Optimizing the Raw Material Supply Chain of the Wood Biomass Power Generation Industry for Different Stakeholders‘ Benefits: An Analysis of Inner Mongolia, China

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Abstract: A large number of sand shrubs have been planted in western China, especially in Inner Mongolia. Sand shrubs produce a large amount of stump residue, and wood biomass power generation enterprises that use stump residue as raw materials have emerged in Wushen Banner and other areas. In this paper, the Mixed Integer Linear Programming (MILP) model is used to optimize the raw material supply chain of forest biomass power generation enterprises. Optimizations with different objectives represent the choices of different stakeholders. The optimization results are listed as follows. (1) The self-issuance behavior of enterprises is inconsistent with the enterprise behavior required by social planners; (2) When social planners only pay attention to environmental benefits, the utilization rate of raw materials in towns located far from a power plant will be greatly reduced, which is not conducive for the reuse of stump residue; (3) When social planners consider economic, environmental, and social benefits simultaneously, the utilization rate of raw materials in each town will be significantly improved, resources will be effectively utilized, and certain economic benefits will be realized; (4) It is possible to reduce the difficulty of achieving optimization goals by promoting industrial development and encouraging technological progress.

Keywords: wood biomass; raw material supply chain; mixed integer nonlinear programming model

1. Introduction

Western China is one of the most important poverty-stricken areas in China, and faces many challenges including serious desertification, water shortage, and lagging social and economic development [1]. Many kinds of sand shrubs have been planted in the western area by the government to solve the desertification problem, including Caragana korshinskii, Hippophae rhamnoides, and Tamarix chinensis, among others [2]. As of 2010, the protected forests in the desert areas of the western region accounted for 49.73% of the total shrub area in China, of which the sand shrubs in Inner Mongolia accounted for 13.10% [3]. Due to the growth characteristics of shrub species, they must be regularly stumped, which refers to cutting all the branches above the root and neck of the shrubs to enhance the budding ability; stumping allows shrubs to grow thick and straight branches to improve their quality [4]. The sand shrubs in Inner Mongolia produce a large amount of stump residues. Correspondingly, there has arisen a wood biomass energy industry that uses these materials to generate electricity, and has brought economic, environmental, and social benefits to the area [5].
At present, the development of the wood biomass power generation industry remains imperfect due to the immaturity of the raw material supply chain [6]. Many studies have been conducted on the optimization of this supply chain. These studies can be classified according to different optimization targets. Some studies have focused on the optimization of the economic benefits of the raw material supply chain. Because economic benefits can be represented by the cost of the raw material supply chain [7–9], these optimization strategies primarily focus on supply chain costs. Specifically, Sara et al. (2004) analyzed the raw material procurement costs, storage costs, storage losses, transportation costs, and other aspects to determine how to reduce the supply chain cost of the raw materials for forest biomass power generation [10]. Higgins and Postma (2004) investigated how to reduce the raw material supply cost by optimizing the utilization of transportation tools [11]. Gronalt et al. (2007) studied how to optimize transportation costs to reduce the supply cost by redesigning the raw material supply chain across the region [12]. Other studies have focused on the optimization of the environmental benefits of the raw material supply chain. Because environmental benefits can be represented by the carbon dioxide (CO$_2$) emissions of the raw material supply chain [13–15], these optimization strategies primarily focus on CO$_2$ emissions. Specifically, Oberscheidert et al. (2013) minimized the CO$_2$ emissions of the entire industrial chain by establishing and optimizing a multiwarehouse transportation route model [16]. Klein et al. (2016) used the life-cycle method to analyze the impacts of different raw material tree species on CO$_2$ emissions in the supply chain of the wood biomass energy industry, and then investigated the optimization of the raw material tree structure to optimize the CO$_2$ emissions of the entire supply chain [17]. There are also some studies that have considered both economic and environmental benefits, and have thus sought to optimize multiple objectives. For example, Cambero and Sowlati (2016) established a mixed-integer programming model with multiperiod economic and environmental dual-objective optimization, and the augmented $\varepsilon$ algorithm was used to solve the Pareto optimal solution under dual targets [18].

With the development of the wood biomass power generation industry, the number of jobs absorbed by the raw material supply chain has gradually increased; correspondingly, research on the optimization of the number of jobs absorbed by the raw material supply chain has emerged. Because the social benefits of the wood biomass power generation industry are commonly expressed by the jobs that the industry can absorb [18], related studies on the optimization of the social benefits of the raw material supply chain have been carried out [9,19,20]. Specifically, Cambero and Sowlati (2014) conducted a literature review of the methods of optimizing the raw material chain of the wood biomass industry [6,21]. Shabani and Sowlati (2013) constructed a theoretical model that uses a Mixed integer Linear Programming (MILP) model to study how to optimize the amount of jobs that can be absorbed by the raw material supply chain of the wood biomass industry [6]. Recently, Sowlati (2013) used this model to quantitatively analyze the raw material supply chain in British Columbia, Canada [18]. As is evident from the preceding literature review, the investigation of the optimization of the amount of jobs that the raw material supply chain can absorb is a relatively new research area.

Existing research on the supply chain of raw materials for wood biomass power generation is generally based on industrial development. In addition to single-target optimization based on industrial development, this study also considers the state of the raw material supply chain as selected by social planners with different policy objectives, and the effects of these different policy objectives on the use of stump residue are compared. Specifically, this work uses the economic cost of the supply chain to represent economic benefits, CO$_2$ emissions from the supply chain to represent environmental benefits, and the hours of employment absorbed by the supply chain to represent social benefits. A MILP model is then constructed, and an empirical study using data from the Mu Us Thermal Power Plant in Wushen Banner, Inner Mongolia and a method called the “augmented $\varepsilon$ algorithm” are executed. This study attempts to answer the following questions: How can the supply chain of the wood biomass power generation industry that uses sand shrubs as raw materials be optimized? What impacts do different supply chain states have on the use of stump residue? How does the government choose between different policy objectives? This article provides a certain reference for
the layout of the supply chain of biomass power generation enterprises, and also provides guidance for government policy choices.

2. Materials and Methods

2.1. Model Assumptions

For the model construction to be more concise and closer to reality, the relevant theories and field investigations were combined to put forward the following assumptions.

(1) The model is static, and none of the parameters change over time.

(2) The raw material supply chain of the wood biomass power generation industry can be divided into four links: harvest, yarding, storage, and processing. Any two adjacent links are connected by transportation. The total numbers of green job hours, CO$_2$ emissions, and economic costs are the total numbers of each respective link.

(3) Because the labor intensiveness of each link of the raw material supply is similar, the health and age of the labor force are not considered in the model presented in this paper. The green job hours are the product of the job fraction and the quantity of raw material supply.

(4) The demands for the remaining residue of sand shrubs by two entities, the acquisition station and the power plant, are known. The power plant only accepts raw materials provided by the local farmers or purchase stations of Wushen Banner, and does not accept raw materials supplied by other places. Additionally, the raw material supply site only supplies raw materials to the local township acquisition stations, and there is no cross-regional supply of raw materials.

(5) It is assumed that the sizes of the alternative acquisition stations are the same and are homogenized.

(6) Only maximizing the green job potential, minimizing the economic costs, and minimizing the CO$_2$ emissions are considered for the site selection of the acquisition station. The constraints of topography and other factors are not considered.

(7) There are no quantitative restrictions on the tools and equipment used for harvesting, processing, and transportation, and the efficiency of use has no effect on green job hours, economic costs, or CO$_2$ emissions.

(8) The daily wages of labor in different supply links are consistent.

(9) The wood biomass in the area is not sliced in the woodland, and is only sliced at the acquisition station or power plant.

(10) Because the jobs after optimization achieve both economic and environmental benefits that satisfy the concept of “green jobs” proposed by the United Nations Environment Programme in 2008, the term “green job” is adopted in this study to refer to the employment absorbed by the raw material supply chain. In general, the opportunities of green jobs can be expressed by the number of hours of the jobs. Considering the seasonal dispersion of the wood biomass supply itself, as well as the unity of the measure, the number of hours of green jobs is used as a measurement of the opportunities of green jobs offered by the raw material supply chain.

2.2. Symbol Description

In the construction process of a MILP model, it is necessary to model the objective function and the actual constraints. The model primarily includes the variables listed in Table 1.
Table 1. Collection and parameters.

| Symbol | Description |
|--------|-------------|
| I      | Collection by stump remains supply site |
| Z      | Collection by alternative acquisition stations |
| P      | Collection by wood biomass power plant |
| $b^h_{izp}$ | Hours of green jobs per unit slice from supply point $i$ to power plant $p$ via acquisition station $z$ (hours/ton) |
| $c^e_{izp}$ | Costs per unit slice from supply point $i$ to power plant $p$ via acquisition station $z$ (yuan/ton) |
| $e^h_{izp}$ | CO$_2$ emission per unit slice from supply point $i$ to power plant $p$ via acquisition station $z$ (kg/ton) |
| $c^c_{izp}$ | Hours of green jobs per unit slice from supply point $i$ directly to power plant $p$ (hour/ton) |
| $c^c_{ip}$ | Costs per unit slice from supply point $i$ directly to power plant $p$ (yuan/ton) |
| $e^c_{ip}$ | CO$_2$ emission per unit slice from supply point $i$ directly to power plant $p$ (kg/ton) |
| $m^c_z$ | Hours of green jobs per unit slice from every alternative acquisition station (hour/ton) |
| $m^e_z$ | CO$_2$ emissions of every alternative acquisition station (kg) |
| $V_{izp}$ | Biomass quantity transformed from supply point $i$ to power plant $p$ via acquisition station $z$ (tons) |
| $W_{ip}$ | Biomass quantity transformed from supply point $i$ directly to power plant $p$ (tons) |
| $Z_z$ | Dummy variable; the value is 1 if the acquisition station is established; otherwise, it is 0 |
| $O_a$ | The total amount of raw materials from wood biomass energy available in the region; numbers from 1 to 6 respectively represent Wushenzhao Town, Tuke Town, Wulantaole Town, Gelutu Town, Sulide Town, and Wudinghe Town |
| $R_k$ | A slicer’s maximum slicing ability |
| $M$ | The number of the target function ($M = 1, 2, 3, 4, 5$). |
| $N$ | The equal interval of the k-th target function. |

Note: ① The supply of sand shrub trunks refers to that located in Wushen Banner, Inner Mongolia, which mainly includes Wushenzhao Town, Tuke Town, Wulantaole Town, Gelutu Town, Sulide Town, and Wudinghe Town; ② The working hours per unit of green jobs include the harvesting time, gathering time, storage time, slicing time, and transportation time; ③ The cost per unit slice includes harvesting costs, gathering costs, storage costs, slicing costs, and transportation costs; ④ The CO$_2$ emissions include those from harvesting, gathering, storage, slicing, and transportation; ⑤ The building costs of acquisition include land costs, electric costs, workshop costs, machine costs (crusher and filleting machines, etc.), business license costs, and insurance costs.

2.3. Theoretical Model

2.3.1. Objective Functions

The function of total green job hours is:

$$\text{Total hour} = \sum_{i \in I} \sum_{z \in Z} \sum_{p \in P} b^h_{izp} V_{izp} + \sum_{i \in I} \sum_{z \in Z} c^h_{izp} W_{ip} + m^h_z.$$  \hspace{1cm} (1)

The function of total economic costs is:

$$\text{Total cost} = \sum_{i \in I} \sum_{z \in Z} \sum_{p \in P} c^e_{izp} V_{izp} + \sum_{i \in I} \sum_{z \in Z} c^c_{izp} W_{ip} + m^e_z Z_z.$$  \hspace{1cm} (2)

The function of total CO$_2$ emissions is:
Total $\text{CO}_2 = \sum_{i \in I} \sum_{z \in Z} \sum_{p \in P} b_{izp} V_{izp} + \sum_{i \in I} \sum_{z \in Z} c_{ip} W_{ip} + m^h z_z. \quad (3)$

Different objective functions can represent the interests of different stakeholders; take minimizing the supply chain costs as an example. Raw material costs are an important component of corporate costs. For wood biomass power generation enterprises, the cost of purchasing raw materials accounts for the highest proportion of the daily operating costs [22]. Via field investigations, it can be found that one of the most important reasons for the competitive inferiority of wood biomass power generation companies in China is the unstable supply of biomass materials. Moreover, from the point of view of the enterprise itself, environmental and sustainability aspects are often not linked to economic success [23]. Based on these factors, optimizing the cost of the raw material supply chain is a top priority for forest biomass power generation enterprises. Therefore, single-objective optimization that minimizes the economic costs of the supply chain can reasonably reflect reality to a certain extent, and is a possible path for enterprises to optimize their behavior.

The social planner will pay more attention to environmental and social benefits than to economic benefits. Under the increasing pressure of environmental protection, social planners must consider environment benefits. Countries with large governments, such as China, may consider environmental benefits to be the only target of their policies when they are under pressure to reduce emissions. Such examples can be found in the Beijing–Tianjin–Hebei region, in which a large number of high-polluting and energy-consuming enterprises have been shut down. If a social planner only considers environmental benefits, he or she will prefer the state of the supply chain after the single-objective optimization of the $\text{CO}_2$ emissions function. Although governments that focus only on environmental benefits are extremely rare, the comparison of different supply chain states has some interesting implications.

A more rational social planner must simultaneously consider social, environmental, and economic benefits, which means that all three objective functions will be included in the optimization range. Social planners must pay attention to social benefits because higher employment will result in a lower local crime rate, a more stable social environment, and a higher average income. In addition, China is currently pursuing green growth in manufacturing [24]. The government provides a lot of subsidies to the renewable energy industry, so the government may have higher environmental requirements for such enterprises. Social planners must also pay attention to economic benefits because the rapid development of industry will result in higher taxes and many additional benefits to the government.

### 2.3.2. Constraints

#### Raw Material Supply Constraints

The sum of the biomass quantity $V_{izp}$ of the slices transported from the supply site $i$ through the acquisition station $z$ to the power plant $p$ and the unsliced biomass quantity $W_{ip}$ directly transported from the supply site $i$ to the power plant $p$ is less than or equal to the total amount of available biomass resources of the area.

$$\sum_{i \in I} \sum_{z \in Z} \sum_{p \in P} V_{izp} + \sum_{i \in I} \sum_{p \in P} W_{ip} \leq O_0 \quad (4)$$

#### Demand Constraints

The sum of the amount of unsliced biomass $W_{ip}$ directly transported from the supply site $i$ to the power plant $p$ and the amount of biomass $V_{izp}$ transported from the supply site $i$ through the acquisition station $z$ to the power plant $p$ is not less than the demand $Q$ of the power plant.

$$\sum_{i \in I} \sum_{z \in Z} \sum_{p \in P} V_{izp} + \sum_{i \in I} \sum_{p \in P} W_{ip} \geq Q_p \quad (5)$$
The amount of biomass $V_{izp}$ from the supply site $i$ through the acquisition station $z$ to the power plant $p$ must not be less than the demand quantity $Q_z$ of the acquisition station.

$$\sum_{i \in I} \sum_{z \in Z} \sum_{p \in P} V_{izp} \geq Q_z \tag{6}$$

Technological Constraints

The amount of biomass $V_{izp}$ from the supply site $i$ through the acquisition station $z$ to the power plant $p$ is not greater than the maximum slice capacity $R_o$ of the slicer.

$$\sum_{i \in I} \sum_{z \in Z} \sum_{p \in P} V_{izp} \leq R_o \tag{7}$$

Other Constraints

If $\sum_{i \in I} \sum_{z \in Z} \sum_{p \in P} V_{izp} > 0$, then $Z_z = 1$; \hfill (8)

If $\sum_{i \in I} \sum_{z \in Z} \sum_{p \in P} V_{izp} = 0$, then $Z_z = 0$; \hfill (9)

$$V_{izp}, W_{ip}, Z_z \geq 0; \tag{10}$$

$$V_{izp}, W_{ip}, Z_z \geq 0. \tag{11}$$

2.3.3. Optimization Model

The theoretical framework of the optimization model is as follows.

$$\text{Max} \text{Total hour} = \text{Total hour} + \epsilon \text{Total } (T_1 + T_2) \tag{12}$$

s.t.

$$\begin{align*}
\text{Total cost} - T_1 &= \epsilon_1 \tag{13} \\
\text{Total CO}_2 - T_2 &= \epsilon_2 \tag{14} \\
\text{(4)}\text{–(11)}
\end{align*}$$

The constraint Equations (13) and (14) are the original objective functions after including $\epsilon$, and Equations (4)–(11) are the constraints existing in reality, including the raw material supply constraints, demand constraints, technical constraints, and other constraints. The decision variables for the MILP model used in this article are $V_{izp}$, $W_{ip}$, and $Z_z$.

2.4. Augmented $\epsilon$ Constraint Algorithm Method and Model Solution

The methods for solving multi-objective programming mainly include the hierarchical sequence method, analytic hierarchy process, and $\epsilon$ constraint algorithm. An augmented $\epsilon$ constraint algorithm was adopted in the present study to address the MILP problem [25].

The augmented $\epsilon$ constraint algorithm avoids the possibility that the $\epsilon$ algorithm will output a nonoptimal solution [26]. Based on the original $\epsilon$ constraint algorithm, the augmented $\epsilon$ constraint algorithm introduces a dimensionless slack variable. Adding to the original model in a sufficiently small proportion ensures that only nondominated solutions are searched. Different optimization results are solved by continuously adjusting the right-side values of the remaining constraint objective functions until the optimal solution is found. The specific steps are as follows.
(1) Determine the optimal and worst values for the economic costs function and the CO\textsubscript{2} emissions function. The optimal value of each function can be solved via single-objective optimization, and the worst value needs to be obtained by the following equations.

The worst value of the economic costs function is as follows:

\[
\text{Total cost}_{1}^{\text{max}} = \min \text{Totalcost}(x)
\]

s.t.
\[
\begin{align*}
\text{Totalhour}(x) &= \text{Totalhour}_{1}^{\text{max}} \\
\text{Totalco}_{2} &= \text{Totalco}_{2}^{\text{min}} \\
x &\in X
\end{align*}
\]

The worst value of the CO\textsubscript{2} emissions function is as follows:

\[
\text{Total co}_{2}^{\text{max}} = \min \text{Total}(x)
\]

s.t.
\[
\begin{align*}
\text{Totalhour}(x) &= \text{Totalhour}_{2}^{\text{max}} \\
\text{Totalcost}(x) &= \text{Totalcost}_{2}^{\text{min}} \\
x &\in X
\end{align*}
\]

Finally, the differences between the optimal values and the worst values of the economic cost function and the CO\textsubscript{2} emissions function can be respectively calculated, and are defined as \(R_1\) and \(R_2\).

(2) Let \(N_1\) and \(N_2\) be the numbers of equal partitions between the economic costs function and the CO\textsubscript{2} emissions function, respectively. \(N_1 + 1\) and \(N_2 + 1\) are the numbers of equal division points, and there are also, respectively, \(N_1 + 1\) and \(N_2 + 1\) dominant solutions to be explored for each objective function. Let \(M_1\) and \(M_2\) comprise the index of the equal division point, and it is specified that \(M_1\) and \(M_2\) are respectively numbered from 1. For each point \(M_1 = 1, \ldots, N_1\) \((M_2 = 1, \ldots, N_2)\), let its constraint level be \(\varepsilon_k = I_k + M_k^{*}(R_k + N_k^{-1})\).

(3) The optimal solution of the objective function is determined by constantly changing the value of \(\varepsilon_k\).

2.5. Materials

According to field research, the Mu Us Biomass Thermal Power Company in Inner Mongolia was selected as the optimization research object. The company was established in 2006 and was incorporated into the grid for only two years. It began its commercial operation in 2009. The company was the first bio-power plant in China to use sand shrubs as raw materials. According to field research, the company’s operations have greatly boosted local employment. Therefore, this enterprise was used as an empirical case to verify the effectiveness of the MILP model based on the green employment potential optimization of sand shrub resources.

This study mainly used two types of data, namely statistical data and field research data. The statistical data was primarily sourced from the China Forestry Statistical Yearbook 2017 [27], China Energy Statistics Yearbook [28], and China Statistical Yearbook [29]. The field research data primarily includes data on farmers, acquisition stations, and forest biomass power generation enterprises in Wushen Banner, Inner Mongolia. Among them, the data on farmers primarily includes the basic situations of the farmers’ families, the land operations, the sources of the farmers’ income, and the material assets of the farmers. The data on the acquisition stations primarily includes the land operation, the purchase of raw materials, and the processing situation. Finally, the data on the enterprise primarily includes the overall situations of the enterprises, the availability of raw materials for biomass enterprises, the consumption of raw materials, the sales of biomass products, and the tax subsidies for forest biomass energy.
3. Results

The results of the empirical analysis are presented in the following order. The first is the result of the single-objective optimization of the economic cost of the supply chain, which may be the preferred supply chain state of enterprises only concerned with economic benefits. The second is the result of the single-objective optimization of the carbon dioxide emissions of the supply chain, which may be the choice of social planners with stringent emission-reduction mandates. Finally, the result of multi-objective optimization is presented, which may be the preferred supply chain state of more rational social planners.

Table 2 presents the values of the decision variables when economic costs achieved the lowest values with the raw material supply constraints, demand constraints, technological constraints, and other constraints. The lowest values of economic cost are presented in Table 3. Compared with the situation before optimization, the number of acquisition stations in each town decreased significantly. The decline of the acquisition stations was the most pronounced in Sulide Town and Wudinghe Town, and caused the low utilization of resources.

Table 2. The amounts of raw materials in different paths after optimization.

| Region      | Acquisition Stations | Transportation Volume | Resource Utilization |
|-------------|----------------------|-----------------------|----------------------|
|             |                      | Supply Land → Acquisition Station → Power Plant (Ten Thousand Tons) | Supply Land → Power Plant (Ten Thousand Tons) | Total |
| Wushenzhao  | 5                    | 0.5                   | 3.1                  | 3.6   | 72.24% |
| Tuke        | 4                    | 0.4                   | 3.68                 | 4.08  | 92.23% |
| Wulantaole  | 5                    | 1.1                   | 1.96                 | 3.06  | 81.89% |
| Gelutu      | 5                    | 0.6                   | 3.59                 | 4.19  | 98.28% |
| Sulide      | 2                    | 0.3                   | 2.67                 | 2.97  | 42.59% |
| Wudinghe    | 1                    | 0.1                   | 0                    | 0.1   | 3.24%  |
| Total       | 22                   | 3                     | 15                   | 18    |        |

Table 3. The costs of raw materials in different paths after optimization.

| Region      | Cost | Total |
|-------------|------|-------|
|              | Supply Land → Acquisition Station → Power Plant | Supply Land → Power Plant |
| Wushenzhao  | 83.42| 186.00| 269.42 |
| Tuke        | 68.89| 261.79| 330.67 |
| Wulantaole  | 195.73| 166.75| 362.48 |
| Gelutu      | 108.49| 289.39| 397.88 |
| Sulide      | 56.25| 243.91| 300.17 |
| Wudinghe    | 20.22| 0.00  | 20.22  |
| Total       | 533.00| 1147.84| 1680.84 |

Unit: ten thousand yuan.

A schematic representation of the supply chain (Figure 1) may help explain the results.

As described in the second assumption, the raw material supply chain of the wood biomass power generation industry can be divided into four links, and any two adjacent links are connected by transportation. According to our field investigation, the transportation from harvest to storage is mostly completed by tractors and other agricultural machinery, which are low-cost transportation methods. The transportation from storage to the power plant is mostly via truck, so the cost is higher. Therefore, this part of the supply chain transport costs constitutes the main component. The number of acquisition stations farther away from power plants fell.
Figure 1. The schematic representation of the supply chain.

3.1. Single-Objective Optimization under the Target of Maximizing Environmental Benefits

Table 4 presents the values of decision variables when the CO\textsubscript{2} emissions achieved the lowest value, and Table 5 presents the lowest values of CO\textsubscript{2} emissions. Overall, the optimized results with CO\textsubscript{2} emissions as the optimization goal were found to resemble those with economic costs as the optimization goal. However, the number of acquisition stations in Wudinghe Town became zero, which may be because Wudinghe Town is located away from the power plant, thereby increasing the amount of CO\textsubscript{2} emitted from the construction of acquisition stations and transportation.

Table 4. The amounts of raw materials in different paths after optimization.

| Region       | Acquisition Stations | Supply Land → Acquisition Station → Power Plant (Ten Thousand Tons) | Supply Land → Power Plant (Ten Thousand Tons) | Total | Resource Utilization |
|--------------|----------------------|------------------------------------------------------------------------|-------------------------------------------------|-------|----------------------|
| Wushenzhao   | 5                    | 0.5                                                                    | 3.1                                             | 3.6   | 72.24%               |
| Tuke         | 4                    | 0.4                                                                    | 3.68                                            | 4.08  | 92.23%               |
| Wulantaole   | 5                    | 1.1                                                                    | 1.96                                            | 3.06  | 81.89%               |
| Gelutu       | 5                    | 0.6                                                                    | 3.59                                            | 4.19  | 98.28%               |
| Sulide       | 3                    | 0.4                                                                    | 2.67                                            | 3.07  | 44.03%               |
| Wudinghe     | 0                    | 0                                                                     | 0                                               | 0     |                      |
| Total        | 22                   | 3                                                                     | 15                                              | 18    | –                    |

Table 5. The costs of raw materials in different paths after optimization.

| Region       | CO\textsubscript{2} Emission | Total |
|--------------|-------------------------------|-------|
|              | Supply Land → Acquisition Station → Power Plant | Supply Land → Power Plant |
| Wushenzhao   | 39.5                          | 31    | 70.5 |
| Tuke         | 31.2                          | 44.16 | 75.36|
| Wulantaole   | 77.15                         | 21.56 | 98.71|
| Gelutu       | 48.6                          | 46.67 | 95.27|
| Sulide       | 32.8                          | 40.05 | 72.85|
| Wudinghe     | 0                             | 0     | 0    |
| Total        | 229.25                        | 183.44| 412.69|

Unit: ten thousand kilograms.

From the comparison of the two supply chain states, it is evident that the supply chain state chosen by the company itself is not optimal for CO\textsubscript{2} emissions, and it can be considered that there is a certain conflict between economic and environmental benefits. It is also clear that optimization with the single objective of optimizing environmental benefits will significantly reduce the raw material utilization rate in Sulide Town and Wudinghe Town.
3.2. Multi-Objective Optimization

(1) Relevant parameters.

After linear programming, the optimal value of the economic target was determined to be 680.84 million yuan, and the highest cost was 2031.74 million yuan; the optimal value of the CO\(_2\) emissions target was 412.69 million kilograms, and the worst value was 562.70 million kilograms. The augmented \(\varepsilon\) constraint algorithm was solved five times to solve this problem. The correlation coefficients of the economic costs objective function and the CO\(_2\) emissions objective function as the constraints were therefore optimized, as presented in Tables 6 and 7.

Table 6. The relevant parameters with the economic costs objective function as the restriction.

| \(M\) | \(R\) | \(N\) | \(\varepsilon_t\) |
|------|------|------|-------------|
| 1.00 | 350.90 | 5.00 | 1751.02 |
| 2.00 | 350.90 | 5.00 | 1821.20 |
| 3.00 | 350.90 | 5.00 | 1891.38 |
| 4.00 | 350.90 | 5.00 | 1961.56 |
| 5.00 | 350.90 | 5.00 | 2031.74 |

Table 7. The relevant parameters with the CO\(_2\) emissions objective function as the restriction.

| \(M\) | \(R\) | \(N\) | \(\varepsilon_t\) |
|------|------|------|-------------|
| 1.00 | 150.01 | 5.00 | 442.69 |
| 2.00 | 150.01 | 5.00 | 472.69 |
| 3.00 | 150.01 | 5.00 | 502.70 |
| 4.00 | 150.01 | 5.00 | 532.70 |
| 5.00 | 150.01 | 5.00 | 562.70 |

(2) Multi-objective optimization under the target of maximizing economic, environmental, and social benefits.

The optimal value of the green job objective function was solved under the constraints of economic costs and CO\(_2\) emissions. The values of the decision variables are presented in Table 8, and the optimal values of green jobs are presented in Table 9. The green job hours were found to be significantly improved, which demonstrates the ability of the model. The number of acquisition stations was found to be 22, which is lower than the actual number of acquisition stations. The optimal green job hours were found to be 399.61 million hours, which is equivalent to 1369 jobs, thus achieving an increase of 380 jobs as compared to reality. Additionally, the optimal supply was found to be 189,200 tons, and the resource utilization rate was greatly improved. Compared with single-objective optimization, the number of acquisition stations in Wudinghe Town was found to be 1. As the establishment of acquisition stations will lead to increases in jobs, costs, and CO\(_2\) emissions, it is speculated that the establishment of an acquisition station in Wudinghe Town should be the result of a balance of forces.

Table 8. The amounts of raw materials in different paths after optimizing green jobs.

| Region          | Acquisition Stations | Transportation Volume | Total Resource Utilization |
|-----------------|----------------------|-----------------------|---------------------------|
|                 |                      | Supply Land \(\rightarrow\) Acquisition Station | Supply Land \(\rightarrow\) Power Plant | \(\rightarrow\) Power Plant |  |
| Wushenzhao      | 5                    | 0.5                   | 3.05                      | 3.55                      | 71.29% |
| Tuke            | 4                    | 0.4                   | 3.65                      | 4.05                      | 91.62% |
| Wulantaole      | 3                    | 1.54                  | 1.14                      | 2.68                      | 71.65% |
| Gelutu          | 6                    | 2.21                  | 1.98                      | 4.19                      | 98.35% |
| Sulide          | 3                    | 1.38                  | 1.77                      | 3.15                      | 45.19% |
| Wudinghe        | 1                    | 0.75                  | 0.55                      | 1.3                       | 42.20% |
| **Total**       | **22**               | **6.78**              | **12.14**                 | **18.92**                 |          |

Unit: ten thousand tons.
Table 9. The amounts of raw materials in different paths after optimizing green jobs.

| Region      | Green Job Hours | Number of Converted Jobs |
|-------------|-----------------|--------------------------|
|             | Supply Land → Acquisition Station → Power Plant (Ten Thousand Hours) | Total |                      |
|             | 17.00           | 30.30                    | 47.50   | 162.67                |
| Wushenzhao  | 14.00           | 40.15                    | 54.15   | 185.45                |
| Tuke        | 55.44           | 14.82                    | 70.26   | 240.62                |
| Wulantaole  | 81.77           | 25.74                    | 107.51  | 368.18                |
| Gelutu      | 52.44           | 26.55                    | 78.99   | 270.51                |
| Sulide      | 30.75           | 10.45                    | 41.20   | 141.1                 |
| Total       | 251.40          | 148.21                   | 399.61  | 1368.53               |

In comparison with the first two types of single-objective optimization, the utilization rate of raw materials in Wushenzhao Town and Tuke Town decreased slightly (less than 2%), that in Wulantaole Town was relatively significant (10.24%), that in Gelutu Town remained at no significant change, that in Sulide Town increased slightly (2.6% and 1.16%), and that in Wudinghe Town was greatly improved (38.96% and 42.20%).

3.3. Sensitivity Analysis of Important Parameters

The following four parameters were selected for sensitivity analysis: power plant raw material demand, transportation distance, daily processing capacity of chippers, and unit labor costs. The bases for selection were as follows. (1) Raw material demand: the change in the demand by power plants will directly affect the green job hours, economic costs, and CO₂ emissions in the raw material supply chain. Therefore, it is necessary to explore the impact of the changes in demand parameters on green job hours; (2) Transportation distance: transportation links are important links in the wood biomass raw material supply chain. The transportation distance is closely related to the location of the acquisition station, which can affect the employment potential generated by the entire supply chain. Therefore, the transportation distance was selected as the most important parameter for sensitivity analysis; (3) Daily processing capacity of chippers: the amount of raw materials that can be acquired and processed daily by the acquisition station in the processing chain depends largely on this variable; (4) Unit labor price: this variable has a direct impact on economic costs. Additionally, because wages have an impact on the enthusiasm of farmers to participate in the industry, this variable can also affect the number of green jobs to a certain extent.

The impacts of these four parameters on green job hours, economic costs, and CO₂ emissions were therefore separately analyzed. The results of sensitivity analysis are displayed in Table 10.

Table 10. Results of sensitivity analysis.

| Parameter          | The Range of Changes in Parameters | The Range of Changes in Target Function’s Value |
|--------------------|-----------------------------------|-----------------------------------------------|
|                    |                                   | Green Job Hours (Hour) | Economic Cost (Yuan) | CO₂ Emission (Kilograms) |
| Raw material demand| +10%                              | +359,500               | +1,454,100           | +321,600                |
|                    | −10%                              | −282,800               | −1,910,000           | −262,800                |
|                    | +10%                              | +224,100               | +767,500             | +320,600                |
| Transportation distance| −10%                              | −161,300               | −746,100             | −255,600                |
| Daily processing capacity of chippers| +10%                              | +219,400               | +640,600             | +21,900                 |
|                    | −10%                              | −158,900               | −567,600             | −18,900                 |
| Unit labor price   | +10%                              | +236,600               | +254,800             | +75,100                 |
|                    | −10%                              | −211,200               | −232,100             | −67,800                 |
Power plant demand, transportation distance, unit processing volume, and unit labor price were found to have very large impacts on green job hours. When these variables fluctuate within ±10% and ±20%, the demand and unit labor price were found to have the greatest impacts on employment, followed by the transportation distance, and finally the daily processing capacity of chippers.

4. Discussion

The aim of this study was to optimize the raw material supply chain of the wood biomass energy industry based on different stakeholder optimizations. A MILP model was constructed, and the augmented ε constraint algorithm and data from Wushen Banner were employed to realize the analytical analysis of this model. Some observations are summarized as follows.

First, it can be found from the comparison between the existing supply chain state and the optimized supply chain state that there is room for optimization in the raw material supply chain of wood biomass power generation.

Whether optimizing economic costs from a corporate perspective, optimizing environmental benefits from a social planner perspective, or taking both social and environmental benefits into account, the raw material supply chain of wood biomass power generation can be optimized. According to the optimization variables, the optimization of the supply chain of forest biomass power generation materials can be started from two aspects. (1) Starting from the MILP model, it is possible to optimize the raw material supply chain of wood biomass power generation by changing the number of acquisition stations; the optimization effect of this method is better. (2) Starting from the sensitivity analysis, changes in the power plant demand, the daily processing capacities of slicers, and the transportation distance have significant impacts on the achievement of the target. Specifically, during the process of sensitivity analysis, it was found that the raw material demand has a small impact on CO$_2$ emissions, and the change in the demand for raw materials will significantly increase the number of hours of green employment without excessively increasing CO$_2$ emissions. Additionally, the transportation distance was found to have little effect on the number of hours of employment, indicating that the reduction in green employment caused by the reduction in the transportation distance is not significant; the economic cost savings from reducing the transportation distance and CO$_2$ emissions are relatively more significant. The increase in the daily processing capacities of chippers and the decline in labor prices will better optimize economic cost targets and employment hours goals, while not excessively increasing CO$_2$ emissions. However, on the one hand, the price of labor is determined by the market; on the other hand, lowering the price of labor may cause damage to workers’ rights and interests. Therefore, efforts to reduce the difficulty of achieving the objective function can be primarily made by changing the other three parameters.

Secondly, it can be found from the comparison of different supply chain states after optimization that the self-issuance behavior of enterprises is inconsistent with the enterprise behavior required by social planners.

Optimization with the objective of minimizing economic costs represents the state of the raw material supply chain that enterprises may choose. In contrast, the single-objective optimization of environmental benefits or the multi-objective optimization of economic, social, and environmental benefits represent the states of the raw material supply chain that a social planner may choose. Many differences in the states of several supply chains can be determined from the number of acquisition stations, the distributions of acquisition stations in different towns, and the utilization of raw materials. It can be argued that these differences are primarily due to the trade-offs between different goals; for example, setting up an acquisition station is conducive to achieving social goals, but not to achieving environmental or economic goals. When only a single optimization goal of economic or environmental benefits is considered, there will be fewer acquisition stations in the town farther away from the power plant, so the utilization rate of raw materials will be relatively low. When social planners begin to consider social, environmental, and economic benefits, the utilization rate of raw
materials in remote towns will be greatly improved, which is conducive to the utilization of sand shrub stump residue.

Compared with existing studies, the present study found that, for the supply chain of raw materials for wood biomass power generation, the efficiency of a supply chain optimized with the single objective of environmental benefits is relatively low. Specifically, considering only environmental benefits may lead to low raw material utilization rates in towns that are located far from a power plant. When optimizing the supply chain via the simultaneous consideration of the economic, environmental, and social benefits, the raw material utilization rate of each town can be significantly improved.

Based on the results of this study, suggestions for enterprises and the government are proposed. It is suggested that enterprises pay more attention to the collection of information on the raw material supply chain and scientifically deploy sites for their own acquisition. From the perspective of the government, the raw material supply chain of the wood biomass power generation industry requires government policy intervention. First, even from the perspective of the single-objective optimization of economic benefits, the existing raw material supply chain has not yet reached its full potential, which may be a result of market failure caused by incomplete corporate information. Secondly, government policy is often implemented from the standpoints of economic and social benefits; however, the results of MILP are far from reality, and therefore, government intervention is required for optimization. Finally, it was found from the sensitivity analysis that the development of the entire industry and technological improvement will effectively reduce the optimization difficulty; thus, the government is advised to encourage and support this industry.

5. Conclusions

In this paper, the optimization model of the raw material supply chain was constructed, and the research objective was realized by conducting two single-objective optimizations and one multi-objective optimization. The conclusions of this study are as follows.

First, the optimization of the wood biomass raw material supply chain can be realized by optimizing the quantity and distribution of raw material acquisition stations. In addition, technological improvements by enterprises, such as increasing the daily processing capacities of chippers, will contribute to the reduction of the difficulty of optimizing the target.

Second, the selection of optimization targets will have a significant impact on the utilization of plain stump residues. This is mainly reflected in the low utilization rate of raw materials in the supply chain that was optimized with environmental benefits as the single objective. The government should make comprehensive considerations when choosing policy objectives, avoid single-issue policy objectives, and choose more balanced and diversified policy objectives.

This paper presents a case study in which data from a power plant in Inner Mongolia was utilized. However, the investigation revealed that there are problems in the supply chain of raw materials for biomass power generation in many regions of China. One of the main directions of future research will probably be the application of the supply chain optimization model on a larger scale, and the exploration of how to improve the supply chain. Another research direction may be the optimization of the model itself, so as to determine the specific location of acquisition sites on a smaller scale and ultimately provide a more detailed reference for enterprise decision-making.

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