Optimal Production Scheduling for Energy Efficiency Improvement in Biofuel Feedstock Preprocessing Considering Work-In-Process Particle Separation

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Abstract

Biofuel is considered a promising alternative to traditional liquid transportation fuels. The large-scale substitution of biofuel can greatly enhance global energy security and mitigate greenhouse gas emissions. One major concern of the broad adoption of biofuel is the intensive energy consumption in biofuel manufacturing. This paper focuses on the energy efficiency improvement of biofuel feedstock preprocessing, a major process of cellulosic biofuel manufacturing. An improved scheme of the feedstock preprocessing considering work-in-process particle separation is introduced to reduce energy waste and improve energy efficiency. A scheduling model based on the improved scheme is also developed to identify an optimal production schedule that can minimize the energy consumption of the feedstock preprocessing

under production target constraint. A numerical case study is used to illustrate the effectiveness of the proposed method. The research outcome is expected to improve the energy efficiency and enhance the environmental sustainability of biomass feedstock preprocessing.

Key words: *Biofuel manufacturing; Feedstock preprocessing; Optimal production scheduling; Particle separation.*

1. Introduction

The energy crisis is one of the most serious threats challenging the sustainable development of human society due to the intricacies of energy issue itself and the associated climate issue. Reported in the 2014 World Energy Outlook, the world energy demand is projected to increase by 37% by 2040 [1]. The long-term global temperature increase associated with the greenhouse gas (GHG) emissions related to the fossil fuel energy consumption is expected to be 3.6°C [1].

Renewable energy, defined as the energy that comes from the resources which are naturally replenished on a human timescale [2], is considered being able to mitigate the environmental impacts due to the consumption of traditional fossil fuel energy. As one of the major forms of renewable energy, biofuel is considered a promising alternative and has received worldwide attention [3-8]. Global production of biofuel in 2013 is about seven times of the production scale of 2000 [9]. It is expected that about 27% of transportation fuel can be provided by biofuel by 2050 and approximately 2.1 Gt of GHG emission reductions per year can be achieved [10].

Biofuel is generally made by converting biomass such as corn stover, sorghum stalks, big bluestem, and wheat straw into bioethanol or biodiesel through the different processes in biofuel manufacturing system. As shown in **Error! Reference source not found.**, one typical cellulosic biofuel manufacturing system based on biochemical pathway is composed of two major processes: feedstock preprocessing and biochemical conversion. Feedstock preprocessing aims to reduce biomass moisture content and particle size so that the biomass can be in the desired format for further biochemical conversion. The preprocessing generally consists of grinding and drying as shown in Figure 2. The stage I grinding is executed by a set of grinders to break the input biomass into particles. The drying is usually executed by a rotary dryer to reduce the moisture content and improve the grindability of the particles yielded from the stage I grinding. The stage II grinding is usually executed by a set of milling machines to further comminute the dried particles to satisfy the size requirement of the final product of feedstock preprocessing.

Figure 1 A typical cellulosic biofuel manufacturing system based on biochemical pathway

Figure 2 A typical feedstock preprocessing system

The biochemical conversion consists of acid pretreatment, enzymatic hydrolysis, and fermentation [11, 12] as shown in Figure 3. Pretreatment can break the lignin seal and the crystalline structure of the cellulose existing in the biomass particles to increase the accessible

surface area of the cellulose to the enzyme for hydrolysis [13]. In hydrolysis, the exposed cellulose is broken down into fermentable sugars [14, 15]. In fermentation, fermentable sugars can be fermented into biofuel such as ethanol.

Figure 3 A typical biochemical conversion system

Various studies on biofuel manufacturing have been conducted. For the feedstock preprocessing, the relationships between energy consumption and particle properties under different comminution configurations (e.g., biomass types, machine types, and machine operating conditions) have been analyzed [16-21]. The drying process modeling [22, 23], the impacts on the grindability [24, 25] and storage [26, 27], and drying performance for different biomass types under different process conditions [28-30] have been investigated. For the biochemical conversion, research efforts have been devoted to the areas including the investigation of various types of biomass sources [12, 31-34], development of pretreatment technologies [35], genetically modification of microbe for efficient enzymatic hydrolysis and fermentation [36], analyses of manufacturing process parameter effects and identification of optimal process parameters [37-41], etc.

These studies have facilitated considerable technological advancement in biofuel manufacturing, however, the challenge regarding the intensive energy consumption in the manufacturing process does still exist, which greatly impedes the even wider substitution for the traditional liquid transportation fuel. It is estimated that 1.13 MJ fossil energy is used for producing 1MJ corn-derived ethanol, among which more than 60% of the energy is consumed in

the manufacturing process [42]. In this paper, we will contribute to addressing this challenge by focusing on the research of energy efficiency improvement in the feedstock preprocessing to improve the environmental sustainability of the biofuel manufacturing.

A more detailed scheme of the existing feedstock preprocessing can be illustrated by the upper part of Figure 4. J_1 parallel grinders in stage I grinding (denoted as M_{1j} , $j = 1, \dots, J_1$) are deployed to comminute the input biomass from source (S) into particles. The grinded particles are stored in following work-in-process storage (denoted as B_1). Downstream dryer (denoted as M_{dr}) can dry the particles from B_1 and discharge the dried particles into the following work-in-process storage (denoted as B_{dr}). J_2 milling machines in stage II grinding (denoted as M_{2j} , $j = 1, \dots, J_2$) are deployed downstream to B_{dr} to further comminute the input biomass from B_{dr} . The output of stage II grinding may consist of both fine particles that satisfy the size requirement of the final product of the feedstock preprocessing and coarse particles that still need to be further comminuted. Fine particles will be stored in the storage for the final product (denoted as B_2^f). Coarse particles will be stored in B_2^c and will undergo the stage II grinding again for further size reduction.

Figure 4 A detailed biomass feedstock preprocessing system and size distribution evolution

The corresponding evolution of the particle size can be illustrated by the lower part of Figure 4. The particles are classified into H different ranges according to their sizes. Coarse particles are indexed from the range 1 to h . Fine particles are indexed from the range $h + 1$ to H . An H -dimension vector $\mathbf{D}$ is used to denote the particle size distribution of a given batch of biomass. The elements of $\mathbf{D}$ can represent the weight percentage of the particles in each range. The particle size distribution of the input biomass from source (S) is denoted by $\mathbf{D}_0$. After stage I grinding, drying, and stage II grinding, the particle size distributions are represented by $\mathbf{D}_1$, $\mathbf{D}_{dr}$, and $\mathbf{D}_2$ respectively.

The major limitation of the aforementioned feedstock preprocessing is that there is no work-in-process particle separation after the stage I grinding based on different particle sizes. All the particles after stage I grinding are stored in the same work-in-process storage B_1 and will be dried as they are and undergone the stage II grinding to obtain the final qualified products of feedstock preprocessing. Actually, part of the particles after the stage I grinding can meet the size requirement of the final product of the preprocessing and thus only drying is necessary for

this part of particles to make it satisfy the quality standard regarding moisture content. Without such a work-in-process particle separation, unnecessary energy consumption in stage II grinding is incurred due to the comminution of the particles that have already met the size requirement of the final product of feedstock preprocessing. In addition, the coarse particles are more difficult to be dried compared to the same amount of fine particles due to the smaller surface area, which will decelerate the vaporization speed in drying. The temperature of the drier has to be set at the level such that the required moisture content can be removed from the coarse particles in a given mixed batch. At this temperature, the fine particles may suffer a risk of being overcooked and the drying energy is also over consumed.

To address the aforementioned limitations and improve the energy efficiency of the feedstock preprocessing, an improved feedstock preprocessing scheme that incorporates the work-in-process particle separation after the stage I grinding is proposed. Two different dryer configurations for both coarse particles and fine particles are considered based on the separated work-in-process particles after the stage I grinding. Optimal production scheduling model based on this improved feedstock preprocessing scheme is also developed to minimize the total energy consumption under the throughput constraint. The rest of the paper is organized as follows. In Section 2, the proposed preprocessing scheme with the work-in-process particle separation after the stage I grinding and the corresponding optimal production scheduling model are introduced. A case study with three scenarios is given in Section 3 to illustrate the effectiveness of the proposed method. Finally, Section 4 concludes this work and suggests some future extensions.

2. Proposed Method

The proposed feedstock preprocessing scheme with the work-in-process particle separation after the stage I grinding is shown in the upper part of Figure 5. Compared to the existing layout as shown in Figure 4, two different work-in-process storages after the stage I grinding, i.e., B_1^c and B_1^f , are deployed to store coarse and fine particles, respectively. Two drying modes are incorporated so that the coarse particles and fine particles can be dried separately through selecting the input materials either from B_1^c or B_1^f . For the coarse particles selected from B_1^c , they will be dried with the same temperature that is used in the existing configuration. The dried coarse particles will be stored in the work-in-process storage B_{dr} for the stage II grinding. For fine particles selected from B_1^f , they will be dried at a lower temperature setting compared to the existing configuration. The dried fine particles can be directly stored in B_2^f without being processed by the milling machines in the stage II grinding. The evolution of particle size of this improved process scheme is given in the lower part of **Error! Reference source not found.**. The major difference compared to the lower part of Figure 4 is that the fine particles (size indexed from range $h + 1$ to H) after the stage I grinding and drying can be delivered to the storage location of the final product of the preprocessing without the stage II grinding.

Figure 5 Proposed biomass feedstock preprocessing system with the work-in-process particle separation after the stage I grinding and size distribution evolution

Considering the scheme demonstrated in Figure 5, a mixed integer programming (MIP) model is built to schedule the production of the feedstock preprocessing. The production horizon is slotted into a set of time intervals with equal duration L . Let $t, t=1, 2, \dots, T$, be the index of these time intervals. The grinders of the stage I grinding and the milling machines of the stage II grinding are operated with a batch-by-batch manner. The time to process one batch of input materials is defined as the cycle time of the grinder or milling machine. We assume that these two types of machines have the same cycle time. The duration of each slotted time interval (L) is set to be the cycle time. The decisions of production scheduling of the two stages of grinding, e.g., turning on/off a certain grinder or milling machine, selecting input materials either from B_{dr} or B_2^c for the stage II grinding, etc., are implemented at the beginning of each time interval. The dryer is operated with a continuous manner to reduce moisture contents of the input materials to a given level. It has no effects on the size distribution of the input materials. The decisions of production scheduling of the dryer, e.g., turning on/off the dryer, selecting coarse or

fine particles in drying, etc., are implemented at the beginning of each time interval. A fixed empty out time exists for the dryer to switch from drying coarse particles to fine particles or vice versa, i.e., the particles scheduled to be dried in the current time interval cannot enter the drier until the particles in the drier that are scheduled to be dried in the previous time interval are emptied out if the type of the scheduled particles in the current interval is different from the particles scheduled in the previous interval. This empty out time is assumed to be less than the duration of time interval (L). In addition, we also assume that 1) the biomass degradation and dry mass loss can be ignored; and 2) the startup and shut down time/energy of the grinders, milling machines, and drier can be ignored in this paper.

We first model the particle size evolution as follow. The evolution of particle size distribution over time can be represented by differential equation as shown in (1).

$$\frac{d\mathbf{D}_t}{dt} = \mathbf{p}\mathbf{D}_t \quad (1)$$

where $\mathbf{D}_t$ is the size distribution vector of the particles at the beginning of interval t . It has a dimension of $H \times 1$. $\mathbf{D}_t = [d_1(t), \dots, d_h(t), d_{h+1}(t), \dots, d_H(t)]'$, whose element $d_n(t)$ denotes the weight percentage of the particles with the size index of n , $n=1, \dots, H$. $\mathbf{p}$ is particle size distribution changing rate matrix. Transform (1) into difference form, we can obtain (2).

$$\mathbf{D}_{t+1} = \mathbf{D}_t + \mathbf{p}\mathbf{D}_t Dt = (\mathbf{I} + \mathbf{p}Dt)\mathbf{D}_t = (\mathbf{I} + \mathbf{A})\mathbf{D}_t = \mathbf{P}\mathbf{D}_t \quad (2)$$

where $\mathbf{I}$ is the unity matrix with the dimension of $H \times H$; $\mathbf{A}$ is the matrix with the dimension of $H \times H$ to denote the change of the size distribution in Dt ; $\mathbf{P} = \mathbf{I} + \mathbf{A}$ is the size distribution transition matrix with the dimension of $H \times H$. The matrix $\mathbf{A}$ can be calculated by (3) referring to [43, 44].

$$\mathbf{A} = (\mathbf{B} - \mathbf{I})\mathbf{S} \quad (3)$$

where $\mathbf{S}$ and $\mathbf{B}$ are the selection matrix and breakage matrix with both dimensions of $H \times H$. $\mathbf{S}$ is a diagonal matrix whose element $s_{n,n}$ denotes the percentage of particles in the range n that will be selected to be broken into small particles. $\mathbf{B}$ is a lower triangular matrix, whose column vector $\mathbf{b}_n$ represents the detailed breaking possibility distribution for the particles selected in range n . For example, $b_{h+1,1}$ means the percentage of the selected coarse particles in the range 1 being grinded into fine particles in the range $h + 1$. For further explanation of the selection matrix and breakage matrix, please refer to [43, 44].

Before we further derive the evolution of particle size distribution in different processes utilizing the aforementioned theory, we need to make an important assumption as follows: the particles in each work-in-process storage are well-mixed, and thus the size distribution of any batch of the particles selected from the storage is identical to the size distribution of all the particles in the storage at a given time point. Note that this assumption is also applied to the raw materials stored in the source (S).

Let r_{1t}^c and r_{1t}^f be the weight percentage of coarse particles and fine particles in the output obtained after the stage I grinding at the beginning of interval t (i.e., they are processed by the stage I grinding during interval $t-1$), respectively. Using (1)-(3), we can obtain r_{1t}^f and r_{1t}^c as shown in (4)-(5).

$$r_{1t}^f = \mathbf{1}^f \times \mathbf{P}_1 \mathbf{D}_{0,t-1} \quad (4)$$

$$r_{1t}^c = \mathbf{1}^c \times \mathbf{P}_1 \mathbf{D}_{0,t-1} \quad (5)$$

where $\mathbf{1}^c = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$; and $\mathbf{1}^f = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$. $\mathbf{P}_1$ is the size distribution transition matrix of the stage I grinding. $\mathbf{D}_{0,t-1}$ is the particle size distribution vector of the raw materials in the source (S) that are processed by the stage I grinding in interval $t-1$. We assume that $\mathbf{D}_{0,t}$ keeps constant over time, and thus r_{1t}^f and r_{1t}^c will not change over time by given $\mathbf{P}_1$.

Let $r_{dr,t}^c$ and $r_{dr,t}^f$ be the weight percentage of coarse particles and fine particles in the output obtained after drying at the beginning of interval t (i.e., they are dried by the dryer during interval $t-1$), respectively. Similarly, we can obtain $r_{dr,t}^f$ and $r_{dr,t}^c$ as shown in (6)-(7).

$$r_{dr,t}^f = \mathbf{1}^f \times \mathbf{D}_{dr,t}^f = \mathbf{1}^f \times \mathbf{P}_{dr} \mathbf{D}_{1,t-1}^f \quad (6)$$

$$r_{dr,t}^c = \mathbf{1}^c \times \mathbf{D}_{dr,t}^c = \mathbf{1}^c \times \mathbf{P}_{dr} \mathbf{D}_{1,t-1}^c \quad (7)$$

where $\mathbf{P}_{dr}$ is the size distribution transition matrix of the drying. As assumed earlier, the drying process will not alter the size distribution of the input materials, i.e., $\mathbf{P}_{dr} = \mathbf{I}$. $\mathbf{D}_{1,t}^c$ and $\mathbf{D}_{1,t}^f$ are the size distribution vectors of the coarse particles and fine particles in B_1^c and B_1^f at the beginning of interval t , respectively. The first h elements of $\mathbf{D}_{1,t}^c$ are same as the first h elements in $\mathbf{P}_1 \mathbf{D}_{0,t-1}$, while the elements $h+1$ to H are set to be zero. $\mathbf{D}_{1,t}^f$ can be obtained with similar way that the first h elements are set to be zero, while the elements $h+1$ to H are same as the corresponding elements in $\mathbf{P}_1 \mathbf{D}_{0,t-1}$. $\mathbf{D}_{dr,t}^c$ is the size distribution vector of the coarse particles in B_{dr} at the beginning of interval t (i.e., they are dried by the dryer during interval $t-1$). $\mathbf{D}_{dr,t}^f$ is the

size distribution vector of the fine particles in B_2^f at the beginning of interval t (i.e., they are dried by the dryer during interval $t-1$). We can see that $\mathbf{D}_{1,t}^f$ and $\mathbf{D}_{1,t}^c$ can keep constant since $\mathbf{P}_1 \mathbf{D}_{0,t-1}$ does not change over time. Therefore, $\mathbf{D}_{dr,t}^c$ will not change over time since $\mathbf{D}_{1,t}^c$ can keep constant. Considering two drying modes, the output of drying process is either fine particles (i.e., $r_{dr,t}^f = 1$) or coarse particles (i.e., $r_{dr,t}^c = 1$) depending on the selection of input materials either from B_1^f or B_1^c .

Let $r_{2t}^{cB_{dr}}$ be the weight percentage of coarse particles in the output particles obtained after the stage II grinding at the beginning of interval t (i.e., they are processed by the stage II grinding during interval $t-1$) when the input materials are from B_{dr} . Let $r_{2t}^{fB_{dr}}$ be the weight percentage of fine particles in the output particles obtained after the stage II grinding at the beginning of interval t (i.e., they are processed by the stage II grinding during interval $t-1$) when the input materials are from B_{dr} . Let $r_{2t}^{cB_2^c}$ be the weight percentage of coarse particles in the output particles obtained after the stage II grinding at the beginning of interval t (i.e., they are processed by the stage II grinding during interval $t-1$) when the input materials are from B_2^c . Let $r_{2t}^{fB_2^c}$ be the weight percentage of fine particles in the output particles obtained after the stage II grinding at the beginning of interval t (i.e., they are processed by the stage II grinding during interval $t-1$) when the input materials are from B_2^c . Using similarly method, these parameters can be calculated by (8)-(11).

$$r_{2,t}^{cB_{dr}} = \mathbf{1}^c \times \mathbf{P}_2 \mathbf{D}_{dr,t-1}^c \quad (8)$$

$$r_{2,t}^{f,B_{dr}} = \mathbf{1}^f \times \mathbf{P}_2 \mathbf{D}_{dr,t-1}^c \quad (9)$$

$$r_{2,t}^{c,B_2^c} = \mathbf{1}^c \times \mathbf{P}_2 \mathbf{D}_{2,t-1}^c \quad (10)$$

$$r_{2,t}^{f,B_2^c} = \mathbf{1}^f \times \mathbf{P}_2 \mathbf{D}_{2,t-1}^c \quad (11)$$

where $\mathbf{P}_2$ is the size distribution transition matrix of the stage II grinding. $\mathbf{D}_{2,t-1}^c$ is the particle size distribution vector of the input materials in B_2^c that are processed by the stage II grinding in interval $t-1$. Similarly, $r_{2,t}^{c,B_{dr}}$ and $r_{2,t}^{f,B_{dr}}$ can keep constant by given $\mathbf{P}_2$ since $\mathbf{D}_{dr,t}^c$ does not change over time. However, $r_{2,t}^{c,B_2^c}$ and $r_{2,t}^{f,B_2^c}$ cannot keep constant since $\mathbf{D}_{2,t}^c$ will change over time due to the fact that the materials stored in B_2^c may either from B_{dr} or B_2^c itself. $\mathbf{D}_{2,t}^c$ can be calculated by (12).

$$\mathbf{D}_{2,t}^c = \frac{\dot{e}}{e} x_{2(t-1)}^c \mathbf{D}_{2(t-1)}^c + \mathbf{E}(\mathbf{1}^c) \times \frac{\dot{a}}{a} x_{2j(t-1)} \times R_{2j} \times \frac{\dot{e}}{e} (\mathbf{P}_2) \mathbf{D}_{dr,(t-1)}^c x_{2j(t-1)}^{B_{dr}} + (\mathbf{P}_2 - \mathbf{I}) \mathbf{D}_{2(t-1)}^c x_{2j(t-1)}^{B_2^c} \frac{\dot{u}}{u} / b_{2t}^c \quad (12)$$

where b_{2t}^c is the work-in-process storage level at the beginning of interval t in B_2^c . R_{2j} is the production rate of the milling machine M_{2j} . $\mathbf{E}(\mathbf{1}^c)$ is an $H \times H$ diagonal matrix with the element $e_{n,n} = (\mathbf{1}^c)_n$, $n = 1, \dots, H$. x_{2jt} is the binary decision variable to denote the production schedule of the j^{th} milling machine in the stag II grinding during interval t . It takes the value of one if milling machine M_{2j} in stage II grinding is determined to produce in interval t , and zero otherwise. $x_{2jt}^{B_{dr}}$ is the binary decision variable to denote if the input materials for milling machine M_{2j} are from B_{dr} or not during interval t . It takes the value of one if milling machine

M_{2j} is determined to process the materials from B_{dr} in interval t , and zero otherwise. Similarly, $x_{2jt}^{B_2^c}$ is the binary decision variable to denote if the input materials for milling machine M_{2j} are from B_2^c or not during interval t . It takes the value of one if the input materials for milling machine M_{2j} are from B_2^c in interval t , and zero otherwise.

For the dryer, it may have two drying modes, i.e., drying coarse particles and drying fine particles. In the interval when mode switch happens, the incoming particles scheduled to be dried cannot enter the dryer until the remaining particles that are scheduled in the previous interval are emptied out. Let τ be this empty out time. We assume that during this empty out time τ , the dryer is still in working state with energy consumption. Let y_t^c and y_t^f be the decision variables to denote if coarse particles and fine particles are selected to be dried in the dryer during interval t , respectively. They take the value of one if coarse and fine particles are used, respectively; and zero otherwise. Let $f_{c \rightarrow f}(t)$ and $f_{f \rightarrow c}(t)$ be the binary variables to represent whether the particles in the dryer are switched from coarse particles to fine particles and fine particles to coarse particles during interval t , respectively. They can be formulated by (13) and (14).

$$f_{c \rightarrow f}(t) = \begin{cases} 1, & \text{if } y_{t-1}^c = 1 \text{ and } y_t^f = 1 \\ 0, & \text{otherwise} \end{cases} \quad (13)$$

$$f_{f \rightarrow c}(t) = \begin{cases} 1, & \text{if } y_{t-1}^f = 1 \text{ and } y_t^c = 1 \\ 0, & \text{otherwise} \end{cases} \quad (14)$$

Considering this empty out time τ , the effective drying time ET_{dr} can be calculated by (15).

$$ET_{dr} = \begin{cases} L, & \text{if } f_{c \rightarrow f}(t) = 0 \text{ and } f_{f \rightarrow c}(t) = 0 \\ L - t, & \text{otherwise} \end{cases} \quad (15)$$

Let x_{1jt} be the binary decision variable to denote the production schedule of the j^{th} grinder in the stage I grinding during interval t . It takes the value of one if grinder M_{1j} is determined to produce in interval t , and zero otherwise. The objective function can be formulated as

$$\begin{aligned} \min_{\substack{x_{1jt}, x_{2jt}, B_{dr}, B_{dr}^c, \\ y_t^c, y_t^f, f_{c \rightarrow f}(t), f_{f \rightarrow c}(t)}} & \left(\sum_{t=1}^T \sum_{j=1}^{J_1} x_{1jt} \cdot L \cdot P_{1j} + \sum_{t=1}^T \sum_{j=1}^{J_2} x_{2jt} \cdot L \cdot P_{2j} + \sum_{t=1}^T (y_t^c - f_{f \rightarrow c}(t)) \cdot P_{dryer}^c \cdot L \right. \\ & \left. + \sum_{t=1}^T (y_t^f - f_{c \rightarrow f}(t)) \cdot P_{dryer}^f \cdot L + \sum_{t=1}^T f_{f \rightarrow c}(t) \cdot P_{dryer}^{f \rightarrow c} \cdot L + \sum_{t=1}^T f_{c \rightarrow f}(t) \cdot P_{dryer}^{c \rightarrow f} \cdot L \right) \end{aligned} \quad (16)$$

where P_{1j} and P_{2j} are the rated power of machine M_{1j} and M_{2j} , respectively. P_{dryer}^f and P_{dryer}^c are the rated power of the dryer when drying fine particles and coarse particles, respectively. $P_{dryer}^{f \rightarrow c}$ is the average power of the dryer during the interval when the drying mode is switched from drying fine particles to drying coarse particles. $P_{dryer}^{c \rightarrow f}$ is the average power of the dryer during the interval when the drying mode is switched from drying coarse particles to drying fine particles.

The constraints are formulated as follows:

1. Capacity constraint of each work-in-process storage

$$\begin{aligned} 0 \leq b_{1t}^c \leq V_1^{c,max}; 0 \leq b_{1t}^f \leq V_1^{f,max}; \\ 0 \leq b_{dr,t} \leq V_{dr}^{max}; 0 \leq b_{2t}^c \leq V_2^{c,max} \end{aligned} \quad (17)$$

where $b_{1t}^c, b_{1t}^f, b_{drt}$, and b_{2t}^c are the work-in-process level at the beginning of interval t in B_1^c , B_1^f, B_{dr} , and B_2^c , respectively; and $V_1^{c,max}, V_1^{f,max}, V_{dr}^{max}$ and $V_2^{c,max}$ are the capacity of the B_1^c , B_1^f, B_{dr} , and B_2^c , respectively. $b_{1t}^c, b_{1t}^f, b_{drt}$, and b_{2t}^c can be calculated by (18)-(21).

$$b_{1t}^c = b_{1(t-1)}^c + r_{1,t}^c \sum_{j=1}^{J_1} x_{1j(t-1)} \times R_{1j} \times L - (y_{t-1}^c - f_{f@c}(t-1)) \times R_{dr} \times L - f_{f@c}(t-1) \times R_{dr} \times L \quad (18)$$

$$b_{1t}^f = b_{1(t-1)}^f + r_{1,t}^f \sum_{j=1}^{J_1} x_{1j(t-1)} \times R_{1j} \times L - (y_{t-1}^f - f_{c@f}(t-1)) \times R_{dr} \times L - f_{c@f}(t-1) \times R_{dr} \times L \quad (19)$$

$$b_{drt} = b_{dr(t-1)} + ((y_{t-1}^c - f_{f@c}(t-1)) \times L + f_{f@c}(t-1) \times L \phi) \times R_{dr} \times (1-w) - \sum_{j=1}^{J_2} x_{2j(t-1)} \times x_{2j(t-1)}^{B_{dr}} \times R_{2j} \times L \quad (20)$$

$$b_{2t}^c = b_{2(t-1)}^c + r_{2,t}^{c,B_{dr}} \sum_{j=1}^{J_2} R_{2j} \times L \times x_{2j(t-1)} \times x_{2j(t-1)}^{B_{dr}} + r_{2,t}^{c,B_2^c} \sum_{j=1}^{J_2} R_{2j} \times L \times x_{2j(t-1)} \times x_{2j(t-1)}^{B_2^c} - \sum_{j=1}^{J_2} R_{2j} \times L \times x_{2j(t-1)} \times x_{2j(t-1)}^{B_2^c} \quad (21)$$

where R_{1j} represents the production rate of grinder j of the stage I grinding; R_{dr} represents the particle input rate of the dryer; and w is the vaporized moisture content of the input biomass. Note that we assume the capacity of the B_2^f for the final products of feedstock preprocessing is infinity and the supply of the raw materials in source (S) can always be ensured.

2. Minimum duration of a specific drying mode

$$\sum_{t=t'}^{t'+d-1} \phi_{c@f}(t) + f_{f@c}(t) \leq 1, \quad t' \in [1, T-d+1] \quad (22)$$

It states that the dryer should spend at least d intervals before switching to the other mode.

3. Input material selection for the milling machines in the stage II grinding

$$x_{2jt}^{B_{dr}} + x_{2jt}^{B_2^c} = x_{2jt}, t = 1, \dots, T, j = 1, \dots, J_2 \quad (23)$$

It states that machine M_{2j} cannot select the input materials from both B_{dr} and B_2^c during the same interval.

4. Throughput constraint

$$\begin{aligned} & \sum_{t=2}^{T+1} \sum_{j=1}^{J_2} [R_{2j} \times L \times r_{2t}^{f, B_{dr}} \times x_{2j(t-1)} \times x_{2j(t-1)}^{B_{dr}} + R_{2j} \times L \times r_{2t}^{f, B_2^c} \times x_{2j(t-1)} \times x_{2j(t-1)}^{B_2^c}] \\ & + \sum_{t=1}^T [L \times (y_t^f - f_{c \rightarrow f}(t)) + L \times \phi \times f_{c \rightarrow f}(t)] \times R_{dr} \times (1 - w)^3 \geq D \end{aligned} \quad (24)$$

where D is the target production. It states that the throughput in the planning horizon should be no less than the target production.

This scheduling model is formulated as an MIP. Commercial software packages are mature and convenient for this type of formulation. CPLEX [45] is used in this paper to solve the formulation. In CPLEX, in order to reduce the number of decision variables and computational burden, three tuple sets [46] are constructed to define the variable x_{ijt} ($i=1,2$), $x_{2jt}^{B_{dr}}$ and $x_{2jt}^{B_2^c}$ respectively. Tuple set is a data structure that can help to aggregate related data in a compact way. For example, x_{ijt} ($i=1,2$) is declared using a tuple set as shown in Figure 6. The logical relationship between $y_t^c, y_t^f, f_{c \rightarrow f}(t)$, and $f_{f \rightarrow c}(t)$ are represented using conditional constraints as shown in Figure 7.

```

// State is the on/off state of a machine at time t
tuple State{
    int s; //s is in a range of value 1..2;
    int m; //m is the machine index, for s=1, m in 1..J1; s=2, m in 1..J2
    int t; //t is within the range Time; Time = 1.. TimeHorizon
}
// StageMachineTime is a set to represent states of all the machine
{State} StageMachineTime = {<s,m,t>| s in Stage, m in 1..MachineinEachStage[s],
                             t in Time};
//decision variable X_i,j,t in manuscript
dvar boolean X[<s,m,t> in StageMachineTime];

```

Figure 6 Decision variable declaration using tuple sets in CPLEX

```

//DryModeSwitch:
forall(t in 2..TimeHorizon ){
    (yf[t] + yc[t-1]==2) => (fc2f[t] ==1);
    (yc[t] + yf[t-1]==2) => (ff2c[t] ==1);
    (yf[t] + yc[t-1]<=1) => (fc2f[t] ==0);
    (yc[t] + yf[t-1]<=1) => (ff2c[t] ==0);
}

```

Figure 7 Conditional constraint on drying mode switch in CPLEX

3. Case Study

A biomass feedstock preprocessing system with three grinders in the stage I grinding, one rotary dryer, and ten milling machines in the stage II grinding as shown in Figure 8 is considered as a numerical case. An eight-hour production shift is examined. The throughput requirement is set to be 200 tons ($D = 200$). The production horizon is slotted into a set of 15-minute intervals. The cycle time of the grinders and milling machines is set to be 15 minutes. The time needed to switch from one mode to the other one is 5 minutes for the dryer ($t = 5$), and the vaporized moisture content by drying is 15% ($w = 0.15$). The required minimum duration of the dryer before switching to another drying mode is 1 hour. The production rates of the grinders and milling machines, and the particle input rate of the dryer are given in Table 1. The rated power of the grinder and milling machine is shown in Table 2. The rated power of the dryer is provided in Table 3. The capacity of each work-in-process storages, corresponding initial level, and particle size distribution are given in Table 4.

Figure 8 Layout of the biomass feedstock preprocessing system in this case study

Table 1 Production rate of the grinder and milling machine and particle input rate of the dryer (ton/hour) [47]

Grinder	Milling Machine	Dryer
14.6	4.25	42

Table 2 Rated power of grinder and milling machine (kW)

Grinder	Milling Machine
219	105

Table 3 Rated power of the dryer (kW)

Operation mode	Coarse particles	Fine particles	Coarse $\rightarrow$ Fine*	Fine $\rightarrow$ Coarse*
Rated power (kW)	14700	13440	8960	9800

* (A $\rightarrow$ B) denotes the average power of the dryer when the particle type in the dryer is switched from A to B.

Table 4 Parameters of work-in-process storages

	B_1^c	B_1^f	B_{dr}	B_2^c	B_2^f
Capacity (ton)	40	40	40	40	$+\infty$
Initial content(ton)	10.5	10.5	10.5	10.5	0
Initial size distribution	$\mathbf{D}_{1,1}^c$ *	$\mathbf{D}_{1,1}^f$ *	$\mathbf{D}_{dr,1}$ *	$\mathbf{D}_{2,1}^c$ *	-

* $\mathbf{D}_{1,1}^c=[0.274,0.294,0.432,0,0,0]$; $\mathbf{D}_{1,1}^f=[0,0,0,0.367,0.367,0.266]$; $\mathbf{D}_{dr}=[0.274,0.294,0.432,0,0,0]$; $\mathbf{D}_2^c=[0.026,0.052,0.922,0,0,0]$

The particles are categorized into 6 ranges (>0.75 inch, $0.50\sim 0.75$ inch, $0.25\sim 0.50$ inch, $0.16\sim 0.25$ inch, $0.08\sim 0.16$ inch, <0.08 inch). The raw materials that will be used by grinders of the stage I grinding are assumed to be in the first range, i.e., $\mathbf{D}_{0,t} = [1, 0, 0, 0, 0, 0]'$. Particles with the size larger than 0.25 inch are treated as coarse particles, and the ones less than 0.25 inch are regarded as fine particles (i.e., $H = 6, h = 3$). The size distribution transition matrix for the stage I and stage II grindings are:

$$\mathbf{P}_1 = \begin{bmatrix} 0.14 & 0 & 0 & 0 & 0 & 0 \\ 0.15 & 0.17 & 0 & 0 & 0 & 0 \\ 0.22 & 0.23 & 0.25 & 0 & 0 & 0 \\ 0.18 & 0.25 & 0.27 & 0.30 & 0 & 0 \\ 0.18 & 0.20 & 0.28 & 0.32 & 0.50 & 0 \\ 0.13 & 0.15 & 0.20 & 0.38 & 0.50 & 1 \end{bmatrix} \quad \mathbf{P}_2 = \begin{bmatrix} 0.005 & 0 & 0 & 0 & 0 & 0 \\ 0.010 & 0.14 & 0 & 0 & 0 & 0 \\ 0.175 & 0.24 & 0.22 & 0 & 0 & 0 \\ 0.245 & 0.26 & 0.28 & 0.28 & 0 & 0 \\ 0.290 & 0.21 & 0.29 & 0.33 & 0.45 & 0 \\ 0.275 & 0.15 & 0.21 & 0.39 & 0.55 & 1 \end{bmatrix}$$

Three scenarios are considered in this case. Scenario 1 represents a baseline situation, whose material flow is represented by Figure 4 without particle separation. For the stage II grinding, since it may have two sources, i.e., B_{dr} and B_2^c , a rule for the selection of input materials is defined: once B_2^c has enough particles to support the operation of all milling machines for one cycle, all the milling machines of stage II grinding are fed with the particles

from B_2^c ; otherwise particles from B_{dr} are used. In scenario 2, the improved scheme with particle separation in feedstock preprocessing is adopted while the proposed production scheduling model is not considered. The material flow in this scenario is shown in Figure 5. Both the dryer and milling machines may have two different material sources. For the dryer, we assume that the drying mode changes exactly once per hour. For the milling machines, the rule for material selection is same as the rule defined in scenario 1. In scenario 3, the proposed improved scheme for feedstock preprocessing is adopted and corresponding scheduling model is also incorporated.

CPLEX is used to solve the proposed formulation with the above given parameters on a desktop with Intel(R) Core TM i5 2.67GHz processor and 4 GB memory. The computational time is approximately 18 minutes. The comparison of total energy consumption, throughput, energy consumption per unit production, and carbon dioxide emission is shown in Table 5.

Table 5 Result comparison of three scenarios

	Total Energy Consumption (kWh)	Throughput (ton)	Energy Consumption per Unit Production (kWh/ton)	Reduction of Energy Consumption per Unit Production	CO2 Emission Reduction (ton)
Scenario 1	89886.0	200.13	449.14	-	-
Scenario 2	81461.5	200.30	406.70	9.45%	5.81
Scenario 3	78816.8	200.21	393.68	12.35%	7.63

As we can see from Table 5, using the proposed scheme with work-in-process particle separation after stage I grinding, significant reduction of energy consumption can be achieved without sacrificing production throughput. Compared to scenario 1, the proposed preprocessing scheme using the scheduling model (scenario 3) can reduce the energy consumption per unit production by 12.35%. The CO2 emission reduction is also estimated. Using the proposed scheme and scheduling model, 7.63 ton CO2 emission can be reduced for an 8-hour shift (using

the metric that 1 kWh electricity generation will lead to 6.89551×10^{-4} ton CO₂ emissions [48]). If we consider the production for one month (three shifts per day and 22 working days per month), the energy saving and CO₂ emission reduction can be scaled up to 730567kWh and 503 tons, respectively.

As mentioned in Section 1, feedstock preprocessing is one of two major processes in biofuel manufacturing. Department of Energy has set the goal that the cost of feedstock preprocessing needs to be reduced to 25% of the total cost of entire biofuel manufacturing process by 2017 [47]. The reduction of the energy consumption in feedstock preprocessing is considered a critical way to achieve such a goal. The results of the reduction of energy consumption per unit production in feedstock preprocessing in this study can contribute to the energy saving of the entire biofuel manufacturing process. It demonstrates a promising prospect in addressing the concern that the energy consumption in biofuel manufacturing is higher than the energy that can be supplied by the produced biofuel.

4. Conclusions and Future Work

In this paper, an improved biomass feedstock preprocessing scheme considering the particle separation after the stage I grinding is proposed. The optimal production scheduling model based on the proposed scheme is also developed using mixed integer programming formulation to minimize the energy consumption of feedstock preprocessing without sacrificing production throughput. The identified optimal schedule can significantly reduce the energy consumption and greenhouse gas emissions compared to the baseline model.

Future extensions of this work could be the dynamic scheduling of the feedstock preprocessing considering random market demand and the integration of the feedstock

preprocessing with biochemical conversion process to further enhance the energy efficiency and environmental sustainability of the biomass manufacturing.

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