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Dynamic scheduling of a flow shop with on-site wind generation for energy cost reduction under real time electricity pricing

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ABSTRACT

On-site renewable electricity generation represents an attractive option for manufacturing enterprises to deal with time varying electricity prices while reducing their carbon footprint. Production scheduling can be used to take full advantage of the installed renewable energy capacity for electricity cost reduction. A dynamic scheduling approach is proposed to minimize the electricity cost of a flow shop with a grid-integrated wind turbine. Time series models are used to provide updated wind speed and electricity prices as actual data becomes available. The production schedule and energy supply decisions are adjusted based on the new information. The approach is demonstrated using a case study.

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1. Introduction

Owing to increasing concerns over climate change and energy cost, many companies are carefully scrutinizing the entire life cycle of their products to identify opportunities to reduce energy/carbon footprint. The energy consumed during manufacturing contributes to the environmental footprint and also operation cost, which gives many companies the incentive to improve energy efficiency. One strategy for doing this is to scrutinize manufacturing scheduling. When compared with equipment changes, energy responsive scheduling requires less capital investment [1]. Scheduling studies have been done for different shop types (e.g., flow shop [2,3] and job shop [4]), various settings (e.g., hypothetical [3,4] and real world [2]), and different electricity pricing schemes (e.g., flat electricity rate [2,4] and time-of-use tariff [3]).

A second company strategy to reduce the carbon footprint is to adopt renewable energy technologies such as wind turbines. Such technologies offer substantial reductions in carbon intensity and are becoming more cost competitive. Some manufacturing facilities have begun to implement on-site renewable energy generation to reduce their reliance on the power grid, control their peak power demand, and regulate their energy costs in the face of increased use of time-varying electricity pricing schemes.

Both energy-aware production scheduling and utilization of renewable power offer opportunities to reduce the carbon intensity of manufacturing. However, research that simultaneously considers both of these options is rare. Only a handful of studies consider wind energy as part of the manufacturing scheduling problem. For example, Moon and Park [5] integrated wind power into a flexible job shop under a time-of-use electricity pricing scheme; this study assumed a fixed profile for wind power generation [5]. Liu considered multiple sources of renewable energy: solar and wind power [6], but this study was limited to a single machine scheduling problem.

Standard scheduling problems are NP-hard, and can only be solved in a reasonable time for small scale instances; larger problems require heuristics [3,4,6]. Considering energy as an additional objective makes the problem even more difficult. Still, the results of current studies are promising: they confirm that it is possible to reduce energy cost through scheduling or scheduling with consideration of renewable energy sources. Furthermore, some studies showed that adding environmental constraints might not compromise throughput [2]. And, some of the studies suggested that if multi-objective linear mathematical programming is employed (with time and carbon footprint [3,5,6] as objectives), throughput can be maintained [3] and the total weighted flow time can be minimized [6].

For all of the aforementioned research, either electricity prices were “known” ahead of time, or the production schedule was not adjusted as better information on the renewable energy supply and electricity price became available. That is, the energy-responsive manufacturing schedule was “static.” To minimize the energy costs with on-site renewable energy generation under real time electricity pricing, dynamic scheduling is needed, i.e., the production schedule needs to be revised to respond to updated forecasts of electricity price and the supply of renewable energy. This paper presents a dynamic scheduling approach to minimize the electricity cost of a flow shop with a grid-integrated wind turbine. Wind power is considered because of its rapid growth over the past five years. Between 2008 and 2014, 31% of the electricity capacity installed in the U.S. was in the form of land-based wind farms [7].

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2. Model description

We employ a time-indexed mixed integer linear programming (MILP) model for flow shop scheduling under real time pricing while maintaining a pre-determined production throughput. Since the wind turbine is connected to the power grid, turbine-generated electricity may be used within the facility or sold to the grid according to the real time electricity prices. This decision will be made by the MILP model. Time series models are used to forecast hourly electricity prices and wind speeds based on recent data. Manufacturing schedules are updated hourly when new price and wind speed information become available. That is, all schedules are adjusted at the beginning of each hour according to current machine and jobs completion status.

2.1. Flow shop scheduling and energy supply model

In this model, a flow line with m processes is considered; each process has only one machine. There are multiple parts for each job of type j. Each machine i needs to process parts without interruption, and the buffers between each process have limited space for work in process. The energy to run the machines is from the power grid, the wind turbine, or a combination of both. The generated wind power can either be used for production or fed into the power grid to generate revenue (feed-in tariff). The flow shop setup is shown in Fig. 1.

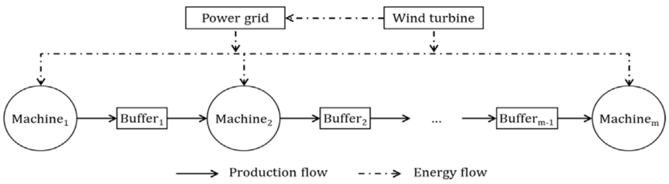

Fig. 1. Overview of the flow shop set up.

For this manufacturing facility, several assumptions are made: (1) all machines have three states, i.e., off, basic, and working; (2) there is a power consumption spike when a machine changes states from off to basic; (3) machines cannot switch states while processing a part; (4) all machines must finish their current job before beginning a new job; (5) processing order, processing time, and power consumption of each job type can be different on each machine; (6) there are buffers between machines, and their sizes can vary; (7) all machines are automated and the part handling time is 0; (8) the wind power and electricity price varies over time, but can only change on an hourly basis; (9) the levelized cost (the prorated cost of using the wind turbine) for wind energy is assumed to be \$0.04/kWh [8].

A brief discussion of model terminologies follows. The machine index is $i \in \{1, 2, \ldots, m\}$ and the job type index is $j \in \{1,2, \ldots, N_0\}$. The time index is $t \in \{1,2, \ldots, t_E\}$, and the time interval associated with t is 2 min. Therefore, the planning horizon in this model is $2 \cdot t_E$ min.

The size of the buffer that follows machine i is B_i, the basic power of machine i while idling is b_i. The required production quota for job type j is N_j. When a part of job type j is being processed on machine i, the processing time is $p_{i,j}$, and the working power is $q_{i,j}$. When the schedule is updated, the number of parts of job type j completed on machine i is $w_{i,j}$ and the time required to finish the current part of job type j on machine i is $v_{i,j}$. If $v_{i,j}$ is zero, the machine can start any job after the schedule update and F_i indicates if $v_{i,j}$ is zero. At time t, the forecasted wind power is WE_t, the forecasted real-time electricity price is P_t (\$/kWh), and the feed-in tariff (revenue) of the wind electricity into the grid is Ft_t (\$/kWh).

The decision variables are: $a_{i,t}$ is 1 if machine i is turned on at time t, and 0 otherwise. $x_{i,t}$ is 1 if machine i is on at time t, and 0 otherwise. $z_{i,j,t}$ is 1 if machine i is processing a part of job j at time t, and 0 otherwise. $y_{i,j,t}$ equals to 1 if a part of job j is started on machine i at time t, and 0 otherwise. $N_{i,j,t}$ is the part of job j finished on machine i at time t. $B_{i,t}$ is the inventory level of buffer stock at the downstream side of machine i at time t. EC (\$) is the expected total energy cost. pp_t (kW) is the power purchased from the grid at time t. ps_t (kW) is the power sold to the grid at time t. ϕ_t equals 1 if the wind energy is used to support the machines at time t, and 0 otherwise. ξ_t equals 1 if the power needed to run machines at time t exceeds the power generated by the wind turbine that is used to run the machines, and 0 otherwise. θ_t, $\alpha_{i,t}$, $\beta_{i,j,t}$ and $\tau_{i,t}$ are auxiliary variable to linearize $\xi_t \cdot \phi_t$,$\xi_t \cdot x_{i,t}$,$\xi_t \cdot y_{i,j,t}$ and $\xi_t \cdot a_{i,t}$. All variables at $t = 0$ are 0.

The objective of the MILP model is to minimize the expected total energy cost:

$$\mathrm{Min} EC = \sum_t (pp_t \cdot P_t - ps_t \cdot Ft_t) \quad (1)$$

Which is subject to,

$$F_i = \Sigma_j v_{i,j}, \forall i \in M \quad (2)$$

$$x_{i,t} \geq z_{i,j,t}, \forall i \in M, j \in J, t \in T \quad (3)$$

$$\Sigma_j z_{i,j,t} \leq 1, \forall i \in M, j \in J, t \in T \quad (4)$$

$$a_{i,t} \geq x_{i,t} - x_{i,t-1}, \forall v_{i,j} > 0, i \in M, t \in \left(v_{i,j}, t_E\right] \quad (5)$$

$$a_{i,t} \leq 1 - x_{i,t-1}, \forall v_{i,j} > 0, i \in M, t \in \left(v_{i,j}, t_E\right] \quad (6)$$

$$a_{i,t} \geq x_{i,t} - x_{i,t-1}, \forall F_i = 0, i \in M, t \in [1, t_E] \quad (7)$$

$$a_{i,t} \leq 1 - x_{i,t-1}, \forall F_i = 0, i \in M, t \in [1, t_E] \quad (8)$$

$$z_{i,j,t} \geq y_{i,j,t}, i \in M, j \in J, t \in T \quad (9)$$

$$\sum_{k=t}^{t+p_{i,j}-1} y_{i,j,k} \leq 1, \forall i \in M, j \in J, t \in T \quad (10)$$

$$\sum_{k=t}^{t+p_{i,j}-1} z_{i,j,k} \geq y_{i,j,t} \cdot p_{i,j}, \forall i \in M, j \in J, t \in \left(v_{i,j}, t_E\right] \quad (11)$$

$$z_{i,j,t} = 1, y_{i,j,t} = 0, a_{i,t} = 0, \forall i \in M, j \in J, t \in \left[1, v_{i,j}\right] \quad (12)$$

$$N_{i,j,t} = w_{i,j}, \forall i \in M, j \in J, t \in \left[1, p_{i,j}\right), v_{i,j} = 0 \quad (13)$$

$$N_{i,j,t} = \sum_{k=1}^{t-p_{i,j}+1} y_{i,j,k} + w_{i,j}, \forall i \in M, j \in J, t \in \left[p_{i,j}, t_E\right], v_{i,j} = 0 \quad (14)$$

$$N_{i,j,t} = w_{i,j}, \forall i \in M, j \in J, t \in \left[1, v_{i,j}\right), v_{i,j} > 0 \quad (15)$$

$$N_{i,j,t} = w_{i,j} + 1, \forall i \in M, j \in J, t \in \left[v_{i,j}, p_{i,j} + v_{i,j}\right), v_{i,j} > 0 \quad (16)$$

$$N_{i,j,t} = \sum_{k=v_{i,j}}^{t-p_{i,j}+1} y_{i,j,k} + w_{i,j} + 1, \forall i \in M, j \in J, t \in \left[p_{i,j} + v_{i,j}, t_E\right], v_{i,j} > 0 \quad (17)$$

$$w_{i,j} \geq w_{i+1,j} + z_{i+1,j,t}, \ \forall i \in M \ \{m\}, j \in J \quad (18)$$

$$N_{i,j,t-1} \geq N_{i+1,j,t-1} + z_{i+1,j,t}, \forall i \in M \ \{m\}, j \in J, t \in (1, t_E] \quad (19)$$

$$N_{i,j,t_E} \geq N_j, \forall i \in M, j \in J \quad (20)$$

$$B_{i,t} = \sum_j \left(w_{i,j} - w_{i+1,j} - z_{i+1,j,t}\right), \forall i \in M \ \{m\}, t \in \{1\} \quad (21)$$

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