energy demand (Diekema et al., 2005: Annevelink and de Mol, 2007; Busato and Berruto, 2008).

Graham et al. (2000) used a Geographical Information System (GIS) model to estimate the minimum marginal cost of biomass delivery in eleven states of the United States. Their work accounted for the direct costs of transportation and the indirect costs associated with the environmental impact of biomass supply. Perpina et al. (2009) have also proposed a GIS based model, which identifies an optimal biomass transportation plan subject to various scenarios. It focuses on the availability of biomass materials and the feasibility of delivery networks in the Valencian Community in Eastern Spain. Frombo et al. (2009) have developed a similar GIS-based model with the aim of identifying a least cost configuration for woody biomass delivery networks.

A number of studies aimed at modeling and quantifying the impact of variability in the types of biomass materials, as well as their associated water and soil contents, on farms-to-conversion transportation costs (Gemtos and Tsiricoglou, 1999; Petrou and Mihiotis, 2007; Miao et al., 2012). Hamelinck et al. (2005) developed a spreadsheet modeling framework to estimate and compare the cost of transporting biomass to Western Europe from selected farms in Eastern Europe and Latin America, given various scenarios pertaining to transportation distance, timing and scale. They concluded that, despite a higher transport cost, biomass from Latin American sources is often cheaper due to lower harvesting and collection costs. Moreover, Gronalt and Rauch (2007) estimated and compared the minimum total cost of biomass transport in centralized and decentralized configurations of a biomass supply chain in central Austria using a heuristic network scheduling model. This model was subject to biomass supply and demand constraints. Nilsson (1999) developed a dynamic simulation model to analyze the transport alternatives to supply straw from farming as a fuel for heating. It highlights the significance of transport costs in straw supply chains as this fuel needs to be collected and delivered from dispersed agricultural areas to intermediate storages before it is finally delivered to heating plants.

A life cycle analysis approach was proposed by Forsberg (2000) to calculate the environmental consequences of transporting biomass for energy from Sweden to Holland. This approach accounted for the inventory of emissions, such as CO_2 and NO_x, as well as other pollutants and particulate matters. They demonstrated that the use of biomass could provide net environmental benefits according to the aforementioned environmental criteria. Ravula et al. (2008) compared two policy strategies for scheduling the trucks in a biomass logistic system using a discrete event simulation model. The first policy was based on minimizing travel time and the second was based on the least-cost assignment of trucks, provided a sector-based regional distribution of them. They found that scheduling according to travel time leads to a lower total cost compared to sector-based contracts.

In summary, the transport phase in biomass supply chain is associated with various models developed in order to analyze the feasibility of the alternative routes, decide on the means of transport (types, their capacity and schedule), minimize supply chain costs and travel time, and to minimize the environmental impacts of supply chain activities.

2.5. Biomass energy conversion

In the conversion stage, decision makers need to deal with decisions as varied as location analysis for conversion facilities, conversion technology selection, and capital and operational planning of the conversion facilities.

In the realm of location analysis for conversion facilities, Velazquez-Marti and Fernandez-Gonzalez (2010) proposed a hybrid GIS-linear programming approach to identify the optimal (least-cost) locations for a network of bioenergy conversion factories given a pre-determined set of feasible locations. Zhang et al. (2011) proposes a two-stage approach to identify the optimal location for a biomass conversion facility in the Upper Peninsula of Michigan. In the first stage, a GIS model is used to identify the potential locations for this facility on the basis of the availability of transportation and distribution networks. In the second stage, the candidate locations are compared using a transportation model that estimates and combines the transport costs. The location associated with the least total transport cost is selected. In addition, Vera et al. (2010) developed a model that sought the best location for a biomass power plant, which would maximize a profitability index using an evolutionary optimization algorithm. Similarly, a nonlinear programming model is proposed that optimizes the net present value (NPV) of bioenergy production subject to alternative locations for an energy conversion facility (Rentizelas and Tatsiopoulos, 2010). Mixed integer linear programming models have also been widely used to identify the optimal locations of biomass power plants, dealing with 0–1 decisions on potential locations (Dyken et al., 2010: Leduc et al., 2010a,b; Bai et al., 2011; Kim et al., 2011b; Zhu et al., 2011). Through a comprehensive analysis of the various methods developed for optimal locating of biomass-to-biofuel conversion facilities, including their advantages and disadvantages, Johnson et al. (2012) have concluded that mixed-integer programming have been the most preferred approach for optimally locating a biofuel facility. Stochastic programming has also been used for location analysis of energy conversion facilities subject to uncertainties on biomass availability, energy demand, and transport costs (Kim et al., 2011a; Sodhi and Tang, 2009).

Conversion technology selection decisions also play a key role in structuring of biomass supply chains as it influences/constraints the choice of biomass materials, type of pre-treatment needed, capital and operational costs of the supply chain, and its environmental impacts (McKendry, 2002b). In this sense, You and Wang (2011) have developed a bi-objective multi-period mixed-integer liner programming optimization model with decisions on conversion pathways and technologies. The model takes into account life cycle costs and environmental performance (GHG emissions) as optimization objectives, identifying a range of suboptimal (compromised) least cost supply chain configuration solutions with an acceptable level of GHG emissions. Cameron et al. (2007) have developed a total cost minimization model for biomass-based power generation. They evaluated two alternative conversion technologies. One of the technologies has a higher capital cost but with a higher energy efficiency rate (biomass gasification) and the other has a lower capital cost but with a lower energy efficiency rate (direct combustion). The paper shows that for low cost biomass supply scenarios the low efficiency conversion option is more economic. However, for high cost biomass supply scenarios the high efficiency option should be selected despite higher capital costs.

In capital and operational planning of conversion facilities, Rentizelas et al. (2009) developed a nonlinear optimization model to maximize the investment yield of a bioenergy conversion facility in Thessaly–Greece, incorporating regulatory, technical and supply chain constraints. The main propose of the optimization model was to generate a biomass conversion capacity and operational plan that meets energy demand in the most economical way using multiple sources of biomass. Further, a game theoretic approach was used to identify equilibrium biomass conversion capacities (Nasiri and Zaccour, 2009). It has considered the interactions among different players of a biomass supply chain, such as the distributor, the facility developer and the farmer where price incentives and biomass quantities served as decision variables. Papadopoulos and Katsigiannis (2002) have developed a dynamic programming model to identify the optimum capacity and fuel mix of a proposed biomass CHP plant in the eastern Macedonian-Thrace region of Greece. To evaluate the impact of variability of biomass materials on the operational and environmental performance of bioenergy plants, a number of researchers have used discrete-event simulation models (Hall et al., 2001; Sims and Venturi, 2004; Mahmoudi et al., 2009). Alternatively, Mansoornejad et al. (2010) adopted a dynamic programming approach, maximizing the process flexibility of a biomass conversion facility in response to uncertainties in energy prices and demand. This recursive optimization is subject to decision variables on biomass materials/technology selection and constraints on conversion capacity, availability of capital and other feasibility criteria. Huang et al. (2010) have proposed a capacity and infrastructure planning model for bioenergy production facilities, which are subject to forecasts on future spatial and temporal variations in biomass sources and availability.

In summary, Fig. 2 presents a taxonomy of the models developed for biomass supply chain operations management.

3. Challenges and issues

On the basis of the existing literature regarding biomass supply chain modeling, certain issues and challenges have been identified. These issues could directly or indirectly influence the design and planning of biomass supply chain operations, manifesting the need to novel modeling approaches to address them. They have been classified into six categories technical, financial, social, environmental, policy/regulatory and institutional/organizational issues, as follows:

3.1. Technical and technological issues

Resource and supply chain efficiencies and process productivity are among the main technical/technological challenges of biomass supply chains:

A major challenge in biomass supply chains is to ensure that biomass is exploited in a resource efficient manner. There is evidence that biomass resources consumption for energy production is often performed without having a proper plan of replacement planting (McKendry, 2002a: Adams et al., 2011). Considering the seasonality of biomass, these inefficiencies could trigger future scarcities of biomass resources, hindering the resilience of biomass supply chains. In terms of feedstock supply, there exists a shortage of biomass supply for power plants. The current feedstock management systems are not able to meet the requirements of large scale bioenergy developments, because they are only designed for small-to-medium scale handling and logistics requirements (Hoogwijk et al., 2003).

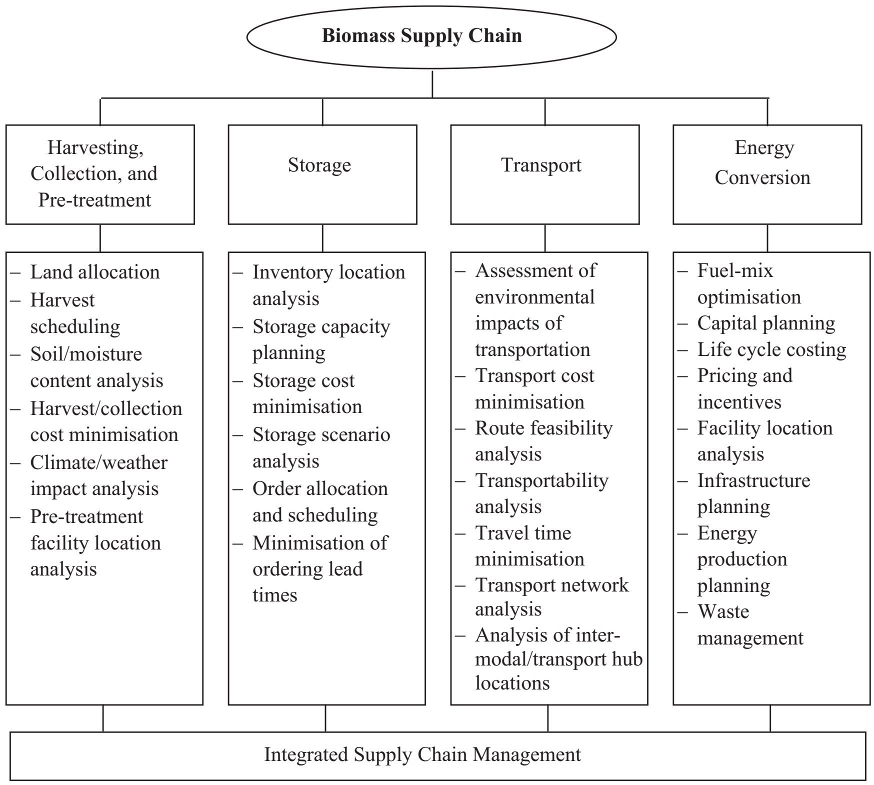

Fig. 2. A taxonomy of biomass supply chain operations management models.

In such circumstances, supply chain efficiency and careful inventory planning would become vital for the survival of large-scale biomass energy plants. From a supply chain efficiency perspective, it is also critical to choose a proper harvesting and collection plan, as well as to optimally locate bioenergy plants, considering factors such as the sources of biomass, transportation options and logistics costs. In addition, the configuration of biomass supply chains is very much depending on the choice between centralized (with a large conversion plant) and decentralized (with several distributed small plants) bioenergy production (Yilmaz and Selim, 2013). This poses a complex multi-phase location/technology/capacity/route analysis problem, optimizing for multiple conflicting objectives, which may lead to suboptimal solutions that require careful consideration of the tradeoffs among the objectives in order to identify a compromise solution (Cucek et al., 2012). From an inventory planning perspective, choosing a proper storage system according to holding costs and storage risks of different types of biomass, is a complex decision to make. It involves a large degree of uncertainty about the quality and quantity of biomass materials (Gold and Seuring, 2011; Kurian et al., 2013).

There is also concern about unproductive biomass conversion facilities. Among them are ineffective conversion techniques and a lack of proper maintenance planning of the physical assets and equipments (Saidur et al., 2011). The inconsistencies in quality and moisture content of biomass materials also contribute to unproductive conversion processes (Kurian et al., 2013).

It should be mentioned that from a sustainability perspective, the above exploitation and supply chain inefficiencies along with unproductive conversion facilities could remarkably offset and undermine the carbon efficiency gains of biomass energy production (Grant and Clark, 2010).

3.2. Financial issues

The capital intensity of biomass energy production has been cited as a key barrier of meeting energy demand in terms of the utilization of biomass resources (Rentizelas et al., 2009). This has created a thirst to bring down the operational costs of bioenergy production. It has been shown that a considerable share of these costs is associated with biomass supply chain comprised of harvesting, collection, storage, and transportation costs (Diamantopoulou et al., 2011). As the supply chain portion of costs is highly contingent upon the availability and type of biomass, the scale of delivery and the size and location of conversion facilities, arriving at a least cost supply chain design requires a life-cycle costing that integrates all steps of a biomass supply chain. In doing so, Frombo et al. (2009) have developed a three-stage linear programming model, optimizing for strategic, tactical, and operational costs of biomass supply chains. Similarly, Papapostolou et al. (2011) have suggested a mixed-integer linear programming model that optimizes the net income generated from a biomass supply chain while optimizing for the amount and timing of infrastructure investments, the quantities of biomass materials to be cultivated, and the energy production quantities, subject to constraints on biomass demand, land use, and water resources. It should be mentioned that spreading the risk of investment by diversifying the sources of revenues (by utilizing biomass to meet energy demand for electricity, heating and cooling) makes biomass supply chains more flexible to changes in energy demand but makes the supply chain planning process even more complex (Rentizelas et al., 2009).

Some of the other financial barriers that influence the performance of bioenergy supply chains are the uncertainty about the performance of emerging conversion technologies, uncertainty about the rates of return of bioenergy investments, uncertainties about the insurability of these investments, and the complex behavior of biomass markets due to volatilities in both energy and food industries (CEC, 2008; Saidur et al., 2011; Adams et al., 2011). In this sense, Gebreslassie et al. (2012) constructed a multiple objective stochastic optimization model, optimizing simultaneously the expected annualized costs (i.e. a levelized sum of capital and operational costs) and the financial risk of a biomass supply chain. The financial risk is captured by measuring conditional value-at-risk and downside risk objective functions. The paper concludes that having resource switching capabilities in biomass supply chains, where the source of biomass materials can change on the basis of a changing energy demand would reduce the financial risk when a least cost option is targeted. However, resource switching capabilities are subject to availability and technology constraints and feasibilities. Biomass materials have varied combustion characteristics and switching among them might require retrofitting the conversion facilities, which in turn, requires additional capital costs.

3.3. Social issues

Investment in renewable energy sources is linked to the creation of new jobs and employment opportunities in all stages of the biomass energy supply chain (Thornley et al., 2008). Social cohesion and stability, regional development, decrease in rural migration, increase in net labor income, and self-sufficiency in energy production were also observed as social benefits of the bioenergy (Krajnc and Domac, 2007). However, the lack of a participatory decision making in many bioenergy projects has led to conflicts with communities. This is due to the fact that the social benefits were not perceived locally and the negative impacts of biomass supply chains and power plants on local environments and land uses were not appropriately understood and mitigated (Upreti, 2004). In addition, a recent study concludes that, on average, there have been more occupational injuries and illnesses associated with the whole-life supply chain of biomass boilers than with that of conventional ones (Saidur et al., 2011).

Another social challenge in biomass energy supply chain planning and management is the minimization of possible conflicts with food supply chains (Tilman et al., 2009). The increase in biomass-for-energy plantation will reduce the amount of land available for agriculture. This situation is aggravated in recent years due to unparalleled government incentives to agriculture and bioenergy, favoring the latter (Ignaciuk et al., 2006). Some argue that biomass supply chains, if designed and planned improperly, could interfere with local and global supply chain of other goods and materials (by over pressuring an already overwhelmed transport sector) driving the prices of commodities further up (Pimentel et al., 2009). This may also contribute to increasing the traffic in rural routes, more traffic related accidents, more problems with staff retention in transport sector, higher rates of deterioration for roads and transport fleet, decreasing the esthetics of the countryside, and even causing higher rates of migration from certain rural areas.

Moreover, a pure focus on cost-effective biomass supply chains (favoring the economy of scale) could lead to overexploitation and removal of biomass materials to an extent that removes the self-sufficiency of communities by deteriorating their heating supply and, consequently, increasing their overall energy dependency and supply costs (Evans et al., 2010). It is suggested that if the type of biomass materials, targeted lands, and quantities of production are carefully selected (using comprehensive decision making models that take the life cycle impacts of biomass supply chains into the considerations), many of the associated social issues could be avoided (Koh and Ghazoul, 2008).

3.4. Environmental issues

One of the main drivers of promoting renewable energy use is its environmental benefits, such as reducing greenhouse gas emissions or using waste as a source of energy production. Therefore, it is very critical to ensure the sustainability of bioenergy production processes with respect to ecological services and land-use, emissions, resource efficiency and waste management (Banos et al., 2011; Nikolopoulou and Ierapetritou, 2012).

Some of the ecological challenges associated with biomass supply chains are loss of biodiversity, loss of natural habitats and wildlife, and soil degradation (Anderson and Fergusson, 2006; Awudu and Zhang, 2012). These consequences mainly stem from transportation activities and space requirements. Additionally there exists a considerable requirement for water resources and land (Awudu and Zhang, 2012). Obtaining feedstock from unsustainable sources is another considerable challenge (Adams et al., 2011; Saidur et al., 2011).

Biomass supply chain activities, from harvesting to production, are also attached to carbon emissions, which could be to an extent that offset the emission reduction benefits of switching to biomass (Charles et al., 2007). In particular, relying on overseas biomass supply could be associated with a significant amount of carbon emission as a result of biomass transport and may offset the expected carbon savings (Grant and Clark, 2010).

Mobini et al. (2011) have developed a discrete-event model to simulate the carbon emissions in forest biomass logistics. It identifies an equilibrium biomass delivery strategy balancing carbon emissions and supply chain costs. Zhang et al. (2012) developed an Arena-based simulation model (Arena, 2013) to not only estimate the total costs of biomass supply chain but also to account for the energy consumption and GHG emissions as a result of the supply chain activities. These criteria were then used to identify the optimal location of a biomass conversion facility in Upper Peninsula Michigan given nine alternative locations. Lam et al. (2010) proposed a clustering/zoning approach to map the carbon footprint profile of the alternative biomass supply chain routes (from the points of supply to alternative energy conversion locations). Elghali et al. (2007) have constructed a multiple criteria decision analysis framework for integrated sustainability assessment of biomass supply chain operations. It suggests a framework to assess the whole supply chain of bioenergy production facilities on the basis of GHG emission savings, resource efficiency, share of local biomass materials in energy production, opportunities for innovation, and stakeholders' participation in design and planning of the supply chain.

In the sense of the above studies, there is a need to adopt decision models capable of filtering routes and biomass sources that are less sustainable while optimizing for operational performance of supply chains (Rondinelli and Berry, 2000; Cai et al., 2009; Nasiri and Huang, 2009). This, in turn, needs a comprehensive understanding of the life cycle impacts of the biomass supply chain operations, which is hugely depends on the availability of quality data. This is itself a challenge as activities involved in biomass supply chains are greatly varied and diverse in terms of types of technologies, facilities, materials, and processes.

3.5. Policy and regulatory issues

The capital and operational performance of a biomass supply chain is affected by the policy measures and regulations in place to support renewable energy production, in general, and bioenergy, in particular. These support mechanisms are varied from indirect incentives or direct payments to renewable energy producers to the ones crafted to promote bioenergy production.

Fossil fuel tax has been practiced in many countries as an indirect way of supporting renewable energy (Berry and Jaccard, 2001). However, this tax is mainly imposed on transportation sector and does not provide support to biomass-to-electricity projects. In turn, this extra cost burden on transport sector could backfire and elevate the cost of transportation in biomass supply chains, lowering the commercial viability of some bioenergy production projects.

Further in the realm of policies related to the choice of fuels in transportation, we should mention renewable fuels standard (RFS) in the United States and the biofuel mandate in Europe. RFS is a US federal policy that places a minimum target on the share of renewable sources in transportation fuels. The goal is to have 36 billion gallons of renewable fuels blended into transportation fuels (EPA, 2013). Despite some benefits of RFS (such as decreasing dependency on fossil fuels and creation of jobs), there are some implications for biomass chains ranging from increased cost of biomass transport as a result of increased fuel prices to the surge in use of less sustainable forms of biomass (such as corn) for biofuel production. As a result, this policy is unintentionally discouraging the use of solid biomass for electricity and heat, and thus undervalues the associated supply chains. In Europe, since 2003, a similar mandate requires that at least 10% of transportation fuels come from biofuels (EU, 2003). Again, this mandate has lead to a surge in use (and importing) of soybeans and sugar cane for biodiesel production and similarly undervalued the use of solid biomass for electricity and heat. Now with new evidence on the actual environmental performance of food-based biomass (Searchinger et al., 2008), the European Parliament's Environmental (ENVI) Committee has recently voted on setting a cap on use of food-based biofuels, calling for more investment in use of solid biomass from non-food based plantation and agricultural residues (EU, 2013).

In electricity sector, setting preferential purchase prices for renewable energy (or feed-in-tariff policy) has been a major driving force behind the surge in biomass applications in electricity generation sector in Europe (Lipp, 2007). The downside of this direct financial support is that it may encourage the use of less sustainable and less economically viable biomass materials, and in particular, the import of biomass from overseas, opting for a highly carbon-intensive transportation (Charles et al., 2007). In the United States, implementing mandatory market shares (or targets) for renewable electricity (or renewable portfolio standard policy) has encouraged the utilization of renewable technologies that are closer to market saturation (REN21, 2007). In this mechanism, the choice of technology and energy prices will remain unregulated, creating a competitive market among renewable energy producers where each will aim at reducing its production costs (Nasiri and Zaccour, 2010).

In summary, to establish an integrated regional planning of biomass supply chains, national and local policy instruments should go beyond providing direct/indirect supports and instead encourage the competition in bioenergy sector and incentivize more sustainable supply chain solutions (Roos et al., 1999). Also, the focus of the existing supporting policies has been on the selection of technologies and less attention was paid to the selection of biomass materials (from sustainable sources). Moving in this direction will reduce the life cycle costs and environmental impacts of biomass supply chain processes and will increase the productivity of bioenergy production (Searchinger et al., 2008).

3.6. Institutional and organizational issues

When it comes to promotion of biomass energy, and in particular the performance of biomass supply chains, it is important to account for the role of institutional values, interests, and rules of parties involved (Costello and Finnell, 1998). Biomass supply chain parties (farming, inventories, transport, and conversion) may follow different ownership arrangements, standards, and organizational norms.

The farms supplying the biomass materials could be owned locally or internationally, creating varied supply priorities, attitudes toward supply chain risks, and decision making processes. Relying on community-owned biomass suppliers, it is vital to incorporate their preferences and attributes into biomass supply chain operational decision models, to ensure the continuity and efficiency of supplies (Altman and Johnson, 2008; Gold, 2011).

As a result of internationalization of biomass supply chains, there is also a key challenge with respect to acceptance and adoption of supply chain standards. There are no such standards to serve as operational benchmarks and to support decision making in biomass supply chains with information on types of biomass, quality assurance of materials and processes, selection of suppliers, and so on. Currently, the European Committee for Standardization is developing a series of standards on sustainable practices, that includes a sub-section on verification and auditing of biomass-for-energy supply chains (CEN, 2013).

The differences in organizational norms and cultures have also been cited as a key barrier in creation of institutional capacity and coordination among parties involved in biomass supply chains (McCormick and Kaberger, 2007). Seasonality of biomass supply, variation in types of biomass materials, and dynamism of energy markets requires that the organizations involved in biomass supply chains smartly perceive such uncertainties and response to change accordingly. However, change management practices in biomass supply chains are still in infancy. There is a clear need to adopt models capable of incorporating organizational preparedness (toward change and uncertainties) in biomass supply chain decisions to ensure operational agility and contingency (Christopher and Towill, 2001; Mafakheri et al., 2008, 2012).

A summary of the challenges and issues associated with biomass supply chain operations is presented in Table 1.

4. Future research

In light of the aforementioned challenges, a number of avenues for future research in modeling of biomass supply chain operations could be identified:

As biomass technologies are emerging, with a high pace of change, we are in need of adopting decision models that support technology selection under a changing technological environment and with respect to several dynamic criteria and constraints, such as price, the availability and reliability of suppliers, and environmental requirements (Shehabuddeen et al., 2006; Elhedhli and Gzara, 2008). Departing from case-based approaches, there is also a need for developing models that provide a more generic framework for estimations regarding the availability of biomass resources and their expected exploitation and supply chain costs (Esteban and Carrasco, 2011). Moreover, due to the volatility of biomass supply and demand, there is a need to develop inventory and fleet management models that are capable of addressing these uncertainties (Iakovou et al., 2010).

Despite the development of a range of models that address the issue of coordination in supply chains (Ayoub et al., 2007; Holweg and Pil, 2008; Mafakheri and Nasiri, 2013), this issue is widely neglected when it comes to biomass supply chains. An example would be Buchholz et al. (2009) who proposes a multiple criteria decision analysis approach to integrate the stakeholders' judgments on technical, financial, social, environmental, and regulatory issues surrounding biomass supply chains. However, the model is static and does not account for supply chain dynamism and uncertainties. Individual stakeholders are seeking to minimize their overall costs over time, and nevertheless, the energy supply and environmental requirements of a biomass supply chain can be optimized if there is coordination among various stakeholder groups. In this sense, there exists a gap with respect to the models capable of capturing the potential for cooperative decision-making with regard to biomass supply chains and the coordination of

Table 1
Summary of the challenges associated with biomass supply chain operations.

Challenges	Description of issues
Technical and technological	Unavailability of biomass Seasonality of biomass Inefficiencies of conversion facilities Infeasibility of large-scale production Conflicting decisions (technologies, locations, and routes) Complex location analysis (source points, inventory facilities, and production plants)
Financial	High capital costs (a thirst for operational savings) The limits for the economy of scale Unavailability and complexity of life cycle costing data Lack of infrastructural requirements Inflexibility to energy demand Risks associated with new technologies (insurability, performance, rate of return) Extended market volatilities (energy and food markets)
Social	Lack of participatory decision making Lack of public/community awareness Local supply chain impacts vs. global benefits Health and safety risks Conflicts with food supply chain Extra pressure on transport sector Decreasing the esthetics of rural areas
Environmental	Loss of biodiversity and natural habitats Soil overexploitation and degradation GHG emissions throughout the supply chain activities Excessive use of water Unavailability of data on environmental impacts
Policy and regulatory	Impact of fossil fuel tax on biomass transport Lack of incentives to create competition among bioenergy producers Focus on technology options and less attention to types of biomass materials Lack of support for sustainable supply chain solutions
Institutional and organizational	Varied ownership arrangements and priorities among supply chain parties Lack of supply chain standards Impact of organizational norms and rules on decision making and supply chain coordination Immaturity of change management practices in biomass supply chains

individual players' objectives towards a range of collective supply chain goals.

Reviewing the literature on biomass supply chain management, one can also find that there is a lack of approaches that focus on the management of stakeholder relationships and the resolution of potential conflicts (Gold and Seuring, 2011). This is of particular importance because, due to low energy density of biomass materials, several suppliers are often involved (Iakovou et al., 2010). In this regard, there is also a need to adopt decision models for selection of appropriate suppliers (Mafakheri et al., 2011; Tavana et al., 2012), given the fact that the environmental, social, and financial performance of a biomass supply chain highly relies on that of its suppliers.

For the purpose of bioenergy expansion in the EU, incentive schemes and funding opportunities should be developed to encourage farmers' to invest in energy crops (McCormick and Kaberger, 2007). In doing so, investigating the sensitivity of bioenergy investments and different incentive schemes can be of great value when it comes to orchestrating effective policies that encourage investment.

Additionally, as mentioned in review of challenges, there is currently a limited amount of research that focuses on the integrated socioeconomic-environmental evaluation of bioenergy production supply chains. Despite a substantial growth in the field of sustainable/green supply chains (for example, see Seuring and Muller, 2008), there is still a very limited number of models that deal with the critical issues of designing a sustainable biomass supply chain. Few consider environmental, social and economic aspects through an integrated approach (Iakovou et al., 2010).

Moreover, there is also a need to develop models that quantify the impact of biomass supply chains with regard to health and ecosystem protection (Hall and Scrase, 1998). This could be performed through a system analysis framework using System Dynamics (SD) modeling (He-rui et al., 2012). Such models could provide a holistic understanding by incorporating various components of a bioenergy production supply chain, including biomass resources, transport systems, conversion technologies and energy services, paying particular attention to their interactions over time (Gold and Seuring, 2011).

In the light of the policy and regulatory issues, there are still very limited research on the assessment of the impact of incentives and supporting policy choices on the capital and operational performance of biomass supply chains (Nasiri and Zaccour, 2009). This is of particular importance in transport and energy conversion components. The cost of biomass transport will increase with carbon/fuel taxes. The capacity (and production scheduling) of bioenergy generation facilities (with direct impacts on the whole supply chain) is defined in line with the market demand for bioenergy that is subject to the type and timing of supporting policies. In this regard, Cruz et al. (2009) proposed a modeling framework that incorporates intervention strategies in order to respond to fluctuation in bioenergy markets. Their model is simulated under a number of scenarios for market fluctuations and intervention-response strategies. There is also a need to further studies on how to address and prevent Bullwhip effect in biomass supply chains, where volatilities in energy demand will lead to significant fluctuations in upstream supply chain (harvesting, storage and transportation) activities (Tako and Robinson, 2012). If the outcome of such models could be coupled with and fed into the operational models of biomass supply chain, it can establish a comprehensive life cycle costing and asset management model for bioenergy production.

Reviewing the literature, one could also realize that there might be discrepancies between theoretical models and the existing practices in biomass industry. There are many models of supply chain operations in the literature that are developed out of the need in real problems, but it is actually the case that some models are presented and explored through only illustrative numerical examples. As a result, identifying the issues and challenges in adoption of theoretical models capturing biomass supply chain operations into real-world practices and the lessons learned from these applications remain as future research avenues.

5. Conclusions

Supply chain management is of significant importance when it comes to developing a successful bioenergy production system. In this paper, existing literature as well as challenges relating to design, planning and management of biomass supply chains were reviewed from a modeling perspective. Our review concluded that when it comes to modeling there is limited research about certain aspects of biomass supply chains.

Our gap analysis has identified a number of existing shortcomings and opportunities for future research. First, the impact of technological change and market volatilities have to be investigated through more sophisticated, albeit more generic, supply chain models, which are capable of incorporating the uncertainties and dynamism that are embedded in biomass supply chains. Second, there is a need for a more thorough investigation of the issue of stakeholders' coordination. Such investigation should aim to improve the collective performance of biomass supply chains and to resolve the potential conflicts. In addition, there is still little evidence about the extent of the impact of policy drivers and incentives regarding the design and management of biomass supply chains. Moreover, the practice of designing and managing a biomass supply chain in a sustainable manner is overshadowed by categorizing biomass as a renewable source of energy. There are research avenues in the development of models that integrate economical, societal, environmental, and regulatory aspects of biomass supply chain decisions.

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