"INTEGRATING SCHEDULING WITH BATCHING AND LOT-SIZING: A REVIEW OF ALGORITHMS AND COMPLEXITY"

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INTEGRATING SCHEDULING WITH BATCHING AND LOT-SIZING: A REVIEW OF ALGORITHMS AND COMPLEXITY

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In many practical situations, batching of similar jobs to avoid set-ups is performed whilst constructing a schedule. On the other hand, each job may consist of many identical items. Splitting a job often results in improved customer service or in reduced throughput time. Thus, implicit in determining a schedule is a lot-sizing decision which specifies how a job is to be split. This paper proposes a general model which combines batching and lot-sizing decisions with scheduling. A review of research on this type of model is given. Some important open problems for which further research is required are also highlighted.

Key words: algorithms, batching, complexity, lot-sizing, scheduling

INTRODUCTION

Throughout this paper, we refer to *batching* as the decision of whether or not to schedule ***similar jobs*** contiguously. On the other hand, *lot-sizing* refers to the decision on when and how to split a production lot of ***identical items*** into sublots.

Batching of similar jobs is mainly done to avoid set-up times or set-up costs. Picture, for example, a production line for colour plastics. Customer orders for several hundred different colour shades may await production. These orders can be divided into major colour groups, such as reds, blues, etc., and within a colour group, say red, they may range from very light to dark red. Set-up times between colours from the same group are small, since it would be usual for production to graduate from lighter to darker shades. However, a large set-up is required when production switches from reds to blues, for example, since a thorough cleaning of the production line is necessary between the current colour (dark red) and the next colour (light blue). Because of these time-consuming and costly set-ups between different colour groups, production line efficiency is maximized by choosing a long run-length for each colour group. On the other hand, consider the orders for reds and blues, some of which may not be urgent, whereas others are due imminently. Customer service may then be improved by having smaller batches; for example, instead of producing a single large batch of reds in the current month and a single large batch of blues next month, it may be preferable to produce smaller batches of reds and blues in the current month to accommodate urgent orders and to process the remaining orders next month. Note that smaller batches tend to reduce average inventory levels.

Batching problems also occur in other environments, such as mechanical parts manufacturing. In the latter, it is common to adopt principles of group technology[1], whereby the factory layout is such that machines are grouped into cells. Each group technology cell then produces several families of jobs with similar production requirements. No machine set-ups are needed between two consecutively scheduled jobs from the same family, although a set-up is required between jobs of different families. In group technology, it is conventional to schedule contiguously all jobs from the same family. As shown in our colour plastics example above, this is not necessarily the best strategy. It may be better to partition each family of jobs into several batches, where all jobs of a batch are scheduled contiguously, and then schedule the batches. Solving these types of problems, therefore, requires both batching and scheduling.

We now concentrate on situations in which a job or lot consists of many identical items. Most scheduling models assume that no shipment of items is possible until the entire job is completed. However, in this case, the customer may be out of stock while awaiting delivery. Assume, for example, that a customer has a low inventory of some product and places a replenishment order consisting of a number of pallets to cover expected demand for the next few months. It may take several weeks to process the complete order. However, customer service is improved, firstly by producing a few pallets in the near future to cover the customer's demand during the current month, and then by satisfying the remaining part of the order at some later date. It is now apparent that if items or sublots may be shipped immediately upon completion, decomposing a job into sublots may improve customer service.

In multi-stage systems such as flow-shops, open-shops or job-shops, the creation of sublots permits the overlapping of different operations on the same job and may therefore reduce throughput time. Most scheduling models allow a job to be transferred to the next machine only when it is completed on the current machine. In a model which allows lot-sizing, however, a sublot can be transferred to the next machine and processed, while other items from the same job, but of a different sublot, are processed on the current machine. We refer to this process of allowing overlaps through the creation of sublots as *lot-streaming.* Thus, when the decomposition of jobs is allowed, a solution procedure requires the creation of sublots through lot-sizing or lot-streaming, as well as the scheduling of sublots.

There is a vast body of literature dealing with batching and lot-sizing[2,3], on the one hand, and with scheduling[4], on the other. However, both worlds seem to be very much apart. The scheduling literature nearly always assumes that batching and lot-sizing decisions are already taken. Similarly, research on batching and lot-sizing seldom considers sequencing issues. There are surprisingly few publications that contain elements of both fields. From the discussion above, however, it should be clear that batching, lot-sizing and scheduling decisions are strongly inter-related. Moreover, in the advent of CIM (Computer Integrated Manufacturing), batching, lot-sizing and scheduling decisions will have to be taken concurrently, i.e., they will be integrated and computer-controlled. Our motivation for studying the integration of scheduling with batching and lot-sizing should now be apparent.

This paper reviews research on scheduling which, additionally, involves an element of batching or lot-sizing. The next section describes a general model which requires both batching and lot-sizing decisions to be taken; this is followed by a discussion of applications of the model. The general model allows all trade-offs to be considered when integrating batching, lot-sizing and scheduling in a complex environment. An ultimate aim is to tackle this general model. Since solving the general model is beyond the scope of current methodology, subsequent sections survey research on submodels that integrate scheduling with batching and lot-sizing respectively. The paper concludes with some suggestions for further research.

A GENERAL MODEL

We now give a description of a general model which captures the notions of batching and lot-sizing. In all of the problems considered, *jobs* are to be scheduled on one or more *machines*.

Firstly, we describe a *single machine* problem. There are N jobs, each of which is assigned to one of F *families*. Each job j ($j = 1, \ldots, N$) becomes available for processing at time zero and requires a *processing time* p_j on the machine. Furthermore, job j contains q_j identical *items* (each requiring a processing time p_j/q_j). Implicit in a schedule is a partition of a job into *sublots*; all items of a sublot are scheduled contiguously. We distinguish between *discrete sublots* for which the processing requirement for a sublot is p_j/q_j times the (integer) number of items in a sublot, and *continuous sublots* where any split of the processing time p_j defines the sublots of job j. In the latter case, a sublot with processing time p, where $0 < p \leq p_j$, contains pq_j/p_j items, irrespective of whether this quantity is an integer. The continuous sublots model provides a good approximation to the discrete sublots case when q_j is large and is often much easier to analyze.

We now extend our model to the case where there are M machines. It is possible for different sublots of the same job to be processed concurrently on different machines. However, at any time, a sublot can be processed on at most one machine.

A *parallel machines* problem requires p_j units of processing of each job j to be performed; the machines are identical, so there is no requirement that the processing must be scheduled on a particular machine. The more general uniform and unrelated parallel machine models in which processing times depend on the assignment of sublots to machines are not discussed here.

Our model for *multi-stage* systems is now explained. A *flow-shop* requires each sublot to be processed on machines $1, \ldots, M$ in that order. In an *open-shop*, each sublot is processed once on each machine, but the machine routing, which can differ between sublots, forms part of the decision process. In a flow-shop and open-shop, the processing time p_{jm} of each job j on each machine m $(m = 1, \ldots, M)$ is specified. Different sized sublots are allowed on different machines, although in the flow-shop, no processing of a sublot on machine m $(m = 2, \ldots, M)$ is allowed until all sublots containing items from this machine-m sublot are completed on machine $m-1$. The more general *job-shop* problem in which different machine routings are prescribed for different jobs is not discussed here.

In all problems, each machine can process at most one sublot at a time. A schedule specifies sublot sizes, indicates which sublots are scheduled on which machine and defines a processing order for the relevant sublots on each machine. Machine set-ups for single and parallel machine problems are necessary as follows. If a sublot of a job from family g is sequenced first on a machine, a *major set-up* requiring time s_{0g} is needed. Also, after a sublot of a job from family f is scheduled, a major set-up requiring time s_{fg} is needed before a sublot of a job from family g $(g \neq f)$ is processed next. No major set-up is necessary between sublots of jobs belonging to the same family, however. Additionally, a *minor set-up* time t_j is required immediately before a sublot of job j is processed. If for each family g we have that s_{fg} is independent of f for $f \neq g$, i.e., if $s_{0g} = s_{fg} = s_g$ for all families f and g, where $f \neq g$, then set-up times are *sequence independent*; otherwise they are *sequence dependent*. We have defined a *set-up time* model in which no processing can occur on a machine while it is undergoing a set-up. A *set-up cost* model replaces these set-up times with set-up costs: c_{0g}, c_{fg} and b_j are costs corresponding to s_{0g}, s_{fg} and t_j respectively. We make the reasonable assumption that set-up times and costs satisfy the *triangle inequality*, i.e., $s_{fh} \leq s_{fg} + s_{gh}$ and $c_{fh} \leq c_{fg} + c_{gh}$, for all distinct families f, g and h including the case $f = 0$. For flow-shop and open-shop problems where the machines are not identical, set-ups may vary between machines; hence an additional index m may be necessary to specify set-up times and costs on machine m ($m = 1, \ldots, M$).

For each job j, we define a *due date* d_j which is applicable to each item i of job j, i.e., $d_i = d_j$. Furthermore, a positive (importance) *weight* w_j is divided equally over all q_j items of job j, i.e., $w_i = w_j / q_j$ for each item i of job j. Consider a typical item i of job j which belongs to sublot k in some schedule. In an *item completion time* model, item i is deemed to be completed immediately after its processing is finished. Alternatively, it may be assumed that item i is completed only when the processing of sublot k is finished or when the processing of job j is finished. These cases define *sublot completion time* and *job completion time* models respectively. Thus, having specified the model, the *completion time* C_i of each item i is easily determined for any schedule. Also, for each item i, its *lateness*

$$L_i = C_i - d_i$$

its *tardiness*

$$T_i = \max\{C_i - d_i, 0\}$$

and

$$U_i = \begin{cases} 1 & \text{if } C_i > d_i, \\ 0 & \text{otherwise,} \end{cases}$$

can be found. Possible objectives to be minimized are the ***maximum completion time*** $C_{\max} = \max_i\{C_i\}$, the ***maximum lateness*** $L_{\max} = \max_i\{L_i\}$, the ***total (weighted) completion time*** $\sum_i(w_i)C_i$, the ***total (weighted) tardiness*** $\sum_i(w_i)T_i$, or the ***(weighted) number late*** $\sum_i(w_i)U_i$, where each maximum and each summation is over all items i. For set-up cost models, the total set-up cost is added to the appropriate scheduling objective function to give an overall cost to be minimized.

It should be noted that we do not discuss preemption in our general model. As pointed out above, preemption of sublots is not allowed. However, an item can be split between different sublots under our continuous sublots model (although whether this corresponds to item preemption in the conventional sense depends on which objective function is assumed).

We conclude this section by adapting the three-field problem descriptor of Lawler et al.[4] to our general model. In this three-field notation, a problem type is represented by $\alpha|\beta|\gamma$, where α represents the machine environment, β defines the job characteristics and γ is the objective function. Let $\circ$ denote the empty symbol. The first field takes the form $\alpha = \alpha_1\alpha_2$, where α_1 and α_2 are interpreted as follows.

- $\alpha_1 \in \{\circ, P, F, O\}$:
  - $\alpha_1 = \circ$: a single machine;
  - $\alpha_1 = P$: identical (parallel) machines;

- $\alpha_1 = F$: a flow-shop;
- $\alpha_1 = O$: an open-shop.

- $\alpha_2 \in \{\circ, M\}$:
  - $\alpha_2 = \circ$: the number of machines is arbitrary;
  - $\alpha_2 = M$: there are a fixed number of machines M.

We note that for a single machine problem $\alpha_1 = \circ$ and $\alpha_2 = 1$, whereas $\alpha_1 \neq \circ$ and $\alpha_2 \neq 1$ for other problem types. The second field $\beta \subseteq \{\beta_1, \beta_2, \beta_3\}$ indicates job characteristics as follows.

- $\beta_1 \in \{\circ, s_f, s_{fg}\}$:
  - $\beta_1 = \circ$: there are no major set-up times;
  - $\beta_1 = s_f$: families are specified, each having a major sequence independent set-up time on each machine;
  - $\beta_1 = s_{fg}$: families are specified, each having a major sequence dependent set-up time on each machine.

- $\beta_2 \in \{\circ, q_j(\lambda, \mu)\}$:
  - $\beta_2 = \circ$: each job contains a single item;
  - $\beta_2 = q_j(\lambda, \mu)$: jobs containing several items may be split into sublots.
    - $\lambda \in \{c, d, *\}$:
      - $\lambda = c$: jobs are split into continuous sublots;
      - $\lambda = d$: jobs are split into discrete sublots;
      - $\lambda = *$: refers to both problems types $\lambda = c$ and $\lambda = d$.
    - $\mu \in \{j, i, s, *\}$:
      - $\lambda = j$: job completion times;
      - $\lambda = i$: item completion times;

- $\lambda = s$: sublot completion times;
- $\lambda = *$: refers to the three problem types $\lambda = j$, $\lambda = i$ and $\lambda = s$.

- $\beta_3 \in \{\circ, t_j\}$:
  - $\beta_3 = \circ$: there are no minor set-up times;
  - $\beta_3 = t_j$: for each job, a minor set-up time is incurred for each of its sublots on each machine.

Lastly, the third field defines the objective in the form $\gamma = \gamma_1 + \gamma_2 + \gamma_3$, where

- $\gamma_1 \in \{C_{\max}, L_{\max}, \sum C_i, \sum w_i C_i, \sum T_i, \sum w_i T_i, \sum U_i, \sum w_i U_i\}$;

while γ_2 and γ_3 define any major and minor set-up costs as follows.

- $\gamma_2 \in \{\circ, \sum c_f, \sum c_{fg}\}$:
  - $\gamma_2 = \circ$: there are no major set-up costs;
  - $\gamma_2 = \sum c_f$: families are specified, each having a major sequence independent set-up cost on each machine;
  - $\gamma_2 = \sum c_{fg}$: families are specified, each having a major sequence dependent set-up cost on each machine.

- $\gamma_3 \in \{\circ, \sum b_j\}$:
  - $\gamma_3 = \circ$: there are no minor set-up costs;
  - $\gamma_3 = \sum b_j$: for each job, a minor set-up cost is incurred for each of its sublots on each machine.

To illustrate the three-field descriptor, we present three examples.

$1|s_f|L_{\max}$ is the problem of scheduling families of jobs on a single machine to minimize the maximum lateness, where each job contains a single item. Major sequence independent set-up times are necessary when the machine switches to processing jobs from a different family, but there are no minor set-ups.

$P||\sum C_i$ is the problem of scheduling jobs on an arbitrary number of identical parallel machines to minimize the total completion time. Each job contains a single item and no machine set-ups are necessary.

$F2|q_j(c,s)|C_{\max}+\sum b_j$ is the problem of scheduling jobs, each containing several items, in a two-machine flow shop. Jobs may be split into continuous sublots and sublot completion times are assumed. There are no major set-ups, although a minor set-up cost is incurred whenever a sublot is processed on a machine. The objective is to minimize the maximum completion time plus the total set-up cost.

DISCUSSION OF THE MODEL

From the description above, it is clear that *standard* non-preemptive scheduling models which do not allow jobs to be split into sublots and which do not consider set-ups are special cases of our general model. Lawler et al.[4] present an excellent review of standard scheduling theory. Polynomial-time algorithms are known for some standard non-preemptive problems. For a single machine, the maximum lateness problem $1||L_{\max}$ is solved by the earliest due date (EDD) rule of Jackson[5], the total weighted completion time problem $1||\sum w_iC_i$ is solved by the shortest weighted processing time (SWPT) rule of Smith[6] and the number late problem $1||\sum U_i$ is solved by the algorithm of Moore.[7] For parallel machines, the total completion time problem $P||\sum C_i$ is solved by Conway et al.[8] using a generalization of the SPT rule. Finally, for two machines, maximum completion time problems for the flow-shop $F2||C_{\max}$ and open-shop $O2||C_{\max}$ are solved by algorithms of Johnson[9] and Gonzales and Sahni[10] respectively. This collection of problems is of primary concern in this paper. Most other standard non-preemptive problems, including the single machine weighted number late and the total (weighted) tardiness problems ($1||\sum w_iU_i$ and $1||\sum (w_i)T_i$), the parallel machine maximum completion time and total weighted completion time problems ($P||C_{\max}$ and $P||\sum w_iC_i$), the maximum lateness and total completion time problems for the two-machine flow-shop ($F2||L_{\max}$ and $F2||\sum C_i$) and open-shop ($O2||L_{\max}$ and $O2||\sum C_i$), and the maximum completion time problem for the three-machine flow-shop ($F3||C_{\max}$) and open-shop ($O3||C_{\max}$), are NP-hard.[10–16] Each problem in this latter collection is clearly NP-hard under our more general model.

We note that some special cases of our general model reduce essentially to a problem involving batching or to a problem involving lot-sizing. More precisely, if every job consists of a single item (and continuous sublots are not allowed), then we have a *batching problem*. On the other hand, a *lot-sizing problem* results if every family contains a single job. Below, we discuss some applications of the batching and lot-sizing problems.

Applications of the batching problem are varied. Machines which use different colours of paint provide an obvious instance where sequence dependent set-ups are necessary. Alternatively, consider the scheduling of tasks in a computer system. Each task has a requirement for a particular compiler to be resident in the computer's memory before it can be executed. If the appropriate compiler is resident, then the task may start immediately; otherwise a set-up is incurred to bring the relevant compiler into memory. In this example, a sequence independent set-up time is necessary to load the compiler into memory since this operation does not depend on which compiler is previously resident. A final example occurs when labour is a limiting resource.[17] Before a job can be processed on a particular machine, it may be necessary to switch an operator from another machine, thereby incurring a set-up.

We now discuss the practical relevance of our lot-sizing model. In the sublot completion time model, the completion times of the selected sublots define when deliveries occur. It may be argued that a sublot completion time model with set-up costs is of special interest: in effect, the set-up costs represent the extra delivery costs when shipping small quantities in a Just-In-Time environment. Also, the usefulness of lot-streaming in multi-stage systems should be clear from the increased industrial interest in smaller throughput times and the emphasis that recent production scheduling systems place on the desirability of overlapping operations.

The next two sections review research on batching and lot-sizing models respectively. The literature dealing with multi-machine models is sparse since most research has focused on single machine scheduling. Nevertheless, single machine scheduling algorithms are commonly used to schedule bottleneck machines in various production environments. Furthermore, results derived for single machine models often provide the basis for heuristic methods which are used to schedule more complex systems.

BATCHING MODELS

In this section, we review results on the batching model. Recall that for the batching model, every job consists of a single item which cannot be split. A major set-up time or cost is incurred when a machine switches from processing a job in one family to a job in another. There are no minor set-ups in a batching model. Throughout the discussion below, set-ups are assumed to refer to major set-ups.

Our main aim is to describe algorithms and state the computational complexity for the various problems of interest. A summary of results for sequence independent set-ups is shown in Table 1. (Where available, corresponding results for sequence dependent set-ups are given in the text.) Entries in Table 1 are listed according to whether the group technology assumption that all jobs within a family are scheduled contiguously is imposed, to whether a set-up time or set-up cost model is assumed and to whether the number of families F is fixed or arbitrary. It should be understood that both set-up times and costs are implicit under group technology, whereas either times or costs (but not both) are assumed for other entries in Table 1.

Single machine problems

We first discuss problems with sequence independent set-up times and costs under the group technology assumption that all jobs within a family are scheduled contiguously. For the maximum lateness and total weighted completion time problems, jobs within a family are sequenced in EDD order (non-decreasing order of d_j) and SWPT order (non-decreasing order of p_j/w_j) respectively. Furthermore, scheduling of families is straightforward if each family is treated as a single *composite job.*[19] Assume, without loss of generality, that jobs from the same family f ($f = 1, \ldots, F$) are numbered consecutively as $j, \ldots, k$. Furthermore, for the maximum lateness problem, assume that this numbering is consistent with an EDD ordering, i.e., $d_j \leq \ldots \leq d_k$. For both problems, the composite job corresponding to family f has processing time $s_f + \sum_{h=j}^{k} p_h$. The due date of the composite job corresponding to family f in the maximum lateness problem is $\min_{j' \in \{j,\ldots,k\}} \{d_{j'} + \sum_{h=j'+1}^{k} p_h\}$ and in the total weighted completion time problem the weight of the composite job is

Table 1. *Complexity of batching problems with sequence independent set-ups*

Problem	Group Technology	Set-up Times		Set-up Costs	
		Fixed F	Arbitrary F	Fixed F	Arbitrary F
$1\|s_f\|L_{\max}+\sum c_f$	$O(N\log N)$	$O(F^2N^{2F})$	NP-hard	$O(F^2N^{2F})$	NP-hard
$1\|s_f\|\sum C_i+\sum c_f$	$O(N\log N)$	$O(F^2N^F)$	open	$O(F^2N^F)$	open
$1\|s_f\|\sum w_iC_i+\sum c_f$	$O(N\log N)$	$O(F^2N^{2F})$	open	$O(F^2N^F)$	open
$1\|s_f\|\sum U_i+\sum c_f$	open	$O(F^2N^{F+1})$	NP-hard	$O(F^2N^{2F+1})$	NP-hard
$P\|s_f\|\sum C_i+\sum c_f$	open	open	open	open	open
$F2\|s_f\|C_{\max}+\sum c_f$*	$O(N\log N)$	$O(F^2N^{2F})$	open	$O(F^2N^{2F})$	open
$O2\|s_f\|C_{\max}+\sum c_f$	open	open	open	open	open

* Results refer to the permutation flow-shop.

$\sum_{h=j}^{k} w_h$. For the maximum lateness problem composite jobs are sequenced in EDD order, whereas for the total weighted completion time problem composite jobs are sequenced in SWPT order. These algorithms for the maximum lateness and total weighted completion time problems both require $O(N \log N)$ time. Unfortunately, the composite job approach does not extend to the number late problem.

We now turn our attention to the more general set-up time problem in which the group technology assumption is not imposed. Monma and Potts[18] derive results about the ordering of jobs within a family for single machine problems with sequence dependent set-up times; these results remain valid if set-up costs are additionally introduced. For the maximum lateness problem, jobs within each family are sequenced in EDD order, whereas they are sequenced in SWPT order for the total weighted completion time problem. Furthermore, on-time jobs in the weighted number late problem are sequenced in EDD order. Using the methodology of Lawler and Moore[20], a dynamic programming algorithm is derived by Monma and Potts for $1|s_{fg}|L_{\max}$ and $1|s_{fg}|\sum w_i C_i$. State variables indicate the number of jobs of each family that are scheduled (from which the set of scheduled jobs is deduced, since the order of jobs within each family is known), the number of times each of the F^2 types of set-up is used and the family to which the last scheduled job belongs. The completion time of the last scheduled job is easily computed from these state variables which enables objective function contributions to be evaluated. Using these algorithms, the time requirement for $1|s_{fg}|L_{\max}$ and $1|s_{fg}|\sum w_i C_i$ is $O(F^2 N^{F^2+F})$ and for $1|s_f|L_{\max}$ and $1|s_f|\sum w_i C_i$ is $O(F^2 N^{2F})$. For $1|s_{fg}|\sum C_i$, Ahn and Hyun[21] observe that objective function contributions can be evaluated without explicitly computing the completion time of the last scheduled job. Their dynamic programming algorithm avoids state variables which indicate the number of times each type of set-up is used, thereby yielding the time complexity for $1|s_{fg}|\sum C_i$ as $O(F^2N^F)$. A modified dynamic programming approach is needed for $1|s_{fg}|\sum w_iU_i$ because the presence of late jobs stops the computation of the completion time of the last scheduled on-time job from the number of jobs of each family scheduled and the number of each type of set-up. The algorithm of Monma and Potts assumes that each weight is an integer and uses as state variables the number of jobs of each family that are scheduled, the weighted number of late jobs amongst those considered and the family to which the last on-time job belongs; the minimum completion time of the last on-time job is stored as a function value. Using this algorithm, $1|s_f|\sum w_iU_i$ and $1|s_{fg}|\sum w_iU_i$ are solved in $O(F^2N^FW)$ time, where W is the sum of all job weights. This time complexity becomes $O(F^2N^{F+1})$ for $1|s_f|\sum U_i$ and $1|s_{fg}|\sum U_i$ in which $W = N$.

The recursions of Monma and Potts[18] can be modified to provide corresponding algorithms, with identical time complexities, for the maximum lateness and total weighted completion time problems in which set-up costs replace set-up times. Moreover, for $1||\sum w_iC_i + \sum c_{fg}$ the state variables representing numbers of times each type of set-up is used are not needed: set-up cost contributions are added to the objective function when a job is scheduled. The time complexity is therefore reduced to $O(F^2N^F)$, even for sequence dependent set-up costs. We note that this approach for the total weighted completion time problem is essentially equivalent to applying the algorithm of Baker and Schrage[22], where each precedence constraint chain corresponds to enforcing the SWPT sequence on the jobs of a family. For $1||\sum w_iU_i + \sum c_f$ and $1||\sum w_iU_i + \sum c_{fg}$, we require additional state variables indicating the number of times each type of set-up is used. This leads to a dynamic programming algorithm with a time complexity of $O(F^2N^{F^2+F}W)$ for $1||\sum w_iU_i + \sum c_{fg}$ and of $O(F^2N^{2F}W)$ for $1||\sum w_iU_i + \sum c_f$.

Reviewing the complexities of $1|s_{fg}|L_{\max}$, $1||L_{\max} + \sum c_{fg}$, $1|s_{fg}|\sum w_iC_i$, $1||\sum w_iC_i + \sum c_{fg}$, $1|s_{fg}|\sum U_i$ and $1||\sum U_i + \sum c_{fg}$, we observe that each is polynomially solvable when F is fixed. When F is arbitrary, results of Bruno and Downey[23] show that $1|s_f|L_{\max}$, $1||L_{\max}+\sum c_f$, $1|s_f|\sum U_i$ and $1||\sum U_i+\sum c_f$ are NP-hard. The complexity of $1|s_f|\sum(w_i)C_i$, $1|s_{fg}|\sum(w_i)C_i$, $1||\sum(w_i)C_i + \sum c_f$ and $1||\sum(w_i)C_i + \sum c_{fg}$ for arbitrary F remains open, however.

Zdrzałka[24] proposes heuristic methods for $1|s_f = 1|L_{\max}$ in which there are unit set-up times. To facilitate worst-case analysis, he assumes that all due dates are non-positive. When all jobs of a family are scheduled contiguously (as in the group technology assumption), the resulting schedule is shown to have a maximum lateness which does not exceed twice the optimal value. He also suggests an improvement which allows each family to be split into at most two batches. At each iteration of this procedure, a job is shifted from the first to the second batch of its family, after which the resulting batches are resequenced. This improved heuristic requires $O(N^2)$ time and generates a schedule for which the maximum lateness does not exceed 5/3 times that of an optimal schedule.

Mason and Anderson[25] propose a branch and bound algorithm for $1|s_f|\sum w_iC_i$. By incorporating various dominance rules to restrict the search, their algorithm is able to solve problems with up to 30 jobs. Gupta[26] and Ahn and Hyun[21] present heuristic methods for $1|s_{fg}|\sum C_i$. Gupta's method constructs partial schedules using the earliest completion time rule: the job which is appended to the current partial sequence is chosen so that its completion time is as small as possible. Ahn and Hyun suggest an improvement heuristic which attempts to reduce the total completion time of the current sequence by shifting contiguously scheduled jobs from the same family to another position. Computational results show that this improvement heuristic generates superior solutions to those obtained using Gupta's method.

Parallel machine problems

Following the approach of Monma and Potts[18], it is possible to derive dynamic programming algorithms for various parallel machine problems. Unfortunately, the resulting algorithms are of little practical interest because of their enormous space and time requirements. The complexity of $P|s_f|\sum C_i$, $P|s_{fg}|\sum C_i$, $P||\sum C_i + \sum c_f$ and $P||\sum C_i + \sum c_{fg}$ is open.

Under the assumption that all items have a common due date, So[27] proposes three heuristic methods for the following variant of $P|s_f, q_j(d,i), t_j|\sum w_i U_i$. (Although this model involves lot-sizing in addition to batching, it is appropriate to discuss it in this section.) The q_j items of job j ($j = 1, \ldots, N$) are not identical, although, within each job, item weights are assumed to be 'agreeable': items of each job can be listed so that their processing times are non-decreasing and their weights are non-increasing. Two of the heuristics employ pseudopolynomial dynamic programming procedures to generate a schedule. The first schedules the machines sequentially with a view to maximizing the total weight of scheduled items at each stage, while the second solves a single machine problem obtained by aggregating capacities and then assigns the scheduled jobs to the original machines. The third heuristic is a greedy method which, at each iteration, selects and schedules several items of a job on a machine so that they are on time: the items and the machine are chosen so that the ratio of total weight to total processing plus (major and minor) set-up time is as large as possible. Computational tests indicate that the schedules generated by the greedy method are usually at least comparable with those given by the computationally more expensive heuristics which use dynamic programming.

Flow-shop and open-shop problems

Firstly, we concentrate on the maximum completion time problem in a flow-shop with sequence independent set-ups under the group technology assumption that all jobs of a family are scheduled contiguously. For two machines, Sekiguchi[28] shows that jobs within each family are sequenced according to Johnson's rule[9] and he derives a composite job approach to schedule families. This yields an algorithm which requires $O(N \log N)$ time for set-up times and costs. Vakharia and Chang[29] perform a computational comparison of various heuristic methods on problems with more than two machines. They find that a simulated annealing heuristic provides good quality solutions at reasonable computational expense.

When the group technology assumption is not imposed, it is straightforward to construct two-job instances of $F2|s_{fg}|C_{\max}$ and $F2||C_{\max} + \sum c_{fg}$ for which no optimal schedule has identical processing orders on each machine. However, for $F2|s_f|C_{\max}$ and $F2||C_{\max} + \sum c_f$, it is unclear whether processing orders on both machines may be assumed identical. If the permutation flow-shop is considered in which processing orders are constrained to be identical, then it can be shown that jobs within a family are sequenced by Johnson's rule for $F2|s_{fg}|C_{\max} + \sum c_{fg}$. Furthermore, using the same state variables as for $1|s_{fg}|L_{\max}$ and $1|s_{fg}|\sum w_iC_i$, the dynamic programming approach of Monma and Potts[18] can be employed. The completion time of the last scheduled job on the first machine is easily computed from the state variables and its completion time on the second machine is stored as a function value. The resulting algorithm requires $O(F^2N^{F^2+F})$ time for $F2|s_{fg}|C_{\max}$ and $F2||C_{\max}+\sum c_{fg}$, and requires $O(F^2N^{2F})$ time for $F2|s_f|C_{\max}$ and $F2||C_{\max}+\sum c_f$, where the permutation flow-shop is assumed in each case. For arbitrary F, however, the complexity of $F2|s_f|C_{\max}$ and $F2||C_{\max}+\sum c_f$ is open.

No results are currently available for the maximum completion time in a two-machine open-shop. A key issue concerns the existence, or otherwise, of an optimal solution of $O2|s_f|C_{\max}$ and $O2||C_{\max}+\sum c_f$ in which all jobs within a family are scheduled contiguously, i.e., the group technology assumption is satisfied.

LOT-SIZING MODELS

We survey results on lot-sizing models in this section. Recall that for the lot-sizing model, every family consists of a single job. There are no major set-ups between sublots of different jobs, although minor set-ups between sublots may be necessary. Thus, throughout this section, a set-up is assumed to refer to a minor set-up.

As in the previous section, we describe algorithms and state the computational complexity for the various problems of interest. Table 2 summarizes results for the job, item and sublot completion time models. Even though there are minor differences in approach in some cases, the results of Table 2 are valid irrespective of whether a set-up time or a set-up cost model is adopted and of whether discrete

Table 2. *Complexity of lot-sizing problems*

Problem	Completion Times		
	Job: $\mu = j$	Item: $\mu = i$	Sublot: $\mu = s$
$1 \mid q_j(*, \mu), t_j \mid L_{\max} + \sum b_j$	$O(N \log N)$	$O(N \log N)$	$O(N \log N)$
$1 \mid q_j(*, \mu), t_j \mid \sum (w_i) C_i + \sum b_j$	$O(N \log N)$	$O(N \log N)$	open*
$1 \mid q_j(*, \mu), t_j \mid \sum U_i + \sum b_j$	NP-hard	NP-hard	NP-hard
$P \mid q_j(*, \mu), t_j \mid \sum C_i + \sum b_j$	NP-hard	NP-hard	NP-hard
$F2 \mid q_j(*, \mu), t_j \mid C_{\max} + \sum b_j$	open	open	open
$O2 \mid q_j(*, \mu), t_j \mid C_{\max} + \sum b_j$	$O(N)$	$O(N)$	$O(N)$

* $1 \mid q_j(c, s) \mid \sum (w_i) C_i + \sum b_j$ is solvable in $O(N \log N)$ time.

or continuous sublots are assumed.

Single machine problems

We concentrate first on job completion time models for a single machine. A simple interchange argument shows that for the objective functions considered in this paper, there is no advantage in splitting a job into sublots (although if jobs have different release dates, splitting may be beneficial). Thus, standard scheduling algorithms may be useful. For instance, $1|q_j(*,j),t_j|L_{\max}+\sum b_j$ is solved by sequencing jobs in EDD order and $1|q_j(*,j),t_j|\sum w_iC_i+\sum b_j$ is solved by sequencing jobs in non-decreasing order of $(t_j+p_j)/w_j$. However, $1|q_j(*,j)|\sum U_i$ is equivalent to $1||\sum w_iU_i$ (where the weight in the latter problem corresponds to the number of items in a job in the former problem). Thus, $1|q_j(*,j)|\sum U_i$ is NP-hard.

Next, item completion time models are considered. Again, an interchange argument shows that for $1|q_j(*,i),t_j|L_{\max}+\sum b_j$ and $1|q_j(*,i),t_j|\sum w_iC_i+\sum b_j$, there is an optimal solution in which no jobs are split (Santos[30] proves this for the maximum lateness problem and Dobson et al.[31] prove it for the total weighted completion time problem). Solution procedures for these two problems, therefore, are identical with those for the job completion time model. For $1|q_j(*,i),t_j|\sum U_i+\sum b_j$, it is easily verified that jobs are split into at most two sublots which contain on-time and late items respectively. It can also be shown that $1|q_j(*,i),t_j|\sum U_i$ is NP-hard when all jobs have a common due date and that $1|q_j(*,i)|\sum U_i+\sum b_j$ is NP-hard (for arbitrary due dates).[32]

Finally, we concentrate on the sublot completion time model. It is easily verified that $1|q_j(*,s),t_j|L_{\max}+\sum b_j$ is again solved by sequencing jobs in EDD order, without splitting into sublots. Furthermore, identical reductions to those used for the item completion time model can be employed to show that $1|q_j(*,s),t_j|\sum U_i$ and $1|q_j(*,s)|\sum U_i + \sum b_j$ are NP-hard. The problem $1|q_j(c,s)|\sum w_i C_i + \sum b_j$ is solved in $O(N \log N)$ time as follows. Firstly, sublots are sequenced in SWPT order which indicates that all sublots of the same job are scheduled contiguously. Secondly, it can be shown that all sublots of the same job should contain the same number of items. Lastly, the number of sublots for job j ($j = 1, \ldots, N$) is either $\lfloor \sqrt{p_j w_j/(2b_j)} \rfloor$ or $\lceil \sqrt{p_j w_j/(2b_j)} \rceil$ ($\lfloor x \rfloor$ is the largest integer which is less than or equal to x; $\lceil x \rceil$ is the smallest integer which is greater than or equal to x); the one which yields the smaller overall cost is selected. For the case of a single job, $1|q_j(*,s),t_j|\sum(w_i)C_i$ is analyzed by Dobson et al., Santos and Magazine[33] and Naddef and Santos.[34] For $1|q_j(c,s),t_j|\sum(w_i)C_i$, Dobson et al. show that the job should be divided into k sublots, where $k = \lceil \sqrt{(t+8p)/(4t)} - 1/2 \rceil$ (since there is a single job, the subscripts on t, q and p are dropped), where sublot h ($h = 1, \ldots, k$) contains $x_h = q/k + tq(k+1)/(2p) - htq/p$ items. They also propose constructive and improvement heuristics for the N-job problem. Naddef and Santos derive analogous results the single-job problem $1|q_j(d,s),t_j|\sum(w_i)C_i$. They propose an algorithm in which, firstly, k sublots are considered and sublot sizes $\lfloor x_1 \rfloor, \ldots, \lfloor x_k \rfloor$ are set. Remaining items are assigned to sublots using a greedy approach. The entire procedure is repeated with the value of k reduced by one and the better of the two solutions is selected. Naddef and Santos also propose a heuristic for the corresponding N-job problem. For every job, their method schedules all its sublots contiguously. In spite of these results for a single job, the complexity of the N-job problem $1|q_j(*,s),t_j|\sum(w_i)C_i$ is open.

We claim that $P2|q_j(*,*),t_j|\sum C_i$ and $P2|q_j(*,*)|\sum C_i + \sum b_j$ are NP-hard (irrespective of whether discrete or continuous sublots are considered or of whether a job, item or sublot completion time model is assumed). Arguing informally, by assigning large set-up costs, jobs will not be split into sublots. Similarly, a large set-up time relative to the processing time will also prevent a split. Thus, given an instance of the NP-hard problem $P2||\sum w_iC_i$ with integer weights, it is possible to construct an equivalent instance of $P2|q_j(*,*),t_j|\sum C_i$ or $P2|q_j(*,*)|\sum C_i + \sum b_j$ in which the number of items in a job corresponds to the weight in $P2||\sum w_iC_i$.

Monma and Potts[18] show that $P2|q_j(c,*),t_j|C_{\max}$ is NP-hard. A straightforward modification of this reduction shows that $P2|q_j(c,*)|C_{\max} + \sum b_j$ is also NP-hard. Note that $P2|q_j(d,*)|C_{\max}$ is NP-hard since it is equivalent to $P2||C_{\max}$ when each job contains a single item. Monma and Potts[35] also propose a heuristic which is applicable to $P|q_j(c,*),t_j|C_{\max}$. In its first phase, the heuristic applies list scheduling to jobs listed in non-increasing order of set-up times; i.e., the procedure of assigning the first unscheduled job on the list to the machine with the least load is applied until all jobs are scheduled. Provided it leads to a decrease in maximum completion time, the second phase splits the last job assigned to the most heavily loaded machine into two sublots and reschedules one of these sublots in the first position on the least heavily loaded machine. Sublot sizes are chosen so that this pair of machines become equally loaded. A different machine pair is selected similarly and the splitting procedure is repeated until $\lfloor M/2 \rfloor$ pairs are considered or until no reduction in completion time is possible. The procedure requires $O(N \log N)$ time and generates a schedule which has a maximum completion time which does not exceed $5/3 - 1/M$ if $M \geq 4$, $5/4$ if $M = 2$, or $11/8$ if $M = 3$, times that of an optimal schedule. These results are also extended to $P|s_f, q_j(c,*)|C_{\max}$.

Flow-shop and open-shop problems

Firstly, we review the lot-streaming problems $F|q_j(c,*)|C_{\max}$ for which the job, item and sublot completion time models are equivalent. Our discussion assumes an identical number of sublots on each machine. Potts and Baker[36] show that it is sufficient to consider sublot sizes which are the same on the second machine as they are on the first machine and which are the same on machine M as they are on machine $M-1$. When sublot sizes do not vary between machines they are *consistent.* Thus, consistent sublots solve problems with two or three machines. Potts and Baker also derive sublot sizes for $F2|q_j(c,*)|C_{\max}$ when there is a single job containing q items. Let $\rho = \beta/\alpha$, where α and β are the processing times of the job on the first and second machines respectively. If k sublots are allowed on each machine, then sublots containing $\rho^{h-1}q/(1+\rho+\ldots+\rho^{k-1})$ items for $h = 1,\ldots,k$ yield the minimum value $M_k = \alpha(1+\rho^k/(1+\rho+\ldots+\rho^{k-1}))$ of the maximum completion time. If there are set-up costs b_1 and b_2 on the machines, then a search for a value of k which minimizes the overall cost $M_k + (b_1+b_2)k$ can be performed. For the case that there is a single job and two sublots are allowed on each machine, Baker and Pyke[37] describe an $O(M)$ algorithm which finds consistent sublot sizes for $F|q_j(c,*)|C_{\max}$. No results are currently available for the lot-streaming of an arbitrary number of jobs: even $F2|q_j(c,*)|C_{\max}$ is open.

We now analyze $O2|q_j(c,*)|C_{\max} + \sum b_j$. Let b_{jm} denote the set-up cost incurred for each sublot of job j ($j = 1,\ldots,N$) on machine m ($m = 1,2$). Let

$P_m = \sum_{j=1}^{N} p_{jm}$ and $B_m = \sum_{j=1}^{N} b_{jm}$ for $m = 1, 2$. If $p_{j1} + p_{j2} \leq \max\{P_1, P_2\}$ for all jobs j, then applying the $O(N)$ algorithm of Gonzales and Sahni, without splitting jobs, yields an optimal solution with a minimum overall cost ($C_{\max}$ plus total set-up cost) of $\max\{P_1, P_2\} + B_1 + B_2$. Alternatively, if $p_{j1} + p_{j2} > \max\{P_1, P_2\}$ for some job j, then the Gonzales and Sahni algorithm produces a schedule with an overall cost of $p_{j1} + p_{j2} + B_1 + B_2$. If job j is split into sublots of equal size on both machines, then the overall cost becomes $\max\{P_1, P_2\} + B_1 + B_2 + b_{j1} + b_{j2}$. Since no further reduction in the maximum completion time is possible, an optimal solution is selected from these two alternatives on the basis of overall cost. Clearly, to apply this procedure requires $O(N)$ time. A similar, although slightly more complicated algorithm, which also allows just two sublots of the longest job to be created, solves $O2|q(c,*), t_j|C_{\max} + \sum b_j$ in $O(N)$ time.

CONCLUDING REMARKS

We have described a model which, in its most general form, requires decisions to be taken on batching and lot-sizing whilst a schedule is constructed. Very little research appears to have been undertaken on this general model. The limited research on special cases, where either batching or lot-sizing decisions are made, is reviewed in the previous sections. In view of the practical importance of the general model and of the theoretical interest in many of the special cases, it is rather surprising that this area has not received more attention. Some interesting areas for future research are outlined below.

In the area of batching models, one of the most vexing issues is the complexity of $1|s_f|\sum(w_i)C_i$ and $1||\sum(w_i)C_i + \sum c_f$. Other open problems in batching include the complexity of the $F2|s_f|C_{\max}$, $F2||C_{\max} + \sum c_f$, $O2|s_f|C_{\max}$ and $O2||C_{\max} + \sum c_f$. The derivation of a branch and bound algorithm and the design and worst-case analysis of heuristic methods for $1|s_f|L_{\max}$ are also the subject of our current research.

Some of the more interesting problems that arise in lot-sizing and lot-streaming are, at best, only satisfactorily solved for a single job. For instance, although $1|q_j(*, s), t_f|\sum(w_i)C_i$ is well-understood for a single job, no complexity result is available for an arbitrary number of jobs. Even less is known about lot-streaming in flow-shops. Attempts should be made to extend the preliminary results of Potts and Baker[36] so that set-up times can be incorporated and so that more than one job and more than two machines can be handled. An extension of lot-streaming to objectives other than the maximum completion time would also form an interesting research topic.

Finally, we mention the investigation of preemption penalties as a research topic in preemptive scheduling. Conventionally, in the literature on preemptive scheduling, there is no penalty when a job is preempted. In practice, however, it is rather unusual for a machine to be able to operate on a job immediately after processing on the previous job is terminated: it is more likely that some machine idle time is incurred which can be represented by a set-up. This situation can be handled by adopting continuous sublots in our lot-sizing model. Using this approach, Monma and Potts[35] study the worst-case performance of heuristics for $P|q_j(c, *), t_j|C_{\max}$. There is also scope for research on the effect of preemption penalties in single machine problems when jobs have release dates.

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88/46	Yves DOZ and Amy SHUEN	**"From intent to outcome: a process framework for partnerships"**, August 1988.
88/47	Alain BULTEZ, Els GIJSBRECHTS,	**"Asymmetric cannibalism between substitute items listed by retailers"**, September 1988.

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91/05 OB	Susan SCHNEIDER	**"Managing Boundaries in Organisations,"** January 1991
91/06 OB	Manfred KETS DE VRIES, Danny MILLER and Alain NOEL	**"Understanding the Leader-Strategy Interface: Application of the Strategic Relationship Interview Method,"** January 1990 (89/11, revised April 1990)

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