Biomass Supply Chain Management for Energy Polygeneration Systems
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Abstract
The integration of renewable energy sources in existing energy polygeneration systems has clearly emerged as a promising policy towards enhancing the fragile global energy system with its limited fossil fuel resources, as well as for reducing the related environmental consequences. In this paper, we focus on the design and evaluation of sustainable biomass supply chain networks taking into account all major managerial and technological aspects in the context of existing energy systems. Two unique significant bottlenecks that hinder the increased biomass utilization for energy production compared to other renewable energy sources are the cost and complexity of its logistics operations, mainly due to the bulky nature of the products and their dispersed geographical distribution. Moreover, there are important factors that differentiate biomass from traditional supply chains, such as biomass product quality as this is dictated by the relevant energy production technology, weather related variability, localized agricultural capacity and seasonality, and stochasticity of demand. In this context, we propose a conceptual methodological framework that captures the complexity of the decision-making process for the design of biomass supply networks for contemporary energy polygeneration systems. We further map the existing research efforts within the proposed framework, which allows for the identification of existing gaps and overlaps, as well as for proposing future research areas.

Keywords: biomass supply chain management, decision-making, renewable energy sources, energy policy.

1. Introduction
Global energy consumption has been steadily increasing over the past few decades in response to population growth, economic development and life standard improvement throughout the world. Additionally, the usage of fossil fuels causes numerous environmental problems, such as atmospheric pollution, acidification and the emission of greenhouse gases. At the same time, fossil–fuel reserves are continuously shrinking, and its price is gradually
rising, posing challenges for decision makers in allocating energy resources/services within an energy management system. Thus, the integration of renewable energy sources within the contextual framework of existing energy systems has emerged as a promising policy.

Energy management systems are characterized by many factors such as the uncertain availability and properties of multiple resources, efficiencies of technologies and site-specific characteristics of locations. Moreover, many processes are linked to these systems, such as exploration/exploitation, conversion/processing, and supply/demand of energy resources. Such processes are undergoing dramatic changes, stemming from new regulations, re-urbanization, population growth, regional/community sustainable development, transportation shifts and economic expansion, resulting in significant effects on energy activities, socio-economy and environment (Cai et al., 2009). These changes also lead to a few novel features for energy management systems, including: (a) increasing concerns upon environmental impacts caused by conventional energy related activities, joined with rising interest towards renewable-energy-based technologies; (b) progressive advancement and implementation of regional/community sustainable development strategies; (c) frequent intervention of government through energy and environmental policies in order to mitigate emissions and maintain energy security and diversity.

Figure 1. Graphical Representation of an Integrated Energy System (Cai et al., 2009).
Cai et al. (2009) demonstrate the complexity of contemporary renewable energy systems, and thus the challenges of the relevant decision-making (Figure 1). Four types of technologies with different efficiencies, accessibilities and emission ratios are considered in the system, including, (a) supply technologies, including those for exploring/mining and producing energy carriers, such as coal, oil and natural gas; (b) electric conversion technologies, including those for converting fossil fuels, renewable and nuclear energies into electricity; (c) process technologies, including those for transforming energy resources into fuels such as gasoline, diesel and alcohol; (d) end-user technologies, including those transferring various energy carriers to end-user consumptions, such as lighting system, furnace, refrigerator and vehicle. The authors develop a large scale linear programming model for allocating energy activities/resources with minimized economic costs.

In this context, biomass utilization (including vegetation, energy crops, as well as biosolids, animal, forestry and agricultural residues, the organic fraction of municipal waste and certain types of industrial wastes) has emerged among others as a viable alternative for energy production, encompassing a wide range of potential thermo-chemical, physicochemical and bio-chemical processes. Its appeal is due to its potential worldwide availability, its conversion efficiency and its ability to be produced and consumed on a CO₂-neutral basis. Many research efforts document the current and potential role of biomass in the future global energy supply (e.g. Parikka, 2004; Yamamoto et al., 2001). Theoretically, the total bio-energy contribution (combined in descending order of theoretical potential by agricultural, forest, animal residues and organic wastes) could be as high as 1100 EJ, exceeding the current global energy use of 410 EJ (Hoogwijk et al., 2003). However, a careful analysis of all the related literature reveals that there is no consensus regarding the biomass potential among the researchers, but rather their assessments differ strongly.

Two unique significant bottlenecks that hinder the increased biomass utilization for energy production compared to other renewable energy sources are the cost and complexity of its logistics operations, mainly due to the bulky nature of the products and their dispersed geographical distribution. Moreover, there are important factors that differentiate biomass from traditional supply chains, such as biomass product quality as this is dictated by the relevant energy production technology, weather related variability, localized agricultural capacity and seasonality, and stochasticity of demand. To this end, supply chain management bears the challenge to develop efficient policies adapted to an uncertain environment and subject to additional local and inter-regional conditions and constraints, such as the existing
infrastructure, geographical allocation of collection areas, the current regulatory and techno-economic environment, and competition among consumers.

Specifically for energy production from biomass a number of issues critical for all involved stakeholders, such as potential investors, involved regulators and decision-makers need to be tackled, namely:

- Is it financially feasible to develop a biomass energy production system?
- Which are the unique characteristics of biomass supply chains that differentiate them from conventional networks?
- Which decisions should be made on the strategic, tactical and operational levels for developing biomass supply chain networks?
- Which kind of policies are required to achieve bio-energy systems’ sustainability?

In this paper, we propose a conceptual methodological framework that captures the complexity of the decision-making process for the design of biomass supply networks for contemporary energy polygeneration systems. Specifically, in Section 2 we present the generic system components along with the unique characteristics of Biomass Supply Chains (BSCs) that differentiate them from traditional supply chains. Following that, we recognize the natural hierarchy of the decision-making process and propose an integrated methodological framework that spans all levels of the hierarchy (Section 3). We then provide the existing research efforts within the proposed framework in order to identify gaps and overlaps. Finally, we wrap-up with summary and conclusions in the last Section.

2. Biomass Supply Chains

The structure of the global market for biomass and the associated supply chains is evolving quite dynamically. Traditionally, biomass has been used for energy (mainly thermal) production in areas close to its production sites. However, an emerging practice for energy producers is to procure biomass from several suppliers in order to develop the critical mass necessary for the justification of an energy production facility. The increased complexity of this system dictates the need for developing sophisticated customized supply chain planning and coordination methodologies as opposed to the well explored traditional supply chain management (e.g. Meixell and Gargeya, 2005; Min and Zhou, 2002; Sarmiento and Nagi, 1999; Vidal and Goetschalckx, 1997).
Biomass Supply Chains (BSCs) for energy production are comprised in general of four general system components: (i) Biomass harvesting / collection (from single or several locations) and pre-treatment, (ii) storage (in one or more intermediate locations), (iii) transport (using a single or multiple echelons) and (iv) final conversion (Figure 2).

BSCs possess several distinctive characteristics that differentiate them from traditional supply chains. Firstly, agricultural biomass types are usually characterized by seasonal availability, thus dictating the need of storing large amounts of biomass for lengthy time periods, which in turn leads to high inventory holding costs during the year-round operation of a power plant. Moreover, weather related variability and competing uses of waste biomass in a dynamically changing market have to be considered when determining the flows of the material supply network. The complexity of biomass supply chains is even higher for perishable products, as perishability constrains severely both the acceptable transportation lead times and the length of storage time. Furthermore, most forms of biomass tend to have a relatively low energy density per unit of mass compared with fossil fuels. This often makes handling, storage and transportation more costly per unit of energy carried. In addition, BSCs need to be robust and flexible enough to adapt to unpredictable changes in market conditions, as the demand of the
produced energy depends on the type of the conversion facility and / or the price of competitive fuel substitutes.

3. A Hierarchical Decision-making Framework

The design and planning of BSCs for energy polygeneration systems involve a complex hierarchy of decision-making processes. BSCs are characterized by significant additional supply and demand uncertainty, as well as by perishable and often bulky, seasonal products. Furthermore, BSCs’ planning models should be able to capture issues such as harvesting practices, marketing channels, logistics activities, vertical coordination and risk management. Actually, few of these issues emerge as critical in the supply.

In Figure 3 we display the hierarchy of decision-making process for the design and planning of BSCs. We also discuss all the decisions and present a review of related research efforts as these are mapped on the strategic, tactical and operational levels of the hierarchy.

3.1 Strategic Decision-Making

Decisions at the strategic level of the hierarchy concern all stakeholders that are interested in investing / developing energy production plants that would be supported by a supply chain network of biomass-type sources.

Thus, decisions at this level include: contractual agreements with suppliers and consumers for developing the critical mass necessary for the investors, sourcing and utilizing a single or multiple types of biomass for energy production, location and capacity of energy conversion facilities, location of storage facilities, and balancing the financial and environmental impact. Below, these decisions are discussed further, while the relevant research works are properly taxonomized.

3.1.1 Supply and Demand Contracts

The global biomass energy regulatory environment is comprised out of a web of various regulatory interventions and stimulation measures, such as governmental R&D programs, tax cuts and exemptions, investment subsidies, feed-in tariffs for renewable electricity and mandatory blending for biofuels or biofuel quotas. However, these measures are mostly myopic in nature, and they lack the cohesiveness of a stable environment that would encourage investors. Similarly, sufficient biomass resources and a well-functioning biomass market that can assure reliable, sustainable, and lasting biomass supplies are crucial preconditions for the development of sustainable bioenergy systems.
Van Dam et al. (2005) discuss policies for securing renewable resource supplies for changing market demands in a bio-based economy. The authors suggest that the development of a sustainable bio-based economy requires a joint effort from the agricultural sector, industries, governments and consumer organizations, fully utilizing the available scientific infrastructure and multidisciplinary expertise. Junginger et al. (2006) examine the opportunities and barriers in the context of securing sustainable bio-energy trade. A detailed analysis is carried out by Koopmans (2005) to determine the sustainability of biomass energy demand and supply in sixteen Asian countries. Nagel (2000) points out that as a result of the lower fossil fuel prices and the higher investment and operating costs of biomass-fired plants, the energy use of biomass is case-dependent.

The author further documents that different factors can improve the economic viability of bio-energy systems, especially fuel prices/rates of fossil and biogenic fuels, sales of biogenic produced electricity, the investment costs for biomass-fired heating plants as well as co-generation plants. McCormick and Kåberger (2007) propose strategies including policy measures for altering the economics of bio-energy pilot projects to support the learning processes and offer guidance for network building and supply chain coordination.

An essential step in proceeding with the often large investment necessary for developing biomass conversion facilities is the assurance of an uninterrupted supply of adequate biomass, as well as the critical mass of demand over the strategic horizon. To that end, contractual agreements that guarantee long-term supply and demand, while spreading “equitably” total profit among the supply chain partners from agriculture and forestry to energy consumers can

Figure 3. A Methodological Decision-making Framework.
be of great value. Various supply chain contract models have been presented in the literature, which differ based on the contractual clauses between buyers and sellers (Tayur et al., 1999). Several researchers in the field of agricultural science discuss contracting with farmers, such as Hovelaque et al. (2009), Key and MacDonald (2006), Kumar et al. (2002), Ligon (2003), Mathews (2008), Poole et al. (1998), Roumasset and Lee (2007) and Roumasset (1995) discuss and propose methods for estimating the monetary value of agricultural residues used as biofuels, defining the minimum amount that a farmer has to be paid as well as the upper limit up to which the energy end-user can pay for the agricultural residues.

3.1.2 Network Configuration

The design of logistics network is one of the most comprehensive strategic decision problems that need to be optimized for the long-term efficient operation of BSCs. The configuration of BSC networks is comprised of critical decisions that affect the biomass flow and the associated costs. These refer to sourcing, procurement of a single or multiple types of biomass, purchasing quantities from each supplier, allocation and capacity of intermediate warehouses and location of energy conversion facilities, while taking into account key parameters such as the capacity limit of supply nodes or the potential fixed capacity of an existing power plant.

The objective is to design or reconfigure a logistics network so as to minimize annual system-wide costs, including harvesting, collection or purchasing costs, facility (storage, handling and fixed) and inventory holding costs, and transportation costs, subject to variety of service level requirements. The capacities and allocations decided at the strategic level then become constraints for the aggregate planning that takes place at the tactical decision-making level. However, the supply chain configuration not only has to be efficient with respect to the expected conditions, but also robust and flexible enough to adapt to potential changes in these conditions.

**Sourcing.** The rather dispersed geographical distribution of significant biomass potential has raised the interest of researchers who aimed at first identifying the available biomass quantities over a region and then proceed with the selection of the optimal biomass sources. Skoulou and Zabaniotou (2007) conduct a bibliographic research to gather information about the available agricultural residues and animal wastes in Greece, and update their data through interviews with supervisors of related local authorities, such as the Ministry of Central Macedonia and the National Center of Renewable Energy Sources. Geographical Information
Systems (GIS) have been widely used for the evaluation of the biomass supply and characteristics, the selection of collection sites, or even the estimation of the transportation cost to existing power plants. For example, Voivontas et al. (2001) propose a GIS-based decision supporting tool to identify the geographic distribution of the economically exploited waste biomass potential for power production. Noon and Daly (1996) estimate the costs for supplying wood fuel to any one of its twelve coal-fired power plants, and Singh et al. (2008) make an attempt to evaluate the spatial potential of biomass and a mathematical model for collection of biomass in an Indian state. Other studies assess the manure potential for energy production (Batzias et al., 2005; Dagnall et al., 2000; Ma et al., 2005). Ramachandra et al. (2004) propose a Decision Support System for regional biomass assessment; land use analyses were carried out using GIS. Kinoshita et al. (2009) address the widespread adoption of woody biomass energy by presenting a cost model to identify cost-effective harvesting methods. The authors conducted a spatial evaluation of forest biomass usage using a geographic information system (GIS) for a specific Japanese region.

An important strategic decision is whether it is more meaningful to utilize multiple types of biomass for energy production or simply a single type. The exploitation of various types of biomass from different sources has captured the attention of researchers. The work by Nilsson and Hansson (2001) is indicative of the cost reduction potential of the multi-biomass approach. The authors investigate the simultaneous use of straw and reed canary grass and conclude that the specific combination led to a total system cost reduction of about 15–20% compared to a single-biomass case, despite the increased production cost of reed canary grass compared to straw. The cost of producing energy using all the available biomass types in a certain region is determined by Voivontas et al. (2001). A case study for utilizing multiple forest biomass types for local district heating applications is presented by Freppaz et al. (2004), using GIS for logistics modeling. De Mol et al. (1997) study the multiple-biomass approach and discuss the benefits of employing an optimization - instead of a simulation - model to decide the optimal mixture of biomass types. Moreover, Hamelinck et al. (2005) acknowledge in their study the need for widening the operational window of biomass logistics by combining multiple biomass chains to minimize the share of capital costs. Frombo et al. (2009) develop an Environmental Decision Support System in which the woody biomass resources are partitioned into forest and non-forest resources. Rentizelas et al. (2009b) argue that the multi-agricultural biomass approach appears to be attractive for systems where expensive storage solutions are used, in order to reduce the storage space required.
Location of Energy Production Facilities. Identifying location and capacity of energy production facilities have attracted the interest of several researchers which tend to favour GIS-based methodologies. Panichelli and Gnansounou (2008) develop a methodology that employs a GIS-based approach combined with a biomass allocation algorithm for selecting suitable energy facilities location. Graham et al. (1997) examine the effect of location and facility demand on the marginal cost of delivered wood chips from energy crops. Shi et al. (2008) evaluate the feasibility of setting up new biomass power plants and optimizing the locations of plants in a region of China. Zhan et al. (2005) investigate the economic feasibility of locating a switchgrass-to-ethanol conversion facility in the state of Alabama. Another tool for locating conversion facilities is proposed by Papadopoulos and Katsigiannis (2002), while considering economic criteria for assessing the sustainability of the installation. Tembo et al. (2003) develop a mixed integer-programming model to determine the most economical source of biomass and the optimal biorefinery location that maximizes net present profit for a biomass-to-ethanol system. A methodology for the optimization of the installation of new biomass energy systems on a regional level is presented by Dornburg and Faaji (2001).

Capacity of Energy Production Facilities. An analytical framework for determining the optimal power plant size and developing of supply curves is presented by Gan (2007). Jenkins (1997) and Nguyen and Prince (1996) discuss the optimal sizing of a biomass utilization facility. The related power cost and optimum plant size for power plants using three biomass fuels in western Canada are examined by Kumar et al. (2003). Bakos et al. (2008) develop an ‘energy-planning’ model that determines the number of biomass-fuelled power installed in a given area based on available biomass from agricultural residues in the island of Crete, Greece. Celma et al. (2007) study the waste-to-energy possibilities of the industrial olive and wine-grape by-products in Extremadura, whereby specific costs are analyzed assuming the products’ use in a centralized power plant, while taking into account logistics components. Freppaz et al. (2004) develop a Decision Support System for locating plants and computing their optimal capacity. Nagel (2000) formulates a mixed integer linear programming model to determine whether to construct or not a district heating network, a heating plant or a co-generation plant using information regarding the consumers’ annual heat consumption, as well as its seasonal distribution.

Location of Storage Facilities. Designing the location of storage facilities is another critical decision for the design of a BSC. In the case of biomass that is harvested over a relatively
short period of the year, such as straw and short rotation coppice, large quantities need to be stored in order that the supply of fuel is spread evenly on a year-round basis. This requires storage facilities that can be located on the farm/forest, at the conversion facility or at an intermediate site.

Certain authors examine the option of on-field biomass storage (Allen et al., 1998; Cundiff et al., 1997; Huisman et al., 1997). This storage-method has the advantage of low cost. However, biomass material loss is significant and biomass moisture cannot be controlled and reduced to a desired level, thus leading to potential problems in the power plant equipment. Moreover, the farmers may not allow on-farm storage of the biomass for a significant time period, as they may want to prepare the land for the next crop (Sokhansanj et al., 2006). Finally, health and safety issues exist due to increased moisture (Allen et al., 1998; Nilsson and Hansson, 2001).

Various studies consider the use of intermediate storage locations between the fields and the power plant (Allen et al., 1998; Nilsson and Hansson, 2001; Tatsiopoulos and Tolis, 2003). This storage scheme results in a higher delivered cost than a system in which there is only one road transport movement, as it requires that biomass material has to be transported first from farm/forest to the intermediate storage facility/facilities and then from storage to the conversion facility.

Finally, the option of settling the storage facility next to the biomass power plant has also been examined by several authors (e.g. Papadopoulos and Katsigiannis, 2002; Tatsiopoulos and Tolis, 2003). Papadopoulos and Katsigiannis (2002) present an innovative storage layout with biomass drying capability using dumped heat from the power plant. This concept aims at reducing faster the biomass moisture content and prevents material decomposition as well as fungus and spores formation. Using storage facilities attached to the power plant is the only viable option of accelerating the drying process of the biomass, as dumped heat may be used without need for extra energy consumption. However, most power stations or other energy production facilities to which biomass is supplied have limited on-site storage facilities, mainly due to the space required to stock large quantities of seasonal products that bears the physical and financial costs of holding stock (Allen et al., 1998). In this case, inventory management should be effective enough in order to ensure that a few days of supply are available on-site with low risk of stock-out.

Rentizelas et al. (2009b) compared the above mentioned three biomass storage solutions found in the literature, in terms of total system cost. The authors suggest the development of a multi-biomass system, i.e. the exploitation of various types of biomass or/and from different
sources, aiming at reducing the storage space requirements. Another study has also proved that the multi-biomass concept may lead to significant system cost reduction (Nilsson and Hansson, 2001). Detailed description of storage methods as well as data for the cotton biomass behaviour and composition during and after each one of these procedures can also be found in McGowin and Wiltsee (1996) and Huisman et al. (2000).

**Network Design.** Several authors study the design of biomass supply chains. An optimization model has been developed by De Mol et al. (1997) to optimize the network structure and the mixture of biomass types supplied to the energy plant. Rentizelas et al. (2009a) develop a simulation and optimization model to maximize the net present value of the investment for bio-energy supply system’s lifetime; decision variables include the location and capacity of the bioenergy facility, as well as the types and optimal quantities of biomass that have to be procured. Tatsiopoulos and Tolis (2003) present a comparison for cotton-stacks supply chain methods and examine the challenges that arise while trying to organize an integrated logistics network. Economic aspects of other logistics procedures like collection and warehousing are also investigated. Gronalt and Rauch (2007) describe a novel approach for configuring a wood biomass supply network for a certain region, providing their evaluation method for designing regional forest fuel supply networks. Frombo et al. (2009) develop an Environmental Decision Support System (EDSS) and present its application for agro-forest biomass use for energy production at a strategic level. They assume that the plant location is fixed and the variables to be optimized are the plant capacity and the quantity of material to be harvested at a specific location.

### 3.1.3 Ensuring Sustainability

Sustainability of logistics operations is a critical issue that has to be taken into account when designing and executing biomass supply chain networks for energy production. To that end, Forsberg (2000) presents a biomass distribution system investigating the resulting environmental load profiles of several bioenergy chains. Hamelinck et al. (2005) compare a variety of supply chains including transport of raw biomass (logs, bales, chips), refined biomass (pellets, pyrolysis oil) and high-quality liquid biofuels (methanol). They developed a spreadsheet model to enable a techno-economic analysis of the supply chains under study, estimating the relevant energy use and CO2 emissions. Frombo et al. (2009) developed a linear programming model to define the optimal conversion plant size and the harvested biomass quantities of a specific supply chain, in which the plant location is fixed and various
technological options could be employed; thus, the model could be used for comparing combustion, gasification, and pyrolysis processes on the basis of both economic and environmental impact.

Elghali et al. (2007) propose a sustainability framework for the assessment of bioenergy systems to provide practical advice for policy-makers, planners and the bioenergy industry, using multi-criteria decision analysis. Several other studies have recently been published, addressing the critical issue of designing and evaluating sustainable supply chains, in which profitability and environmental impacts are balanced (Linton et al., 2007; Neto et al., 2008; 2009).

3.2 Tactical and Operational Decision-Making

As decision-making on the tactical and operational level for BSCs is quite similar to those of traditional supply chain management, the related discussion here is in brief. At the tactical level decisions include medium-term decisions such as aggregate planning, inventory management, fleet management and selection of collection, storage, pre-treatment and transportation methods. At the operational level day-to-day decisions are encountered such as inventory control, vehicle planning and scheduling or second-stage pre-treatment operations within power plant facilities.

3.2.1 Aggregate Production Planning

Aggregate production planning in BSCs deals with the tactical determination of production, inventory, and work force levels for meeting energy demand requirements over a mid-term planning horizon. Computational stochastic simulation models have been developed for exploiting forest-biomass (Gallis, 1996), cotton residue (Gemtos and Tsiricoglou, 1999) and herbal biomass (Huisman et al., 1997). De Mol et al. (1997) present a simulation - optimization model to calculate energy consumption and cost to transport biomass from its source to its conversion plant. Cundiff et al. (1997) designed a biomass delivery system that considers systems-related issues associated with the harvest, storage, and transport of herbaceous biomass from on-farm storage locations to a centrally located plant. A dynamic simulation model for baling and transporting wheat straw by Nilsson analyses a hypothetical straw-to-energy system for district heating plants in Sweden (Nilsson, 1999a; Nilsson, 1999b). Dornburg and Faaij (2001) developed a mathematical model which analyses and processes past data of biomass distribution cases using linear or exponential regression models in order to predict and solve a similar biomass distribution problem. Hansen et al.
(2002) developed a simulation model of sugar cane harvest and mill delivery in South Africa, whereas Tatsiopoulos and Tolis (2003) simulated the supply of cotton waste to small decentralized combined heat and power plants in Greece. The authors investigate several combinations of transportation and storage methods along with different conversion plant capacities to provide a comprehensive analysis of relevant costs. Moreover, Sokhansanj et al. (2006) simulated the flow of biomass from field to a biorefinery; a framework was developed for a Dynamic Integrated Biomass Supply Analysis (IBSAL) model to quantify resource allocations (such as labour, equipment and structure) for biomass supply and transport operations, and calculate total system cost. Kumar and Sokhansanj (2007) later used this model to compute the cost of collecting switchgrass from the field, storing it, and delivering it to a biorefinery using several collection and transportation options.

**Inventory Management and Control.** Only a few research papers address inventory management and control (Gallis, 1996; Tatsiopoulos and Tolis, 2003; Tembo et al., 2003). The unique characteristics of biomass logistics systems are addressed in three other studies, investigating strategically the interdependencies among them and their effect on supply chain efficiency and cost (Caputo et al., 2005; Hamelinck et al., 2003; Hamelinck et al., 2005). Furthermore, Allen et al. (1998) address the supply chain considerations and costs of using biomass fuel on a large scale for electricity generation at power stations, recognizing the importance of logistics planning and management facets.

**Fleet Management and Vehicle Scheduling.** Ravula et al. (2008b) simulated the transportation system of a cotton gin, using a discrete event simulation model, to determine the operating parameters under various management practices, while they provide a comparison between two policy strategies for scheduling trucks in a biomass logistics system (Ravula et al., 2008a).

### 3.2.2 Selection of Collection, Storage and Pre-treatment Processes

The selection of the right processes for the collection, the storage and the pre-treatment are tactical decisions that the researchers have studied for specific biomass raw materials, such as switchgrass (Cundiff and Marsh, 1996), forest fuel (Eriksson and Björheden, 1989), cotton plant residues (Fischer and Gaderer, 2000; Gemtos and Tsiricoglou, 1992), herbaceous biomass in general (Cundiff and Grissio, 2008), logging residue (Nurmi, 1999) and corn stover (Shinners et al., 2007). McGowin and Wiltsee (1996) analyze several biomass treatment methods. Huisman et al. (2000) provide a generalized comparison of bale storage systems for
biomass, whereas Rentizelas et al. (2009b), after reviewing relevant research, analyze three different biomass storage methods.

During the harvest process some of the decisions that need to be made include the timing for collecting the crops from the fields and the identification of the necessary capacity. Additional decisions include the scheduling of equipment, labor, and transportation equipment. Jiao et al. (2005) present a harvest-scheduling model for a region in Australia with multiple independent sugar cane fields. Recio et al. (2003) embed a mixed integer program into a decision support system (DSS) that provides detailed plans for farmers’ activities such as crop selection, scheduling of field tasks, investment analysis, machinery selection and other aspects of the production process. Higgins and Neville (2002) propose models for dealing with operational decisions for scheduling harvesting operations. Ferrer et al. (2008) obtain the optimal scheduling of the harvest of wine grapes using a linear programming model with the objective of minimizing operational and grape quality costs.

Another tactical level critical decision is the most effective timing of the material’s pre-treatment and specifically, whether it will take place before or after its transportation (e.g. production of wood chips, pellets and other compressed forms to facilitate the transportation and storage of biomass). Finally, De Mol et al. (1997) present a cost minimization mathematical model that determines biomass flows in multi-biomass supply chain networks, and further investigate the technical and economical feasibility of pre-treatment for the optimal network instance.

4. Summary and Conclusions

Logistics and supply chain management are areas of critical importance for the successful energetic utilization of biomass. Stakeholders involved in both the design and the execution of such BSCs need to address systemically an array of decisions spanning all levels of the natural hierarchical decision-making process. To that effect, we presented the generic system components along with the unique characteristics of Biomass Supply Chains (BSCs) that differentiate them from traditional supply chains. Following this, we proposed a conceptual methodological framework that captures the complexity of the decision-making process for the design of biomass supply networks for contemporary energy polygeneration systems. We further mapped the existing research efforts within the proposed framework.

Our analysis demonstrates that biomass-to-energy production is a rapidly evolving research field focusing mainly on biomass-to-energy production technologies. However, very few studies address the critical supply chain management issues, and the ones that do that, focus
mainly on (i) the assessment of the potential biomass and (ii) the allocation of biomass collection sites and energy production facilities. We envision the developed framework to provide systemic guidance for researchers and practitioners alike, in their evolving efforts towards investigating the design and planning of efficient BSC networks.

References


