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Models for integrated resource and operation scheduling

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Abstract

This paper deals with energy and human resource constraints in scheduling models. It outlines the influence of these resources, and the necessity to account for them in scheduling models. A parallel view of these resources is presented, and their characteristics are illustrated in the case study of a tubing plant.

Keywords: scheduling, energy, human resources, integrated models.

1. Introduction

As a part of production management, scheduling has been widely addressed in the process engineering literature (Pinto and Grossmann, 1998). According to Pinedo (Pinedo, 2002), "scheduling deals with the allocation of scarce resources to tasks over time. It is a decision-making process with the goal of optimizing one or more objectives." Most scheduling research deals with sequencing problems, assuming that processing times are constant and known. Many authors noticed that, unfortunately, those theoretical results are hardly applied in real situations.

Sometimes processing times can be variable, due to the scheduling itself. This happens when a resource is shared between some processing stages: operator working simultaneously on several machines, limited power provided to several energy-consuming equipments, etc. Processing times then depend on the operator (availability, efficiency, priority choices), the energy provided, and so on. Consequently, processing times and scheduling decisions are embedded, due to "secondary" resources essential to know the processing behaviour. These resources, generally considered at a real-time control level, have a significant influence on the scheduling objective.

2. Scheduling with secondary resources

Introducing secondary resources in scheduling models means that these resources have specific constraints (e.g. a limited capacity) and/or influence on the objective function (e.g. cost). In these cases, scheduling is not restricted to task sequencing.

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The Resource Constrained Project Scheduling Problem (RCPSP) can be view as a general frame for these problems. A limited amount of renewable resources is shared between the operations. Each operation needs a fixed amount of each resource to be performed. Operation start and end times are then necessary to determine the cumulative resource needs at any time. Precedence constraints represent the sequence of operations. Solving approaches take advantage of problems specificities: few precedence constraints (project scheduling), disjunctive resources (job shop scheduling). However, the problem remains complex. Another solution is to separate operation and secondary resource scheduling in two steps (Boukas, Haurie and Soumis, 1990).
When operations can be performed with a variable amount of resource, processing times are a function of this amount. Resource assignment decisions set the amount of resource for each operation at any time. Integrated scheduling must then solve simultaneously three problems: sequencing, start/end times determination and secondary resource assignment over time (Daniels and Mazzola, 1994).

3. Energy in scheduling models

Energy may be an important part of production costs in the process industry. However, it has been often considered as an uncompressible cost, or hidden in a global bill without seeking for the origin of the consumption. Recently, some research in sustainable development addressed this problem, for strategic and tactic decisions: energy exchange between plants (korhonen, 2002), long-term maintenance scheduling for better energy utilization (Cheung and Hui, 2004). Some years earlier, Kondily *et al.* (Kondily, Shah and Pantelides, 1991) presented an algorithm for the planning of multiproduct energy intensive continuous operations. For short-term decision, Corominas *et al.* (Corominas, Espuña and Puigjaner, 1994) studied energy-saving by heat exchange between operations.

3.1 Processing time

In scheduling problems, energy is treated as a renewable resource, shared by the process units. Capacity constraints represent the amount of energy available at any time (e.g. maximal power). Processing times may depend on the amount of resource provided. Continuous models (linear or not) describe processing time evolution, according to the equipment unit, the product and the operation.
In (Corominas, Espuña and Puigjaner, 1994), the authors notice an energy-time trade off. Cycle time variations are due to decisions on operation start times, taken to optimize heat exchanges by operation synchronization. When processing time depends on the energy provided, another type of decision appears: assignment decisions.

3.2 Energy assignment

Energy delivered to the units varies over time according to operation needs and assignment decisions. Scheduling aims at determining the assignment, along with operations start/end times and operation sequence, which give the best objective.
Assignment models rely on the energy evolution: evolution on the time axis (when does the energy value change?) and on the values axis (how does it change?). For time evolution three policies are possible:

- Free change: the energy provided to the units can change continuously;

- Periodic change: energy delivery is re-evaluated at each period;
- Event change: for example, the configuration changes after the end of an operation.

These policies may be combined to fit with the process behavior, but this induces more complex models. A periodic approach with sufficiently small periods can be a satisfying way to represent in a same model the three policies.

Energy value evolution also obeys to different constraints, according to equipment characteristics. For example, overall energy provided to the process may not increase too rapidly. Similarly, for a single unit, energy increase may be bounded, involving a continuous shape to the energy evolution curve.

4. Human resources in scheduling models

Even though human resources (HR) are more important in manufacturing, they can have a significant action in the process industry. Due to variations of the demand, flexible organizations induce both more complex tasks and more important HR costs. Some research present scheduling approaches, integrating human resources, for parallel machines (Chen, 2004, Daniels, Hoopes and Mazzola, 1996), and flow shops (Daniels and Mazzola, 1994, Daniels Mazzola and Shi, 2004), where processing times vary according to the number of operators allocated to the tasks.

4.1 Processing time

HR are renewable resources, but the capacity is not constant: operator availability varies with shifts, breaks and days-off. We identify three situations where processing times vary due to HR:

- When an operator can run several machines. His work is shared between these machines and consequently productivity decreases on each machine. Various operating modes can be defined, to improve the productivity of one machine or another.
- When work posts need several operators to run. The number of operators assigned to a work post determines the productivity of this post.
- When productivity varies with skill or experience (or learning, etc.). Then individual assignment has an influence on processing time.

Except for fatigue and learning, discrete models represent processing time variations, according to assignment and operating mode choices.

4.2 HR assignment

In theory, the three change policies presented for energy are applicable. However, periodic change (at rest or lunch breaks) and event change (end of operation) are more realistic. These changes affect the number of operators at each work post, or the number of machines assigned to an operator (the workshop configuration), and the individual assignment, according to skill, experience, etc. Finally, they affect the operating modes.

4.3 Personnel scheduling

HR are subject to legal constraints and specific agreements on the work duration, schedule, rest, etc. These constraints introduce interruptions, delays in some operations. Many research deals with this topic, but few approaches integrate it into scheduling

(Mercier, Cordeau and Soumis, 2003). These approaches generally consider a discrete time horizon, and use column generation to deal with these problems.

5. Case study

The case study is a tubing plant in the Montreal area. The plant is divided in three main departments:

- Foundry: native and recycled metal is melted in induction melting furnace. Then, it is cast in individual billets and stored for further processing.
- Drawing mill: billets are heated and drawn into bars.
- Pipe-tubing: billets are heated and extruded to make pipes of different sizes, shapes and lengths.

These melting and heating processes use a huge quantity of energy: electricity, natural gas and steam. Electricity expenses account for more than half the annual energy costs for the plant. Non regular power consumption peaks occur and cause high electricity bills. The subscription is 10 700 kW, while the average consumption power is about 65% of subscription. However, consumption along the day is highly irregular, leading to overspendings. Figure 1 shows the number of overspendings during the day. There are evident cuts at shift changes (7h00, 15h00 and 23h00) and break periods.

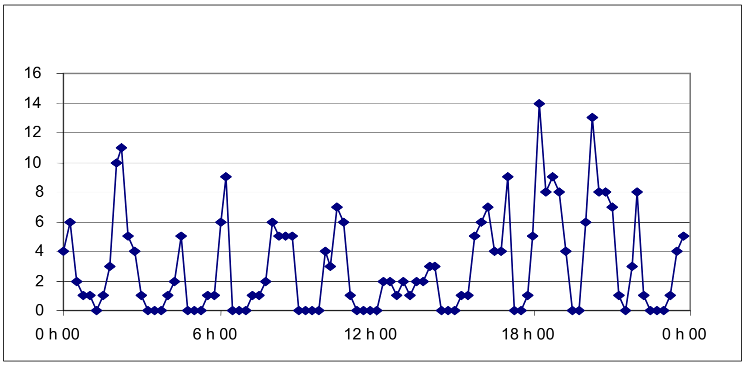

Figure 1. Number of overspendings (mean values between 01-01-2002 and 29-03-2003)

Our goal is to limit these overspendings. A better synchronization of the furnaces would bring more regular electricity consumption and less power peaks, resulting in lower electricity costs. The following linear model minimises the electricity bill for the foundry. It is based on a formulation of the RCPSP (Gélinas, 2004).

There are m furnaces to perform n fusion operations. We assume that operation assignment to the furnaces and sequence on each furnace are known. Job j is composed of three consecutive operations: loading (duration a_j), fusion (duration function of the power provided to the furnace) and unloading (duration b_j). When fusion is completed, a minimal power p_{wait} is provided to the furnace until unloading. Loading and unloading are performed by an operator. The number of operators is limited to R.

Energy consumption and overspendings are estimated by the supplier every 15 minutes. The horizon is divided in U periods of 15 min. Each period u is subdivided in N steps, so that the horizon is also divided in $N.U$ steps. Period u starts at time $t_u = N.u$.

Nomenclature

d_j r_j	Due date of job j ($j \in [1;n]$). Release date of job j.	ef_j^u	Energy assigned to furnace i for the fusion of job $j \in I_i$ during period u.
x_j^t	=1 if the loading operation of job j begins at time t or before.	ew_j^u	Energy spent in furnace i during period u, waiting for unloading job j.
y_j^t	=1 if the unloading operation of job j begins at time t or before.	p_{min}, p_{max}	Min/max power in furnace i.
I_i	Set of jobs assigned to furnace i.	p_{wait}	Power in furnace i waiting for unloading.
A_i	Precedence links of I_i jobs. $A_i = \{(j_1, j_2) \mid j_1$ precedes j_2 in $i\}$.	sp_u	Energy consumption during period u.
e_j^u	Energy necessary to complete operation j at time t_u.	ov_u	Overspending during period u.
E_j	Energy necessary for job j.	P	Power subscription

Constraints

(1)	$x_j^{t+1} \geq x_j^t$	$\forall j, \forall t \in [r_j ; d_j - b_j - a_j - 2]$	Operation continuity.
(2)	$y_j^{t+1} \geq y_j^t$	$\forall j, \forall t \in [r_j + a_j ; d_j - b_j - 2]$	
(3)	$x_j^t = 0$	$\forall j, \forall t \leq r_j - 1$	Loading operations time window.
(4)	$x_j^t = 1$	$\forall j, \forall t \geq d_j - b_j - a_j$	
(5)	$y_j^t = 0$	$\forall j, \forall t \leq r_j + a_j - 1$	Unloading operations time window.
(6)	$y_j^t = 1$	$\forall j, \forall t \geq d_j - b_j$	
(7)	$x_j^{(t-aj)} \geq y_j^t$	$\forall j, \forall t \in [r_j + a_j ; d_j - b_j - 1]$	Precedence constraints.
(8)	$x_{j2}^t \leq y_{j1}^{(t-bj)}$	$\forall t, \forall i, \forall (j1, j2) \in A_i$	
(9)	$e_j^0 = E_j$	$\forall j$	Amount of energy necessary at time t_u to complete operation j.
(10)	$e_j^{u+1} = e_j^u - ef_j^u$	$\forall j, \forall u \in [0; U-1]$	
(11)	$ef_j^u \leq e_j^u$	$\forall j, \forall u \in [0; U-1]$	
(12)	$ef_j^u \leq p_{\max} \cdot \left(\sum_{t=N.u}^{N(u+1)-1} (x_j^{(t-aj)} - y_j^t) - ew_j^u / p_{wait} \right)$		Energy assigned to furnace i for fusion of job $j \in I_i$, during period u.
(13)	$ef_j^u \geq p_{\min} \cdot \left(\sum_{t=N.u}^{N(u+1)-1} (x_j^{(t-aj)} - y_j^t) - ew_j^u / p_{wait} \right)$		
(14)	$ew_j^u \geq p_{wait} \cdot \left(\sum_{t=N.u}^{N(u+1)-1} (x_j^{(t-aj)} - y_j^t) - ef_j^u / p_{\min} \right)$		$\forall j, \forall u \in [0; U-1]$
(15)	$\sum_j \left((x_j^t - x_j^{(t-aj)}) + (y_j^t - y_j^{(t-bj)}) \right) \leq R$ $\forall t \in [0; N.U - 1]$		Loading – unloading operator availability.
(16)	$sp_u = \sum_j \left(ef_j^u + ew_j^u \right)$	$\forall u \in [0; U-1]$	Energy consumption during period u.
(17)	$ov_u \geq sp_u - 1,1.P$	$\forall u \in [0; U-1]$	Overspending during period u.
(18)	$ov_u \geq 0$	$\forall u \in [0; U-1]$	
(19)	$x_j^t \in \{0,1\}$	$\forall j, \forall t \in [r_j ; d_j - b_j - a_j - 1]$	Binary variables
(20)	$y_j^t \in \{0,1\}$	$\forall j, \forall t \in [r_j + a_j ; d_j - b_j - 1]$	
(21)	$e_j^u \geq 0$	$\forall j, \forall u \in [0; U-1]$	Continuous variables.
(22)	$ef_j^u \geq 0$	$\forall j, \forall u \in [0; U-1]$	
(23)	$ew_j^u \geq 0$	$\forall j, \forall u \in [0; U-1]$	
(24)	$sp_u \geq 0$	$\forall u \in [0; U-1]$	

We wish to minimise the energy bill, function of subscription P, consumption sp_u and overspendings ov_u:

$$\min(f_1.P + f_2.\sum_u sp_u + f_3.\sum_u ov_u)$$

This basic model can be modified: operator availability could vary with time (lunch, rest), subscription P could be variable so the model would choose the best subscription to minimise the bill, etc. A Constraint Programming formulation could be used for the cumulative constraints (15), replacing the numerous variables x_j^t and y_j^t by the loading and unloading operation start times.

Conclusion

This paper outlines the importance of secondary resources in scheduling. Energy and human resources are influent on processing times and production costs. Their assignment may change during processing, in order to provide the resources to the operating units. Accounting for these resources in scheduling is still a challenging problem.

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