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Integrating process optimization with energy-efficiency scheduling to save energy for paper mills

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HIGHLIGHTS

- A hybrid energy model is proposed for tissue paper mill.
- An energy efficiency scheduling model for tissue paper mill is developed.
- Proposes a two-level optimization method for tissue paper mill saving energy.
- The maximum energy cost saving ratio of dryer section is 12.53%.
- The maximum energy cost saving ratio of tissue paper mill is 9.03%.

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ABSTRACT

With the surging energy price and environmental concerns, measures to improve energy efficiency have attracted increasing concerns of the manufacture sector, especially energy-intensive manufacturing industries such as tissue paper mills. Energy-efficiency scheduling, as a novel energy-efficient method, has attracted the attention of an increasing number of researchers in recent years. Drying process is the most energy-intensive production process in tissue paper mills, which has a great energy-saving potential. This paper aims to reduce the energy costs for the tissue paper mill, consisting of processing energy cost and set-up energy cost, through integrating drying process optimization with energy-efficient scheduling. First, the energy cost model and the scheduling model were built. Then, the energy cost of the drying process of every job in a given scheduling problem was optimized using particle swarm optimization (PSO). Afterwards, the energy cost was further optimized using energy-efficiency scheduling. In addition, a hybrid non-dominated sorting genetic algorithm II (NSGA-II) was utilized to solve the energy-efficiency scheduling problem. Finally, several real scheduling problems from a real tissue paper mill were addressed using the proposed approach to demonstrate its effectiveness in energy saving. The experiment result showed that there is a great energy-saving potential in the drying process, accounting for up to 12.53% of the total energy consumption. Moreover, the maximum energy saving ratio of the proposed approach could reach 9.03%. On the whole, the proposed approach can provide a new energy-saving method for tissue paper mills or other manufacturing industries.

1. Introduction

According to the EIA 2016, the industrial sector is the largest energy-consuming end-user accounting for about 54% of the world's total delivered energy. Moreover, energy consumption of the industrial sector is increasing by an average of 1.2% every year, from 222 quadrillion British thermal units (Btu) in 2012 to an estimated 309 quadrillion Btu in 2040. Moreover, the use of energy will directly or indirectly generate greenhouse gases. As a result, the world emission of energy-related CO2 in 2012 was 32.2 billion metric tons and will probably reach 43.2 billion metric tons in 2040. Paper manufacturing is an energy-intensive process which accounted for about 7% of delivered industrial energy consumption in 2012 [1]. China, as one of the largest pulp and paper producers, turned out nearly a quarter of the world's total paper in 2010 [2]. In China, the average growth rate of paper production from 2007 to 2016 was 4.43% [3]. Meanwhile, the total final energy consumed by pulp and paper industries increased by an average of 10.56% per year from 2007 to 2015 [4]. Kong et al. pointed

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Nomenclature

A_a	aperture ratio of nozzle
B_{ji}	beginning time of the i-th job in machine j
C_{ad}	specific heat capacity of supply air on the wet side
C_F	specific heat capacity of fiber
C_W	specific heat capacity of water
d	diameter of nozzle
$E_d(i)$	optimal steam cost of job i
E^P	processing energy cost
E^S	set-up energy cost
F_{ji}	end time of the i-th job in machine j
F_h	frequency of the air feeder on the dry side
F_p	frequency of the air exhauster
G	grammage
G_F	bone dry basis weight of the paper
h_c	heat transfer coefficient between the paper and the dryer surface
h_e	heat transfer coefficient between the paper and the air before it enters the vapour hood
h_{id}	heat transfer coefficient between the paper and the air on the dry side
h_{ih}	heat transfer coefficient between the paper and the air on the wet side
H	distance between the nozzle and the paper
H_e	environment humidity
ΔH_{ev}	evaporation heat of water
H_j	number of job processes in machine j
$\{J_i\}_{i=1}^n$	a set of jobs
K_e	mass transfer coefficient between the paper and the air before it enters the vapour hood
K_{id}	mass transfer coefficient between the paper and the air on the dry side
K_{ih}	mass transfer coefficient between the paper and the air on the wet side
K_o	heat transfer coefficient between the paper and the air after it is out of the vapour hood
L	evaporation distance
L_c	max distance between the nozzle and the exhaust port
M	molar mass of water
$\{M_j\}_{j=1}^m$	a set of machines
O_{ji}	equal 1 if the job i process in machine j, otherwise equal 0
P_a	saturated pressure of water vapor around the paper
P_p	water vapor pressure on paper surface
P_j^{PE}	power of machine j
P_j^{SE}	set-up power of the j-th machine
P_r	Prandtl number
R	gas constant
Re_d	Reynolds number on the dry side
S_j^{SE1}	volume flowrate of Steam_1 in the set-up stage
S_j^{SE2}	volume flowrate of Steam_2 in the set-up stage
T_a	air temperature around the paper
T_c	surface temperature of the dryer
T_d	temperature of supply air on the dry side
T_e	environment temperature
$T_{j,i-1,i}$	set-up time of the $(i-1)$-th job shifting to the i-th job in machine j
T_h	temperature of supply air on the wet side
T_p	paper temperature
T_{pd}	temperature of paper on the dry side
V	speed of the dryer
V_p	speed of the paper machine
Wr	wrinkling ratio of the paper machine
X	paper humidity

Greek symbols

α	price of electricity
λ	latent heat of vaporization of water
λ_H	thermal conductivity of air
φ	relative air humidity around the paper

out that the technical energy conservation potentials of pulp and paper industries in China accounted for 23% of primary energy in 2010 [5]. As the price of energy rises constantly and environmental concerns keep growing, paper manufacturing enterprises have made efforts to develop promising technologies to improve energy efficiency. Owing to the difference in schedulers' experience and knowledge, various feasible production scheduling plans can be designed for a given task. Although these scheduling plans are interchangeable, their outcomes of energy efficiency can be different. Hence, energy efficiency should be an optimization objective in a scheduling problem [6]. In recent years, researchers have focused on improving energy efficiency by implementing the optimal production scheduling.

Energy modeling of the production process is the foundation for the improvement of energy efficiency. According to literature [7], energy modeling can be divided into four categories, namely theoretical, empirical, and discrete event-based and hybrid models. Over the past decades, many theoretical models for energy consumption have been developed by researchers [8–10]. Theoretical model, as a powerful tool for energy consumption analysis, can provide a precise mathematical relationship between energy consumption and machining factors. However, it is a complex task to build a theoretical model. Empirical models can provide a simplified energy consumption model using statistic methods. For example, the regression analysis is a common and powerful method for building an empirical model [11]. In addition, the artificial neural network and response surface methodology can also provide an efficient way for building an empirical model [12,13]. Theoretical and empirical models mainly analyze energy consumption in the cutting process, which, however, is only part of energy consumption in the production process. In light of this phenomenon, some researchers proposed modeling energy consumption of the machining process using discrete events [14]. The discrete event-based model can provide an energy consumption analysis in different scenarios (such as start-up, cutting, idle, set-up and stop). In fact, there is no single model that can solve the energy consumption issue in the machining process, so some researchers have tried to solve the energy consumption modeling problem using a hybrid model [15]. The hybrid model is a new efficient way for modeling energy consumption in the machining process that can combine a high-level discrete event model with the theoretical or empirical model.

It is the improvement of energy efficiency of the machining process, rather than the modeling of energy consumption that is the final objective. Scheduling has been proved as a feasible and efficiency way to improve energy efficiency in the machining process. There are some energy-efficiency scheduling researches have been carried out based on real industries. Wang et al. [16] studied a two-objective scheduling problem with energy cost, where the energy cost can be reduced in consideration of time-of-use (TOU) electricity prices and the machine selection at different energy consumption rates. Hadera and Harjunkoski [17] investigated an optimal production scheduling problem of power-intensive steel-making processes with regard to energy cost. The research assumed that the steel plant in a day-ahead electricity market with hourly-varying electricity prices would face financial penalties if its actual electricity consumption were to deviate from the committed level. Last, the production scheduling problem is combined with the