

Biomass for energy: A review on supply chain management models

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ABSTRACT

The present study reviews the status of research on biomass supply chain modeling. Biomass has become increasingly important as a renewable alternative energy source. One of the most critical aspects associated with the use of biomass is its supply chain and all the elements that are part of it. Indeed, in order for the use of this type of energy resource to become viable, its supply chain, from collection and transport to storage and distribution, needs to be well structured and optimized. Modeling is a critical step in developing understanding that leads to improved supply chain efficiency. Thus far, investigations that utilize supply chain models have focused on assessing specific supply chain scenarios, usually with an objective of minimizing cost. Significant opportunity exists to improve and expand the modeling process to allow for efficient supply chain design and operation. During this article will be analyzed several models presented by recent research that approach different situations and scenarios. At the end it is shown that biomass for energy supply chain models must include the analysis of several different variables and include the main disadvantages of its use as well.

1. Introduction

The challenge facing the biomass energy sector is, in a large degree, the challenge presented by its supply chain. In the majority of the situations, large volumes with low density, being low value biomass feedstocks, must be moved from largely spread production and collection sites to centralized processing facilities, then delivered in its final form to consumers. The low economic value of these materials suggest the need for lean supply chain strategies, whereas the variable nature of the feedstock and its availability suggests a need for an agile design for the supply chain. While this pressure is common in supply chain studies, the issue is especially important when considering biomass for energy. The largest fraction of biomass energy cost generated comes from logistics operations [1–4].

Biomass, for the purposes of this study, consists of lignocellulosic material produced through plant growth, therefore starch, sugar, and oil crops are excluded from the analysis [5]. Biomass can be originated from natural regrowth forests, plantation forestry, annual field crop production, algae production, or from residues of any of the above. It can also be derived from industrial processes, municipal waste, or land clearing operations. Final products can include heat, power, and/or fuel (liquid,

solid, or gaseous) for further use. Common forms of biomass energy include pellets, wood chips, and cellulosic ethanol [6–9].

A good logistics strategy is essential for all elements of the supply chain to operate in harmony and insures that the whole system functions as efficiently as possible [8,10,11]. The Council of Logistics Management (a professional organization of logistics managers, which aims to develop the theory and understanding of logistics) defines logistics as the part of the supply chain management responsible for planning, implementation and control of efficient and effective management, flows and storage of products and all associated information, from the point of origin to the point of consumption, in order to satisfy the requirements of the customer service [12–14].

In recent years, the optimization of logistics has been recognized as a unique opportunity for growth, profitability and competitiveness for companies [15–17]. It enhances marketing efforts creating conditions of competitive advantage in the marketplace [5,18]. The optimization creates an added value of place, time, quality and information to the productive chain. In addition, it seeks to eliminate from the process everything that has no value for the customer, all of which only entails costs and unproductive time [19–21]. At same time it implies an optimization of resources, increasing efficiency and improving the quality of

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the service, once the competitiveness in the market forces a continuous reduction of costs [22]. Logistics involves creating value, both for consumers and suppliers and for the company's stakeholders [12,23].

Therefore, since the price of the energy product produced from biomass is relatively low (i.e. 0.16 € per kg for wood pellets [19]), in order for the use of this type of energy resource to become viable, it is necessary that its supply chain from collection and transport to storage and distribution (logistics) be efficient and well defined and optimized [24].

One of the more important issues about biomass logistics is the use of storage, especially when seasonal availability is a characteristic of the feedstock [25–27]. Producers of biomass energy have limited tools available to help them select and optimize their supply chains, which can lead to sub-optimal operations [28,29]. For example, it is not unlikely for a project designer to choose storage methods with lower costs on a per-volume basis, while ignoring the effects this choice can have on overall system efficiency [30–32].

2. The biomass supply chain

Fig. 1 illustrates the general process of a biomass supply chain for energy production.

A typical biomass supply chain may include a combination of the following processes: field preparation, cultivation, harvesting, storage, field/forest transport, road transport and biomass utilization at the production station [33]. Typically, the supply chain is studied from after harvest until delivery [34,35]. Sometimes, harvest operations are omitted (farm gate to factory gate), but characteristics of the harvest operation can dramatically impact downstream performance [36]. In general, the three most common components to the biomass supply chain are harvest operations, transport, and storage [37].

2.1. Biomass harvest

Biomass harvesting can be from a “primary” or dedicated biomass harvest, or as a “secondary” harvest of residues or wastes. It is generally carried out in forests, agricultural fields or at industrial processing centers such as sawmills and furniture industries. Woody biomass is collected in the form of logs, bundles or chips [38–40].

Most types of biomass (agriculture and forest) are characterized by their seasonal availability [41–43]. The time period in which these types of biomass are available is very limited and is determined by the crop harvest period, the weather conditions and the need for replanting of the fields and forests [44]. The limited time period for collecting a large amount of biomass also leads to a significant seasonal need for resources, equipment and workforce [45]. This seasonal demand may increase the cost of obtaining these resources [33,46]. There is thus a need to store large amounts of biomass for a significant period of time if

the end user is to operate throughout the year. Problems introduced by the seasonal availability of biomass can be reduced if multiple feedstocks with different harvest periods are used [47]. The use of two different biomass sources, instead of one, can lead to a cost reduction of 15%–20% [48].

Supply chain processes that can be integrated with collection and harvest (or utilized later in the supply chain) include drying, shredding, densification and packaging [49,50].

According to a study carried out by Suurs [33], forest wood residues and chip wastes collected have the following characteristics:

- **Wood waste** - Wood logs are used in applications in the timber industry. Only a small part of the tree is used as high value timber for the furniture or flooring industries, leaving the remainder of the material for either pulp/paper, biomass energy, or other similar uses. As biomass fuel prices approach paper prices, this wood can begin to be destined for either market. In addition, all wood from smaller branches can also be used for energy production. However, it is important to realize that the supply of wood is heavily dependent on the market mechanisms of its suppliers, as its cost-effective removal often depends on infrastructure and operations for higher value timber harvests, which in turn vary with the global market. Energy production is potentially a very large market for wood, so in the future it may not be available in sufficient quantities to meet demand unless forest area and productivity both increases.
- **Shredded waste** - The branches are usually collected by machines (Fig. 2) that stack them. These residues can be exposed to drying outdoors during the summer, and for about 6 months the moisture content decreases from 55% to 45%–30% [51,52]. The stacked parts are gradually ground in place and then transported directly to the biomass plant. However, this is not an option to consider when the transport distance is too long.

2.2. Transport

Road transportation is the most common means of transportation used when transporting woody biomass from timber industries and forests [53]. Factors favoring the use of road transport include: (i) short distances usually used in the biomass industry, and (ii) the greater flexibility that road transport can offer compared to other modes. Means of transport such as the sea or rail can be considered when the transport distance of biomass is long [54,55].

Several opinions are discussed in the literature about the economic



Fig. 2. Example of a blade shredder producing woodchips (Photograph taken by one of the authors of the article at the premises of the company YGE SA, in Oliveira de Azeméis, northern Portugal).

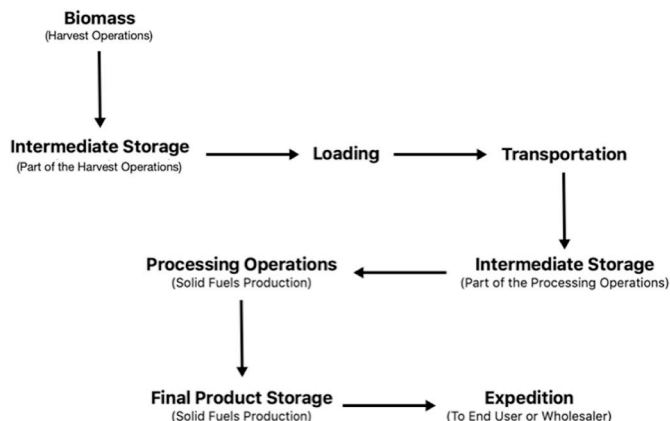


Fig. 1. General process of a biomass supply chain (adapted from Ref. [33]).

viability of using these heavy vehicles [54,56,57] or agricultural/forestry equipment [56] for transporting biomass to the end user [58]. Factors such as average transport distance, biomass density, load capacity and speed of vehicles, as well as their availability, impact their suitability [59].

According to Rentizelas et al. [53] transport costs vary according to distance and transport time. The transport distance mainly affects the fuel consumption of the vehicles and the travel time mainly affects the proportion of depreciation, insurance, maintenance and work allocated to that same trip. According to the author the travel time includes the time of travel and return, as well as the waiting time between shipments and downloads. The loading and unloading of vehicles must also be included whenever the biomass needs to be moved from a collection point to the production station.

According to Ravula et al. [60] road transport costs comprise two subcomponents, the cost of the truck and the cost of the fuel. The cost of components of the truck includes capital costs, maintenance (tires, brakes and lubricant), license, insurance and the costs with the driver. The author assumes that lorries always include the driver and its associated cost, even when the lorry is stopped on any day, that is, the driver cannot be hired as needed.

Due to the low density of biomass types, the capacity of transport vehicles is often limited in volume rather than load weight [61]. As a result, there is usually an increased need for transportation and handling equipment as well as storage space. Low biomass density further increases the cost of collection, handling, transport and storage along the supply chain [62,63], making its management critical.

Therefore, improvements in handling efficiency and transportability are one strategy to improve overall efficiency. Processing can take place at any stage of the supply chain, but often precedes road transport, thus generating improved throughput and lower overall costs [62].

Densification is a common way to achieve this objective. Biomass packaging (i.e. baling or bundling) increases biomass density making it easier to use during logistic operations while reducing the risks of biomass deterioration [54,64]. An example of biomass transport vehicles is shown in Fig. 3.

2.3. Storage

The biomass storage stage is a very critical component of the logistic chain. There are several options with regard to storage that can be categorized as either covered warehouses or exposed open-air storage [40,65,66]. In most cases, solutions are chosen that minimize the cost of

storage, without analyzing the overall effect on the supply chain. Many researchers assume that a covered storage using silos (Fig. 4) for biomass is the best option [54,67–69].

The two types of storage, both open-air and covered, have been analyzed [68,70]. Open-air storage has the advantage of lower cost but, on the other hand, the loss of biomass material is significant, and the moisture content thereof cannot be controlled and reduced to desired levels, leading to quality problems in production [71]. In addition, there are also health and safety problems, such as the risk of fungal and spore formation [64] and spontaneous ignition due to exothermic microbial degradation [53]. Open air storage may be feasible in arid locations [72].

Warehouses sited at the end user's location can be used to dry stored biomass [53,54,73], using, for example, heat from the plant to dry the fuel [69]. Some authors consider the use of intermediate storage locations between the collection fields and the fuel production plant [74]. These intermediate storage facilities can be located in the vicinity of the collection site, that is, in the fields and the forests, but also near the roads [73]. For all biomass fuels where the use of intermediate storage can be modeled, transportation occurs in two steps, first from fields/-forests/timber industries to an intermediate warehouse and then from the warehouse to the production plant.

Processing steps such as grinding, or densification, can be added to the intermediate storage location to reduce storage costs or reduce secondary transport costs. The grinding option to improve storage near the production plant has also been analyzed by several authors [41,74]. As noted, storage for many types of biomass is characterized by seasonal availability, since waste may be collected at a specific time of the year. In these cases, storage locations are usually needed for only a portion of the year.

According to Bowersox and Closs [75] storage facilities can be classified into three categories according to ownership: self-owned warehouses, public warehouses and subcontracted warehouses. Self-owned warehouses are those operated by the company owning the goods. Owning the warehouse and the equipment can add a substantial level of fixed costs in the composition of the total costs, since the company is responsible for all infrastructure expenses. Among the main advantages in its use are the flexibility, control, presence and strengthening of the company's image in the market through the visibility of the brand.

A notable example of public storage facilities is the series of facilities that were created by the Portuguese government after widespread wildfires in 2017 in order to receive all the burnt wood available from the forest. This was done to facilitate the cleanup effort to buffer the



Fig. 3. Truck for biomass transportation (Photograph taken by one of the authors of the article at the premises of the company YGE SA, in Oliveira de Azeméis, northern Portugal).



Fig. 4. Example of silos for biomass products (Photograph taken by one of the authors of the article at the premises of the company YGE SA, in Oliveira de Azeméis, northern Portugal).

massive entrance of raw-materials in the market which could induce an artificial lowering of prices and economic losses to forest land owners. Public storage facilities provide financial flexibility, advantages of economies of scale, and greater expertise in operational and management skills. They may have lower variable costs, due to lower wages, higher productivity and economies of scale. Since there are no investments in fixed assets for the user, this type of storage offers great operational flexibility, such as change of location, size and quantity of products to store.

Outsourced storage facilities are those that function much like public storage facilities but typically come from an agreement between the government and private company or forest land owner association that already has facilities in a certain location to provide the same service that public storage facilities can provide. Because it is a long-term partnership, they tend to generate lower costs than public warehouses, although they may require the participation of the client company in the division of infrastructure costs. Key benefits include specialization, flexibility and economies of scale by sharing management, labor, equipment and information resources with many customers.

The main risks to biomass during storage are the degradation of the quality of the biomass and dry matter losses of the same. The dry matter losses of the solid biomass are influenced by the number of storage steps and storage time [69,73,76–78]. A wise choice of the storage system and the storage time of the biomass can minimize this kind of problems. The type of storage to be used depends mainly on the climate and the stage of the biomass process. It is a common procedure to leave the waste from forestry operations for a few months at the collection site, after cutting, in order to significantly reduce their water content [67,73]. The downside to leaving the biomass at the collection site or landing is that restaging of equipment may be required. This would result in extra costs.

3. Biomass supply chain management models

Biomass supply chain modeling studies typically focus on one or more of the following research objectives:

- Predict supply chain performance,
- Select the most efficient supply chain configuration,
- Optimize sizing of supply chain components to minimize cost, or
- Optimize scheduling of supply chain operations.

In this section, a summary of the studies carried out by various authors on biomass supply chains is presented. Some authors focus on aspects related to the selection of types of biomass and suppliers, others on the best location for the warehouse or biomass processing center, others on the type of storage that should be used for biomass and the type of biomass.

Van Dyken et al. [77] presents a mixed integer linear programming model that can be applied to relevant components of a biomass supply chain such as sources of supply, biomass handling/processing, storage and end use. The proposed generic model has a flexible structure that allows the modeling of supply chains using various types of biomass and technologies.

Hall et al. [79] presents a simulation model to estimate and compare the logistic costs of delivery of two types of forest residues, fallow residues and transition residues to a biomass plant. De Mol et al. [80] consider the design of the supply chain in relation to a classic local network structure. Although the network simulation model presented captures the moisture loss and dry matter losses of the materials in storage, the optimization is not dynamic and ignores the seasonality, considering only an annualized static flow.

Gigler et al. [81] uses another modeling approach describing a methodology for the optimization of agricultural supply chains through dynamic programming, in order to find the lowest collection cost for end use of product. The model works by defining a set of supply chain stages and biomass stages and deals explicitly with product properties, which

are influenced by their handling, processing, transport and storage.

Almansoori & Shah [82] presents a model that takes into account the availability of energy sources, ie raw materials and their logistics, as well as changing demand for hydrogen over long-term planning, leading to the development of a phased infrastructure.

Another model of mixed integer linear optimization is demonstrated by J. Nagel [83]. The methodology allows the management of biomass for energy supply at a regional level, based on the dynamic assessment of economic efficiency. Sedjo [84] also evaluated the economic aspect of the use of forest biomass in energy production.

A mathematical programming model is proposed by Eksioğlu et al. [66] to design the supply chain and manage the logistics of a bio-refinery. The model determines the number, size and location of the bio-refineries needed to produce biofuel using the available biomass. Also, Vera et al. [85] developed a model to find the ideal location and capacity of a power station fueled with waste from olive oil production areas. A mixed integer linear programming model was presented by Leduc et al. [86] to determine the ideal geographic locations and dimensions of methanol heat recovery plants.

Azevedo [87] presents three mathematical models in order to identify the suitable place to place a biomass transformation station, knowing the area of potential zones of biomass production. The problem of finding the best location for a bio-refinery plant, considering the locations, availability of biomass and geographical distribution of the clients, was also studied by Leduc et al. [86].

Bruglieri and Liberti [88] proposes a mixed integer linear programming model for the development of an energy production process involving several biomass products (agricultural products, biological waste, among others) and various types of different biomass plants. The model takes into account the different characteristics of biomass (eg seasonality) and also addresses the issue of the return of biofuels waste to biomass production fields, taking into account the protection of the environment and sustainable development.

Galvão Jr. and Cunha [89] deals with the problem of collecting wood biomass residues by breaking it down into two distinct optimization problems: the problem of selecting wood suppliers that offer lower cost of purchasing and transporting waste and the problem of fleet design and designation of vehicles for collection. Using spreadsheet-based iterative solution techniques, the vendor selection problem was easily solved. The problem of fleet sizing and vehicle designation, due to its complexity, makes the computational resolution effort increase exponentially with the size of the problem. As a consequence, it may be necessary to acquire a strategic solution using efficient heuristics to obtain good quality solutions and appropriate processing times.

Van Belle et al. [64] calculates the total cost of biomass using three different scenarios in which, besides logistical factors (machinery, transport and warehouses), social factors are also integrated. It was verified that the most economically efficient option, found by calculation, is not always the best alternative, since it was not chosen by the majority of loggers.

Zhu and Yao [90] established a multiproduct network flow model, which is a mixed integer linear programming model, which at the same time makes strategic and tactical decisions. Decisions are made, such as making direct transport or trans-shipment via intermediate warehouses, calculating the locations and capacities of the warehouses, as well as the composition and size of the collection team. The types and quantities of biomass collected/purchased, stored and processed in each month, as well as the transport flows in each month are also decided. The study shows that the use of various types of biomass can increase the supply of biomass, reduce seasonality, reduce the cost of biofuels, and eventually increase the profit of the biofuel plant.

Gomes et al. [2] proposes a mixed integer programming model that integrates tactical and operational decisions for biomass supply chain problems. The objective function is the sum of the fixed and variable costs of the collection, storage, storage and transport operations, in order to minimize the total cost of the system. Transport costs are not a

linear function of transported units, but a step function is used where each level corresponds to a vehicle, thus allowing a greater approximation to real costs.

Gunnarsson et al. [70] studies the problem of deciding when and where forest residues should be collected (harvesting areas, sawmills and import ports) and converted into forest fuels (bioenergy), and how such wastes should be transported to and stored in thermal power plants. They take into account a number of decision variables: the type of fuel (biomass) to be used; programming and location of the chipper; storage terminal; transport standards; and an optional contract for the collection and assignment of sawmills to meet the excess demand. This problem was formulated as a mixed integer linear programming problem. The basis of the model can be considered as a version of a two-location problem (facility location problem). The formulation can potentially be expanded to incorporate supplier sources beyond the existing ones, however, it should be anticipated that computationally this requirement will be limiting.

Tatsiopoulos and Tolis [54] defines a linear programming model to determine the amounts of cotton stem biomass to be transported from production fields to warehouses, taking into account supply and demand constraints. The goal is to minimize the sum of collection, transportation and storage costs.

Also, Zhu et al. [91] proposes a mixed integer linear programming model for the biomass conversion industry, which, at the same time, determines the best set of locations for new warehouses, warehouse capacities, effective inventory policy, biomass transport flows, the collection schedule during the year, and the best configuration among a set of candidates for bio-refinery plants.

Cundiff et al. [92] presents a system engineering and modeling approach focused on the issues associated with the collection, storage and transport of herbaceous biomass. The model is developed in order to determine the optimal monthly loading and scheduling of each producer's capacity, based on monthly harvests, for each of four-times variant scenarios. The paper presents a systems approach to the biomass logistic planning problem, incorporating the key issue of loss of product yield during storage. However, it is a fixed model and does not represent flexible network modeling to capture more complex supply systems or alternative processing tasks.

A non-linear decision support model is presented by Freppaz et al. [93]. The problem under consideration is the optimal exploitation of biomass resources at various collection sites and the allocation of some centralized combustion plants. The objective is to find the optimum capacity for heat and energy generation, as well as the optimal use of biomass resources and transportation options.

The model described by Kumar et al. [94] focuses on the collection of biomass and transport systems and presents a multicriteria evaluation model. Economic, social, environmental and technical factors are included in the ranking of the alternatives studied.

Ravula et al. [60] analyzes an important cost factor of a logistics system, the transport (trucks). Two different management policies, one based on travel time and the other based on the allocation of trucks to certain sectors around the production base, were used to develop lorry scheduling. The authors concluded that operations involving truck transportation accounted for about 75% of the total cost of the system.

Rentizelas et al. [53] focuses on the issue of biomass storage. Three types of storage were investigated: a closed warehouse with biomass drying capacity, a covered warehouse without drying capacity and open-air storage. The authors conclude that the application of a cheaper storage solution (storage in the open air) leads to considerable cost savings for the logistics of the entire biomass function.

According to the authors, this reduction far exceeds the additional costs imposed by biomass loss or damage, as well as the increase in the costs of handling the biomass, which characterizes the simplest storage solutions applied. Based on the results of this study, it can be inferred that forms of biomass that can be stored outdoors are preferable, such as logs or woodchips, and mainly when weather conditions are favorable.

On the other hand, an approach using several different biomass forms appears to be attractive to systems with expensive storage solutions (closed storage scenarios). Frombo et al. [95] develops the EDSS (Environmental Decision Support System), based on a Geographic Information System (GIS), to define, plan and manage logistics strategies for energy production from forest biomass. The optimization model used can be classified as a mixed integer nonlinear programming problem.

Ayoub et al. [96] develops the BEDS (Bioenergy Decision System) for the planning and implementation of bioenergy production. With this system they tried to unite in one interface: geographical location systems; optimization software; technological information database; simulation model and system of knowledge evolution.

Sokhansanj et al. [74] developed a model (IBSAL) to simulate the collection, storage and transport, in the supply of agricultural biomass to a biorefinery. Climatic conditions, including rainfall and snow, which influence moisture content and biomass dry matter loss across the supply chain, are also included in the model. This model was applied to a case of collecting and transporting corn cobs and stover, wheat straw and grass. Mobini et al. [97] develops a simulation model based on IBSAL to assess the logistics of a biomass supply chain from forest collection areas to a potential energy consumer. Three different collection systems were considered in this model. The simulation model is able to provide estimates of cost, biomass volume, carbon emissions and equilibrium moisture content of the material delivered during the life of the plant.

A GIS-based decision support system is presented by Panichelli and Edgard [98] for the selection of lower cost bioenergy production sites where there is significant variability in the price of biomass and where more than one bioenergy power plant with a fixed capacity has to be inserted in a given region. Another methodology, also using a GIS, focused on logistical and transport strategies, which can be used to locate a bioenergy power plant network [99]. In addition to the configuration of the supply chain supply component, the production component is also defined, which converts the biomass into fuels.

Many other studies have also been carried out on various biomass conversion issues for bioenergy, such as the transport chains for forest biomass [54], for herbaceous biomass [92] and for cotton stems [100], various cost analyzes on collection [101], production cost analysis and grass collection [102], cost analysis of delivery, including collection, storage and transport costs [53,103], techno-economic assessments [104], bioethanol production life cycle assessment [105] and studies on environmental impacts in activities of the logistic system [62,64]. Fiedler et al. [56,106] Allen et al. also discussed the requirements for the provision of biomass and the supply processes and transport networks in developing cost-effective supply systems for the use of industrially processed biomass resources.

4. Discussion

The majority of supply chain models simulate the mass flow and/or cost of the biomass as it travels through the supply chain, allowing for inputs to be varied so as to measure the effect of these changes on supply chain performance. Parameter variation tends to be either manually carried out or utilizes a linear program algorithm to arrive at an optimal solution. While some of the models carry out a static (one time point) analysis, others are dynamic, providing time-series performance data over the course of a season or year. Very few of the models include stochastic simulation that takes into account uncertainty of performance for any of the supply chain components. Most of the models of individual components in the supply chain are relatively simple characterizations of the system's operation and little to no experimental validation is available to verify that the supply chains function as predicted. As such, significant opportunities exist for improved modeling and validation of biomass supply chains.

A smaller component of the supply chain modeling literature utilizes decision models that simulate not the performance of the supply chain

but the process of selecting an alternative within a supply chain. They provide the opportunity to have a different perspective on supply chain operation and management, which are valuable for addressing problems that cannot be directly addressed by simulation models.

In the majority of studies, the supply chain model is designed and implemented to address a specific question with relation to the supply chain (problem focused), rather than being designed with respect to the model itself (tool focused).

As can be seen in the literature analyzed, there are many different references and approaches to biomass supply chains. Some authors address the issue of supply chains with regard to the selection of types of biomass and logistical options available that minimize the total costs of the chain. Others address the best location for the warehouses or biomass transforming plants. While yet others address the type of storage that should be used for biomass and also on the dimensioning of the fleet of vehicles (the type and quantity of vehicles that must be used in the transportation of biomass) and their scheduling. There are also other approaches that analyze various aspects, defined previously, simultaneously. Some decision support systems and simulation systems are also defined in the literature that help in the whole process of optimizing the collection, transport and storage of biomass.

With regard to the selection of suppliers that minimize the total costs of the biomass supply chain, variables related to the cost of acquiring raw material from suppliers, the monthly production of raw material from suppliers, the period of time necessary for the supplier to produce sufficient raw material to achieve the capacity of the collection vehicle, the maximum permissible time period that the biomass can be stored and the distance from each supplier to the biomass plant or warehouse. The use of various types of biomass (several suppliers) seems to be a very viable solution, so that it can respond to all the demand.

In the analysis of the best location for the warehouse or biomass processing center, the locality is usually chosen near the raw material (biomass) using Geographic Information Systems (GIS). Several models and methods are used in this analysis depending on the type and number of installations required. As examples of most used models can have: Weber, Location-Allocation, Location-Routing, Fixed Charge Location or Capacitated Facility Location, Incapacitated Facility Location, Maximal Covering Location Problem and Set Location Modeling, Hub Location, among many others. Each of these models has its own characteristics and should only be used according to the type of installation desired. However, since these models are often extremely difficult to solve, the most usual approach is the use of heuristic methods to solve such problems.

Regarding the type of storage that should be used for biomass, three general types of storage are generally discussed: covered storage with possibility of drying of biomass, covered storage without drying of biomass and uncovered storage. No studies were found regarding the hypothesis of using own warehouses or subcontracted warehouses.

Another important cost factor for a logistics system is the mode of transportation (vehicles) that is used to move biomass loads from distributed storage locations (suppliers) to warehouses and to biomass (central) processing facilities. The goal of any schedule is to reduce the maximum number of vehicles required to deliver the same number of shipments in order to minimize transportation costs. The vehicles used are usually trucks with different transport capacities. Variables are normally considered as the travel time (round trip) from the supplier to the warehouse or central, loading time at the supplier and time of unloading at the plant or warehouse, days of the vehicle programming period and fuel costs. Transport costs are also usually taken into account, depending on distance (linear transport costs). Some of the studies analyzed also study the hypothesis of subcontracting vehicles as a way of responding to all the necessary demand.

Also found in the literature are some decision support systems and simulation systems that help and are an asset in the whole process of optimizing the collection, transport and storage of biomass. It was verified that most of the analyzed models are static and are defined for

specific case studies, not generally representing the biomass supply chains.

It was therefore concluded that there are few models found that encompass all links in the biomass supply chain. The various constituents of the chain are usually analyzed separately (supplier selection, transportation, plant location, storage). However, there are some authors who propose, in a single model, the junction of several chain links simultaneously. It was also verified that none of the analyzed models studies the possibility of using subcontracted warehouses (outsourcing).

5. Conclusions

This work consisted in the study and characterization of the biomass supply chain models mostly used and identifying the most critical points of the same. Based on the existing literature, the various characteristics that make biomass supply chains unique, namely the low density of biomass, the low sale price of pellets and the high costs, especially at the transport level, became clear. In order for the use of this type of renewable energy to be profitable and competitive, it is necessary that the entire supply chain is well structured and optimized in order to become efficient.

Another of the main characteristics of biomass is its seasonality. The length of time it is available is quite limited and is determined by the harvesting period, the weather conditions and the need for replanting of the fields and forests. The fact that the biomass has a low density, also has the option of being able to be processed beforehand (in fields or forests) in order to optimize its transport. The high moisture content at the time of collection is another important factor to consider, since it can cause problems (fungi generation) at storage level.

As stated here previously there are several models that can analyze the supply chain conditions, including all the variables that are part of the entire biomass collecting process with the objective of becoming more efficient and feasible. Biomass for energy uses is presented nowadays as one of the major possibilities to be an alternative to fossil fuels, however, due to some constraints caused by its low density, low heating value and geographic dispersion, all the elements must be carefully understood to allow an efficient operation and design of the supply chain.

Declaration of competing interest

The authors declare no conflict of interests.

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References

- [1] Pretty JN, et al. An assessment of the total external costs of UK agriculture. *Agric Syst* 2000;65(2):113–36.
- [2] Gomes CFS, Costa HG, de Souza GG. Abordagem estratégica para a seleção de sistemas erp utilizando apoio multicritério à decisão. *Rev Produção Online* 2013; 13(3):1060–88.
- [3] Hamelinck CN, Suurs RA, Faaij AP. International bioenergy transport costs and energy balance. *Biomass Bioenergy* 2005;29(2):114–34.
- [4] Shuit SH, Tan KT, Lee KT, Kamaruddin A. Oil palm biomass as a sustainable energy source: a Malaysian case study. *Energy* 2009;34(9):1225–35.
- [5] Sarkar B, Ganguly B, Sarkar M, Pareek S. Effect of variable transportation and carbon emission in a three-echelon supply chain model. *Transp Res E Logist Transp Rev* 2016;91:112–28.
- [6] de Freitas EP. O uso dos agrocombustíveis no contexto das mudanças climáticas: algumas considerações sobre as políticas de energia em Portugal (UE) e no Brasil. *Produção Acadêmica* 2016;1:211.
- [7] Demirbas A, Omar Al-Sasi B, Nizami A-S. Recent volatility in the price of crude oil. *Energy Sources B Energy Econ Plan Policy* 2017;12(5):408–14.
- [8] Alakangas E, et al. Classification of used wood in European solid biofuel standard: fuel specification and classes (EN 14961-1). editionName: publication; 2010. p. 1932–9.
- [9] Ballou RH. Gerenciamento da cadeia de suprimentos: planejamento, organização e logística empresarial. Bookman; 2001.

- [10] Brewer PC. Using the balanced scorecard to measure supply chain performance. *Peter C Brewer; Thomas WSph. J Bus Logist* 2000;21(1):75.
- [11] Lambert DM, Stock JR. *Strategic logistics management*. IL: Irwin Homewood; 1993.
- [12] Lambert DM, Stock JR, Ellram LM. *Fundamentals of logistics management*. McGraw-Hill/Irwin; 1998.
- [13] Gattorna J. *Managing the supply chain: a strategic perspective*. Macmillan International Higher Education; 1996.
- [14] Copacino WC. *Supply chain management: the basics and beyond*. CRC Press; 1997.
- [15] Novaes A. *Logística e gerenciamento da cadeia de distribuição*. Elsevier Brasil; 2016.
- [16] Mentzer JT, Konrad BP. An efficiency/effectiveness approach to logistics performance analysis. *J Bus Logist* 1991;12(1):33.
- [17] Magad EL. *Total materials management: achieving maximum profits through materials/logistics operations*. Springer Science & Business Media; 2013.
- [18] Ng CK, Smith JK, Smith RL. Evidence on the determinants of credit terms used in interfirm trade. *J Financ* 1999;54(3):1109–29.
- [19] Nunes L, Matias J, Catalao J. Wood pellets as a sustainable energy alternative in Portugal. *Renew Energy* 2016;85:1011–6.
- [20] Eisner H. *Essentials of project and systems engineering management*. John Wiley & Sons; 2008.
- [21] Sarkar B, Shaw BK, Kim T, Sarkar M, Shin D. An integrated inventory model with variable transportation cost, two-stage inspection, and defective items. *J Ind Manag Optim* 2017;13(4):1975–90.
- [22] Sarkar B, Saren S, Sinha D, Hur S. Effect of unequal lot sizes, variable setup cost, and carbon emission cost in a supply chain model. *Math Probl Eng* 2015;2015.
- [23] Chikan A. Integration of production and logistics—in principle, in practice and in education. *Int J Prod Econ* 2001;69(2):129–40.
- [24] Tiwari S, Ahmed W, Sarkar B. Multi-item sustainable green production system under trade-credit and partial backordering. *J Clean Prod* 2018;204:82–95.
- [25] Ahmed W, Sarkar B. Impact of carbon emissions in a sustainable supply chain management for a second generation biofuel. *J Clean Prod* 2018;186:807–20.
- [26] Sarkar B, Ahmed W, Kim N. Joint effects of variable carbon emission cost and multi-delay-in-payments under single-setup-multiple-delivery policy in a global sustainable supply chain. *J Clean Prod* 2018;185:421–45.
- [27] M. Sarkar, B. Sarkar, M. W. Iqbal, and H. Lim, Utilization of energy consumption in a two-echelon supply chain model under carbon emission and setup cost reduction.
- [28] Kneafsey M, et al. Short food supply chains and local food systems in the EU. A state of play of their socio-economic characteristics. *JRC Sci Policy Rep* 2013;123.
- [29] Senge PM, Carstedt G, Porter PL. Next industrial revolution. *MIT Sloan Manag Rev* 2001;42(2):24–38.
- [30] Basu R. *Managing project supply chains*. Routledge; 2017.
- [31] Hitchins DK. *Systems engineering: a 21st century systems methodology*. John Wiley & Sons; 2008.
- [32] Willard B. *The new sustainability advantage: seven business case benefits of a triple bottom line*. New Society Publishers; 2012.
- [33] Suurs R. Long distance bioenergy logistics. An assessment of costs and energy consumption for various biomass energy transport chains. Department of Science; 2002.
- [34] Sarkar M, Sarkar B. Optimization of safety stock under controllable production rate and energy consumption in an automated smart production management. *Energies* 2019;12(11):2059.
- [35] Bhuniya S, Sarkar B, Pareek S. Multi-product production system with the reduced failure rate and the optimum energy consumption under variable demand. *Mathematics* 2019;7(5):465.
- [36] Sarkar M, Sarkar B, Iqbal M. Effect of energy and failure rate in a multi-item smart production system. *Energies* 2018;11(11):2958.
- [37] Sarkar B, Omair M, Choi S-B. A multi-objective optimization of energy, economic, and carbon emission in a production model under sustainable supply chain management. *Appl Sci* 2018;8(10):1744.
- [38] Perlack RD. Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Oak Ridge National Laboratory; 2005.
- [39] Perlack RD, et al. US billion-ton update: biomass supply for a bioenergy and bioproducts industry. 2011.
- [40] Demirbaş A. Biomass resource facilities and biomass conversion processing for fuels and chemicals. *Energy Convers Manag* 2001;42(11):1357–78.
- [41] Caputo AC, Palumbo M, Pelagagge PM, Scacchia F. Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables. *Biomass Bioenergy* 2005;28(1):35–51.
- [42] Madlener R, Bachhiesl M. Socio-economic drivers of large urban biomass cogeneration: sustainable energy supply for Austria's capital Vienna. *Energy Policy* 2007;35(2):1075–87.
- [43] Nilsson D, Hansson P-A. Influence of various machinery combinations, fuel proportions and storage capacities on costs for co-handling of straw and reed canary grass to district heating plants. *Biomass Bioenergy* 2001;20(4):247–60.
- [44] Wood SM, Layzell DB. A Canadian biomass inventory: feedstocks for a bio-based economy-Final report. 2003.
- [45] Beringer T, Lucht W, Schapoff S. Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *Gcb Bioenergy* 2011;3(4):299–312.
- [46] Pedrolí B, et al. Is energy cropping in Europe compatible with biodiversity?—Opportunities and threats to biodiversity from land-based production of biomass for bioenergy purposes. *Biomass Bioenergy* 2013;55:73–86.
- [47] Demirbas MF, Balat M, Balat H. Potential contribution of biomass to the sustainable energy development. *Energy Convers Manag* 2009;50(7):1746–60.
- [48] Yoshioka T, Aruga K, Nitami T, Kobayashi H, Sakai H. Energy and carbon dioxide (CO₂) balance of logging residues as alternative energy resources: system analysis based on the method of a life cycle inventory (LCI) analysis. *J For Res* 2005;10(2): 125–34.
- [49] Capareda S. *Introduction to biomass energy conversions*. CRC press; 2013.
- [50] Mapemba LD. Cost to deliver lignocellulosic biomass to a biorefinery. Oklahoma State University; 2005.
- [51] Larasati A, Liu T, Epplin FM. An analysis of logistic costs to determine optimal size of a biofuel refinery. *Eng Manag J* 2012;24(4):63–72.
- [52] Skoulou V, Zabanitout A. Investigation of agricultural and animal wastes in Greece and their allocation to potential application for energy production. *Renew Sustain Energy Rev* 2007;11(8):1698–719.
- [53] Rentizelas AA, Tolis AJ, Tatsiopoulos IP. Logistics issues of biomass: the storage problem and the multi-biomass supply chain. *Renew Sustain Energy Rev* 2009;13(4):887–94.
- [54] Tatsiopoulos I, Tolis A. Economic aspects of the cotton-stalk biomass logistics and comparison of supply chain methods. *Biomass Bioenergy* 2003;24(3):199–214.
- [55] Forsberg G. Biomass energy transport: analysis of bioenergy transport chains using life cycle inventory method. *Biomass Bioenergy* 2000;19(1):17–30.
- [56] Allen J, Browne M, Hunter A, Boyd J, Palmer H. Logistics management and costs of biomass fuel supply. *Int J Phys Distrib Logist Manag* 1998;28(6):463–77.
- [57] Lam HL, Varbanov P, Klemeš J. Minimising carbon footprint of regional biomass supply chains. *Resour Conserv Recycl* 2010;54(5):303–9.
- [58] Miao Z, Shastri Y, Grift TE, Hansen AC, Ting KC. Lignocellulosic biomass feedstock transportation alternatives, logistics, equipment configurations, and modeling. *Biofuels, Bioprod, Biorefining* 2012;6(3):351–62.
- [59] Mahmudi H, Flynn PC. Rail vs truck transport of biomass. In: *Twenty-seventh symposium on biotechnology for fuels and chemicals*. Springer; 2006. p. 88–103.
- [60] Ravula P, Grisso R, Cundiff J. Comparison between two policy strategies for scheduling trucks in a biomass logistic system. *Bioresour Technol* 2008;99(13): 5710–21.
- [61] Noon CE, Daly MJ, Graham RL, Zahn F. Transportation and site location analysis for regional integrated biomass assessment (RIBA). Oak Ridge National Lab., TN (US); 1996.
- [62] Rentizelas A, Tatsiopoulos I, Tolis A. An optimization model for multi-biomass tri-generation energy supply. *Biomass Bioenergy* 2009;33(2):223–33.
- [63] Chau J, Sowlati T, Sokhansanj S, Preto F, Melin S, Bi X. Techno-economic analysis of wood biomass boilers for the greenhouse industry. *Appl Energy* 2009;86(3): 364–71.
- [64] Van Belle J-F, Temmerman M, Schenkel Y. Three level procurement of forest residues for power plant. *Biomass Bioenergy* 2003;24(4):9.
- [65] Brechbill SC, Tyner WE, Ileleji KE. The economics of biomass collection and transportation and its supply to Indiana cellulosic and electric utility facilities. *BioEnergy Res* 2011;4(2):141–52.
- [66] Ekşioğlu SD, Acharya A, Leightley LE, Arora S. Analyzing the design and management of biomass-to-biorefinery supply chain. *Comput Ind Eng* 2009;57(4):1342–52.
- [67] Thornley P. Airborne emissions from biomass based power generation systems. *Environ Res Lett* 2008;3(1):014004.
- [68] Forsberg G. Biomass energy transport: analysis of bioenergy transport chains using life cycle inventory method. *Biomass Bioenergy* 2000;19(1):29.
- [69] Gasol CM, S R, M R, A AJ, Carrasco J, Gabarrell X. Feasibility assessment of poplar bioenergy systems in the Southern Europe. *Renew Sustain Energy Rev* 2009;13(4):12.
- [70] Gunnarsson H, Rönqvist M, Lundgren JT. Supply chain modelling of forest fuel. *Eur J Oper Res* 2004;158(1):20.
- [71] Iakovou E, Karagiannidis A, Vlachos D, Toka A, Malamakis A. Waste biomass-to-energy supply chain management: a critical synthesis. *Waste Manag* 2010;30(10): 1860–70.
- [72] Maherali H, DeLucia EH. Influence of climate-driven shifts in biomass allocation on water transport and storage in ponderosa pine. *Oecologia* 2001;129(4): 481–91.
- [73] Hamelinck CN, Suurs R, Faaij A. Large scale and long distance biomass supply chains: logistics, costs, energy consumption, emission balances. In: *2nd world Conference on biomass for energy*; 2004.
- [74] Sokhansanj S, Kumar A, Turhollow AF. Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). *Biomass Bioenergy* 2006;30(10):838–47.
- [75] Bowersox DJ, Closs DJ. Logística empresarial: o processo de integração da cadeia de suprimento. In: *Logística empresarial: o processo de integração da cadeia de suprimento*; 2007.
- [76] Cocchi M, et al. Global wood pellet industry market and trade study. In: *IEA bioenergy task, vol. 40. IEA Bioenergy*; 2011. p. 190.
- [77] Van Dyken S, Bakken BH, Skjelbred HI. Linear mixed-integer models for biomass supply chains with transport, storage and processing. *Energy* 2010;35(3): 1338–50.
- [78] Palma A, Pestana M, Azevedo A. Pine resin sector in Portugal—weaknesses and challenges. *Amélia Palma, Miguel Pestana, Anamaria Azevedo. PINE RESIN* 2012: 10.
- [79] Hall P, Gigler JK, Sims RE. Delivery systems of forest arisings for energy production in New Zealand. *Biomass Bioenergy* 2001;21(6):391–9.
- [80] Mol R, Jogems M, Van Beek P, Gigler J. Simulation and optimization of the logistics of biomass fuel collection. *NJAS - Wageningen J Life Sci* 1997;45(1): 217–28.

- [81] Gigler JK, Hendrix EM, Heesen RA, van den Hazelkamp VG, Meerdink G. On optimisation of agri chains by dynamic programming. *Eur J Oper Res* 2002;139(3):613–25.
- [82] Almansoori A, Shah N. Design and operation of a future hydrogen supply chain: multi-period model. *Int J Hydrogen Energy* 2009;34(19):7883–97.
- [83] Nagel J. Determination of an economic energy supply structure based on biomass using a mixed-integer linear optimization model. *Ecol Eng* 2000;16:91–102.
- [84] Sedjo RA. The economics of forest-based biomass supply. *Energy Policy* 1997;25(6):559–66.
- [85] Vera D, Carabias J, Jurado F, Ruiz-Reyes N. A Honey Bee Foraging approach for optimal location of a biomass power plant. *Appl Energy* 2010;87(7):2119–27.
- [86] Leduc S, et al. Optimal location of lignocellulosic ethanol refineries with polygeneration in Sweden. *Energy* 2010;35(6):2709–16.
- [87] Carvalho Chaves MC, Gomes CFS, Pereira ER. Avaliação de biocombustíveis utilizando o apoio multicritério à decisão. *Production* 2014;24(3):12.
- [88] Bruglieri M, Liberti L. Optimal running and planning of a biomass-based energy production process. *Energy Policy* 2008;36(7):8.
- [89] Galvão Jr FA, Cunha CB. Modelagem matemática do problema de coleta de resíduos de biomassa de madeira para fins energéticos. Universidade de São Paulo; 2001.
- [90] Zhu X, Yao Q. Logistics system design for biomass-to-bioenergy industry with multiple types of feedstocks. *Bioresour Technol* 2011;102(23):9.
- [91] Zhu X, Li X, Yao Q, Chen Y. Challenges and models in supporting logistics system design for dedicated-biomass-based bioenergy industry. *Bioresour Technol* 2011;102(2):7.
- [92] Cundiff JS, Dias N, Sherahli HD. A linear programming approach for designing a herbaceous biomass delivery system. *Biol Technol* 1997;59(1):9.
- [93] Freppaz D, Minciardi R, Robba M, Rovatti M, Sacile R, Taramasso A. Optimizing forest biomass exploitation for energy supply at a regional level. *Biomass Bioenergy* 2004;26(1):10.
- [94] Kumar A, Sokhansanj S, Flynn PC. Development of a multicriteria assessment model for ranking biomass feedstock collection and transportation systems. In: Twenty-seventh symposium on biotechnology for fuels and chemicals. H. Press; 2006.
- [95] Frombo F, Minciardi R, Robba M, Sacile R. A decision support system for planning biomass-based energy production. *Energy* 2009;34(3):7.
- [96] Ayoub N, Martins R, Wang K, Seki H, Naka Y. Two levels decision system for efficient planning and implementation of bioenergy production. *Energy Convers Manag* 2007;48(3):15.
- [97] Mobini M, Sowlati T, Sokhansanj S. Forest biomass supply logistics for a power plant using the discrete-event simulation approach. *Appl Energy* 2011;88(4):9.
- [98] Panichelli L, Gnansounou E. GIS-based approach for defining bioenergy facilities location: a case study in Northern Spain based on marginal delivery costs and resources competition between facilities. *Biomass Bioenergy* 2008;32(4):11.
- [99] Perpina C, Alfonso D, Pérez-Navarro A, Penalvo E, Vargas C, Cárdenas R. Methodology based on Geographic Information Systems for biomass logistics and transport optimisation. *Renew Energy* 2009;34(3):10.
- [100] Ravula PP, Grisso RD, Cundiff JS. Cotton logistics as a model for a biomass transportation system. *Biomass Bioenergy* 2008;32(4):11.
- [101] Thorsell S, Epplin FM, Huhnke RL, Taliaferro CM. Economics of a coordinated biorefinery feedstock harvest system: lignocellulosic biomass harvest cost. *Biomass Bioenergy* 2004;27(4):10.
- [102] Sokhansanj S, et al. Large-scale production, harvest and logistics of switchgrass (*Panicum virgatum* L.)—current technology and envisioning a mature technology. *Biofuels, Bioprod, Biorefining* 2009;3(2):17.
- [103] Mapemba LD, Epplin FM, Taliaferro CM, Huhnke RL. Biorefinery feedstock production on conservation reserve program land. *Rev Agric Econ* 2007;29(2):19.
- [104] Gnansounou E, Dauriat E. Techno-economic analysis of lignocellulosic ethanol: a review. *Bioresour Technol* 2010;101(13):11.
- [105] Singh A, Pant D, Korres NE, Nizami AS, Prasad S, Murphy JD. Key issues in life cycle assessment of ethanol production from lignocellulosic biomass: challenges and perspectives. *Bioresour Technol* 2010;101(13):9.
- [106] Fiedler P, Lange M, Schultze M. Supply logistics for the industrialized use of biomass-principles and planning approach. In: Presented at the international symposium on logistics and industrial informatics; 2007.