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Development of a Multicriteria Assessment Model for Ranking Biomass Feedstock Collection and Transportation Systems

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Abstract

This study details multicriteria assessment methodology that integrates economic, social, environmental, and technical factors in order to rank alternatives for biomass collection and transportation systems. Ranking of biomass collection systems is based on cost of delivered biomass, quality of biomass supplied, emissions during collection, energy input to the chain operations, and maturity of supply system technologies. The assessment methodology is used to evaluate alternatives for collecting 1.8×10^6 dry t/yr based on assumptions made on performance of various assemblies of biomass collection systems. A proposed collection option using loafer/stacker was shown to be the best option followed by ensiling and baling. Ranking of biomass transport systems is based on cost of biomass transport, emissions during transport, traffic congestion, and maturity of different technologies. At a capacity of 4×10^6 dry t/yr, rail transport was shown to be the best option, followed by truck transport and pipeline transport, respectively. These rankings depend highly on assumed maturity of technologies and scale of utilization. These may change if technologies such as loafing or ensiling (wet storage) methods are proved to be infeasible for large-scale collection systems.

Index Entries: Multicriteria assessment; biomass collection systems; biomass transportation systems; PROMETHEE; ranking; bioenergy; IBSAL model.

Introduction

To select a system among several alternatives, a number of criteria should be taken into account: costs (investment, operating, and manpower), technology (efficiency and energy consumption), social factors

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(job creation and quality of life), and environmental factors (emission and discharge). A decision-maker faces the problem of selecting the optimal solution, and cannot focus on one criterion at the expense of others. A multidimensional approach helps in solving this type of complex problem. Assessment of multicriteria for different alternatives is required in order to arrive at a credible solution.

Interest in biomass utilization for energy and chemicals has increased recently, in order to reduce the dependence on fossil fuels and also to reduce greenhouse gas (GHG) emissions. Biomass feedstock collection and transportation is an integral aspect of biomass utilization. Feedstock delivery cost constitutes about 35–50% of the total production cost of ethanol or power *(1–3)*. The actual percentage depends largely on geographical factors such as location, climate, local economy, and the type of systems used for harvesting, collection, processing, and transportation. Many studies have evaluated different biomass harvesting, collection, and transportation systems *(4–8)* but most of these studies were designed to optimize economic factors only, producing options of lower cost. There is a scarcity of work on integration of economical, environmental, and social factors for selection of optimum biomass systems.

Investment in biorefineries must consider economic, social, and environmental factors, particularly in which the public interest is involved. The main objective of this paper is to develop a methodology to rank biomass collection and transportation alternatives using a multicriteria approach. The approach is applied to two cases: (1) biomass collection and (2) biomass transportation. For this analysis we consider financial, environmental, and social factors as criteria. Biomass collection alternatives considered in this study are for agricultural residues (corn stover) and include baling, loafing, and ensiling. Biomass transport options include truck, rail, and pipeline.

Methodology

We used a well-known method called preference ranking organization method for enrichment and evaluations (PROMETHEE). The method is described by Brans and Vincke *(9)*, Brans et al. *(10)*, and Brans and Mareschal *(11)*. PROMETHEE integrates quantitative and qualitative criteria to conduct a paired comparison of alternatives, as described in the following section.

Comparing Two Alternatives Based on One Criterion

Suppose a and b are two alternatives and these alternatives are compared over criterion f. We determine the value of each of these two alternatives with respect to the criterion f and designate them as $f(a)$ and $f(b)$. $f(a)$ and $f(b)$ must be maximized in order to delineate between the two alternatives. In a PROMETHEE method a preference function is applied to the criterion *f* to map the difference between *f(a)* and *f(b)* to a degree of preference of one alternative over another. If the difference is significant, the degree of preference is higher and there is more preference of one alternative over another. The associated degree of preference function *P(a,b)* is given as

$$P(a,b) = \begin{cases} 0 & \text{if } \; f(a) \le f(b) \\ p[f(a), f(b)] & \text{if } \; f(a) > f(b) \end{cases} \tag{1}$$

where *P(a,b)* is degree of preference, *f(a)* and *f(b)* are the values of alternatives *a* and *b* over the criteria *f*, and *p*[*f(a)*, *f(b)*] is the preference function.

For practical cases, it is reasonable to assume

$$p[f(a),f(b)] = p[f(a) - f(b)] \tag{2}$$

The degree of preference is a numerical value *P(a, b)*. *P(a, b)* is estimated using Eq. 1 and is dependent on the value of *p[f(a)–f(b)]*. Let the difference between the values of two criteria be

$$d = f(a) - f(b) \tag{3}$$

p(*d*), the preference function, is defined by the decision-maker and the value of this function is always

$$0 \le p(d) \le 1 \tag{4}$$

Hence Eq. 1 becomes (using Eq. 3 in Eq. 1)

$$P(a,b) = \begin{cases} 0 & \text{if } \; f(a) \le f(b) \\ p(d) & \text{if } \; f(a) > f(b) \end{cases} \tag{5}$$

We consider the preference function such that

$$0 \le P(a,b) \le 1 \tag{6}$$

There are four cases that arise when comparing two alternatives *a* and *b*. These are

If *P(a,b)* = 0, then there is indifference between *a* and *b* (i.e., none is preferred).
If *P(a,b)* ~ 0, then there is weak preference of *a* over *b*.
If *P(a,b)* ~ 1, then there is strong preference of *a* over *b*.
If *P(a,b)* = 1, then there is strict preference of *a* over *b*.

Suppose cars A and B are two alternatives and are compared on distance each travel using 1 L of gasoline. The car with higher traveled distance per unit of gasoline used is selected (maximize the criterion). Alternative *a* is represented by car A and alternative *b* is represented by car B.

The criterion is km/L of gasoline. Let distance traveled by cars A and B be 25 and 15 km/L, respectively. Applying the methodology described earlier to this example, $f(a) = 25$, $f(b) = 15$, and $d = f(a) - f(b) = 10$ km/L.

Let us assume a preference function $p(d)$, such that

$$p(d) = 1 \text{ if } d > 0$$
$$p(d) = 0 \text{ if } d < 0$$

Hence in this case, degree of preference, $P(a,b)$, is unity, using Eq. 5. According to the cases defined earlier, there is strict preference of car A over B.

General Case—Comparison of Multiple Alternatives Based on Multiple Criteria

In case of a multicriteria problem, a preference function is defined for each of the criteria. The preference functions translate the difference between the values of two alternatives over a criterion in terms of a degree of preference. The higher the difference between the values of alternatives over a criterion, the larger is the degree of preference. The degree of preference is calculated by comparing pairs of alternatives, using the selected preference function for a criterion. These degrees of preference are used to estimate multicriteria preference index of an alternative over other alternative, considering all the criteria together. This methodology is described later. A preference function also helps in bringing the scale of different criteria to a single uniform scale. For example, if two different criteria, cost ($/t) and emissions (kg C/t), have to be integrated in order to rank two alternatives, the comparison of these criteria need to be converted to the same scale; this is done with the help of a preference function.

PROMETHEE is useful in analyzing problems in which there are multiple criteria and multiple alternatives for solutions. The generalized methodology may be expressed as a ranking of a set of N alternatives based on k criteria (f_i, where $i = 1, \ldots, k$). In this method, a preference index comparing alternatives a and b using multiple $(1, \ldots, k)$ criteria is the weighted average of the degree of preference $P_i(a,b)$ for each individual criterion, and is expressed as $\gamma\,(a,b)$. The weighting assigned to each criterion (w_i) is based on the relative importance of the criterion.

$$\gamma(a,b) = \frac{\sum_{i=1}^{k} w_i P_i(a,b)}{\sum_{i=1}^{k} w_i} \tag{7}$$

where $a, b \in N$

N is the set of alternatives and k is the number of criteria.

This study uses a decision-support software, namely, Decision Lab 2000—Executive Edition *(12)*. Six different preference functions are defined in the Decision Lab 2000. In this study we use two preference functions: linear preference, in which the preference of *a* over *b* increases linearly, and level preference, in which a threshold denotes the change point between indifference and preference.

The sum of the multicriteria preference indexes $\gamma\,(a,b)$, is used to calculate a leaving flow $\varphi^+(a)$, an entering flow $\varphi^-(a)$, and a net flow $\varphi(a)$ for the entire system. Leaving flow denotes the dominance of an alternative over other alternatives and is a measure of outranking character. Entering flow is the measure of outranked character. Net flow is the difference between the two flows.

$$\varphi^+(a) = \sum_{x \in N} \gamma(a,x) \tag{8}$$

$$\varphi^-(a) = \sum_{x \in N} \gamma(x,a) \tag{9}$$

$$\varphi(a) = \varphi^+(a) - \varphi^-(b) \tag{10}$$

PROMETHEE provides two ranking methods: PROMETHEE I—the preferences are confirmed by both leaving and entering flow and ranking is based on leaving flow (if the information provided by two flows for two alternatives are contradicting, this method cannot decide the ranking); PROMETHEE II—ranking is based on net flow. In both the methods, greater the value of flow, higher is the ranking. One of the powerful features of PROMETHEE is its ability to integrate both quantitative and qualitative criteria. Qualitative criteria are defined on a scale. A qualitative scale is a series of ordered semantic values. Each semantic value is associated with a numerical value that is used in calculations. We used a five-point scale to assign values to qualitative criteria (very high = 5, very low = 1). Figure 1 shows the flowchart for the ranking methodology used in this study.

Case 1: Biomass Collection Systems

Biomass feedstock supply is characterized by a large collection area, variation in crop maturity with time and weather, a short window of collection, and competition from concurrent harvest operations. It is important to have an optimized supply system for long-term success of a biomass processing facility such as a biorefinery. Biomass supply logistics consists of harvesting, collection, storage, preprocessing, and transportation *(13)*. In this study collection options for agricultural residues (in this study, corn stover) include the following.

1. Baling (conventional round baling)—harvest grain, shred or rake crop residue, bale biomass, transport bales to the field edge and stack, load bales on a truck and transport to a biorefinery, unload, and grind the biomass.

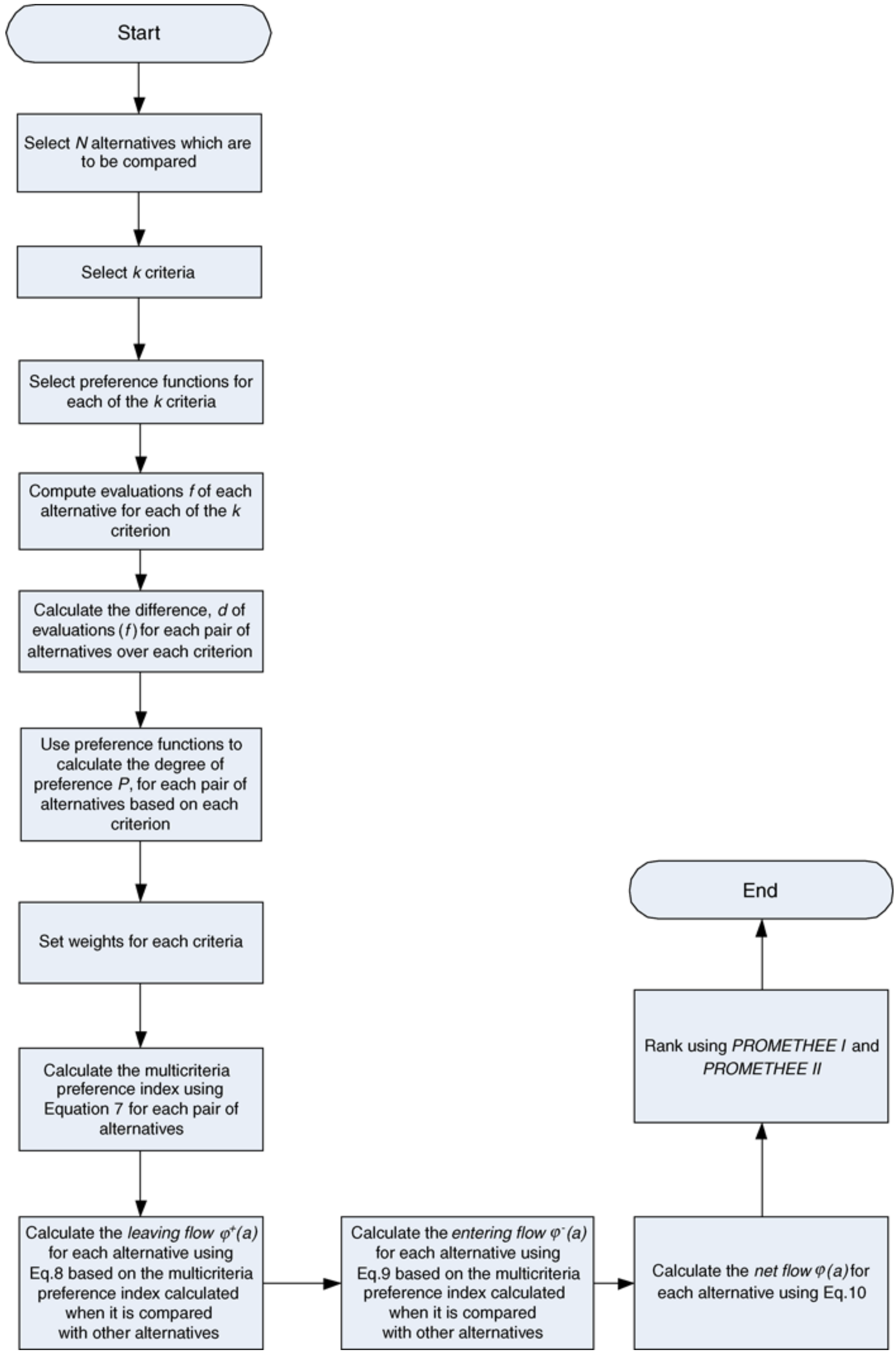

Fig. 1. Flowchart for implementing PROMETHEE.

2. Loafing—harvest grain, shred or rake crop residue, load a stacker (loafer) with biomass, transport the stacker (filled with biomass) to the field edge, unload the stacker, grind the biomass, load the grind into a truck, and transport the filled truck to a biorefinery.

3. Chopping and ensiling—harvest grain, chop stover using a forage harvester, load wagon, transport wagon to the silage, ensile, load, a silage truck, and transport to a biorefinery.

Integrated Biomass Supply Analysis and Logistics

The integrated biomass supply analysis and logistics (IBSAL) model developed by Sokhansanj at the Oak Ridge National Laboratory (ORNL) *(14,15)* is used to estimate the costs, energy use, and emissions for each of the collection options. IBSAL is a dynamic simulation model which simulates flow of biomass from field to a biorefinery. It consists of different submodules detailing discrete process steps, including harvest, baling, grinding, storage, and transportation. The current version of IBSAL model has been developed for straw and corn stover harvesting, collection, storage, preprocessing, and transportation. The model input data include local weather data (average daily temperature, humidity, and precipitations), average yield of biomass, proportion of land that is cultivated to the crop that yields the residue, crop harvest progress data, capacity of the biorefinery, dry matter loss with time in the storage, operating parameters of different agricultural machinery, and capital and operating costs of different agricultural machinery. This model has been built on EXTEND™ platform, available from Imagine That, Inc. *(16)*. Main outputs of the model include delivered cost of biomass to a biorefinery ($/t of biomass delivered), GHG emission (kg C/t of biomass delivered), and energy consumption (GJ/t of biomass delivered). Cost, energy, and emission parameters can be obtained for individual processing steps. The model can also be used to estimate the monthly equipment requirement and the time required to finish each operation. Details of the model can be found in the work of Sokhansanj and Turhollow *(14,15)*. This model runs on the generic data.

Input Data and Assumptions

Five different criteria are considered for comparing and ranking three biomass collection systems. Table 1 shows input data for each criterion considered for corn stover collection systems. Delivered cost of material to a biorefinery represents the economic factor in the analysis. Emissions represent the environmental factor in the analysis. Data for cost, emissions, and energy consumption for different collection systems are calculated using the IBSAL model, for a biorefinery capacity of approx 1.8×10^6 dry t/yr. The values of two qualitative criteria, i.e., quality of material and maturity of the technology, are based on the experience of the authors, in discussion with the industry and in informal consultation with the experts in the area. Note that all cost figures in this study are in 2004 USD.

Table 2 lists the weights (w_i) for each criterion, the preference threshold for criteria differences (α), and the indifference threshold for criteria differences (β) for corn stover collection systems.

Table 1
Input Data for Biomass Collection Systems

Options/ criteria	Cost ($/t)	Quality of material	Emissions (kg C/t)	Energy consumption (GJ/t)	Maturity of technology
Corn stover					
Baling	49.77	Very high	29.6	1.35	Very high
Ensiling	49.99	Average	20.4	0.93	Very low
Loafing	27.36	Low	20.7	0.88	Average

Table 2
Assumptions for Biomass Collection Systems

Items	Cost	Quality of material	Energy	Emission	Maturity of technology
Min./Max.	Min.	Max.	Min.	Min.	Max.
Weights[c] (w_i)	0.30	0.25	0.15	0.15	0.15
Preference threshold[a] (α)	5.00	2.50	0.30	5.00	2.50
Indifference threshold[b] (β)	–	0.50	–	–	0.50

[a]Units for values of different quantitative criteria are cost ($/t), energy (GJ/t), and emission (kg C/t). Values for qualitative criteria are in absolute numbers.
[b]Values for qualitative criteria are in absolute numbers.
[c]Sum of all the weights is 1.

Comments on Selected Criteria and Input Parameters

Delivered cost of biomass—delivered cost is the sum of costs of each unit operation in a particular collection system. Many earlier studies report the delivered cost of agricultural residues to a biorefinery (*see*, e.g., refs. *2,3,6,7,13,17,18*). These studies do not consider costs based on time-dependent biomass supply modeling. The IBSAL model is time dependent and takes into account all the aspects of biomass supply from field to biorefinery including the seasonal nature of the biomass.

Emissions—in this study the carbon emissions during the direct operation of agricultural machinery and transportation of biomass by wagons or trucks represent the environmental impact of different collection systems. The values in Table 1 do not include emissions during indirect use of fossil fuels for fertilizer or pesticides' production. It is assumed that all the agricultural machinery use diesel fuel. Earlier studies have estimated emissions during harvesting and transportation of different types of biomass, but most of these have not considered detailed machinery use in each farm operation (*see*, e.g., refs. *19–23*). The IBSAL model simulates the use of all the equipment and farm machineries required on a farm and hence gives more accurate value.

Energy consumption—Table 1 shows the values of energy consumption per tonne of biomass material supplied. Earlier studies have calculated the energy consumption for different biomass supply systems (*see*, e.g., refs. *19–23*). In this study energy consumption represents the fossil fuel consumed in direct process use and does not take into account the energy consumed in indirect process use such as manufacturing of equipment, fertilizer, and so on. The IBSAL model outputs are specific to the collection systems considered.

Quality of material—this is an important criterion for deciding the best collection systems. Quality of biomass affects the efficiency and output of the biomass conversion process. Supply of material in the form of bales helps in minimizing the dirt and soil in the biomass material. In loafing process dirt may be picked up from the ground and this has a negative impact on fuel or product yield from biomass during conversion. It is difficult to assign a quantitative value to each collection system for this criterion, hence a qualitative scale is chosen for comparison.

Maturity of technology—currently, the most common method of collecting biomass in North America is through baling (*6,7,13,17,18*). This is a mature technology in comparison with loafing and ensiling. Currently, ensiling is not used for biomass collection but research is in progress at the ORNL, Idaho National Laboratory, and elsewhere. Loafing has been studied earlier as collection and storage system but the loafer needs improvement.

Weights of different criteria—weights are critical parameters in a multicriteria assessment. Weighting values assigned within the model depend on the decision-maker and can vary widely. In this study we have assumed weights based on our experience and in consultation with other experts in this area; these are shown in Table 2. A sensitivity analysis, discussed later, illustrates the dependence of the ranking on the relative weighting of criteria.

Preference and indifference threshold—these thresholds represent the limits, above or below which there is a strict preference or indifference. These values are based on experience and in consultation with the experts. A sensitivity analysis for these values is done. The values are shown in Table 2.

Results and Discussion for Case 1

The input and assumption data given in Tables 1 and 2 are used in Decision Lab 2000 to estimate the leaving, entering, and net flows. Table 3 gives the leaving flow $\varphi^+(a)$, entering flow $\varphi^-(a)$, and net flow $\varphi(a)$ for different alternatives.

Based on the PROMETHEE I ranking method, loafing is the best alternative, and we cannot make a judgment between baling and ensiling. According to the results shown in Table 3, φ^+(baling) is greater than φ^+(ensiling) and also φ^-(baling) is greater than φ^-(ensiling). According to

Table 3
Results for Biomass Collection Systems

Options	Leaving flow $\varphi^+(a)$	Entering flow $\varphi^-(a)$	Net flow $\varphi(a)$	Ranking PROMETHEE I	Ranking PROMETHEE II
Corn stover					
Baling	0.31	0.45	–0.14	2	3
Ensiling	0.22	0.34	–0.12	2	2
Loafing	0.50	0.23	0.27	1	1

Table 4
Stability Intervals for Corn Stover Collection Systems

Criteria	Corn stover Unit: percentage values (%)		
	Weight	Min.	Max.
Cost	30	5	49
Emission	15	14	89
Energy consumption	15	14	100
Maturity of technology	15	0	16
Quality of material	25	0	27

PROMETHEE I method, it is difficult to make a decision between baling and ensiling systems. In other words, based on PROMETHEE I, baling and ensiling cases cannot be distinguished. As discussed earlier, the PROMETHEE II ranking is based on net flows. It selects ensiling over baling. Note that the two ranking methods use different calculations to rank the alternatives. A decision-maker would have to look at the actual role of each variable before making a decision. In the case of stover collection systems, loafing is the best system based on both PROMETHEE I and II rankings, which is largely owing to a combination of low costs, emissions, and specific energy consumption. The advantages of these three criteria offset the penalty owing to low quality of material.

A sensitivity analysis on weighting factors is done by establishing stability intervals, which represent the range over which weighting values for different criteria do not influence the PROMETHEE II outcome. Table 4 lists the range of stability intervals for each variable. For example, if we change the weight of cost criteria to any value between 5% and 49% (as shown in Table 4), keeping the values of weights of other criteria the same, the PROMETHEE II ranking of collection systems will not change. This represents a wide range and reflects the low sensitivity of ranking to cost. Similar information is conveyed by stability intervals for emission and energy consumption regarding their impact on ranking. These criteria have low sensitivity on ranking. However, ranking is sensitive to the weights of the criteria—maturity of technology and quality of material.

This is evident by the narrow range of the stability interval for these criteria. The stability interval gives the decision-makers an option of analyzing the impact of changing the weights on ranking of different alternatives.

Similar analysis of biomass collection systems at a lower or higher capacity per year does not change the PROMETHEE I and II rankings. The reason is that collection costs ($/t), emissions (kg C/t) and energy consumption (GJ/t) for collection do not change with capacity.

Case 2: Biomass Transportation Systems

Cost of biomass transportation is a significant component of biomass-delivered cost. Several studies have shown that truck transport cost of agricultural residues' (corn stover) biomass ranges from 20% to greater than 40% of total delivered cost, depending on distance traveled and mode of transportation (*2,7,8,17,24*). A small-scale biorefinery is not economical in comparison with an oil refinery. At a large scale, biomass transportation by truck may not be physically possible owing to traffic congestion and resulting community opposition. Rail transport of biomass reduces the frequency of loads. Pipeline transport would deliver biomass with minimum ongoing community impact. However, selection of a transportation mode cannot be made based on only one issue. Economical, environmental, social, and technical parameters should be integrated to select the best system.

Input Data and Assumptions

We compare three transportation options: truck transport, rail transport, and pipeline transport. The four criteria include cost of biomass transport, carbon emission during biomass transport, traffic congestion, and maturity of technology. Table 5 lists the input parameters for 4×10^6 dry t/yr transport capacity. The following are comments on input parameters and assumptions for transport analysis:

Cost of biomass transport—Biomass transport cost has two components (fixed cost with respect to distance and distance variable cost). An example of fixed cost, independent of distance of transport, is the cost of loading and unloading a truck, whereas distance variable cost is the "per km" cost of transport, covering fuel, depreciation, maintenance, and labor. The yield is the amount of corn stover that can be removed in a sustainable manner (this takes into account percentage of farmers willing to sell, inaccessible fields, storage, and handling losses) and is derived from earlier study by Perlack and Turhollow *(17)* of ORNL, US for corn stover. Details of the assumptions regarding the yield estimation are given in the work of Perlack and Turhollow *(17)*.

Transportation cost by truck has been studied in detail by many authors. In the literature, the fixed cost varies from $3.31 to $6.76/dry t and

Table 5
Input Data for Biomass Transportation Systems

Options/criteria	Cost ($/t)	Emissions (kg C/t)	Traffic congestion	Maturity of technology
Truck transport	25.62	2.68	Very high	Very high
Rail transport	64.65	1.40	Average	High
Pipeline transport	73.20	8.22	Very low	Average

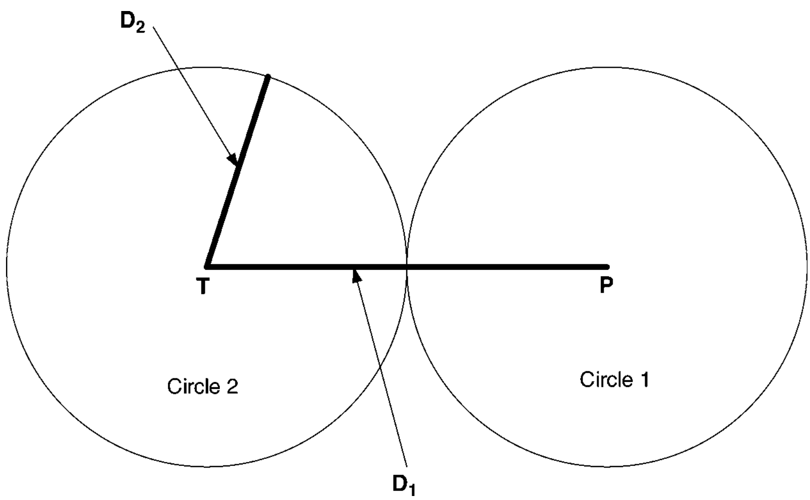

Fig. 2. Configuration of area supplying 4×10^6 dry t of corn stover to a biomass processing facility using rail and pipeline transport.

the variable cost ranges from $0.05 to $0.19/dry t/km. In this study we have taken a blended value of costs reported in earlier studies *(2–4,8)*. A fixed cost of $5.70/dry t and a variable cost of $0.14/dry t/km are used in this analysis. For supplying a biomass processing facility of 4×10^6 dry t/yr capacity by truck only, biomass is required to be collected from a circular area of radius 206 km (based on corn stover yield of 30 dry t/gross km^2).

In this study we have assumed a simple configuration (shown in Fig. 2) of the area for supplying biomass to a 4×10^6 dry t processing facility using rail and pipeline transport. It is important to note that all biomass start their journey on a truck irrespective of its mode of transport afterwards (rail or pipeline).

In Fig. 2 each circular area (circles 1 and 2) has a capacity of supplying 2×10^6 dry t of biomass. In other words, a total of 4×10^6 dry t of corn stover can be collected from the two circular areas. The diameter is a function of biomass yield. In this case, based on a yield of 30 dry t/gross km^2 for corn stover, the radius of each circle is 146 km. A biomass processing facility is located at the center of circle 1 (P) and the rail or pipeline collection terminal is located at the center of circle 2 (T). This is discussed further.

Rail transport of biomass has been studied earlier *(6,25)*. In this study we have used costs reported by a recent study done by Mahmudi and Flynn (published in this volume) for rail transport of straw in North America. The fixed cost of rail transport is \$17.01/dry t and the variable cost of \$0.03/dry t/km. The fixed cost in case of rail transport includes the capital cost of the rail siding, rail cars, and equipment for loading and unloading biomass. The variable cost includes the charges of the rail company, which include capital recovery and maintenance for track and engines and fuel and operating costs. In this study we estimated the delivered cost of rail transport for the configuration shown in Fig. 2. Biomass is collected from each of the circular areas and transported by trucks to the center of each circle. For biomass collected from circle 1, it is transported to the processing facility directly, whereas for circle 2, biomass is collected and transported by trucks to the rail loading terminal T and from there it is transported by rail to the processing facility P. Hence the cost of biomass transportation in case of rail transport has three components: truck transportation cost to the processing facility P from area of circle 1, truck transportation cost to the rail loading terminal T from the area of circle 2, and rail transportation cost from the loading terminal T to the processing facility P. D_1 (292 km) and D_2 (146 km) represent the distances of transport by rail and truck, respectively. Truck transportation cost is estimated based on average distance of transport. This configuration can be generalized for transportation of biomass to any size of biomass processing facility. Rail transport is discussed in detail in Mahmudi and Flynn *(26)*.

Previous studies have evaluated biomass transport by pipeline *(8,24,26,27)*. Biomass is transported by pipeline in the form of a slurry mixture; the carrier fluid is water. Note that the impact of carrier fluid on the end-use of biomass is discussed in an earlier study *(27)*; water transport to combustion-based processes is precluded by high water uptake by the biomass. In this analysis we have derived the cost of pipeline transport of corn stover at a solids' concentration of 20% (wet basis) using data from previous studies and assumed that the end-use of biomass will be in a biorefinery. Corn stover absorbs water quickly and achieves a moisture level of 80%; so 20% slurry of wet corn stover would be 4% dry matter and 96% water *(26)*. The fixed cost of pipeline transport is \$1.82/dry t and variable cost is \$0.11/dry t/km, at a pipeline capacity of 2×10^6 dry t/yr. The distance-fixed cost for pipeline transport includes the capital cost of pipeline inlet and outlet equipment. The distance-variable cost includes the capital cost of pipeline and booster stations and the operating and maintenance cost. The delivered cost of biomass by pipeline is calculated similar to the analysis of rail transport. The pipeline inlet terminal is located at the center of circle 2 (T) and biomass is transported by a pipeline to the processing facility (P). Trucks are used to transport biomass from each of the circular area to the center of the circle; dimensions are the same as for the truck plus rail option.

Table 6
Assumptions for Biomass Transport Systems

Items	Cost	Traffic congestion	Emission	Maturity of Technology
Min./Max.	Min.	Min.	Min.	Max.
Weights[a] (w_i)	0.30	0.30	0.25	0.15
Preference threshold (α)[b]	2.00	2.50	1.00	2.50
Indifference threshold (β)[c]	–	0.50	–	0.50

[a]Sum of all the weights is 1.
[b]Units for values of different quantitative criteria are cost ($/t) and emission (kg C/t). Values for qualitative criteria are in absolute numbers.
[c]Values for qualitative criteria are in absolute numbers.

Emissions: in this study only direct carbon emissions are considered. The carbon emissions from truck transport is based on an energy input of 1.3 MJ/t/km *(20)* and a release of 20 g C/MJ *(28)*. The figure for energy input of rail transport is 0.68 MJ/t/km *(20)*. It is assumed that diesel fuel is used for both truck and rail. The carbon emission from pipeline use is based on the electricity consumption by pumps to transport the biomass slurry. The electrical power is assumed to be produced from a coal power plant; we have used an emission factor of 984.6 g CO_2/kW h *(3)*. The emissions from transport of biomass by each mode are given in Table 5.

Traffic congestion: this is a critical issue when the capacity of biomass processing facility is large. At a capacity of 2×10^6 dry t, a truck would be required every 4 min throughout the year (this calculation is based on a truck capacity of 20-wet t/load, a biomass moisture content of 15%, and plant-operating factor of 0.85, which represents the fraction of time plant runs in 1 yr). This frequency is likely to face public resistance if the plant is close to a community. At the same capacity about 200 car unit trains would be required per day (based on a rail car capacity of 100 wet t). For both the train and pipeline transport options, a significant amount of biomass is still delivered to the biorefinery by truck, but the impact is reduced. In this study we have used traffic congestion as a qualitative criterion. The qualitative assessment for each mode is shown in Table 5.

Maturity of technology: most of the biomass transportation today is by trucks and it is the most common mode of transport. Rail transport is used for transportation of grains for longer distances and a significant quantity of lumber is also shipped by rail. Pipeline transport of biomass is a developing technology. Currently, pipeline is used for transport of pulp in pulp mills on a smaller scale. In this study, we have used maturity of technology as a qualitative criterion. The qualitative assessment for each mode is shown in Table 5. Assumption for each criterion is shown in Table 6.

Table 7
Results for Biomass Transportation Systems

Options	Leaving flow $\varphi^+(a)$	Entering flow $\varphi^-(a)$	Net flow $\varphi(a)$	Ranking PROMETHEE I	Ranking PROMETHEE II
Truck	0.50	0.35	0.15	2	2
Rail	0.51	0.26	0.25	1	1
Pipeline	0.22	0.62	–0.40	3	3

Table 8
Stability Intervals for Biomass Transportation Systems

Criteria	Corn stover Unit: percentage values (%)		
	Weight	Min.	Max.
Cost	30	3	36
Emission	25	17	100
Traffic congestion	30	19	49
Maturity of technology	15	0	29

Results and Discussion for Case 2

Table 7 gives the leaving flow $\varphi^+(a)$, entering flow $\varphi^-(a)$, and net flow $\varphi(a)$ for different transportation alternatives at a capacity of 4×10^6 dry t/yr.

Based on the PROMETHEE I ranking method, rail transport is the best alternative, followed by truck and pipeline transports. PROMETHEE II ranking based on net flows, as discussed earlier, again selects rail over pipeline and truck. Notice that the two ranking systems use different calculations to rank the options. A decision-maker needs to look at both rankings before making a decision. In the case of stover transportation systems, rail transport is the best system based on both PROMETHEE I and II rankings.

Table 8 shows the stability interval for weights of different criteria for biomass transportation systems. In case of transportation systems, stability interval for emission is 17–100%. This represents a wide range and has a small impact of this on the rankings. Ranking is sensitive to weights of cost and maturity of technology within a narrow range. The range of stability interval gives the option to the decision-maker to analyze different situations in which the weights vary. At 4×10^6 dry t, truck traffic congestion will be very high and based on the decision-makers if the weight for traffic congestion is increased more than 49% or decreased lesser than 19%, the ranking will change. Another important factor to note is that in this study we have assumed that electricity for pipeline transport of biomass is generated using coal, which gives a high emission of carbon per tonne of biomass processed. In many regions in North America hydroelectricity and nuclear power are generated. This consideration will greatly influence the emissions, and hence the ranking can change significantly.

Conclusions

The study illustrates a systematic method to rank biomass collection and transportation systems based on a multicriteria assessment. It shows that selection of an option is not only based on economic factors but also on environmental and social factors. This study also illustrates a method to integrate quantitative and qualitative factors in decision-making. PROMETHEE method could be used in various areas for comparison of different systems. In this study focus is on the biomass feedstock systems, but this methodology could be extended to biomass energy conversion systems.

For collection systems, loafing (net flow of 0.27) is the better option than ensiling (net flow of –0.12) and baling (net flow of –0.14). Loafing is ranked at the top using PROMETHEE II methodology. The same methodology for the transportation system at a capacity of 4×10^6 dry t/yr ranks rail transport (net flow of 0.25) at the top followed by truck (net flow of 0.15) and pipeline (net flow of –0.40). This study has used input data specific to the location; the methodology can be used at different locations by inputting regional data.

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