Modelling of Agricultural Waste Biomass Supply Chains for Energy Production

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Abstract
The development of renewable energy sources appears as a meaningful initiative for enhancing the fragile global energy system with its limited fossil fuel resources as well as for reducing the numerous related environmental problems. Amongst others biomass emerges as a viable alternative for energy production. However, one of the most important barriers in increased biomass energetic utilization is the cost of its respective logistics operations. What differentiates biomass supply chains (BSCs) from other supply chains is the significance of factors such as product quality as related to energy production technology, weather related variability, localized agricultural capacity and seasonality, and stochasticity of demand.
In this work, we present a holistic approach that takes into account the major aspects in the design and aggregate planning of agricultural waste BSCs developed for energy production. We propose a modelling framework that captures the complexity of the decision-making process for the design and operation of sustainable, competitive and reliable bio-energy networks, while tackling jointly strategic and tactical decisions. An extensive critical literature review of quantitative-based biomass supply chain modelling efforts is presented and through our analysis, we diagnose some of the future requirements for modelling biomass supply chains. Finally, we sum up with conclusions and suggest areas for future research.

Keywords: biomass logistics, biomass supply chain management, aggregate planning, energy production

JEL Classification: Q2, Q4, O21

Introduction

The development of renewable energy sources appears as a meaningful initiative for supporting the fragile global energy system with its limited fossil fuel resources as well as for reducing the numerous related environmental problems, such as atmospheric pollution, acidification and the emission of greenhouse gases (Goldenberg, 2000; Richardson and Verwijst, 2007). Clearly, biomass utilization emerges as a viable alternative for energy production (Veringa, 2006). The different sources of biomass can be used for different applications by different methods (Jäger-Waldau and Ossenbrink, 2004), but primarily they are utilized for energy production. Energy production from biomass represents an important element within a European Union's energy plan based on renewable resources which calls for an increase in the proportion of RES in the primary energy supply from 6% (1996) to 12% (2010) (European Commission, 1996). Several studies have been performed to forecast the contribution of biomass in the future energy supply, both at a regional and at a global level, as for example in references (Berndes et al., 2003; Yamamoto et al., 2001; Parikka, 2004).

One of the most critical bottlenecks in increased biomass utilization for energy production is the cost of the respective logistics operations. The rising demand for biomass and the increasing complexity of the multi-level involved supply systems outline the need for comprehensive biomass supply chain management (SCM) approaches. The requirements with respect to biomass supply in terms of quality and quantity can differ substantially, depending on the energy demand trends, the energy production technology, the end use of the power generated and, at the same time, on the cost-efficiency and feasibility of its logistics operations. Certain parameters can also limit the effectiveness of biomass production systems including localized agricultural capacities and seasonalities. To that end, SCM bears the challenge to develop solutions adapted to uncertain parameters, taking into account additional local and inter-regional conditions and constraints, such as the existing infrastructure, geographical allocation of collection areas and/or competition among several consumers.

This paper focuses on major aspects of the design and aggregate planning of waste biomass supply chains (BSCs) developed for energy production. At first, the supply chain components and the distinctive characteristics of such networks are summarized, while the decision-making process for the design and planning of sustainable, competitive and reliable bio-energy networks is addressed. Following we discuss advanced supply chain planning systems and provide an extensive critical literature review of quantitative-based biomass supply chain modelling efforts. The models are classified according to relevant features, such as the optimization approaches used, the type of biomass studied and the stochasticity of parameters, among others. Finally, we sum up with conclusions and suggest areas for future research.

Planning models for biomass supply chains: A review

Biomass supply chains

Biomass supply chain networks for energy production encompass five general system components: biomass collection (from single or several locations), pre-treatment (in one or more stages), storage (in one or more intermediate locations), transport (using one or multiple transportation means across a number of consequent echelons) and energy conversion.

Biomass supply chains present several distinctive characteristics that diversify it from a typical supply chain. Specifically, agricultural biomass types are usually characterized by seasonal availability (Skoulou and Zabaniotou, 2007) and thus there is a need of storing large amounts of biomass for a significant time period, if year-round operation of the power plant is desired. The multi-biomass approach, as long as products have similar characteristics and fuel properties, may smooth significantly problems that stem from seasonality (Rentizelas et al., 2009b). Biomass is also characterized by low-density, leading to increased transportation and storage requirements, customized collection and handling. Other important characteristics of such products include limited shelf life, demand and price variability, weather related variability, which make the underlying supply chain more complex and harder to manage. This complexity of biomass supply chains is even more critical for perishable biomass products, where the transportation time of the products through the supply chain and the opportunities to use inventory as a buffer against demand and transportation variability are severely limited. This complexity is compounded when the supply chain encompasses two or more countries.

Theoretically, a large number of bioenergy chains can be envisioned. It is important to obtain insights in the effects of all logistics variables on the total cost and energy consumption of bioenergy chains. This would allow for the identification of best configurations for bioenergy supply systems, as well as improvement options. The key variables of biomass logistics systems have been identified in specific studies, investigating strategically the interdependencies between them and their effect on supply chain efficiency and cost (Mitchell et al., 1995; Allen at al., 1998; Nilsson and Hanson, 2001; Hamelinck et al., 2005; Caputo et al., 2005). Their analysis could support strategic and tactical decision-making on biomass supply chains.

Background of BSCs planning and modelling approaches

The structure of global market for biomass and the associated supply chains is not static. On the contrary, a drastic transformation is currently undergoing. Traditionally, biomass has been used for energy (mainly thermal energy) production in areas of close proximity to its production areas. However, an emerging practice for energy producers is to purchase biomass from several suppliers (sometimes by importing it) to build the necessary critical mass for building an efficient energy production facility. The increasing complexity of this system implies a need for adopting more sophisticated supply chain planning and coordination methodologies that have been successfully used in traditional supply chains. For instance, the academic and practice-oriented literature on increasing the efficiency of supply chains is ample (see e.g. Vidal and Goetschalckx, 1997; Sarmiento and Nagi, 1999; Min and Zhou, 2002; Meixell and Gargeya, 2005).

However, implementing well-established supply chain practices to BSCs is not easy, since biomass supply chain is characterized by significant supply and demand uncertainty, as well as by perishable, often bulky, seasonal products. Thus, in order to adequately plan the operations in BSCs it is necessary to formulate specific planning models that incorporate issues such as harvesting policies, marketing channels, logistics activities, vertical coordination, and risk management, similar to issues regarding fresh agricultural products (Epperson and Estes, 1999).

Assessing BSCs for bio-energy production involves a complex hierarchy of decision-making processes under uncertainty. For the optimal design, planning and coordination of these supply chain networks, decisions have to be classified according to the natural hierarchy of the decision-making process, namely: strategic, tactical and operational (Simchi-Levi, 2003; Chopra and Meindl, 2003). In Figure 1 the design and planning procedure of BSCs is depicted, along with coordination and data flows between them.

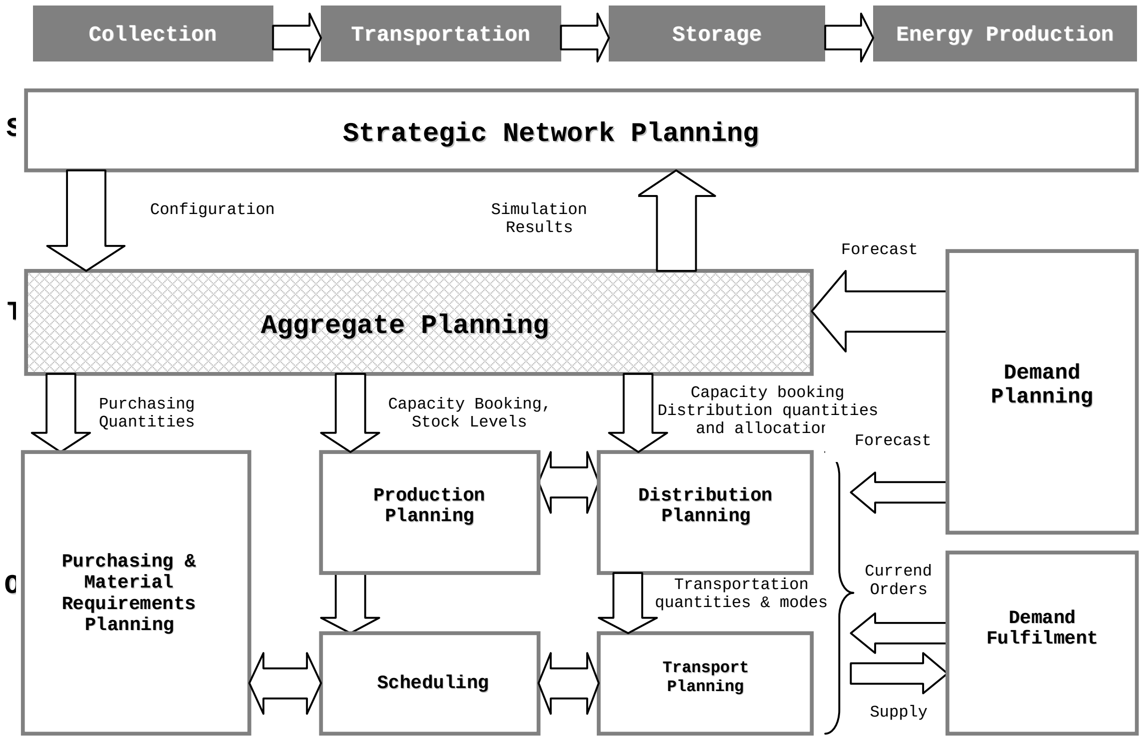

Figure 1: Design and planning of BSCs in strategic (S), tactical (T) and operational (O)

Decisions at the strategic level include indicatively: Biomass supply and demand management, selection of collection sites and conversion facilities, choice of suitable energy conversion processes, design of the supply chain network, selection of collection, pretreatment and storage equipment, conversion facilities' equipment, information technology systems, as well as sustainability of biomass supply networks. At this level, most decisions affect operations and impose a set of constraints to the lower decision-making levels. Decision-making on the tactical and operational level is similar to that of traditional supply chain management. The tactical level includes medium-term decisions such as aggregate planning, supply chain coordination, inventory management or fleet management. The operational level includes day-to-day decisions, such as inventory control, or second-stage pre-treatment operations into the facility (Iakovou et al., 2009).

A taxonomy of literature review

In the present research we review those supply chain planning models focused on strategic and tactical decisions and specifically on the design and aggregate planning of BSCs. From a modelling perspective, the models for supply chain planning can be classified as deterministic or stochastic, according to the certainty of the value of the parameters used (Min and Zhou, 2002). We further refine this classification according to the main mathematical techniques used for finding solutions to these models. In those cases where all of the model's parameters are assumed deterministic, the researchers on biomass supply chains have traditionally used approaches such as spreadsheet modelling, linear programming and mixed integer linear programming. Otherwise, when stochastic modelling approaches are used, these include simulation, sequential quadratic programming, genetic algorithms or heuristics.

From the perspective of modelling approach, we classify the papers into those who employ spreadsheet modelling, mathematical programming, simulation or other methods, along with the software employed and their crucial modelling parameters like stochasticity and use of single or more types of biomass. This taxonomy is clearly presented in Table 1. In a second level, we make a further categorization according to the unique characteristics of the supply chains under study, like transportation means, consideration of environmental impact, storage options examined and others, and present them in Table 2.

Spreadsheet modelling

Spreadsheet modelling has been used widely for the analytical evaluation of biomass supply chain costs. Such packages are useful for decision support systems, scenario modelling and sensitivity analysis (Coles and Rowley, 1996). Allen et al. (1998) perform an analytic supply chain modelling for 5 biomass types using a spreadsheet package, concluding that 20% –50% of biomass delivered cost is due to transportation and handling activities. A comparative economic evaluation of various bioenergy conversion technologies was conducted by Mitchell et al. (1995), using a spreadsheet-based decision support system named Bioenergy Assessment Model (BEAM). The cost of producing short rotation forestry was investigated by using spreadsheet models by Mitchell et al. (1999), focusing mainly on the operations of biomass production, collection and storage.

Hamelinck et al. (2005) study for the first time systematically the influence of various parameters on the performance of complete transport chains, analyzing a generic international logistics scenario that assumes five possible transfer points: the production site, a central gathering point (CGP), two transport terminals (export and import) and the energy plant. A flexible modular spreadsheet has been developed to enable the technical–economic analysis of a large variety of chains. The results from using two biomass-to-electricity conversion technologies were compared by Caputo et al. (2005), concluding that 56%–76% of the total system operational costs are due to the biomass logistics, thus indicating the potential for cost reduction.

Mathematical modelling

In the bioenergy supply chain literature, several optimization methods have been applied. Linear programming (LP), a method that has the advantage of simplicity and assurance of identifying the optimum solution, has been used. For example, a linear programming optimization model has been utilised by Cundiff et al. (1997) to be used primarily as a planning tool for the evaluation of costs associated with biomass transfer from producers situated in close geographical proximity to a centrally located plant. Specifically, it determined an appropriate monthly shipment and capacity expansion schedule for each producer, based on monthly harvests under weather uncertainty. Uncertainty in production levels due to weather is addressed by reformulating the linear program as a two-stage problem with recourse. Tatsiopoulos and Tolis (2003) provide a detailed cotton-stalk supply chain model that employs an LP optimization for the biomass delivery scheduling.

Table 1: Modelling approach and software used in reviewed literature

	Mitchell et al., 1995	Gallis, 1996	Cundiff et al., 1997	Huisman et al., 1997	De Mol et al., 1997	Allen et al., 1998	Nilsson, 1999a&b	Mitchell et al., 1999	Nagel, 2000	Nilsson & Hansson, 2001	Tembo et al., 2003	Tatsiopoulos &Tolis, 2003	Freppaz et al., 2004	Caputo et al., 2005	Hamelinck et al., 2005	Sokhansanj et al., 2006	Kumar and Sokhansanj 2007	Gronalt and Rauch, 2007	Ravula et al., 2008a&b	Rentizelas et al., 2009a	Rentizelas et al., 200b	Frombo et al., 2009
Modelling Approach																						
Energy conversion incl	x							x	x	x			x	x	x					x	x	x
Single-biomass problem	x	x	x	x		x	x	x	x		x	x		x	x	x	x		x			
Multi-biomass problem					x					x			x					x		x	x	x
Uncertain Production		x	x		x		x			x						x	x					
Economics studied	x			x		x		x		x				x	x		x					
Stochastic Demand		x			x		x			x						x						
Deterministic Demand	x		x		x	x		x	x		x	x	x		x			x		x		x
Spreadsheet modelling	x			x		x		x						x	x	x						
Heuristic approach																		x				
LP Programming			x									x	x									x
MILP Programming					x				x		x											
SQ Programming (SQP)																				x		
Genetic algorithm																				x		
Simulation modelling		x			x		x			x						x	x		x	x	x	
Software / Tools																						
LINGO													x									x
OMP					x																	
CPLEX			x																			
MATLAB																				x		
GAMS/CPLEX											x											
GASP IV																						
SIMAN (Arena)							x			x												
SLAMSYSTEM		x																				
EXTEND																x	x					
SIGMA																			x			
PROSIM					x																	
GIS												x	x		x							x
EXCEL	x					x		x						x	x	x						

Table 2: Supply Chain Issues considered / addressed in reviewed biomass supply chain planning models

	Mitchell et al., 1995	Gallis, 1996	Cundiff et al., 1997	Huisman et al., 1997	De Mol et al., 1997	Allen et al., 1998	Nilsson, 1999a&b	Mitchell et al., 1999	Nagel, 2000	Nilsson & Hansson, 2001	Tembo et al., 2003	Tatsiopoulos &Tolis, 2003	Freppaz et al., 2004	Caputo et al., 2005	Hamelinck et al., 2005	Sokhansanj et al., 2006	Kumar and Sokhansanj, 2007	Gronalt and Rauch, 2007	Ravula et al., 2008a&b	Rentizelas et al., 2009a	Rentizelas et al., 200b	Frombo et al., 2009
Harvesting																						
Contract purchase			x	x		x			x					x						x	x	x
Harvesting costs	x	x		x	x		x	x		x	x	x	x		x	x	x					x
Production costs															x							
Storage																						
On - farm storage	x		x	x		x	x	x		x	x				x	x	x		x		x	
Intermediate Storage						x	x			x		x			x	x			x		x	
Warehouse in plant	x											x							x	x	x	
Transportation																						
Contracting with a 3pl			x	x								x			x	x			x	x	x	
Undertaken by farmers												x			x							
Road Transportation	x	x	x	x		x	x	x		x	x	x	x	x		x	x	x	x	x	x	x
Road, Rail or Water					x										x							
Other parameters																						
Processing considered	x		x	x	x	x		x				x			x		x				x	
Environmental impact					x	x			x				x	x	x		x					
Long-distance networks															x							
Short-distance networks	x	x	x	x	x	x	x	x	x	x	x	x	x				x		x	x	x	x
Biomass types studied	Woody biomass	Forest biomass	Switchgrass	Miscanthus Giganteous	Prunings, waste-wood, sewage sludge, waste paper	Forest fuel, Short Rotation Coppice, Straw, Miscanthus	Straw	Short rotation forestry	Biomass	Cerealstraw and reed canary grass	Lignocellulosic biomass feedstock	Cotton stalks	Forest biomass & waste biomass	agro-industrial and wood wastes	Forestry residues and energy crops	Corn stover supply	Switchgrass	Wood biomass & forest fuels	Cotton gin	Wheat Straw, corn stalks, olive & almond tree prunings	Cotton stalks, Almond tree proonings	Forest, agricultural, industry. residues

Frombo et al. (2009) present, a geographic information system (GIS)-based Environmental decision support systems EDSS for the optimal planning of forest biomass use for energy. The strategic decision model is described in detail and corresponds to an LP.

Mixed-integer linear programming (MILP) was used by Nagel (2000) to include binary operators for investment decisions in the variables, by de Mol et al. (1997) to estimate the annual flows of biomass for designed networks under several scenarios, and by Tembo et al. (2003), encompassing alternative feedstocks, feedstock production, delivery, and processing.

A combination of GIS, mathematical modelling and optimization for energy supply at a regional level from forest biomass was presented by Freppaz et al. (2004). The above mentioned authors manage to retain linearity of the model as the optimization concerned only the biomass supply chain and not the whole system, including biomass conversion facility, and because of their assumptions for a deterministic environment.

Simulation modelling

When the models optimize the entire bioenergy system, non-linearity is inevitably been introduced, thus excluding linear programming from the candidate optimization methods. Most of the currently existing non-linear optimization methods have the disadvantage that they cannot ensure the identification of the optimum solution of the problem. Computer simulation modelling has been one of the most common approaches in biomass supply chain modelling. An activity oriented stochastic computer simulation model of forest biomass logistics in Greece, based on the SLAMSYSTEM simulation language, has been developed by Gallis (1996). De Mol et al. (1997) developed a simulation model Biologics (BIOmass LOGIstics Computer Simulation) - in comparison with an optimization model- to gain insight into the costs and energy consumption of the logistics. This model is implemented with the simulation package PROSIM. 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 (1999a, 1999b). The objective of these studies was to evaluate and optimize existing and conceivable alternatives for handling straw with respect to system performance, costs and energy needs. An extended version of the integrated dynamic simulation model SHAM (Straw HAndling Model), was used in a following study (Nilsson and Hanson, 2001) aimed at satisfying a daily average heating demand load.

Sokhansanj et al. (2006) simulate the flow of biomass from field to a biorefinery, by developing a framework for a dynamic Integrated Biomass Supply, Analysis and Logistics model (IBSAL) in order to model climatic and operational constraints, to quantify resource allocations for biomass supply and transport operations, and calculate biomass delivered cost. Kumar and Sokhansanj (2007) used IBSAL to evaluate delivery systems for three biomass collection options. Ravula et al. (2008a) simulate 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 (2008b).

Rentizelas et al. (2009a) present a decision support system (DSS) for multi-biomass energy conversion applications. In order to overcome the limitations of using a specific non-linear optimization method, the authors apply a hybrid method: one optimization method is employed to define a “good” solution and this solution is used as the starting point of the second optimization method that strives to enhance it further. The optimization method used for the first step is a genetic algorithm (GA). A sequential quadratic programming (SQP) optimization method is applied at the second step. In (Rentizelas et al., 2009b) three biomass storage methods are analysed through simulation modeling and are applied to a case study to come up with tangible comparative results. Finally, Gronalt and Rauch (2007) describe a simple stepwise heuristic approach to solve the forest fuel supply network design problem. Furthermore, the relevance of the planning steps is explained for a case study region.

Conclusions and future research

In this work, we present a holistic taxonomy that takes into account the major aspects in the design and aggregate planning of waste biomass supply chains developed for energy production. Logistics and SCM have emerged as areas of critical importance for the energetic utilization of waste biomass and organic substrates. Unfortunately, the existing models address only a minor subset of the decisions needed to be taken at a strategic, tactical and operational level; moreover, they fail to capture the existing complex and stochastic issues due to their severely limiting steady-state assumptions. However, the problem becomes even more challenging by considering the numerous variables, parameters and constraints that could be taken into account in the formulation of such a decision support model.

An extensive critical literature taxonomy of quantitative-based biomass supply chain modelling efforts is thoroughly presented in table format, according to their modelling approach, software used and other supply chain characteristics considered. Several conclusions can be drawn from this taxonomy. One is that the use of integrated planning models for biomass SCM is still quite limited. Although integrated models are inherently more complex, than those dealing with single planning aspects, the potential benefits of these models usually outweigh the added complexity. We also found that there are a limited number of models dealing with operational planning, and for such as inventory management and control, vehicle scheduling.

A second finding is that planning models dealing with biomass products very often fail to capture realistic stochastic, and shelf life features present in the different echelons of the supply chain, probably due to additional complexity. For example, many authors manage to retain linearity and flexibility of the model as the optimization deals only with the biomass supply chain without including the energy conversion processes, and because of their assumptions for deterministic environment. Others take into account stochasticity of demand, as well as the probabilistic production or case-dependant constraints through employing simulation modelling approaches. Simulation models assume a given network structure, whereas mathematical optimization models determine the optimal network structure. The simulation models capture the dynamic flows, while it is difficult to include time-dependent effects or seasonal fluctuations in supply or demand mathematical modelling. Finally, spreadsheet modelling can display analytically the economics of supply chain operations but cannot constitute an integrated decision tool for the optimal design of biomass supply chains.

Our up-to-date taxonomy reinforces the understanding that practical problems in designing and executing waste biomass supply chain networks for energy production are important for investors, policy-makers and decision-makers, while researchers are actively attempting to deal with few of these problems. It is envisioned that the presented review of supply chain planning models for bio-energy networks will serve to establish new directions for the development of realistic biomass supply chain networks for energy production.

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