Outsourcing Management for Supply Chain Operations and Logistics Services

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Chapter 18

Multi-Criteria Decision Making for Supplier Selection in Biomass Supply Networks for Bioenergy Production

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ABSTRACT

Decision-making on outsourcing biomass supply operations for bioenergy production is both of strategic and operational importance and can be modeled as a multi-perspective supplier selection problem characterized by multiple qualitative and quantitative factors, as well as technical and non-technical attributes and constraints. The biomass supply system presents unique features that highly impact the bioenergy production. Network functionality, raw material availability (influenced by seasonality, weather/climate conditions, land suitability, and other parameters), and procurement costs constitute important parameters for the viability of bioenergy production plants. This chapter provides a comprehensive analysis of biomass supply chains, focusing on the special issues of raw material cost fluctuations, biomass seasonality, and the dynamics of biomass demand. It also suggests the effectiveness of a multi-criteria decision making approach for adequately assessing imprecise and uncertain biomass supplier profiles based on Intuitionistic Fuzzy Sets (IFS) in conjunction with a multi-period optimization framework for selecting the best biomass supply mix at a maximum total purchasing value.
INTRODUCTION

Outsourcing is one of the key strategically oriented decisions in Supply Chain Management. It has been extensively shown that outsourcing decisions have significant strategic and operational implications and greatly influence several performance objectives across the entire business (Aron & Singh, 2005, Harland et al., 2005, McIvor et al., 2009, Sanders et al., 2007). Making the right outsourcing decisions can result in lower costs and competitive advantage, whereas poor outsourcing decisions can lead to increased costs, operational breakdowns, disrupted services and even an overall business failure. Efficient and effective outsourcing decision making in an organisation requires a clear understanding of its corporate strategy, core competencies, potential risks and overall costs, as well as a thorough justification of possible outsourcing arrangements for meeting business objectives (McIvor et al., 2009, Sanders et al., 2007).

Systematic decision-making is particularly significant in problems of outsourcing biomass supply operations for bioenergy production (Frombo et al., 2009). If a biomass production/processing operation is considered of strategic importance to the corporate, the option of keeping it in-house needs to be explored. From an operational point of view, if the corporate is already engaged in biomass supply operations and its performance is considered superior and/or its operations performance improvement is likely, outsourcing may not be a solution. Thus, if the corporate does not intend to expand towards this strategic direction and/or does not acquire specialized knowledge in biomass production/processing, outsourcing options may be the case.

So far, there is a low degree of (and often a lack in) strategic and operational integration between biomass suppliers and buyers, mainly due to the complexity of this kind of supply chains, compared to the traditional ones, and the existence of binding requirements for joint efforts from all relevant stakeholders, such as government organizations, industries, parties from the agricultural sector, consumer organizations etc. For the development of a healthy and sustainable bioenergy sector there is a need for establishing a well-functioning and flexible biomass market that can ensure reliable and sustainable biomass supplies. Towards this direction, there is a number of research studies suggesting various supply chain arrangements and coordination options, as well as possible contractual agreements between buyers and sellers with the aim to ensure supply and demand over a strategic time horizon (Gjerdrum et al., 1999, Lee and Chu, 2005, McCormick & Kabberger, 2007).

A biomass supply system presents several unique features that highly influence the bioenergy production and requires special technical and managerial knowledge (Van Dyken et al., 2010). Decision making on outsourcing biomass supply activities needs to take into account the complexity of their characteristics, such as: i) the dynamics of the demand in the production system, ii) biomass-specific features, such as time dependent availability (e.g., seasonality, yield) in terms of biomass quantities and types, iii) the disperse nature of the supply chain’s locations, as well as iv) certain biomass properties and quality characteristics (e.g., moisture, bulk density, energy density, energy yield etc.), which are important for the supply network functionality. Handling, collection and pre-processing/pre-treatment of biomass are influenced by biomass properties, process technologies and equipment used and all these factors have a critical impact on the whole bioenergy production system. Procurement costs are also vital for the bioenergy production viability. Cost fluctuations for various biomass types determined in a complex manner by continuously changing aggregate demand and supply conditions, along with the uncertainty of biomass availability and properties, may dictate alternative supply options to be considered by the decision makers with respect to the planning period. Furthermore, of significant interest is re-
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cently the exploitation of biomass residues, which exhibit beneficial features, as they do not interfere with primary food needs competition and can be purchased usually at low prices (Papapostolou et al., 2010). This research-wise intriguing nature of biomass can be utilized as an important input to the primary resources supply side.

All the aforementioned features of the biomass supply systems influence their operation in an often uncertain way. Raw material costs can vary, thus critically affecting the viability of the whole supply chain, material flows may become less smooth and risks/variations in biomass supply lead-times may be high, unless the supply network is carefully designed, operated and continuously controlled by an adequate management system. Therefore, a biomass/bioenergy supply system needs to be flexibly designed, coordinated and operated, in order to utilize the most economical and available feedstock options at any time of the year. One way to deal with the seasonality of the biomass supply requirements and achieve cost-effective supply utilization is via procurement from different suppliers (Min and Zhou, 2002, Toka et al., 2010). Outsourcing can be one of the means that enables a company to cope with seasonality and production capacity adjustments effectively. However, any biomass supply schemes should be evaluated by bio-energy producers to ensure that biomass/biofuels supply chains are profitable, competitive and viable. Thus, any decision on strategic outsourcing of biomass supply chain activities needs to be carefully made, due to the special characteristics of the biomass supply network.

In general, supply chain procurement activities in the bioenergy industry are of critical importance, especially when they are related to energy efficiency enhancement. Energy-related outsourcing to specialized companies has been recently reported in many countries around the word and has shown to be a valuable facilitator of energy efficiency improvements (Thollander & Ottosson, 2011). In Europe, outsourcing energy-related business activities to specialized companies known as Energy Service Companies (ESCOs) has been proven a significant aim in reducing the European Union’s use of energy. However, there is some criticism about the added value brought by the ESCOs energy-related activities, as well as some arguments about ESCOs being useful only for certain industrial sectors. The extent of their usage is associated to local markets structures, rules and regulations, national and regional energy authorities, technology advances, as well as the particular role and activities of the ESCOs (Thollander & Ottosson, 2011). Along the same lines, biomass-related outsourcing decisions need to be made on the basis of examining all case-dependent factors related to specific barriers and facilitators of outsourcing that may potentially lead to competitive advantages. One of the most critical steps in the outsourcing decision making process is supplier selection.

This chapter emphasizes the need for systematically selecting the best combination of supply alternatives featuring the optimal biomass supplier profiles in order to maximize the total benefits for the whole supply chain and minimize the associated production and logistics costs. Such a selection requires considering variations in the availability of various biomass types throughout the year, as well as time fluctuations in their cost. Designing a biomass supply chain becomes a time-dependent problem and can be addressed by examining and developing the adequate supply schemes in different periods of time.

This chapter attempts to examine possible adequate biomass supply schemes resulting in the development of a comprehensive methodology for making the optimal supplier(s) selection in a complex biomass supply network. The particular objectives of the chapter are: i) to discuss current issues in evaluating biomass supply chain performance, ii) to examine the alternative supply schemes accommodating a variety of biomass types to serve bioenergy production plants and iii) to present a systematic methodology for supplier
selection in a biomass/bioenergy supply network. Towards these directions, there are two questions that need to be answered:

- Which is the optimal combination of suppliers that can adequately provide the right raw materials for bioenergy production to conversion plants in certain periods of time?
- How much of the required biomass materials should be purchased from each selected supplier in each time period?

The biomass supplier selection problem is characterized by a high degree of uncertainty because of subjective preferences/evaluations of the decision makers, unexpected demand variations and raw material prices, fluctuations in biomass availability in time and yield, variations in the procurement lead times for each supplier. These uncertainties are inherent in the decision making process and can be identified through a fuzzy-based methodological approach that can guide a risk-informed decision making process on outsourcing procurement activities.

An interesting generalization of fuzzy sets is Intuitionistic Fuzzy Sets – IFS (Atanassov, 1986). IFS can be applied to handle, not only the uncertainty of decision makers to quantify biomass supplier selection criteria and suppliers’ performances, but also to handle decision makers’ likes and dislikes which need not to be complementary (Boran et al., 2009, Ye, 2010). An IFS includes the membership and the non-membership function of an element to a conventional fuzzy set, as well as a third function that is called the hesitation degree. This third function is useful to express lack of knowledge and hesitancy concerning both membership and non-membership of an element to a set. Expression of hesitation is particularly helpful for decision makers when they need to select a proper combination of suppliers in a highly uncertain supply network such as a biomass supply system (Wu, 2008). This chapter proposes the utilization of IFS in biomass supplier selection problems. An IFS-based method (Li, 2005) can be applied to derive biomass suppliers’ ratings, for each considered time period. The output of the method can be further utilized by a linear programming optimization model to determine the combination of suppliers in different periods of the time horizon.

BACKGROUND

The background section of the chapter provides a critical discussion on various biomass types and their characteristics and identifies those features, which exhibit distinct impact on supply chain operations. Next, biomass supply chain management considerations are examined through a brief review of relevant studies and finally the problem of supplier selection is discussed by considering various methods developed by a large number of researchers that provide valuable insights on outsourcing and purchasing issues.

Biomass and its General Characteristics

Biomass can be defined as the organic matter that has been directly or indirectly derived from contemporary photosynthesis reactions, and hence can be considered a part of the present carbon cycle (Van Dyken et al., 2010). It is recognized as one of the most promising renewable energy resources when utilized in a sustainable way. In fact, biomass derived energy is the renewable energy made from any organic material from plants or animals. There is a plethora of different types of biomass that is appropriate for biofuels (biodiesel, bioethanol) production, as well as for heat and power generation, and can be broadly categorized into different categories, based on biomass primary production origin and utilization purpose, namely energy crops, forestry, agricultural residues, wastes and aquatic biomass. These
various types of biomass are today considered to produce energy in the form of heat, power and/or biofuels through specific conversion routes. For instance, feedstocks (primary biomass sources) for biodiesel production include virgin oils from energy crops, such as rapeseed, soy, canola, sunflower, cotton seed, etc., animal fats, such as tallow, renderings, etc., recycled or waste oil, such as waste cooking oil, as well as aquatic biomass, such as the algae. For bioethanol production, biomass may be derived from forestry, energy crops, such as sorghum, sugar beet, cynara, etc., and energy crop residues.

There are several specific characteristics of biomass; first the existence of the large variety of biomass types that poses advantages, such as the possibility to select from a wider range of feedstock options for bioenergy production, and disadvantages, such as the different (and usually necessary) pre-treatment operations that may need to be included in the supply chain for each feedstock option, as well as the requirements for flexible bioenergy production facilities.

A second important characteristic of biomass is its seasonal nature. Not all biomass types are available anytime over a year. Certain types of biomass are harvested during a relatively short period of the year and, therefore, large quantities need to be stored in order to be used for bioenergy production, on a year-round basis. For this reason, warehousing facilities of often large capacity are required to facilitate storage of seasonal biomass material under certain storage conditions. In addition, because of the disperse nature of biomass, collection and transportation activities need to be extensively carried out. Thus, a careful examination and optimization of these activities are required so that the biomass supply chain become sustainable and competitive. A third important issue is the quality of the various biomass types for bioenergy production. Quality issues strongly influence the product’s quality specifications and production process requirements. The inhomogeneous biomass nature, as well as its lower than fossil fuels’ energy content, constitute major problems for obtaining viable and reliable bioenergy production solutions and often require special pre-treatment operations. Finally, other biomass properties, such as density, moisture content, viscosity, energy yield, flash point etc. greatly affect all steps of the production process and the quality of the final products (Kazantzi et al., 2010, Rentizelas et al., 2009b, Sokhansanj & Turnhollow, 2004, Van Dyken et al., 2010). For instance, moisture controlling plays an important role in biomass material storage. High moisture content results in material loss from fermentation during storage, thus requiring an additional pretreatment process (drying), while moisture content affects also the pelletizing process (Mani et al, 2004, Rentizelas et al., 2009b, Sokhansanj & Turnhollow, 2004). In addition, most biomass types have a relatively low energy density per unit of mass compared to fossil fuels and this often makes handling, storage and transportation more costly per unit of energy carried (Toka et al., 2010).

However, it is not only availability and the aforementioned special characteristics of biomass that need to be considered when designing a biomass supply network, but also two more, important issues: the one is the fact that feedstock prices (one of the most or the most significant cost input) fluctuate with time, depending on the continuously changing market conditions, and the other is the raising concerns about the food versus fuel/energy production issues. Both issues are of strategic importance to the supply chain investment options and have a great impact on the sustainability of the biomass / bioenergy production systems. Waste-to-energy production schemes seem to be now an attractive option to avert the intensive utilization and depletion of limited resources (Huang et al., 2010, Papapostolou et al., 2010). Because of the aforementioned characteristics that emphasize the unique but also variable nature of biomass, the pertinent supply chain strategic and operational decisions are crucial for establishing profitable and sustainable bioenergy production units.
basis that this chapter suggests the development of a comprehensive and systematic framework for examining and selecting sustainable supply options of biomass supply systems that pay particular attention on their flexible functionality and optimal procurement costs.

**Biomass Supply Chains**

The unique features of biomass types discussed in the previous sub-section render the biomass supply system a very complex network that requires special planning, coordination and control that may significantly differ from the traditional supply chain management practices (Huang et al., 2010, Van Dyken et al., 2010). So far, biomass has been mainly used for energy production in areas close to its production sites. However, the emerging practice is to procure biomass from several suppliers thus developing the critical mass that will be finally required for a more distributed and, at the same time, sustainable energy production system (Toka et al., 2010). The biomass supply network should be conveniently designed so as to facilitate a broader bioenergy market, while remaining competitive through the various seasons over the year.

In general, besides biomass production (cultivation) and collection, the following logistics activities can be identified in biomass supply systems (Gigler et al., 2002):

- Handling, such as pelletizing or chipping
- Pre-processing/pre-treatment to upgrade or improve the quality of the feedstock, such as drying, grading, etc.
- Transportation and storage (often in conjunction with pretreatment options, such as natural drying during long-term storage).

In addressing biomass supply issues a generic biomass supply network should be considered first, which may be modified according to specific constraints and requirements of the integrated biomass / biofuels system. Such a generic biomass supply structure is presented in Figure 1, in which a number \( (N_i) \) of various production or supply sites \( i \) (representing associated producers or suppliers) that produce a number \( (N_p) \) of different biomass types \( b \) (primary resources or feedstock) are considered. Suppliers serve a number \( (N_p) \) of bioenergy production facilities \( p \) with certain amounts \( (F_{pib}) \) of a variety of feedstock types that they may produce. The suppliers’ network also include the suppliers/collectors of waste biomass and any already available biomass types, in addition to cultivated energy crops, such as waste cooking oil that may be provided to bioenergy producers at certain quantities and at typically low prices. In addition, any variations in the generic biomass production, handling and transportation operation scheme are allowed, since various biomass types require different production, handling and sequencing options within a whole biomass supply system.

One of the most important parameters indicative for the viability of the production units that convert primary biomass resources into final energy products is the procurement cost of biomass at the gate of these units. As Boukis et al (2009) state, this cost consists of the following parts:

- The production cost of primary sources
- The pre-treatment cost
- The transportation cost of primary sources to the conversion unit
- The profit of the primary source producer and the transporter

The pre-treatment cost can either be realized in the resources production area or in the conversion facility. In the first case the cost is added to the procurement cost, whereas in the second it is included in the operating costs of the production process. Also, the production cost of primary sources largely differs between the case in which biomass is already available (such as in the case of agricultural residues) and the case in which...
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Figure 1. Representation of a generic biomass supply network

biomass is purposely produced (such as in the case of energy crops). Moreover, costs involved in biomass crop cultivation may significantly vary based on cultivation practice and location.

Therefore, different scenarios for possible biomass supply chain activity arrangements may be explored. For instance, biomass producers may be responsible for both production and transportation of feedstock to the conversion plants or they may only be responsible for the production, whereas biomass buyers may then be in charge of delivering the primary resources to their bioenergy production units. In the first case the producer is the transporter, and thus the profit of the producer accounts for both the production and the transportation to the plants (Boukis et al., 2009). In this regard, outsourcing is considered with respect to production and transportation activities (including any on-farm and intermediate storage, handling and possibly required pretreatment activities). In the second case, the bionergy producer does not actually outsource transportation and warehousing activities, but only examines purchasing alternatives. The different kinds of arrangements are depicted in Figures 2 and 3.

A review of detailed operations involved in biomass supply systems was given by Sokhansanj and Turnhollow (2004), who described alternative ways to handle different types of biomass material with the use of appropriate tools and machines. Their study also indicated that moisture controlling, densification and system modeling are necessary for biomass supply chain optimization. Moisture controlling plays an important role in biomass material storage (Hamelinck et al., 2005). High moisture content results in material loss from fermentation during storage, and thus decomposition increases proportionally with mois-
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Figure 2. Biomass supply network representation with producer as the transporter

Figure 3. Biomass supply network representation with buyer as the transporter
ture content. It was also found that the moisture content of the biomass material affects the palletizing process, which may precede the power generation process (Rentizelas, 2009b). Moreover, the densification process of the biomass material increases bulk density and results in easier handling and transporting performance, as well as higher combustion efficiency (Hamelinck et al., 2005). Various factors (e.g., material characteristics, temperature, moisture content, feed rate, particle size and palletizing pressure) are responsible for the variability of cost and power requirements (Hamelinck et al., 2005, Sokhansanj and Turnhollow, 2004). Therefore, the supply side of the system requires special knowledge and experience in managing, operating and controlling its activities in the best possible way.

Several researchers examined certain biomass storage options that include on the field storage, at the conversion plant or at an intermediate site (Allen et al., 1998, Papadopoulos and Katsigiannis, 2002, Ravula et al., 2008a, Rentizelas et al, 2009b, Tatsiopoulos and Tolis, 2003, Van Dyken et al., 2010). It has been found that temporary storage located on the field reduces transportation distance, thus making it more cost-efficient and convenient in handling for the suppliers (Ravula et al., 2008a). Allen et al. (1998) observed that most energy production plants have limited on-site storage spaces. However, all options for the supply network design must be considered and various scenarios need to be evaluated towards creating an economically appealing and sustainable integrated system. In Figure 1, all possible storage arrangements, along with direct and indirect transportations to bioenergy production plants, are implied.

**Biomass Supply Chain Management Considerations and Supplier Selection Criteria**

It is interesting to note that many researchers have attempted to address the problem of planning, simulating and optimizing the biomass supply chain and logistics activities, including collection, storage, pretreatment and transportation of primary resources (Cundiff et al., 1997, De Mol et al., 1997, Fiala, 2005, Gigler et al., 2002, Kumar & Sokhansanj, 2007, Papapostolou et al., 2011, Perlack & Turhollow, 2003, Recio et al., 2003, Rentizelas et al., 2009a, Van Dyken et al., 2010). This amount of literature is indicative of the significance of the logistics arrangements in the biomass supply framework.

A comprehensive review on existing research efforts addressing special issues regarding the design and evaluation of biomass supply chain networks was provided by Toka et al (2010). The researchers developed a hierarchical decision-making framework for the design of biomass supply networks incorporating strategic, tactical and operational aspects and identified opportunities, as well as bottlenecks (such as logistics costs and complexity) that distinguish biomass supply chains from traditional supply chain systems. An interesting study with practical implications was carried out by Sokhansanj et al. (2006), who developed a detailed dynamic simulation model for the collection and transportation of large quantities of biomass that aims at estimating the total cost and energy usage of the biomass collection and transportation system. Simulation models were also used in other studies (Kumar & Sokhansanj, 2007, Ravula et al, 2008a, Ravula et al., 2008b, Rentizelas, 2009a). Another valuable tool in modeling biomass sourcing and utilization is the Geographical Information Systems (GIS) that have been widely acknowledged recently in the area of biomass supply analysis and modeling (Beccali et al., 2009, Fiorese and Guariso, 2010, Fombo et al, 2009, Papapostolou et al., 2010, Vianna et al., 2010). Given the complexity of decisions in planning and managing a biomass supply network, there are also approaches that explore the use of multi-criteria decision making models. For example, in a study carried out by Kumar et al. (2006) a multicriteria assessment
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method for ranking biomass feedstock collection and transportation options was developed, taking into account economic, social, environmental and technical criteria. It is though apparent that any collection and transportation alternatives need to be evaluated within a total supply chain perspective rather than considering any of these activities in isolation. As Allen et al. (1998) indicated, the supply activities are highly interconnected within the supply chain network and any decisions made at any point upstream or downstream would strongly affect the whole supply chain functionality, thus influencing the instability of the system. For example, a harvesting or a collection system which may be cost effective itself can result in the need for expensive storage systems that can, in turn, affect the quality of the feedstock to be used for bioenergy production. Therefore, decisions made upstream influence the quality of the primary resources required for a certain bioenergy productive process. On the other side of the spectrum, making decisions on strategic bioenergy production options (which is usually the case), such as the size, capacity and location of facilities, dictates upstream activities that need to deliver biomass to the right locations at the right time in the right quantities and quality.

Except from planning a biomass supply system, inventory management and outsourcing are important issues that need to be considered. Because of the high degree of uncertainty inside the biomass supply system and the specific characteristics of biomass materials, proper supply chain management would offer substantial benefits for the whole biomass/bioenergy supply chain, including decreased inventory and related costs, reduced material flow times and better matching between demand and supply sites. The simplest method to prevent insufficiency of material and improve material flow throughout the system is to use storage as a material buffer, but this will drastically increase cost. In fact, higher uncertainties in demand result in higher amounts of stock material in the inventory. One solution to deal with this kind of uncertainties is the outsourcing option (Wu, 2008). However, despite the importance of the uncertainty implications and the dynamically changing aggregate supply and demand conditions, rather a few studies have considered inventory management issues in the biomass supply chain framework (Allen et al., 1998, Gallis, 1996, Tatsiopoulos and Tolis, 2003). A very interesting perspective in such biomass supply systems, which is also evidence in the network structure in Figure 1, is the multi-biomass approach, which has been investigated by several researchers and practitioners and is usually expected to reduce biomass production and storage costs. Nilsson and Hansson (2001) indicate the reduced cost potential of the multi-biomass approach. In addition to lower storage time and cost, smoother material flows are observed, taking advantage by the different maturity times of biomass materials. De Mol et al. (1997), as well as Hamelinck et al. (2005), examined multi-biomass utilization alternatives for supply chain economic enhancement. Crop rotation is another interesting approach in multi-biomass utilization as indicated by the study of Power et al. (2008). Rentizelas et al (2009b) analyzed the multi-biomass approach and showed that this alternative approach provides significant savings on storage, especially in relatively expensive storage systems. In the multi-biomass approach, reduction in the availability of one type of resources may have a minor impact on both system cost and layout, which implies that the diversity of feedstock resources provides a reliable and sustainable solution for supporting a long-term bioenergy production.

Toward this direction, it is also essential to consider feedstock portfolio optimization, which typically involves tradeoffs between multiple factors, such as conversion rates, procurement cost, moisture content, and feedstock geographic locations to conversion plants. Huang et al. (2010) observed that biomass with higher conversion rate but lower cost and lower moisture content are preferred over others. Feedstock portfolio
optimization aims at achieving a consistent supply of high quality, low cost feedstock year round. A number of relevant factors, such as dependability, quality, quality consistency, procurement cost, etc. are of particular importance in selecting the optimal feedstock mix from a vendors market. As mentioned previously, feedstock variability, high production, transportation and storage costs, as well as large capital investment in feedstock handling infrastructure, lead to supply uncertainty and high total biomass supply cost. Price volatility and uncertainties in biomass availability and accessibility may lead to consider the development of an appropriate suppliers’ base, thus potentially mitigating the risks associated with these uncertain factors.

Based on the literature findings on suppliers’ suitability for the special case of a biomass supply system, seven categories of selection/evaluation criteria can be identified:

1. **Reliability**: reliable biomass supplies are considered prerequisites for the development of sustainable bioenergy systems (Toka et al., 2010). Reliability is a qualifying factor at which a supplier has to perform very well (namely at a highly acceptable level) in order to be considered by the buyer. The specific criteria that relate to supplier reliability include adherence to contract terms and ensuring of on-time order delivery and agreed biomass quality. Suppliers need to provide the proper feedstock at the correct amount within the appropriate time at the right conditions.

2. **Responsiveness**: it refers to how fast the supplier can respond to the product (biomass) demand, for which uncertainty is high. Unexpected demand variations may cause significant operational and schedulability problems in the production operations. On the other hand, availability and seasonality of biomass materials are time-dependent characteristics of the supplies that can also lead to supply chain malfunctioning and providers are responsible to cope with it.

3. **Flexibility**: as mentioned above, uncertain conditions, such as fluctuating requirements, force suppliers to react accordingly in order to accommodate the buyer’s needs. Noordewier et al. (1990) defined supplier flexibility as the extent to which a supplier is willing to make adjustments to accommodate customers’ changing needs. As Cannon and Homburg (2001) state, suppliers show flexibility by granting exceptions to meet customer requests and offering modular product and service. In biomass supply cases, flexibility also refers to the ability of the supplier to make any necessary sourcing arrangements in case of changing conditions, in order to provide the appropriate alternative biomass types that match technical requirements of the bioenergy production process and facilitate the uninterrupted biomass flow.

4. **Cost aspects**: for the majority of decision makers procurement cost constitutes the most important factor (after reliability performed at an acceptable level). It has been consistently shown that even small price increases can cause customers to switch suppliers (Cokins, 2001). However, a static evaluation of purchasing costs does not seem to be adequate, since it is based on present prices. In the real world, actual costs are usually much higher than expected costs because of the inherent uncertainties in the functionality of the supply chain, which may lead to a number of problems (such as long lead times, stock-out situations, inventory built-up, weak coordination and communication, etc) that can in turn increase purchasing costs (Cachon, 2004, Cokins, 2001, White et al., 2005). In the case of biomass and other feedstock materials, market prices can be reasonably viewed as uncertain inputs to
the developed model determined by continuously changing aggregate demand and supply conditions in the pertinent primary feedstock markets.

5. **Quality aspects**: it can be considered as one of the top priorities for procurement decision makers. As mentioned in the section referring to the biomass characteristics, feedstock quality greatly affects bioenergy production performance. Feedstock types with different quality characteristics are expected to have different impact on final product’s specifications. In addition, variability in quality is a very undesirable aspect of products provided by the suppliers considered. Thus, quality aspects evaluated here include biomass properties such as moisture, density, energy content, etc or quality specifications compliance, as well as defect rates, variability in quality characteristics and quality certification possession.

6. **Assets and infrastructure**: other important criteria are the relative location of the biomass production site or proximity to buyer, as well as the existing transportation infrastructure, since these affect not only the economic performance of the supply chain, but also the whole collaborative framework of vendors and buyers. This criteria category also considers evaluating the facility size, fleet size, warehouses number and capacity of the biomass production system.

7. **Environmental and safety related issues**: these criteria reveal the supplier’s philosophy and strategic considerations with respect to environmental issues that are very crucial nowadays. Safety considerations in biomass production are also considered of major importance by default.

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**Multi-Criteria Decision Making for Supplier Selection**

One of the most significant stages in the outsourcing decision making process is vendor selection. Wadhwa and Ravindran (2007) showed an overview of the outsourcing process, in which the procurement activity is divided into several steps, including the identification of non-core competencies, the identification of candidate activities to be outsourced, the establishment of goals and draft outsourcing agreements, the identification and selection of outsourcing vendors, as well as the negotiations of measures, monitoring, control and evaluation of the outsourcing activity performance. Considering the biomass/bioenergy market that is not mature yet and can demonstrate a high degree of variability, outsourcing decisions in such a turbulent domain, though strategic in nature, may clearly exhibit a tactical component, and thus need to be evaluated on a short- or medium-term basis. This may also constitute one of the reasons for the scarce and limited literature on outsourcing biomass supply activities. However, it is worth noting that Toka et al. (2010) discuss several research studies that identify a number of factors which significantly influence strategic decision-making on biomass supply for bioenergy production. The authors point out that for sustainable bioenergy systems a well-functioning biomass market and a cohesive and stable environment that encourages investors in this sector are absolutely necessary and need to be considered in the long-run and not in a fragmented manner by utilizing only certain regulatory interventions and stimulation measures, such as tax cuts and exemptions, investment subsidies etc. In the same work, outsourcing-related contractual agreements for long-term biomass supply were also discussed and various supply chain contract models, which vary with respect to the corresponding contractual clauses between buyers and sellers, have been identified based on relevant literature.
Once a decision to outsource is made, the next most critical activity is selecting the appropriate vendors. In many organizations the process of vendor selection is performed in an empirical manner. In today’s competitive operating environment choosing a competent group of reliable vendors is crucial and become vital for the viability of certain industries, such as in energy production. However, supplier selection is a multi-objective problem with conflicting objectives that if addressed empirically, the solution would be far from optimal; not even efficient in most cases (Alam et al., 2009).

Since the 1960s the general supplier selection problem has received considerable attention by researchers and purchasing practitioners that have realized the competitive advantage of an effective purchasing function towards improved overall business performance. Supplier selection entails the process of reviewing, evaluating and choosing suppliers to become company’s business partners within the overall supply chain. Evaluating suppliers’ performance is a continuous process that needs to be carried out from various perspectives. Multi-Criteria Decision Making (MCDM) methods are appropriate to deal with supplier selection problems since the supplier selection criteria involved in the evaluation process are usually multiple and conflicting. De Boer et al. (2001) presented an extensive overview of decision methods and tools used for supporting supplier selection. A detailed review was carried out recently by Agarwal et al. (2011). This review was based on sixty eight research articles, including eight review articles, found in the relevant literature from 2000 to 2011.

A typical classification of the quantitative MCDM methods for supplier selection found in literature was suggested by Vahdani and Zandiieh (2010), who identified six categories of MCDM approaches: (i) multi-attribute decision making, (ii) multi-objective optimization, (iii) statistics/probabilistic approaches, (iv) intelligent techniques, (v) fuzzy multi-attribute decision making/fuzzy multi-objective decision making, and (vi) others. The first category considers a number of predetermined alternatives for supplier selection by using multiple attributes as criteria. This category includes the Analytical Hierarchy Process (AHP), which was first introduced by Saaty (1987), the conjoint analysis, the linear weighting method and the outranking method. The second category involves optimizing a function of multiple quantifiable objectives and obtaining the alternatives that best satisfy a number of associated constraints. For example, the ε-constraint method, the Data Envelopment Analysis (DEA) and the goal programming belong to this category of techniques. The third category makes use of past data and employs statistics and probability theory to yield inferences on the best supplier choices. This category includes categorical methods, cluster analysis and uncertainty analysis. The fourth category encompasses intelligent techniques, such as case-based reasoning, expert systems, genetic algorithms and neural networks, to address the supplier selection problem. The fifth category entails methods that acknowledge the fuzziness in evaluating the supply alternatives, such as fuzzy AHP and fuzzy TOPSIS (Technique For Order Preference by Similarity to Ideal Solution). Finally, the last category of methods in the area of supplier selection encompasses all other methods that are left out of the previously determined categories, such as the positioning matrix technique, the unidirectional hierarchical relationship technique, the activity-based costing approach etc. An initial step in any MCDM method is the adoption of appropriate supplier selection criteria (the reader is referred to the previous subsection where a detailed list of evaluation criteria for biomass suppliers is given). An early work carried out by Dickson (1966) discussed twenty three vendor selection criteria and became a reference for subsequent studies, such as those in Ellram (1990), Roa and Kiser (1980) and Stamm and Golhar (1993). Weber et al. (1991) reviewed a large number of related papers, which showed that quality, delivery and net price have
been the highest rated supplier selection criteria, followed by production facility, geographical location, financial position and capacity. They also considered quantitative approaches in supplier selection and concluded that mathematical programming models and statistical approaches were the most frequently employed methods. Along the same lines, Karpak et al. (2001) suggested three basic criteria for supplier selection, namely cost, quality and delivery reliability and utilized a goal programming technique for deriving the optimal quantity of orders, subject to demand and supply constraints in a multiple replenishment purchasing problem. Some researchers, though, argue that programming methods are not capable of adequately incorporating qualitative factors that are important in the supplier selection decision making process (Ting and Cho, 2008, Wu, 2008).

The AHP method was also used by many researchers to address the supplier selection problem using qualitative and quantitative criteria. Nydick and Hill (1992) applied the AHP technique and considered four evaluation criteria, namely quality, price, delivery and service to assess vendor performance. The same method was employed by many other researchers (Barbarasoglu and Yazac, 1997 Yahya and Kingsman, 1999, Massella and Rangoue, 2000 Tam and Tummala, 2001, Lee et al., 2001). The AHP was also used by Handfield et al. (2002), who considered certain environmental criteria for supplier selection. Moreover, the AHP method was compared with the total cost of ownership (TCO) technique in a study carried out by Bhutta and Huq (2002), who focused on four basic criteria, namely manufacturing costs, quality, technology and service. Extensions of the AHP, such as the Analytical Network Process (ANP) developed by Saaty (1996) have also been used (Sarkis and Talluri, 2002). Although AHP and its extensions can incorporate multiple qualitative and quantitative key factors, they do not cope well with a large number of pairwise comparisons needed, which result in significant time and effort requirements. In addition, AHP based methods do not cope well with uncertainty and risk. These methods assume that performance criteria are static and do not capture their dynamic nature that affect suppliers’ performance. Considering, for example, cost as a fixed objective parameter is often unreasonable and may ultimately lead to wrong decision results.

In an attempt to overcome the above limitations, hybrid models and fuzzy-based approaches have been developed. A representative example of a hybrid model is the one proposed by Ghodsypour and O’Brien (1998), who combined AHP and linear programming to account for both tangible and intangible criteria and optimize order allocation among suppliers.

Ghodsypour and O’Brien (1998) distinguished two approaches in selecting suppliers. The first approach considers selecting the best single supplier, who can satisfy all necessary requirements. The second approach is to choose an appropriate combination of suppliers when no single supplier satisfies all the requirements. The latter case, which is termed as multiple sourcing, can be particularly helpful in biomass supplier selection, since it supports the reliability of supply for seasonal materials, such as biomass feedstock. This approach can protect from possible shortages or stock-out situations and achieve uninterrupted and sufficient supplies, which are of critical importance for the development of sustainable bionergy systems. In a next research effort, Ghodsypour and O’Brien (2001) proposed a hybrid model based on AHP combined with mixed integer nonlinear programming. Sanayei et al. (2008) also suggested a hybrid approach combining the multi-attribute utility theory and linear programming for rating and choosing the best suppliers and determining the optimum order quantities, in order to maximize the total additive utility function. Specifically for multiple sourcing, researchers have suggested different methods of mathematical programming such as linear programming (Pan, 1989), multi-objective programming (Current and Weber,
1994), goal programming (Buffa and Jackson, 1983), DEA and multi-objective programming (Weber et al., 2000), AHP and goal programming (Wang et al., 2004), and AHP combined with mixed integer multi-objective programming (Xia and Wu, 2006).

Fuzzy-based approaches may be used to cope with uncertainties in supplier selection problems which involve a dynamically changing supply market with high degree of uncertainties regarding mainly qualitative factors. There are two broad categories of fuzzy-based methods (Vahdani and Zandieh, 2010). In the first category, there are methods, which imprecisely represent weights of selection criteria and performances of suppliers with fuzzy numbers. In the second category, there are methods, which make use of linguistic terms to evaluate criteria and suppliers. In the literature there are also hybrid fuzzy-based approaches, which combine fuzzy techniques with AHP (Chan et al., 2008) or TOPSIS (Wang et al., 2009). Finally, some extensions of fuzzy sets have been proven valuable to deal specifically with uncertainties in complex supplier selection settings. Such an extension is Intuitionistic Fuzzy Sets (IFS), which allow decision makers to express also their hesitation degree or ambiguity when they evaluate the performance of alternative suppliers and determine the importance of the selection criteria. Representative examples of IFS applications in supplier selection problems can be found in (Boran et al., 2009, Ye, 2010). The next section of the chapter presents a more realistic, practical and risk-informed decision making approach for estimating, rating and optimizing the biomass supplier profiles with respect to time in a multi sourcing dynamic environment. The suggested approach involves multiple decision makers in a group decision making setting and adopts a method from the multi-attribute utility theory that has been presented by (Li, 2005) and applied in other application domains (Hernandez and Uddameri 2010). This approach combined IFS with linear programming to find optimal weights for the performance/selection criteria. In addition, a comparison index similar to the one suggested in TOPSIS (Hwang and Yoon 1981) was used for determining the ratings of the biomass suppliers. The approach is further extended, in the next section of the chapter, by utilizing the ratings of the suppliers as an input to a linear, multi-period optimization model in order to determine the optimal combination of suppliers in different periods of the time horizon.

A MULTI CRITERIA DECISION MAKING APPROACH FOR BIOMASS SUPPLIER SELECTION

Based on the aforementioned considerations, the multi-perspective, multi sourcing biomass supplier selection problem is characterized by high uncertainty and special technical attributes and constraints. Such a problem can be adequately addressed by combining an IFS-based algorithm to conveniently rate supplier alternatives with a multi-period optimization model that aims to maximize total purchasing values by determining optimal combinations of suppliers with their respective optimal types and amounts of biomass supplies for each time period.

Intuitionistic Fuzzy Decision Making for Biomass Supplier Selection

Before proceeding to describe how the biomass supplier selection problem can be tackled, some necessary introductory concepts of Intuitionistic Fuzzy Sets (IFS) need to be briefly introduced. An IFS, $I$ in a finite set, $E$ can be defined as (Atanassov, 1986):

$$I = \{<x, \mu_I(x), v_I(x) >| x \in E\}$$

(1)

where $\mu_I : E \rightarrow [0,1], v_I : E \rightarrow [0,1]$ and
0 ≤ μ_j(x) + v_j(x) ≤ 1 ∀ x ∈ E  μ_j(x) and 
v_j(x) denote respectively the degree of membership
and non-membership of x to E.

For each IFS, i ∈ E, π_j(x) = 1 − μ_j(x) − v_j(x)
is called the hesitation degree of whether x belongs
to I. If the hesitation degree is small, then knowledge
whether x belongs to I is more certain, while if it is
great, then knowledge on that is more uncertain. Thus, an ordinary fuzzy set can be written
as:

{ < x, μ_j(x), 1 − μ_j(x) > | x ∈ E } (2)

An IFS-based method adopted from (Li, 2005)
to evaluate biomass suppliers upon multiple
selection criteria is presented as follows. Suppose that there is a set of biomass suppliers
S = {S_1, S_2,..., S_n} who have to be evaluated.
Each supplier is evaluated on m selection/evaluation
criteria, i.e. the set of criteria is denoted by
X = {X_1, X_2,..., X_m}. There is also a group of
k decision makers responsible to evaluate the suppliers’ performances with respect to each
criterion. In the following sub-section, the steps
of the approach are described along with a numerical example.

Step 1: Evaluate the Performance
of the Selection Criteria

In this first step of the approach, the values of
μ_j, v_j and π_j, which define the degree of membership, non-membership and the hesitation of
each supplier S_j ∈ S respectively, regarding each
criterion X_j ∈ X are calculated, according to the fuzzy concept of “appropriateness”. These values
can be determined by asking all k decision makers
to express their opinion whether each supplier
S_j is appropriate or not with respect to each
evaluation criterion X_j. Suppose that from the k
decision makers, k_j answered that S_j is appropri-
ate to fulfill the criterion X_j (i.e., k_j decision
makers expressed a positive opinion for the supplier
with respect to the criterion), k_j answered
that S_j is not appropriate to fulfill the criterion
X_j (i.e., k_j decision makers expressed a negative
opinion for the supplier with respect to the crite-
ron) and k_j gave no answer due to their lack of
knowledge/indeterminacy about the appropriate-
ess of S_j with respect to the criterion X_j (it
should be noted that k = k_1 + k_2 + k_3). Then the values of μ_j, v_j and π_j are calculated as follows:

μ_j = k_1 / k, v_j = k_2 / k and π_j = k_3 / k

(3)

Given the indeterminacy of decisions makers,
a certain hesitation in the degree of membership
μ_j that is denoted by lower μ^l_j and upper μ^u_j
bounds, exists and is expressed as follows:

μ^l_j = μ_j and μ^u_j = μ_j + π_j = 1 − v_j

(4)

The upper bounds of memberships are useful to
consider the case that decision makers overcome
their hesitation in favour of the suppliers.

Consider, for example, that three candidate
suppliers, S_1, S_2 and S_3, have been identified
and can supply biodiesel producers with certain
feedstock types; supplier S_1 can provide rapeseed
(RP), supplier S_2 can provide both rapeseed (RP)
and sunflower (SN) and supplier S_3 can deliver
waste cooking oil (WCO).

Suppose that 11 evaluation criteria (X_1, X_2,...,
X_11) are taken into consideration. Table 1 presents
the criteria classified into seven broad evaluation
categories and their associated definitions and
symbols. It should be noted that the criteria cat-
egories are consistent with the evaluation attributes
of biomass supply systems presented previously,
in the background section of the chapter.
Let us also suppose that there are 10 \((k=10)\) decision makers, who evaluate the alternative suppliers with respect to the previously determined criteria. Their collective evaluation results (based on equation (3)) are presented in Table 2.

Note in Table 2 that, for example, 4 out of 10 decision makers evaluated that the supplier \(S_1\) fulfills appropriately the criterion \(X_1\) (i.e., the membership value is equal to 0.4), 5 out of 10 decision makers evaluated that the supplier \(S_1\) is not appropriate with respect to criterion \(X_1\) (i.e., the non-membership value is equal to 0.5) and one decision maker was hesitant upon the performance of supplier \(S_1\) with respect to criterion \(X_1\) (i.e., the hesitation degree is equal to 0.1).

Table 3 presents the lower / upper bounds for the evaluation of each supplier, in the case in which all decision makers insist on overcoming their hesitation. For example, consider that the appropriateness of the supplier \(S_1\) upon criterion \(X_1\) can have a value between 0.4 (lower bound) and 0.5 (upper bound).

### Step 2: Specify Weights for the Selection Criteria

In the second step, the weights for the selection criteria have to be specified. We suppose that this task is a responsibility of the director of the supply chain that is the person responsible for the overall management and coordination of the supply chain. The director follows a “Hundred-Dollar Test” - like prioritization method to subjectively allocate \$100 dollars (or \(€100\) Euros) to the selection criteria, a method also called Cumulative Voting proposed by Leffingwell and Widrig (2003) in the software engineering application domain for prioritizing software requirements.

---

**Table 1. Criteria categories, definitions, and associated symbols**

<table>
<thead>
<tr>
<th>Category</th>
<th>Criteria</th>
<th>Definition</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability</td>
<td>Adherence to contract terms</td>
<td>The performance of a supplier in satisfying all requirements described as terms in the contract</td>
<td>(X_1)</td>
</tr>
<tr>
<td></td>
<td>On-time orders / agreed quality and conditions of the orders</td>
<td>The performance of a supplier in delivering the ordered material to the right place, at the agreed upon time, at the required conditions and in the required quantity</td>
<td>(X_2)</td>
</tr>
<tr>
<td>Responsiveness</td>
<td>Lead time</td>
<td>The average actual required time from the moment the supplier receives an order to the moment it ships</td>
<td>(X_3)</td>
</tr>
<tr>
<td></td>
<td>Return product velocity</td>
<td>Average time required for process of returning the defective orders and reshipping the order to customer</td>
<td>(X_4)</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Flexible functionality / Revise order</td>
<td>Agility of supplier in responding to demand changes / ability to offer product variety</td>
<td>(X_5)</td>
</tr>
<tr>
<td>Cost / Financial aspects</td>
<td>Total cost / Total discount cost</td>
<td>Including component production/pretreatment cost, shipment cost, order cost, etc.</td>
<td>(X_6)</td>
</tr>
<tr>
<td></td>
<td>Payment terms</td>
<td>Suitability of terms and conditions regarding payment of invoices, open accounts, sight drafts, credit letter and payment schedule</td>
<td>(X_7)</td>
</tr>
<tr>
<td>Quality</td>
<td>Quality characteristics</td>
<td>Quality aspects (defect rates, biomass properties, such as moisture, density etc.)</td>
<td>(X_8)</td>
</tr>
<tr>
<td></td>
<td>Quality System Certification</td>
<td>Quality certifications acquired</td>
<td>(X_9)</td>
</tr>
<tr>
<td>Assets / Infrastructure</td>
<td>Company’s location, size and infrastructure</td>
<td>Including location (proximity to customer), transportation infrastructure, facility size, fleet size, warehouse number and capacity etc.</td>
<td>(X_{10})</td>
</tr>
<tr>
<td>Environment / Safety</td>
<td>Environmentally conscious aspects / Safety conditions</td>
<td>Environmentally conscious biomass production and handling, safety conditions at field and in handling/transporting material</td>
<td>(X_{11})</td>
</tr>
</tbody>
</table>
Table 2. Evaluation of suppliers with respect to criteria

<table>
<thead>
<tr>
<th></th>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu_{ij}$</td>
<td>$v_{ij}$</td>
<td>$\mu_{ij}$</td>
</tr>
<tr>
<td>$X_1$</td>
<td>0.4</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>$X_2$</td>
<td>0.4</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>$X_3$</td>
<td>0.1</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>$X_4$</td>
<td>0.4</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$X_5$</td>
<td>0.1</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>$X_6$</td>
<td>0.6</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>$X_7$</td>
<td>0.7</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>$X_8$</td>
<td>0.8</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>$X_9$</td>
<td>0.9</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>$X_{10}$</td>
<td>0.4</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>$X_{11}$</td>
<td>0.4</td>
<td>0.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 3. Lower and upper bounds for the evaluation of suppliers with respect to criteria

<table>
<thead>
<tr>
<th></th>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu^{l}_{ij}$</td>
<td>$\mu^{u}_{ij}$</td>
<td>$\mu^{l}_{ij}$</td>
</tr>
<tr>
<td>$X_1$</td>
<td>0.4</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>$X_2$</td>
<td>0.4</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>$X_3$</td>
<td>0.1</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>$X_4$</td>
<td>0.4</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$X_5$</td>
<td>0.1</td>
<td>0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>$X_6$</td>
<td>0.6</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>$X_7$</td>
<td>0.7</td>
<td>0.8</td>
<td>0.1</td>
</tr>
<tr>
<td>$X_8$</td>
<td>0.8</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td>$X_9$</td>
<td>0.9</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td>$X_{10}$</td>
<td>0.4</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>$X_{11}$</td>
<td>0.4</td>
<td>0.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Multi-Criteria Decision Making for Supplier Selection in Biomass Supply Networks

The amount of “money” assigned to each supplier selection criterion represents its relative weight in relation to the other criteria. An amount of $100 dollars can be distributed in any way that represents the preferences of the director to the criteria. It is also possible some amount of money to be not distributed to any of the criteria. To take into account indeterminacy, the director may also specify how many additional dollars can be possibly given to each criterion. In this way, the degree of membership $\rho_i$ and the degree of hesitancy $n_i$ of each criterion $X_i$ to the fuzzy concept of “importance”are specified. Therefore, the weight $\omega_i$ of each criterion $X_i$ is a number that lies within the interval $[\omega_i^l, \omega_i^u]$, where:

$$\omega_i^l = \rho_i , \omega_i^u = \rho_i + n_i , 0 \leq \omega_i^l \leq \omega_i^u \leq 1 ,$$

$$\sum_{i=1}^{m} \omega_i^l \leq 1 \text{ and } \sum_{i=1}^{m} \omega_i^u \geq 1 \quad (5)$$

The first two columns of Table 4 present lower and upper bounds of the weights of the criteria in the numerical example. For example, the weight of criterion $X_1$ is between 0.15 (lower bound) and 0.3 (lower bound). These values have been realized as follows: 0.15 denotes that 15 dollars were allocated to $X_1$, while this value can be increased up to 0.3 (upper bound) by considering an additional amount of money equal to 15 dollars (i.e., the hesitation degree is equal to 0.15). Values of weights which are less than 0.1 correspond to allocating only cents to criteria, denoting low values in the criteria weights.

**Step 3: Determination of Optimal Weights for the Selection Criteria**

By adopting the approach suggested in (Li, 2005), an optimal set of weights can be determined for the criteria that can be used to calculate the weighted average rating (score) $z_j$ for each supplier $S_j$. The following linear optimization model can be solved to determine optimal weights of the criteria:

| Table 4. Lower and upper bounds of criteria weights and optimal criteria weights |
| --- | --- | --- |
| $X_1$ | 0.15 | 0.3 | 0.191 |
| $X_2$ | 0.18 | 0.2 | 0.2 |
| $X_3$ | 0.1 | 0.2 | 0.1 |
| $X_4$ | 0.01 | 0.05 | 0.05 |
| $X_5$ | 0.08 | 0.1 | 0.084 |
| $X_6$ | 0.13 | 0.25 | 0.13 |
| $X_7$ | 0.03 | 0.05 | 0.034 |
| $X_8$ | 0.1 | 0.1 | 0.1 |
| $X_9$ | 0.02 | 0.05 | 0.02 |
| $X_{10}$ | 0.05 | 0.05 | 0.05 |
| $X_{11}$ | 0.04 | 0.05 | 0.04 |
Multi-Criteria Decision Making for Supplier Selection in Biomass Supply Networks

Table 5. Lower and upper bounds of weighted ratings for suppliers

<table>
<thead>
<tr>
<th></th>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z^l_1$</td>
<td>0.431</td>
<td>0.506</td>
<td>0.532</td>
</tr>
<tr>
<td>$z^u_1$</td>
<td>0.634</td>
<td>0.610</td>
<td>0.714</td>
</tr>
<tr>
<td>$z^l_2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$z^u_2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$z^l_3$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$z^u_3$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$$ \max \left\{ z_j = \frac{\sum_{j=1}^{n} \sum_{i=1}^{m} (\mu_i^u - \mu_i^l) \omega_i}{n} \right\} $$

Subject to: $\omega_i^l \leq \omega_i \leq \omega_i^u \forall i = 1, \ldots, m$

$$ \sum_{i=1}^{m} \omega_i = 1 $$

The final column in Table 4 shows the optimal weights of criteria computed by solving the above linear programming optimization model for the example case, while the maximum weighted average rating ($\max(z_j)$) is computed and found to be equal to 0.196.

Step 4: Computation of Supplier Ratings

By utilizing the optimal criteria weights, the lower ($z^l_j$) and upper ($z^u_j$) bounds of the weighted rating (scores) $z_j$ for each supplier $S_j$ can be computed. These ratings are calculated as follows (Li, 2005):

$$ z^l_j = \sum_{i=1}^{m} \mu_i^l \omega_i = \sum_{i=1}^{m} \mu_i \omega_i \forall j = 1, \ldots, n $$

$$ z^u_j = \sum_{i=1}^{m} \mu_i^u \omega_i = 1 - \sum_{i=1}^{m} v_i \omega_i \forall j = 1, \ldots, n $$

Table 5 presents the lower and upper bounds for each supplier weighted score calculated by applying equations (7) and (8).

To obtain the final ranking of each supplier $S_j$, a comparison index $\xi_j$ based on the TOPSIS method can be used (Hwang and Yoon 1981, Li, 2005) that is given as follows:

$$ \xi_j = \frac{D(A^*_j, B)}{D(A^*_j, B) + D(A^0_j, G)} $$

In equation (9), $A^*_j$ is an intuitionistic fuzzy set that represents the optimal ranking value of the supplier $S_j$, $G$ is the intuitionistic fuzzy set that corresponds to the ideal alternative supplier and $B$ is the intuitionistic fuzzy set that corresponds to the negative ideal supplier. These intuitionistic fuzzy sets are given as follows:

$$ A^*_j = \{< S_j, z^*_j, 1 - z^*_j > \} = \{< S_j, \sum_{i=1}^{m} \mu_i \omega_i, \sum_{i=1}^{m} v_i \omega_i > \} $$

$$ G = \{< g, 1, 0 > \} \text{ and } B = \{< b, 0, 1 > \} $$

In equation (9), $D$ stands for the Hamming Distance measure for intuitionistic fuzzy sets (Szmidt and Kacprzyk, 2000). By making the calculations of distances, the comparison index $\xi_j$ of a supplier $S_j$ can be defined as follows:

$$ \xi_j = \frac{z^u_j}{1 + z^u_j - z^l_j} $$
Thus, the alternative suppliers can be ranked in an increasing order of the comparison index and the most appropriate supplier is the one with the highest comparison index. In the numerical example, the comparison index of each supplier is listed in Table 6. These comparison indices are normalized in the interval [0..1] to compute the final rating of each supplier listed in parentheses in Table 6. Thus, the best supplier is $S_3$, while the ranking of the three suppliers is given by $S_3 \succ S_2 \succ S_1$.

### Step 5: Total Purchasing Value and Order Allocation Optimization

The next step for addressing the biomass supplier selection problem is to answer the following questions:

- Which supplier(s) should be chosen based on the previously derived evaluation outcomes (ratings)?
- When?
- What type of biomass feedstock should be supplied by each selected supplier?
- How much feedstock will be supplied by each selected supplier?
- How would total budget for the biomass purchasing function be allocated?
- What would be the maximum total purchasing value in each time period considered?

A decision-making time horizon $H$ needs to be determined. Within this horizon, the variations in the market conditions are anticipated and expressed in terms of time-dependent changes in biomass quantities, available types and prices of supply, as well as demand. The decision-making time horizon $H$ is discretised into $N_t$ periods. This leads to a set of purchasing operation periods defined as $T = \{t|t = 1, 2, ..., N_t\}$. Within each time period, purchasing conditions are assumed to be stable.

At this point, it is important to note that candidate vendors need to be evaluated regularly (e.g. on a two-week or monthly basis) because of the time-dependency of most of the aforementioned criteria.

By applying repeatedly the previous methodological steps for each time period, different suppliers’ scoring profiles can be calculated per time period (as shown in Table 7 for the numerical example considered). For example, the ranking of the three suppliers calculated before corresponds to the suppliers’ scoring profile for March.

After obtaining the suppliers’ scoring profiles for each considered time frame, an optimization model using the suppliers’ ratings as coefficients of the linear programming objective function need to be developed, as follows:

**Objective Function**

$$\text{Max}(TPV_i) = \sum_{k \in B} \sum_{j \in A} w_{ij} F_{ij} \quad \forall t \in T$$

where:

- $TPV_i$ = Total Purchasing Value in time period $t$ (including not only economic performance but total purchasing value in qualitative and quantitative terms)
- $i$ = supplier index

---

**Table 6. Comparison indexes for suppliers**

<table>
<thead>
<tr>
<th>$\xi_1$</th>
<th>$\xi_2$</th>
<th>$\xi_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.471 (0.278)</td>
<td>0.576 (0.340)</td>
<td>0.647 (0.382)</td>
</tr>
</tbody>
</table>
Multi-Criteria Decision Making for Supplier Selection in Biomass Supply Networks

Table 7. Total ratings matrix for each supply alternative per time period (monthly basis)

<table>
<thead>
<tr>
<th>Supplier</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>January</td>
<td>1</td>
<td>0.301</td>
<td>0.374</td>
</tr>
<tr>
<td>February</td>
<td>2</td>
<td>0.291</td>
<td>0.350</td>
</tr>
<tr>
<td>March</td>
<td>3</td>
<td>0.278</td>
<td>0.340</td>
</tr>
<tr>
<td>April</td>
<td>4</td>
<td>0.250</td>
<td>0.325</td>
</tr>
<tr>
<td>May</td>
<td>5</td>
<td>0.231</td>
<td>0.334</td>
</tr>
<tr>
<td>June</td>
<td>6</td>
<td>0.132</td>
<td>0.320</td>
</tr>
<tr>
<td>July</td>
<td>7</td>
<td>0.105</td>
<td>0.217</td>
</tr>
<tr>
<td>August</td>
<td>8</td>
<td>0.187</td>
<td>0.280</td>
</tr>
<tr>
<td>September</td>
<td>9</td>
<td>0.220</td>
<td>0.329</td>
</tr>
<tr>
<td>October</td>
<td>10</td>
<td>0.215</td>
<td>0.380</td>
</tr>
<tr>
<td>November</td>
<td>11</td>
<td>0.290</td>
<td>0.372</td>
</tr>
<tr>
<td>December</td>
<td>12</td>
<td>0.280</td>
<td>0.350</td>
</tr>
</tbody>
</table>

- \( b \) = biomass type index
- \( i_b \) = index of supplier \( i \) providing biomass type \( b \)
- \( w_{t,i} \) = significance weight of supplier \( i \) in time period \( t \)
- \( t \) = index of the time period considered (e.g. one month)
- \( F_{t,i_b} \) = amount of biomass type \( b \) to be delivered from supplier \( i \) in time period \( t \)
- \( I_b \) = set of suppliers of feedstock type \( b \)
- \( B \) = set of feedstock types
- \( T \) = set of designated time frames

Capacity Constraints

A supplier \( i \) can provide biomass of type \( b \) up to a certain amount, \( F_{t,i_b} \), in each period of time:

\[
F_{t,i_b} \leq F_{t,i_b}^{\text{max}} \quad \forall t \in T, \forall i_b \in I_b, \forall b \in B \quad (14)
\]

Demand Constraints

In each time window \( t \), the procured amounts of all biomass types \( b \) from all suppliers providing biomass \( b \), \( i_b \), must sum up to the demand for feedstock, \( D_t \), in order to meet plant’s requirements:

\[
\sum_{b \in B} \sum_{i_b \in I_b} F_{t,i_b} \leq D_t \quad \forall t \in T \quad (15)
\]

There may also be some budget and quality related constraints that can mathematically be described as follows:

Budget constraints

\[
\sum_{b \in B} \sum_{i_b \in I_b} C_{t,i_b} \leq C_t^{\text{max}} \quad \forall t \in T \quad (16)
\]

where \( C_t^{\text{max}} \) refers to the total purchasing budget in time period \( t \) and \( C_{t,i_b} \) is the total cost for purchasing biomass type \( b \) from supplier \( i \) in time period \( t \). This cost may change over the total time horizon considered. Thus, the costs need to be estimated periodically (in time intervals \( t \), e.g. on a monthly basis).
Multi-Criteria Decision Making for Supplier Selection in Biomass Supply Networks

Table 8. Data on suppliers’ capacity per month

<table>
<thead>
<tr>
<th>Month</th>
<th>Capacity (tn/mo)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$S_1$</td>
</tr>
<tr>
<td>January</td>
<td>1</td>
</tr>
<tr>
<td>February</td>
<td>2</td>
</tr>
<tr>
<td>March</td>
<td>3</td>
</tr>
<tr>
<td>April</td>
<td>4</td>
</tr>
<tr>
<td>May</td>
<td>5</td>
</tr>
<tr>
<td>June</td>
<td>6</td>
</tr>
<tr>
<td>July</td>
<td>7</td>
</tr>
<tr>
<td>August</td>
<td>8</td>
</tr>
<tr>
<td>September</td>
<td>9</td>
</tr>
<tr>
<td>October</td>
<td>10</td>
</tr>
<tr>
<td>November</td>
<td>11</td>
</tr>
<tr>
<td>December</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 9. Purchasing costs for each supply alternative, total demand and purchasing budget

<table>
<thead>
<tr>
<th>Cost (€/tn)</th>
<th>Total Budget (€)</th>
<th>Total Demand (tn/mo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>5,5</td>
<td>9000</td>
</tr>
<tr>
<td>$S_2$ for $b_1$</td>
<td>8</td>
<td>1000</td>
</tr>
<tr>
<td>$S_3$ for $b_2$</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>$S_3$</td>
<td>6,5</td>
<td></td>
</tr>
</tbody>
</table>

Quality Constraints (Optional)

Quality constraints are imposed in order to ensure that required production quality levels are maintained

\[
\sum_{i \in I_t} F_{t, b} q_{t, i} \leq D_t Q_{t, b} \quad \forall t \in T, \forall b \in B \quad (17)
\]

where $Q_{t, b}$ denotes the buyer’s maximum acceptable defect rates for each biomass type $b$ in time period $t$ and $q_{t, i, b}$ is the defect rate of the supplier $i$ with respect to biomass type $b$ at time $t$.

Non Negativity Constraints

\[
F_{t, b} \geq 0 \quad \forall t \in T, \forall i \in I_b, \forall b \in B \quad (18)
\]

In particular, for the aforementioned example a set of indicative data can be used (as seen in Tables 8 and 9), based on which the following model is applied to yield the optimal order quantities from the best suppliers considered, in order to maximize total purchasing value for e.g. March:

\[
\max (TPV_{3}) = w_{3, 1} F_{3, 3_{1}} + w_{3, 2} F_{3, 3_{2}} + w_{3, 3} F_{3, 3_{3}} + w_{3, 4} F_{3, 3_{4}} + w_{3, 5} F_{3, 3_{5}} + w_{3, 6} F_{3, 3_{6}}
\]

or

\[
\max (TPV_{3}) = 0.278 F_{3, 3_{1}} + 0.340 F_{3, 3_{2}} + 0.340 F_{3, 3_{3}} + 0.382 F_{3, 3_{4}}
\]
subject to

\[ F_{3,1_{RP}} \leq 350 \]  \hspace{1cm} (20)

\[ F_{3,2_{RP}} \leq 200 \]  \hspace{1cm} (21)

\[ F_{3,2_{SN}} \leq 400 \]  \hspace{1cm} (22)

\[ F_{3,3_{WCO}} \leq 150 \]  \hspace{1cm} (23)

\[ F_{3,1_{RP}} + F_{3,2_{RP}} + F_{3,2_{SN}} + R_{3,3_{WCO}} \leq 1000 \]  \hspace{1cm} (24)

\[ c_{31}F_{3,1_{RP}} + c_{32}F_{3,2_{RP}} + c_{32}F_{3,2_{SN}} + c_{33}F_{3,3_{WCO}} \leq 9000 \]  \hspace{1cm} (25)

or

\[ 5.5F_{3,1_{RP}} + 8.0F_{3,2_{RP}} + 8.0F_{3,2_{SN}} + 6.5F_{3,3_{WCO}} \leq 9000 \]  \hspace{1cm} (26)

and

\[ F_{t,b} \geq 0 \]

\[ \forall t \in T, \forall i_b \in \{ S_{1_{RP}}, S_{2_{RP}}, S_{2_{SN}}, S_{3_{WCO}} \}, \]  \hspace{1cm} (27)

\[ \forall b \in \{ RP, SN, WCO \} \]

Similarly, the linear programming problem can be repeatedly solved by applying the same model for each month while making use of the respective parameters, which are shown in Tables 7, 8 and 9. Table 10 indicates the optimal values of biomass amounts purchased by the selected suppliers each month to meet the bioenergy production requirements, along with the maximum total purchasing value obtained by solving the aforementioned model. Also, the resulting suppliers’ selection profiles and biomass amounts scheduling for the example considered can be seen in Figure 4.

It is worth noting that the results obtained by this methodological approach in the examined case show that suppliers \( S_2 \) and \( S_3 \) seem to usually compete for being selected as best suppliers. This finding can be justified by the fact that supplier \( S_3 \) represents a low-cost biomass supply alternative (providing inexpensive WCO), whereas \( S_2 \) exhibits flexibility in offering the adequate feedstock amounts of two different

<table>
<thead>
<tr>
<th>Months</th>
<th>b1 from ( S_1 )</th>
<th>b1 from ( S_2 )</th>
<th>b2 from ( S_2 )</th>
<th>b3 from ( S_3 )</th>
<th>TVP</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1</td>
<td>200</td>
<td>300</td>
<td>400</td>
<td>100</td>
</tr>
<tr>
<td>February</td>
<td>2</td>
<td>100</td>
<td>300</td>
<td>450</td>
<td>150</td>
</tr>
<tr>
<td>March</td>
<td>3</td>
<td>250</td>
<td>200</td>
<td>400</td>
<td>150</td>
</tr>
<tr>
<td>April</td>
<td>4</td>
<td>160</td>
<td>300</td>
<td>340</td>
<td>200</td>
</tr>
<tr>
<td>May</td>
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<td>50</td>
<td>150</td>
<td>250</td>
<td>550</td>
</tr>
<tr>
<td>July</td>
<td>7</td>
<td>0</td>
<td>50</td>
<td>200</td>
<td>750</td>
</tr>
<tr>
<td>August</td>
<td>8</td>
<td>0</td>
<td>150</td>
<td>300</td>
<td>550</td>
</tr>
<tr>
<td>September</td>
<td>9</td>
<td>50</td>
<td>200</td>
<td>350</td>
<td>400</td>
</tr>
<tr>
<td>October</td>
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<tr>
<td>November</td>
<td>11</td>
<td>200</td>
<td>250</td>
<td>400</td>
<td>150</td>
</tr>
<tr>
<td>December</td>
<td>12</td>
<td>200</td>
<td>200</td>
<td>250</td>
<td>350</td>
</tr>
</tbody>
</table>
biomass types (rapeseed and sunflower). It is also obvious that seasonality plays indeed a major role in choosing the appropriate biomass supply solutions. Finally, an interesting research direction perspective would be to examine the supply performance alternatives, for which demand-driven supply chain models are developed and simulation techniques are employed to experiment with different market scenarios.

CONCLUSION

This work has focused on analyzing MCDM methodologies for supplier selection in a biomass supply network, which exhibits a number of identified particularities. First, the distinct biomass characteristics were reviewed within the context of their utilization as feedstock for bioenergy (power, heat and biofuels) production on the basis of literature findings. Next, certain biomass supply chain arrangements were explored and insightful pertinent management considerations were discussed. Furthermore, a comprehensive review on supplier selection methodologies have been carried out with an emphasis on the implications of the approaches on biomass-centered supplier performance evaluation. Finally, an appropriately adapted hybrid methodology for market-sensitive decision making on optimal supplier selection in a biomass supply network was developed.

This chapter attempted to demonstrate that the high degree of complexity and uncertainty inherently involved in biomass supply systems renders their management an essentially challenging and dynamically evolved issue with strong impact on the viability of bioenergy production. Outsourcing activities in biomass supply need to take into account the dynamics of the demand in the production system, as well as the cost fluctuations and seasonality of raw material. In achieving sustainable and profitable bioenergy production, it is substantial to consider multiple feedstock sources whose selection for supplying the network depend on time and market conditions. Thus, such a complex and dynamically changing biomass supply environment with high degrees of uncertainties need to be captured by a more realistic and risk informed decision making approach for estimating, rating and optimizing the biomass supplier profiles with respect to time in a multi sourcing dynamic environment.
FUTURE RESEARCH DIRECTIONS

This work can serve as a starting point for further research to be carried out in the area of decision making on biomass supply options and outsourcing biomass logistics operations in general. As indicated previously, the biomass supplier selection problem constitutes a complex and dynamically evolving issue with many conflicting objectives that can not be easily optimized simultaneously via a single multi-objective programming approach. Thus, a more insightful procedure towards determining the more efficient, yet satisfactory, solutions would be perhaps the most appropriate way to go in this particular problem setting. One possible methodology was indicated in this study. However, more research may be conducted to assess the reliability of decision making on biomass supplier selection by examining the behavior and ratings of biomass supply schemes in the presence of criteria uncertainties. For instance, a strategic risk-informed analysis may need to be incorporated in the decision making to account for a number of input uncertainties in the respective models (such as risk of biomass price increases, technology alterations, regulatory changes etc. for a long time horizon). Thus, it would be insightful to conduct further research on examining more meaningful biomass supply solutions that are not expected to attain the form of a simple suppliers profile with fixed ratings but rather risk-reward distribution profiles and associated Pareto fronts, which would be intimately linked to ranges of possible outcomes and assorted probabilities in efficient supplier selection, thus enabling the identification of potential compromise solutions by the decision-maker.

REFERENCES


Multi-Criteria Decision Making for Supplier Selection in Biomass Supply Networks


