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Modeling and optimization of biomass supply chains: A review and a critical look

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Abstract: Due to the effect of greenhouse gas emissions and increasing energy demand, consumption of more sustainable and renewable energies has increased. Biofuels derived from biomass can play a key-role nowadays as one of the main sources of renewable energies. Therefore, more and more researchers have been involved in modeling and optimizing biomass supply chains. This paper presents an overview of biomass supply chains. After an outline of the main definitions and a description of typical activities in biomass supply chain; a classification of optimization methods and models developed in this context is detailed. All selected papers are classified and discussed according to (1) objective functions, (2) decision levels and (3) solution methods. Finally, a critical look at current researches and possible new directions are presented.

Keywords: Biomass, Biofuel, Supply chain, Logistics, Modeling, Optimization

1. INTRODUCTION

Increasing concerns about energy security and climate change caused by greenhouse gas emissions from fossil fuel consumption have encouraged many researchers to be involved in developing sources of renewable energies. Biofuel derived from biomass can play a crucial role in this context.

Biomass is defined as "a biological material derived from living or recently living organisms"(Biomass Energy Center (2011)). There are three main biomass generations: 1) First generation which includes edible crops such as corn and sugarcane, 2) second generation which includes non-edible crops such as stems, leaves, husk and so on, 3) third generation mainly based on algae.

The flow of biomass from the land to its end use for producing bioenergy is called the biomass supply chains. The efficiency of this chain is critical for the economic variability of biorefinery: indeed as the biomass itself is rather cheap, the logistic costs represent an important fraction in the price of a ton of biomass delivered to the biorefinery. This supply chain includes different types of activities which can be classified into four main categories: harvesting and collecting biomass, storing, transporting and pre-processing (Gold and Seuring (2011)). Each of these categories has its own sub-activities. For example, pre-processing includes drying, pelletization, ensiling and pyrolysis.

Biomass can be a flexible energy source, capable of generating electricity, heat, biofuels or a combination of them. The advantage of using biomass for energy generation is its ability to be stored and used on demand (Hall and Scrase (1998); Demirbas (2003)). It is a clean energy, renewable and completely natural, and it does not have any carbon dioxide side effect in its use. It has the potential to reduce the dependency on fossil fuels which are the main source of carbon dioxide release in the atmosphere.

Despite the advantages of using biomass for energy generation, in order to utilize it efficiently, several difficulties should be overcome, including biomass availability, cost and quality, conversion performance, transportation cost and the performance of the logistic system (Shabani et al. (2013)). All these difficulties induce a high cost of biomass supply chain management. Employing more advanced technologies, such as pre-processing or more efficient transportation system is one way to deal with some of these challenges. For example, by using pre-processing operations, biomass can be dried in order to reduce the cost of transportations (Flisberg et al. (2012)). In addition, another approach that can be used to reduce the cost of energy produced from biomass and to increase its competitiveness is to improve its supply chain and optimize its design (Bowyer (2012)).

For planning and managing biomass supply chains, several practical models were developed with the help of tools such as operations research and mathematical optimization based on computer algorithms. This paper presents an overview of biomass supply chains. The aims of this review are (1) Introducing typical main activities in biomass supply chains, (2) classifying recent researches in the context of biomass supply chains based on different criteria and (3) looking critically to current researches and suggesting possible new directions.

The structure of the paper is as follows: in section 2 the basic terms and definitions are explained, section 3 introduces typical main activities in biomass supply chains such as harvesting and collecting biomass, pre-processing and transportation. Section 4 classifies the different objective functions in biomass supply chains (minimizing overall costs and maximizing overall profits, maximizing

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Net Present Value). Section 5 reviews studies which deal with decision levels (strategic decisions, tactical decisions and operational decisions). Section 6 classifies the solution methods (heuristics, multi-criteria decision analysis, Geographic Information System (GIS) and simulation). Section 7 provides a survey on recent papers in biomass supply chains. Section 8 critically discusses the strengths and weakness of the considered studies. Finally, concluding remarks are brought in section 9.

2. LOGISTICS, SUPPLY CHAIN, BIOMASS, BIOFUEL – TERMS AND DEFINITIONS

Logistics is the management of the flow of goods or services between the source points and destination points in order to satisfy the needs of customers. However, the New Oxford American Dictionary defines logistics as "the detailed coordination of a complex operation involving many people, facilities, or supplies". French Association for logistics (ASLOG (1984)) defines logistics as the set of methods and techniques to bring in adequate the right resources at the right places, at the right times and with the right amounts, by considering cost optimization .

The definition of supply chain is different among writers in different fields and there is no clear and comprehensive definition for this concept or its activities in the literature. The literature is full of unclear words and concepts, such as integrated purchasing strategy, integrated logistics, supplier integration and buyer-supplier partnerships to express elements of this field. More generally, a supply chain can be described as a network (graph) where the nodes correspond to production activities, end customers, storage, pre-processing, transshipment, etc, connected by arcs to model product flows.

Biomass Energy Center (2011) defines Biomass as "Biological material derived from living, or recently living organisms. In the context of biomass for energy production this is often used to mean plant-based material, but biomass can also concern any animal and vegetal derived material".

A biofuel is defined as "any fuel whose energy is obtained through a process of biological carbon fixation. Carbon fixation is a process that takes inorganic carbon (in the form of things like CO2) and converts it into organic compounds" (Biofuel.org.uk (2010)).

Biofuels can be classified to three generation of processing technology. The first generation liquid biofuels (e.g. bioethanol) can come from a number of edible resources (starches, sugars, animal fats, and vegetable oils).

The second generation biofuels are not made from edible biomass crops. They are obtained from residues of crops and forest, industrial wastes and non-food energy crops.The most frequently feedstock source for second generation biofuels are cellulosic materials (switchgrass, wheat stalks, corn stalks, residues of wood, miscanthus and short rotation coppice) and waste biomass.

The third generation biofuels are made from algae. They like the second generation, are not made from edible feedstocks, and the obtained fuel is indiscernible from its petroleum equivalents.

3. ACTIVITIES

The biomass supply chains includes different types of activities; such as chipping, handling, baling, transporting, storing and pre-processing operations (Sambra et al. (2008)). An example of pre-processing operation is drying for reducing the cost of transportation, which is usually needed before using biomass for energy generation (Flisberg et al. (2012)). Figure 1 shows a simplified picture of the biomass supply chain.

3.1 Harvesting and collecting biomass

For gathering and removing the biomass from fields, we should harvest and collect biomass. The moisture content and the end use of biomass also affect the way biomass is collected. The collection method, in terms of efficiency and costs, can affect storage and transportation. There are some factors that we should consider in the model such as frequency of harvesting, selective harvesting, undesirable ecological impact of harvest machinery and so on (Liu et al. (2013)). There are some common biomass collection activities such as baling, loafing, dry chopping, wet chopping, multi-pass harvesting, single-pass harvesting and whole-crop harvesting.

3.2 Pre-processing

There are different types of pre-processing such as ensiling, drying, pelletization, torrefaction and pyrolysis (Gold and Seuring (2011)). The most common types are drying and pelletization and drying. Pelletization could be defined as "drying and pressing of biomass under high pressure to produce cylindrical pieces of compressed and extruded biomass". Drying reduces the moisture of biomass (Möller and Nielsen (2007)). Ensiling is "the process of creating silage via anaerobic fermentation" (USEPA (2012)). Torrefaction is "a thermal pre-treatment technology performed at atmospheric pressure in the absence of oxygen. Temperatures between 200 and 300 degrees are used, which produces a solid uniform product with very low moisture content and a high calorific value compared to fresh biomass" (Uslu et al. (2008)). Pyrolysis is described as "the direct thermal decomposition of biomass in the absence of oxygen. Temperatures employed in pyrolysis are 400-800 degrees. The products are gas, liquid and solid char, and their relative proportions depend on the pyrolysis method, the characteristics of the biomass and the reaction parameters" (Uslu et al. (2008)). Increasing density without reducing the energy content makes the biomass cheaper to transport. This will impact transportation costs and combustion efficiency at bio-refineries. Therefore, it is important to consider pre-processing in the biomass supply chain management. By using pre-processing, we can decrease deterioration risks and increase biomass energy value (Gold and Seuring (2011)). Paolucci et al. (2016) propose a two-tier approach to optimize the supply chain of a pyrolysis-based biomass.

3.3 Storage

Biomass should often be stored from the time of harvesting until it is needed by the bio-refinery. Normally, a storage

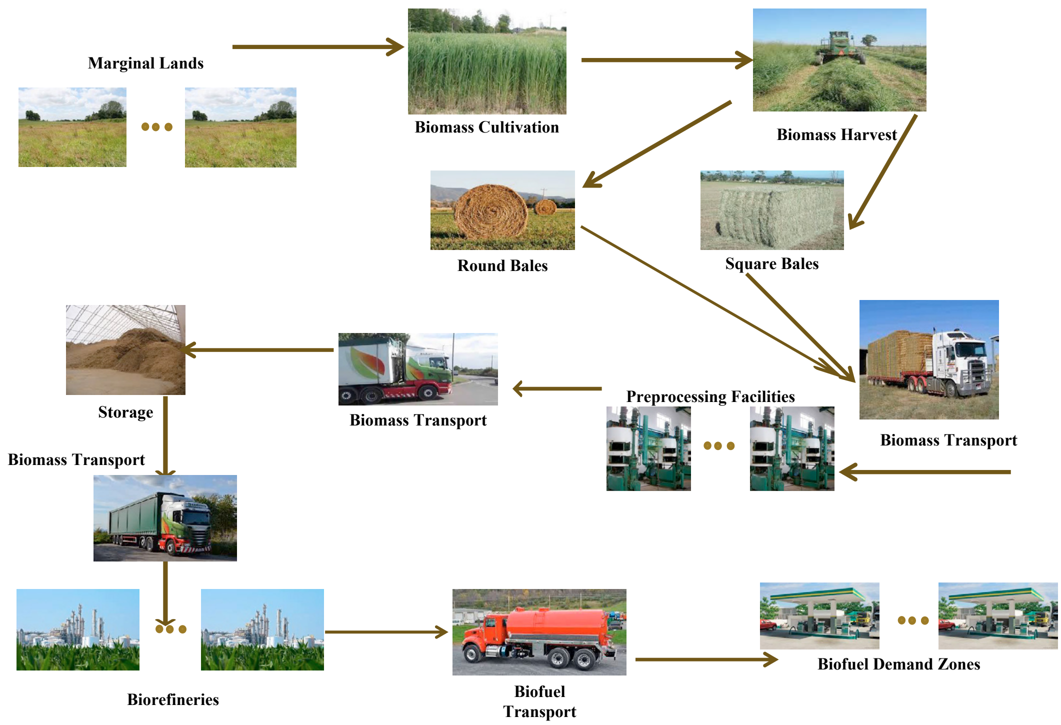

Fig. 1. Biomass Supply Chain

system is required to minimize dry matter loss and protect biomass. Depending on weather and biomass, storage can be open air or roof covered and air fan (Gold and Seuring (2011)). It can be located near the farm or at a centralized storage. Depending on the size of bio-refinery, availability of biomass and frequency of harvesting, different size and number of centralized storage locations can be considered (Liu et al. (2013)).

3.4 Transportation

Several transportation modes can be employed such as roads, railways, waterways or a combination of them. Road transport is normally used for short distances and it has a significant flexibility. Rail transport is applied for medium to long distance. Water transport is suitable for long distance. Depending on the type of biomass, shape, distance to be crossed and the demand of customers, one or several transportation modes can be selected (Axelsson et al. (2012)). Transport system should be from farms to pre-processing, from pre-processing to centralized storage location, from centralized storage to bio-refineries and from biorefineries to demand points.

As mentioned, there are many activities in biomass supply chain management. These activities can be separated into three major segments:

- Upstream
- Midstream
- Downstream

The upstream segment includes biomass production, harvest, pre-process and storage. All the activities from biomass production to delivery to biorefinery are considered in upstream segment. The midstream segment just focuses on biorefinery and its internal processes. The downstream segment includes storage of biorefinery and its distribution to customers (De Meyer et al. (2014)).

4. CLASSIFICATION OF OBJECTIVE FUNCTIONS

In order to classify researches in the field of biomass supply chains, different criteria can be considered among which the objective functions. An objective function or optimization criterion can be the result of an effort to express a business goal in mathematical terms for using it in decision analysis, operations research or optimization studies. In biomass supply chains, overall goals can be different. In this section, some papers have been reviewed.

4.1 Minimizing overall costs

Minimizing overall costs is the most common objective among biomass supply chain models. Ekioglu et al. (2009a) present a mathematical model that can be used to design the supply chain. The objective function is to minimize the annual costs of harvesting, storing and transporting ethanol, locating and operating biorefineries. Leão et al. (2011) propose a methodology to plan the development of an optimized supply chain for a biodiesel plant. The objective function is to minimize the costs involved in operations related to the agricultural, industrial and logistical chains. Leduc (2008) develops a linear mixed integer programming model to determine the optimal geographic locations and sizes of methanol plants and gas stations in Austria his objective function is to minimize costs with respect to biomass and methanol production, transportation and investments for the production plants and the gas stations.

4.2 Maximizing overall profits

In some studies, researchers prefer to define their objective function in a way to maximize overall profit. Bowling et al. (2011) present a mathematical programming model to maximize profits by considering product sales, feedstock cost, transportation cost, pre-processing hub location assignment, central facility location assignment, and other operating costs for facility location and supply chain optimization. Parker et al. (2010) propose a robust optimization model for biorefinery with GIS-based spatial distributions of biomass resource. An et al. (2011) present a mathematical model to design a lignocellulosic biofuel supply chain system with a case study based on a region in Central Texas to maximize the overall profits.

4.3 Maximizing Net Present Value

Other authors, instead of minimizing overall costs or maximizing overall profits, researchers seek to maximize the Net Present Value (NPV). Alex Marvin et al. (2012) propose an economic optimization of a Biomass-to-Ethanol Supply Chain to determine the location of biorefineries as well as capacities and amount of biomass to harvest in order to maximize the Net Present Value (NPV) of the entire supply chain. Walther et al. (2012) design regional production networks for second generation synthetic biofuel with a case study in Northern Germany. A multi-period MIP-model is presented by considering location, capacity and technology planning for designing production networks for second generation synthetic bio-diesel with the objective of maximizing Net Present Value.

4.4 Multiple-objective

In some studies, multi-objective optization is employed to find a tradeoff between conflicting criteria. Santibanez-Aguilar et al. (2014) consider economic and environmental aspects for finding the optimal planning of biorefinery in Mexico. They focus on different types of agricultural biomass, wood chips, sawdust and commercial wood for producing ethanol, hydrogen and biodiesel. A multi-objective model is proposed for selecting the feedstock type, processing technology and a set of products in a bio-refinery supply chain. The objectives are: 1) maximizing the overall profit considering the costs of feedstock, products, and processing, and 2) minimizing the life cycle environmental impacts. **?** propose a multi-objective optimization of biomass-to-liquids processing networks. The first economic objective function is to calculate the total annualized cost, and the second objective is to measure environmental performance and life cycle greenhouse gas emissions. You and Wang (2012) design sustainable cellulosic biofuel supply chains under economic, environmental, and social objectives. The first objective function is to minimize total annualized cost, the second objective function is to measure the life cycle greenhouse gas emissions and the social objective is to measure the number of added local jobs. A multi-period mixed integer linear programming model is proposed by considering the main features of cellulosic ethanol supply chains, such as seasonality of feedstock supply, geographical diversity, availability of biomass resources, etc.

5. CLASSIFICATION OF DECISION MAKING LEVELS

According to the definition of supply chain management and logistics, there are a lot of variables that can affect decisions to be made, such as location, capacity and technology of facility, inventory planning, fleet management and so on. There are three main decision making levels in this domain which can be seen in Figure 1.

5.1 Strategic decisions

Strategic decisions concern long-term goals (e.g. one to several years). They focus on location, capacity and type of storages, pre-processing and bio-refineries. Sourcing biomass, allocation of biomass between facilities and transportation modes, can be considered a strategic decisions, even if they can be modified more often.

Many studies have been done on the strategic decision levels of biomass supply chain management. Akgul et al. (2011) present a mixed integer linear programming model to determine the optimal planning of a bioethanol supply chain with the objective of minimizing the total supply chain cost. The model aims at optimizing locations and sizes of the biorefineries as well as allocation of biomass feedstock to those biorefineries by maximizing the profit over the entire supply chain, including the feedstock suppliers and fuel producers. Tursun et al. (2008) propose a mixed integer linear programming model to determine the optimal size and time for constructing each plant in the system and the amount of raw material processed by each plant as well as the distribution of bioenergy crops and ethanol. Wang et al. (2012) propose an optimization model for determining locations and sizes of biomass-based facilities in energy crop supply chains. Leduc et al. (2010) present optimal locations for poly-generation systems with simultaneous production of electricity, district heating, ethanol and biogas in Sweden. The objective is to reduce the total production cost and the environmental impact. **?** propose a decision support system for forest biomass exploitation. It provides the abilities of plant locating and computing their optimal sizes. Chen and Fan (2012) develop a mixed integer stochastic programming model in order to provide a strategic planning of bioenergy supply chain systems and to obtain optimal feedstock resource allocation in an uncertain decision environment.

Table 1 illustrates the kinds of strategic decisions considered in a set of representative works. All these papers apply mathematical programming to multi-period horizons. These classification criteria are:

- The existence of several conversion facilities supplied with biomass
- Locating conversion facilities
- The existence of several types of biomass

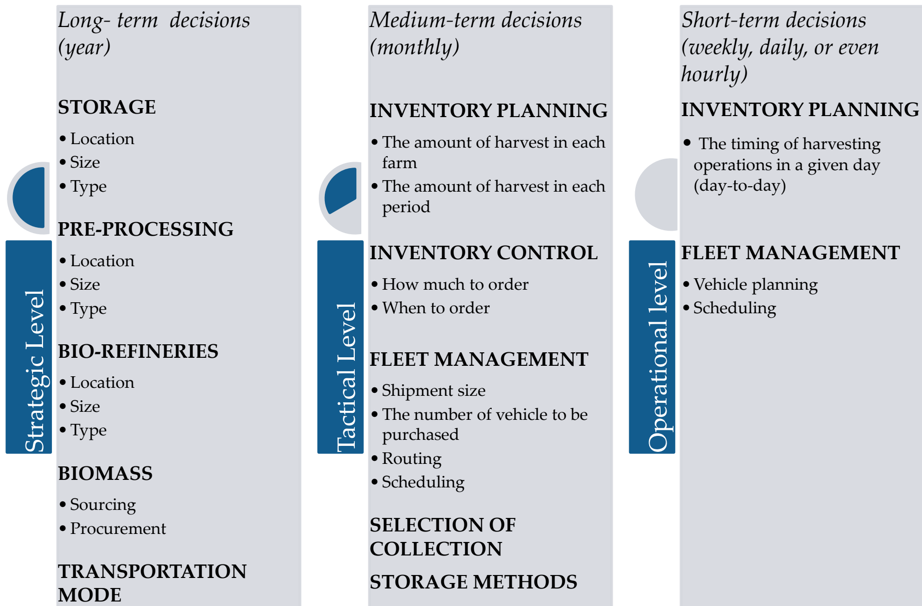

Fig. 2. Decision making levels

- The existence of centralized storages (e.g. ignoring the on-farm storages, in-forest storages and buffer stocks of conversion facilities)
- Locating centralized storages
- The existence of pre-processing facilities

For example, Ekioglu et al. (2009b) propose a mathematical model to design a supply chain and manage the logistics of a biorefinery. Two biomass resources such as corn stover and woody biomass (forest residues, pulpwood and saw timber) are considered. The model deals with a multi-period tactical horizon which is one year with week steps. The number, size and location of biorefineries and the amount of biomass, shipped and processed during each time period are determined. Zhu et al. (2011) present a mixed integer program for dedicated-biomass-based bioenergy industry. Two transportation modes such as trucks and trains are considered and two types of products (switchgrass and residues) are transported within the system. The model considers a multi-period tactical horizon which is one year with month steps.

5.2 Tactical decisions

Tactical level involves decisions that are made for medium-term goals (one to several months). Tactical decisions focus on logistics aspects, such as inventory planning, fleet management, pre-treatment and transportation modes.
Some studies have been done on the tactical decision levels of biomass supply chain management. Gunnarsson et al. (2004) propose a mixed integer programming model for tactical/strategic forest fuel supply chain management with case study in Sweden by focusing on supply procurement decisions as well as multiple time steps. Dunnett et al. (2007) develop a model to schedule operations over 12 periods of one month for a biomass supply chain by considering harvesting, densification, drying, storage, and transportation activities. Zhu et al. (2011) consider challenges such as low bulk density, restrictions on harvesting season and frequency, weather effects, scattered distribution over a wide geographical area and so on, to design biomass supply chain. Shabani and Sowlati (2015) propose a hybrid multi-stage stochastic programming-robust optimization model for the supply chain of a forest-based biomass. The tactical supply chain planning of a power plant over a one-year time horizon with monthly time steps is taken into account.

5.3 Operational decisions

Operational decisions deal with decisions that are made for short-term goals (e.g. weekly, daily or hourly). It focuses on details of operations, day-to-day inventory control and vehicle routing, in order to provide efficient operation of biorefineries and process in biomass supply chain management.

Most papers focus on strategic and tactical levels. However, a few studies have been done in the operational decision levels of biomass supply chain management. Van Dyken et al. (2010) develop a linear mixed integer model for biomass supply chains, by considering transportation, storage and processing operations over 12 weekly time steps. This study deals with operational supply chain planning, however the model is not applied in a real case study. Gemtos and Tsiricoglou (1999) focus on procedure of harvesting cotton residues in Greece. This paper investigates possibilities for storing the material in a simple and economical way and proposed a method for collecting and packaging the residue.

6. CLASSIFICATION OF SOLUTION METHODS

In many studies, optimization techniques have been applied to manage the biomass supply chains from strategic, tactical and operational points of view. Most of these studies are based on mathematical programming, although some researches involve heuristics and simulations. This

Table 1. Publications applying mathematical programming for multi-period horizon

Publication	**Multi-biomass**	**Facilities**				
		Several Conversion facilities		**Centralized storages**		**Pre-processing**
		Existing	**To Locate**	**Existing**	**To Locate**	**Existing**
Tembo et al. (2003)	X	X	X			
Ekioglu et al. (2009b)	X	X	X			
Huang et al. (2010)	X	X	X			
An et al. (2011)	X	X	X	X		X
Giarola et al. (2011)	X	X	X			
Papapostolou et al. (2011)	X					
Shastri et al. (2011)				X	X	
You and Wang (2012)	X	X	X			X
Zhu et al. (2011)		X	X	X	X	
Zhu and Yao (2011)	X	X		X	X	
Akgul et al. (2012)	X	X	X			
Bernardi et al. (2013)	X	X	X			
Sharma et al. (2013)				X		
Zhang and Hu (2013)		X	X			X
Xie et al. (2014)	X	X	X			

section covers major relevant studies on mathematical programming and multi-criteria decision analysis of biomass supply chains. It also discusses principal heuristic methods. The solutions methods can be categorized into five groups:

- Mathematical programming
- Heuristics
- Multi-Criteria Decision Analysis (MCDA)
- Geographic Information Systems (GIS)
- Simulation

6.1 Mathematical programming

Mathematical programming is one of the best developed and most utilized branches of operational research. It consists in optimizing a function of several variables under a set of constraints. In industrial application, the variables often define an allocation of limited resources among competing activities. It considers the optimum allocation of limited resources among competing activities, under a set of constraints imposed. In another word, mathematical programming can be defined as a mathematical representation, targeted at programming or planning the best possible allocation of resources. Depending on the characteristics of the variables, objective function and constraints, these models can be divided into four categories:

- Linear programming
- Integer programming
- Mixed Integer programming
- Non-linear programming

Cundiff et al. (1997) design an herbaceous biomass delivery system based on a linear program that considers weather and uncertainty in production levels. By reformulating the linear program as a two-stage model, the problem is solved. The overall objective is to minimize the transportation costs. Judd et al. (2010) present an optimal storage and transportation System for a cellulosic Ethanol bioenergy plant. By developing integer programming models, optimal locations are determined with the goal of minimizing the transportation and storage location costs. Bruglieri and Liberti (2006) develop mixed-integer non-linear programming model for planning the installation of several processing plants types used in the production process. Quantity of the biomasses to produce and transportation decisions such as transport of materials to the respective plants are considered. Huang et al. (2010) propose multistage mixed integer linear programming to model biofuel supply chains, the goal is to minimize the cost of the entire supply chain of biofuel as well as satisfying demand and other side constraints. Chinese and Meneghetti (2005) present a MILP model to determine the optimal structure of the supply chain by considering a real-life problem of supplying a biofuel plant with forest fuel. Kim et al. (2011) propose an optimization model for the design of supply chain case study in the Southeastern United States. The raw materials come from six forestry resources such as logging residuals, thinnings, prunings, inter-cropped grasses, and chips.

6.2 Heuristics

Heuristic approaches look for a relatively good solution in a short time to solve complex problems. This kind of methods is generally very fast, however, they do not guarantee optimality. From some of the advantages of heuristics, we can mention the ability of optimizing even non-linear and non-continuous functions, as well as the capability of dealing with a large number of variables and also finding a good solution in short time. The most sophisticated heuristics called metaheuristics include various mechanisms to escape local optimal. There are different types of metaheuristic algorithms such as Particle Swarm Optimization (PSO), Simulated Annealing (SA), Genetic Algorithm (GA), and so on. Metaheuristic methods have been developed for a different variety of optimization problems and some of them are based on the natural principles.

Reche López et al. (2008) propose a binary Particle Swarm Optimization method for locating biomass power plants and compared it with simulated Annealing and Tabu Search for this problem. The objective function is to maximize overall profits. Initial investment and collection, transportation, maintenance and operation costs are considered, as well as benefits from the sale of electrical energy. Venema and Calamai (2003) use Location Allocation for planning bioenergy systems. Vera et al. (2010) use Binary Honey Bee Foraging (BHBF) for finding the optimal size, location, supply area and net present value of an electricity plant in Spain. They work on olive tree pruning residues. By using Genetic Algorithms (GA), Binary Honey Bee Foraging (BHBF) and Binary Particle Swarm Optimization (BPSO), optimal location and plant size is determined. It is concluded that the performance of BHBF algorithm is better than BPSO and GA, since it converges quickly to the optimal solution. López et al. (2008) use an artificial intelligence method, Particle Swarm Optimization, for determining the optimal supply area and location of a forest biomass power plant. The objective function is to maximize the net present value by considering the initial investment, collection, transportation, maintenance and operating costs.

6.3 Multi-Criteria Decision Analysis

Multi-Criteria Decision Analysis (MCDA) is defined as "a decision aid and a mathematical tool allowing the comparison of different alternatives or scenarios according to many criteria, often conflicting, in order to guide the decision makers towards a judicious choice" (Roy (1996)).

Čuček et al. (2012) propose a multi-criteria optimization for maximizing the economic performance of the supply chain as well as minimizing different environmental footprints. The aim of this study is to develop the regional supply chains by considering important environmental and social footprints. Plain et al. (2001) evaluate the bioelectricity production by using multiple criteria analysis of bioenergy projects. Ma et al. (2005) use the Analytic Hierarchy Process (AHP) method to perform land suitability by considering economic factors, environmental and social constraints.

6.4 GIS-based

A Geographic Information System (GIS) is a computer-based system that capture, store, manage, retrieve, analyze, and display spatial or geographical information. GIS applications are used to analyze spatial information and edit data in maps such as determining accessible roads near the farms and calculating the length of a road.

Alam et al. (2012) optimize the supply chain of the forest biomass power plant by a GIS-based integrated optimization model. This study focuses on two types of biomass: harvesting residues such as leftover tops, branches and other parts of the trees harvested and utilized biomass like non-merchantable trees. The objective function is to minimize the total piling, processing, felling, extraction and transportation costs. In order to estimate transportation costs from forest cell to the power plant, GIS data are used. Geijzenforffer et al. (2008) use a GIS-BIOLOCO to design a biomass supply chain by considering the accessibility of biomass, logistics, costs and environmental aspects. The goals are to maximize financial revenue, energy return and to minimize costs and emissions. In this study, the transportation costs and expected supply of biomass are computed more accurately. Frombo et al. (2009) develop a GIS-based for the optimal use of wood biomass and the optimal selection of plant size, location, and technology.

6.5 Simulation

Computer simulation first appeared as a scientific tool in meteorology and nuclear physics during World War II, and till now it has been a vital tool in an increasing number of disciplines. Computer simulation is a powerful method for studying complex systems. The simulation process includes selecting a model, constructing an implementation of the model in computer, calculating the results of the algorithm and visualizing the output data. Compared to mathematical programming, simulation allows a fine-gain modeling and can cope easily with random events. However, it computes a set of performance indicators from a given set of parameters and a lot of runs are required to find the optimal values of these parameters.

Many studies used computer simulation in biomass supply chains management. Gallis (1996) proposes a Decision Support System based on simulation language for representing forest biomass units flow from felling to storage. A forest biomass operations simulation model is developed which includes different operational systems, equipment, wages, interest rates and their effects on cost per unit. Several scenarios of scheduling forest biomass operations are considered in order to minimize cost and increase resource utilization. De Mol (1997) develops the simulation model Biologics (Biomass Logistics Computer Simulation) to calculate the costs and energy consumption of the biomass logistics with the simulation package PROSIM. Nilsson (1999) propose a dynamic simulation model for straw handling to optimize system performance and reduce the costs and energy. Nilsson (2000) analyzes the influence of various climatic, geographical and biological factors on costs for delivering the fuel straw to heating plants by using a dynamic simulation model. Kumar and Sokhansanj (2007) propose the Integrated Biomass Supply Analysis and Logistics (IBSAL) model for evaluating the delivery system. The objective of this study is to reduce the overall cost of delivered biomass such as collection and transportation costs of switchgrass. The cost of different strategies for collection, storage, and transportation of switchgrass are considered. Ravula et al. (2008) propose a First-In-First-Out (FIFO) logistic system of a cotton gin in southeast Virginia to analyze the average truck utilization and the effects of decreasing the number of trucks. Sokhansanj et al. (2006) simulate the collection, storage, and transport operations for supplying agricultural biomass to a biorefinery by developing the framework of a dynamic integrated biomass supply analysis and logistics model (IBSAL). Resource allocations (e.g. labor, equipment and structure) for biomass supply and transport operations are determined.

7. SURVEY ON BIOMASS SUPPLY CHAIN MANAGEMENT

Although biomass production and conversion processes have been studied for some time, the decision makers discovered more recently that the logistic system could constitute the Achilles' heel of future biorefineries. The aim of this section is to identify recent optimization methods and models which are more general and sophisticated than early papers.

Akgul et al. (2011) present mixed integer linear programming models to determine the optimal planning of a bioethanol supply chain for minimizing the total supply chain cost. The models' purpose is to optimize the locations and scales of the bioethanol production plants as well as biomass and bioethanol flows between regions, and also the number of transport units required for the transfer of these products between regions. The optimal bioethanol production and biomass cultivation rates are also determined. This work is based on a neighborhood flow approach. In this study, the following elements are considered:

- Biomass cultivation and biofuel production rates
- Geographical biomass availability
- Transport (price, modes, distances, and availabilities)
- Capital investment costs
- Locations and scales of biofuel production facilities
- Flows of biomass and biofuel between regions
- Locations of biofuel demand centers and their biofuel demand
- Biofuel production costs and unit biomass cultivation
- Modes of transport for delivery of biomass and biofuel

Logistics system design for biomass-to-bioenergy industry with multiple types of feedstocks is presented by Zhu and Yao (2011). A mixed integer linear programming is developed to determine the types and amounts of biomass harvested and purchased, the locations of warehouses, the size of harvesting team, the amounts stored and handled in each month, the transportation of biomass in the system and so on. This paper shows the gains of using multiple types of biomass feedstocks by comparing it with the case of using a single feedstock (switchgrass). The model includes three types of biomass such as switchgrass, corn stalk and wheat straw.

Akgul et al. (2012) introduce a systematic optimization framework for the optimal design of a UK-based hybrid first/second generation ethanol supply chain. The proposed model has been applied to a case study of ethanol production in the UK. The biofuel supply chain includes the following nodes: biomass cultivation sites, biofuel production facilities and demand centers. Biomass or biofuel are transported between these nodes. The objective of the model is to minimize total supply chain cost which includes the total investment cost, production costs, transportation costs and outsourcing (import) costs.

Judd et al. (2012) propose a logistic system by considering the use of Satellite Storage Locations (SSLs) for temporary storage and loading of round bales. Three equipment systems are considered for handling biomass at the SSLs, and they are placed either permanently or they are mobile in order to go from one Satellite Storage Location to another. A mathematical programming-based approach is used to determine SSLs and the number of equipments for minimizing the total cost. Furthermore, the problem is addressed to develop a cost effective feedstock logistic system for a bioenergy plant.

Designing and planning of bioethanol and sugar production under demand uncertainty are presented by Kostin et al. (2012). The authors propose a two-stage stochastic mixed integer linear programming approach for the optimal design and planning of bioethanol Supply chain under uncertainty in product demand. Their case study is in the Argentinean sugarcane industry. The analysis of the stochastic results shows that there are two critical factors that affect the supply chain performance under uncertainty. The first one is the production capacity and the second one is the amount of storages and transportation units.

Fazlollahi and Maréchal (2013) propose a method for the initial design of integrated urban energy systems. This paper proposes a systematic procedure including process design and energy integration techniques with simultaneous consideration of multi-periods and multi-objective aspects, economic and environment targets. It combines the use of optimization techniques with a data base of thermo-economic models that are used to build conversion technologies. Moreover, power generation is assumed as an opportunity for the utility company.

8. CRITICAL LOOK

A significant literature is now available in the area of biomass supply chains management. One of the most important and most difficult objectives in biomass supply chain is to design a whole logistic system, including a transportation network, feedstock supply, pre-processing, biomass distribution, and tactical operation schedules. Many researches were conducted on a single part or some parts of the logistic system. For instance, Rentizelas et al. (2009) propose an optimization model for multi-biomass by focusing on bioenergy conversion. The objective is to fully satisfy the energy demand of the customers. Rentizelas and Tatsiopoulos (2010) present a hybrid optimization method for locating a bioenergy facility. This paper just focuses on bioenergy facility and its distribution network. The proposed non-linear model considers the maximization of net present value. Still, too few papers optimize the whole supply chain. Zhang and Hu (2013) present a mixed integer programming model for the overall supply chain design. The objective is to minimize the total cost. Bowling et al. (2011) propose a mathematical formulation for finding the optimal production planning and locating the facilities.

After harvesting, biomass should be pre-processed to reduce moisture. There are five types of pre-processing (Ensiling, drying, pelletization, torrefaction and pyrolysis). Increasing density without reducing the energy content makes the biomass cheaper to transport. This will impact transportation costs and combustion efficiency at biorefineries. So, it is important to consider pre-processing in the biomass supply chain management but a few papers add pre-processing in the chain.

There are excessive papers that only considered one type of biomass. Zhang et al. (2013) propose an integrated optimization model just for switchgrass-based bioethanol supply chain. Cundiff et al. (1997) present a switchgrass supply chain for one biorefinery by considering multi-period horizon. However in reality, in many cases, we have multiple types of biomass at our disposal. A few papers deal with multi-biomass: Zhu and Yao (2011) consider different types of biomass (e.g. switchgrass, corn stalk and wheat straw). Akgul et al. (2012) propose an optimization model for a hybrid first and second generation ethanol. This paper considers wheat as a first generation and miscanthus, short rotation coppice and wheat straw as second generation. Moreover, some single plants have several parts that can be used for producing bioenergy (e.g. rape can provide seeds, chaff and straw), but still, very few papers consider different parts of the same plant.

Since crops can be harvested at different periods (e.g. in Europe, rape is harvested in July while miscanthus (a kind of cane) is cut in April), it can be difficult to supply a refinery over the whole year by considering several biomasses. In our opinion, more research is required to see how a refinery can use these successive crops efficiently, without building expensive storages.

The transportation options of biomass feedstock include roads, railways, waterways, and/or a combination of two or multiple options. In most of the papers, only the road transport for biomass is considered. Zhang et al. (2013) present an optimization model by considering the road transportation. Cundiff et al. (1997) design a biomass delivery system by using a linear programming approach. Road transportation (e.g. truck) is considered from storage locations to the central plant. However, Zhu et al. (2011) propose a logistic system design for bioenergy industry by considering different transportation modes (truck & trains).

The case studies in published papers try to show that computations are done correctly, but the credibility of results depends directly on the reliability of the data and the results cannot be better than the data. Collection of a large amount of reliable data is a major problem.

Most equipment costs of a supply chain (from the fields to the refinery) are induced by farm operations. The papers which try to determine details and dimensions of the harvesting and packing equipment are still rare and harvesting equipment are not detailed enough.

Concerning the computational aspects, the case studies for metaheuristic programming models are in general very small or highly aggregated. This is due to the excessive running times of current solvers. Heuristics can be used to go faster, but these can lead to the results in sub optimal solutions. An interesting and intermediate option would be to apply relaxation and/or decomposition techniques to those large scale models. Most of papers do not employ these techniques.

9. CONCLUSION

This paper surveys the recent researches on biomass supply chain optimization. The main definitions related to biomass supply chain and typical activities such as harvesting and collecting biomass, pre-processing, storage and transportation are explained. The key researches in this field are classified by considering different criteria such as decision levels (strategic, tactical and operational) as well as objective functions in biomass supply chain models (minimizing overall costs, maximizing overall profits, maximizing Net Present Value and multi-objective). This paper also presents an overview of the optimization methods in biomass supply chains which can be listed in different categories (heuristics, multi-criteria decision analysis, Geographic Information System (GIS) and simulation). By reviewing quantitative models available for biomass supply chains, a critical look and new research directions in biomass researches are discussed.

The review shows that the majority of studies focus on the strategic levels. However, few studies have been done on the operational levels of biomass supply chains. There are also a considerable number of studies using mathematical programming, but the papers which employ multi-criteria decision analysis and heuristics methods are still rare. Most of the studies are based on cost optimization by considering single objective and just few authors consider multiple-objective. Still, too few papers optimize the whole supply chain and consider storage and pre-processing between farms and biorefineries and also most papers represent just on-farm storage and simple pretreatment. Most of biomass supply chain models are based on single type of biomass and very few authors deal with multi-biomass and different parts of biomass. In addition, most authors consider the road transport for biomass and very few of the reviewed studies deal with multi-modal transport. Future researches must be done in order to fill the gaps listed above.

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