"HEURISTICS FOR THE DISCRETE LOTSIZING AND SCHEDULING PROBLEMS WITH SETUP TIMES"

by

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Heuristics for the Discrete Lotsizing and Scheduling Problem with Setup Times

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Abstract

In this paper the Discrete Lotsizing and Scheduling Problem (DLSP) with setup times is considered. DLSP is the problem of determining the sequence and size of production batches for multiple items on a single machine. The objective is to find a minimal cost production schedule such that dynamic demand is fulfilled without backlogging.
DLSP is formulated as a Set Partitioning Problem (SPP). We present primal and dual heuristics to solve SPP, using column generation. The quality of the solutions can be measured, since the heuristics generate lower- and upper bounds. Computational results on a personal computer show that the heuristics are rather effective, both in terms of quality of the solutions as well as in terms of required memory and computation time.

Keywords: Column Generation, Heuristics, Set Partitioning, Lotsizing with Setup Times.

1 Introduction

The Discrete Lotsizing and Scheduling Problem (DLSP) is the problem of determining a minimal cost production schedule for multiple items on a single machine. Demand for each item is dynamic and backlogging is not allowed. The time horizon is segmented into a finite number of periods and in each period at most one item can be produced. Before production can start, a setup is made. The setup cost and the time required for a setup are item dependent. Production takes place to fulfil either present or future demand. In the latter case inventory holding costs are incurred in addition to the production costs.
Mathematically, DLSP can be formulated as the following integer program:

DLSP :

$$Z_{DLSP} = \min \sum_{i=1}^{N} \sum_{t=1}^{T} (S_i v_{i,t} + h_i I_{i,t} + p_{i,t} y_{i,t}) \tag{1}$$

subject to

$$\sum_{i=1}^{N} y_{i,t} + \sum_{i \in \mathcal{A}} v_{i,t} \leq 1 \qquad t = 1, .., T. \tag{2}$$

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$$I_{i,t-1} + y_{i,t} - d_{i,t} = I_{i,t} \qquad i = 1,..N;\ t = 1,..,T. \tag{3}$$

$$v_{i,t-a_i+\tau} \geq y_{i,t} - y_{i,t-1} \qquad i \in \mathcal{A};\ t = a_i + 1,..,T;\ \tau = 0,..,a_i - 1 \tag{4a}$$

$$v_{i,t} \geq y_{i,t} - y_{i,t-1} \qquad i \notin \mathcal{A};\ t = 1,..,T \tag{4b}$$

$$I_{i,t} \geq 0 \qquad i = 1,..,N;\ t = 1,..,T. \tag{5}$$

$$y_{i,t}, v_{i,t} \in \{0,1\} \qquad i = 1,..,N;\ t = 1,..,T. \tag{6}$$

In this model $y_{i,t}$ equals one if production for item i takes place in period t and $y_{i,t}$ equals zero otherwise. If the machine is being setup for item i in period t, the binary decision variable $v_{i,t}$ equals one. Furthermore, the nonnegative decision variable $I_{i,t}$ represents the on-hand inventory level of item i at the end of planning period t. The initial stock position for item i is given by the predetermined variable $I_{i,0}$. The objective (minimizing the sum of setup costs, inventory holding costs and production costs) is expressed by (1). To explain the setup cost structure we first define a **batch** of item i as an uninterrupted sequence of periods in which production takes place for item i. Setup costs for item i (S_i) are incurred in each of the a_i periods in which the machine is being setup before the production of a batch. If the setup time is zero, setup costs are incurred in the first production period of a batch. The holding costs and the production costs for item i in period t are expressed by the terms $h_i I_{i,t}$ and $p_{i,t} y_{i,t}$ respectively. The set of machine capacity constraints (2) guarantees that in each period the machine is either in setup or in production for at most one item, or the machine is idle. The sets of constraints (3) and (5) assure that the demand $d_{i,t}$ for item i in period t is fulfilled without backlogging. Without loss of generality we assume binary demand, i.e. $d_{i,t} \in \{0,1\}$ (see Magnanti and Vachani 1990). Constraints (4a) ensure that a production batch for item $i \in \mathcal{A}$ can only start after a fixed setup time of a_i periods. Here $\mathcal{A}$ is defined as the set of items with positive setup time, thus $\mathcal{A} = \{i = 1,\ldots,N | a_i > 0\}$. Constraints (4b) are coupling constraints between setup and production variables for items $i \notin \mathcal{A}$. Finally, the binary character of the setup and production variables is expressed by (6) while the initial machine state is specified by the predetermined variables $y_{i,\tau}$ for $\tau = 0,..,\max(0, a_i - 1)$.

DLSP has received much attention in recent literature. Van Wassenhove and Vanderhenst (1983) describe a hierarchical production planning scheme in which the single item DLSP appears as a subproblem. Magnanti and Vachani (1990) describe a solution procedure based on polyhedral methods for DLSP with zero setup times. In addition, they formulate -but do not solve- the problem with setup times. Fleischmann (1990) suggests a branch and bound procedure for DLSP with zero setup times. Lower bounds are obtained through Lagrangean relaxation of the machine capacity constraints and upper bounds are derived by successive approximation techniques. Fleischmann and Popp (1988) adapt the procedure in Fleischmann (1990) to handle sequence-dependent setup cost. Recently, Salomon et al. (1989) have introduced a model classification for several DLSP variants, including parallel machine problems and problems with nonzero setup times. In addition, they prove that DLSP with zero setup times is NP-Hard, and finding a feasible solution to the DLSP constraints (2), (3), (4), (5) and (6) is NP-Complete, even if all setup times are equal to one period. For a fixed number of items, Dynamic Programming (DP) algorithms that solve DLSP in pseudo-polynomial time are given. However, these algorithms are mainly of theoretical interest, since computation times and memory requirements grow too large for problem sizes of practical interest. Finally, for the single item problem with zero setup times and constant production costs Kuik et al. (1989) suggest variable splitting methods and introduce an $O(T \log T)$ algorithm, based on DP.

This paper is organized as follows. In Section 2 we describe three heuristics for DLSP with nonzero setup times. The heuristics are based on column generation techniques in which the master problem is formulated as a Set Partitioning Problem. Similar techniques have been successfully applied to a large number of (integer) linear programming problems, like the generalized assignment problem (Cattrysse and Van Wassenhove 1989), crew scheduling problems (Lavoie et al. 1988), routing problems (Desrosiers et al. 1984) and capacitated lot sizing problems (CLSP) by Cattrysse et al. (1990).
In the three heuristics new columns are generated using DP, but the heuristics differ in the way the master problem is solved. The first heuristic uses the *primal* simplex method, the second heuristic uses the *dual* simplex method, while the third heuristic uses a dual ascent procedure combined with subgradient optimization. In addition, the heuristics contain procedures to search for feasible solutions.
Section 3 reports on a computational comparison between our heuristics and Section 4 presents some conclusions and suggests directions for further research.

2 Column generation heuristics

To solve DLSP we discuss a column generation approach (see e.g. Lasdon 1970). The *master problem* is formulated as a Set Partitioning Problem (SPP):

SPP :

$$Z_{SPP} = \min \sum_{i=1}^{N} \left(\sum_{k=1}^{K_i} c_i^{(k)} x_i^{(k)} + M s_i \right) \tag{7}$$

subject to

$$\sum_{i=1}^{N} \sum_{k=1}^{K_i} a_{i,t}^{(k)} x_i^{(k)} \leq 1 \qquad t = 1,..,T \tag{8}$$

$$\sum_{k=1}^{K_i} x_i^{(k)} + s_i = 1 \qquad i = 1,..,N \tag{9}$$

$$x_i^{(k)}, s_i \in \{0,1\} \qquad i = 1,..,N; k = 1,..,K_i \tag{10}$$

In this model formulation superscripts k refer to the k-th production schedule added to SPP and K_i is the total number of production schedules added to SPP for item i. For the k-th production schedule, constants $c_i^{(k)}$ equal the cost of this schedule and constants $a_{i,t}^{(k)}$ are defined as:

$$a_{i,t}^{(k)} = \begin{cases} 1 & \text{if } y_{i,t} = 1 \text{ or } v_{i,t} = 1. \\ 0 & \text{otherwise.} \end{cases}$$

Furthermore, decision variables $x_i^{(k)}$ are equal to one if for item i the k-th production schedule is implemented and zero otherwise. Slack variables s_i are introduced for item i to guarantee a feasible solution to the master problem. If $s_i = 1$, then Z_{SPP} is at least equal to some large penalty cost M and the solution to SPP does not contain a production schedule for item i. Consequently, the corresponding DLSP solution is infeasible. The objective (7) minimizes the sum of production costs and penalties. The set of constraints (8) state that in any period t at most one item is in production or in setup and equations (9) ensure that for each item either a production schedule is executed or a penalty M is added to the total cost. The binary character of the decision variables is represented by (10).

New columns (production schedules) for the master problem are generated by solving the single item subproblems $DLSP_i(u)$ for each item $i = 1, \ldots, N$. Here, $u = (u_1, \ldots, u_T)$ denotes the vector of dual variables corresponding to (8) in the LP relaxation of SPP. The single item subproblems are formulated as follows:

$DLSP_i(u)$ $(i \in \mathcal{A})$

$$Z_{DLSP_i}(u) = \min \sum_{t=1}^{T} ((S_i - u_t)\, v_{i,t} + (\overline{p}_{i,t} - u_t)\, y_{i,t}) - \overline{P}_i \tag{11}$$

subject to

$$y_{i,t} + v_{i,t} \leq 1 \qquad t = 1, .., T \tag{12}$$

$$D_{i,t} \leq \sum_{\tau=1}^{t} y_{i,\tau} \leq C_{i,t} \qquad t = 1, .., T \tag{13}$$

$$v_{i,t-a_i+\tau} \geq y_{i,t} - y_{i,t-1} \qquad t = a_i + 1, .., T;\ \tau = 0, .., a_i - 1 \tag{14}$$

$$y_{i,t}, v_{i,t} \in \{0, 1\} \qquad t = 1, .., T \tag{15}$$

Note that in this formulation the inventory variables have been eliminated, using the substitution $I_{i,t} = \sum_{\tau=1}^{t} y_{i,\tau} - D_{i,t}$, where $D_{i,t}$ equals the number of production periods required to fulfil demand for item i up to period t, or

$$D_{i,t} = \max(0, \lceil (\sum_{\tau=1}^{t} d_{i,\tau} - I_{i,0}) \rceil)$$

Constants $\overline{p}_{i,t}$ are equal to $h_i(T - t + 1) + p_{i,t}$ and $\overline{P}_i$ equals $\sum_t h_i(T - t + 1)d_{i,t} - Th_i I_{i,0}$.

Finally, the constants $C_{i,t}$ are upper bounds on the number of production periods for item i up to period t. These upper bounds are used in the additional cuts (13), and account for the fact that capacity needs to be reserved for production and setup of items $j \neq i$. The constants are computed recursively as:

$$C_{i,T} = D_{i,T}$$

and for $t = T-1,..,1$

$$C_{i,t} = \min(C_{i,t+1}, \max(0, t - \sum_{j \neq i}(D_{j,t} + \delta(D_{j,t})a_j) - a_i))$$

where $\delta(x) = 1$ if $x > 0$ and $\delta(x) = 0$ otherwise.

For items $i \notin \mathcal{A}$ the term $(S_i - u_t)v_{i,t}$ in the objective function (11) is replaced by the term $S_i v_{i,t}$ while equations (12) are no longer valid and removed from the model formulation. Finally, equations (14) are replaced by $v_{i,t} \geq y_{i,t} - y_{i,t-1}$.

It should be noted that problem $DLSP_i(u)$ is a single item *capacitated* lotsizing problem with setup times, time dependent costs, and additional restrictions imposed on cumulative production quantities. Although in general this type of lotsizing problems is NP-Hard (see Bitran and Yanasse 1982), $DLSP_i(u)$ can be solved efficiently by Dynamic Programming (DP) due to the restriction that production quantities in each period are limited to be either zero or one.

The DP recursion for solving $DLSP_i(u)$ is based on an evaluation of the value function $F_t(n,k)$ for each period $t = 1,\ldots,T$. The value function represents the minimal total costs of production from period 1 upto period t, where n is the cumulative number of production periods from period 1 upto period t, and k is the *machine status* in period t. The machine status $k = -\ell$ ($\ell = 1,\ldots,a_i$) when the machine is in setup during ℓ periods, while $k = 0$ when the machine is idle, and $k = 1$ when the machine is in production. Lower- and upper bounds on cumulative production in period t can easily be incorporated in the recursion scheme by assigning to $F_t(n,k)$ a finite value when $D_{i,t} \leq n \leq C_{i,t}$ only.
Assuming that the initial machine state is idle and initial inventory position is zero ($F_0(n,k) = 0$ if $(n,k) = (0,0)$ and $F_0(n,k) = \infty$ if $(n,k) \neq (0,0)$), and assuming that $D_{i,t} \leq n \leq C_{i,t}$, the value function for item $i \in \mathcal{A}$ in periods $t = 1,..,T$ is computed as:

$$F_t(n,k) = \begin{cases} \min\{F_{t-1}(n-1,1), F_{t-1}(n-1,-a_i)\} + \overline{p}_{i,t} - u_t & \text{if } k = 1 \\ \min\{F_{t-1}(n,1), F_{t-1}(n,0)\} & \text{if } k = 0 \\ \min\{F_{t-1}(n,1), F_{t-1}(n,0)\} + S_i - u_t & \text{if } k = -1 \\ F_{t-1}(n,k+1) + S_i - u_t & \text{if } k \in \{-a_i,..,-2\} \end{cases}$$

while $F_t(n,k) = \infty$ if $n < D_{i,t}$ or $n > C_{i,t}$.

The T-period minimal costs for item i are obtained as $\min_k\{F_T(D_{i,T},k)\} - \overline{P}_i$, while the running time of the DP-recursion is $\mathcal{O}(a_i D_{i,T} T)$. An adapted version of this recursion -with running time $\mathcal{O}(T D_{i,T})$- is used for items $i \notin \mathcal{A}$.

It is a well known result that when all feasible production schedules are generated, $Z_{SPP} = Z_{DLSP}$. However, the number of feasible production schedules may be prohibitively large and moreover, SPP is NP-Hard (see Garey and Johnson 1979). Therefore, we are committed to heuristics when solving SPP. With respect to these heuristics, two questions arise:

- How to compute good lower bounds to SPP ? (Section 2.1)
- How to generate feasible solutions (upper bounds) to SPP ? (Section 2.2)

2.1 Computation of lower bounds

To obtain lower bounds to SPP we solve the Linear Programming relaxation LP(SPP). For the relaxed problem LP(SPP) it is known that at the end of the column generation procedure $Z_{LP(SPP)} = \max_{u \le 0}\left(\sum_{i=1}^{N} Z_{DLSP_i(u)} + \sum_{t=1}^{T} u_t\right)$ (see e.g. Fisher 1981). Although $Z_{LP(SPP)} \le Z_{DLSP}$, it appears from computational results (see Section 3) that the LP-relaxation of SPP yields tight bounds quite often.

During the column generation procedure new production schedules are only added if they contribute to an improvement of the solution to LP(SPP), i.e., if they *price out*. To define this principle formally, let $w = (w_1, .., w_N)$ be the set of dual variables corresponding to equations (9) of LP(SPP). Then, a production schedule for item i prices out when $Z_{DLSP_i(u)} < w_i$.

The first two procedures for solving LP(SPP) use the simplex method to solve LP(SPP). One of them is called Primal Column Generation Procedure (PCGP) because it solves LP(SPP) using the *primal* simplex method, while the other is called Dual Column Generation Procedure (DCGP), since it uses the *dual* simplex method to solve LP(SPP). The procedures can be summarized as follows:

Primal (Dual) Column Generation Procedure:

Step 1: Generate for each item a number of feasible production schedules, using (randomization) heuristics.

Step 2: Solve LP(SPP) using the *primal* (*dual*) simplex method for PCGP (DCGP) and pass the dual variables u, corresponding to constraints (8), to the subproblems $DLSP_i(u)$.

Step 3: Generate one new production schedule for each item i by solving $DLSP_i(u)$ and add this production schedule to LP(SPP) if it prices out. If no production schedule prices out, then *STOP*. Otherwise, go to step 2.

PCGP (DCGP) was first implemented in a straightforward way, using the primal (dual) simplex method available in linear programming library XMP (Marsten 1981). However, since LP(SPP)

is highly degenerate it may occur that simplex methods used by standard LP-packages such as XMP do not converge very fast. Aucamp and Steinberg (1982) explain this phenomenon by showing that in case of degeneracy the values of the dual variables corresponding to an optimal basic solution may provide misleading information about shadow prices.
In order to accelerate convergence speed, we suggest an alternative procedure to search for good values of the dual variables u. The procedure is based on a *dual ascent* heuristic. An extensive survey of dual ascent heuristics in combination with Lagrange relaxation is given by Guignard and Rosenwein (1989). Our heuristic searches for feasible and (approximately) optimal solutions to the *dual* of LP(SPP), by iteratively increasing several variables w while decreasing a single u variable at a time. More formally, the procedure is described as follows:

Dual Ascent Procedure (Multiplier Adjustment Procedure):

Initialisation: Let dual variables u be predetermined and compute dual variables w as:

$$w_i = \begin{cases} 0 & \text{if } \delta_i < 0 \\ M & \text{if } \delta_i > M \\ \delta_i & \text{otherwise} \end{cases}$$

where $\delta_i = \min_k \{c_i^{(k)} - \sum_{t=1}^{T} a_{i,t}^{(k)} u_t\}$. Furthermore, let $\Delta_i^{(k)}$ be the slack variables defined as $\Delta_i^{(k)} = c_i^{(k)} - \sum_{t=1}^{T} a_{i,t}^{(k)} u_t - w_i$.

Step 1: Let $\mathcal{K}_{i,t}$ be the set of columns for which $a_{i,t}^{(k)} = 0$ and define $\mathcal{I}_t^{(1)} = \{i \mid K_{i,t} = \emptyset\}$. Compute $\alpha_{i,t} = \min_{k \in \mathcal{K}_{i,t}} \Delta_i^{(k)}$ and let $\mathcal{I}_t^{(2)}$ be the set of items for which $\alpha_{i,t} > 0$. Set $\beta_t = \min[\min_{i \in \mathcal{I}_t^{(1)}} \{M - w_i\}, \min_{i \in \mathcal{I}_t^{(2)}} \{\alpha_{i,t}, M - w_i\}]$. Let $\mathcal{I}_t = \mathcal{I}_t^{(1)} \cup \mathcal{I}_t^{(2)}$ and determine $t^* = \arg\max_t \beta_t(|\mathcal{I}_t| - 1)$

Step 2: Update $u_{t^*} := u_{t^*} - \beta_{t^*}$ and $w_i := w_i + \beta_{t^*}$ for all $i \in \mathcal{I}_{t^*}$. Moreover, update slack variables $\Delta_i^{(k)} := \Delta_i^{(k)} - \beta_{t^*}$ for all $i \in \mathcal{I}_{t^*}$ and $k \in \mathcal{K}_{i,t^*}$. If $\beta_{t^*} > 0$ go to Step 1, otherwise STOP.

Since the dual ascent procedure does not usually reach the optimum to the dual of LP(SPP), we attempt to improve the lower bound. To do so, we define LR(SPP) as the problem which occurs when applying Lagrangean Relaxation to the set of constraints (8) of SPP. Mathematically, LR(SPP) is formulated as:

$LR(SPP):$

$$Z_{LR(SPP)}(u) = \min \sum_{i=1}^{N}(\sum_{k=1}^{K_i}(c_i^{(k)} - \sum_{t=1}^{T} a_{i,t}^{(k)} u_t)x_i^{(k)} + M s_i) + \sum_{t=1}^{T} u_t \tag{16}$$

subject to

(9), (10)

New lower bounds are now obtained by applying *subgradient optimization* to LR(SPP). The dual variables u are updated during a fixed number of iterations according to the following formula:

$$u_t := \min(0, u_t + \lambda(1 - \sum_{i=1}^{N}\sum_{k=1}^{K_i} a_{i,t}^{(k)} x_i^{(k)})) \text{ for } t = 1,..,T.$$

where λ is a positive scalar step size, determined as:

$$\lambda = \frac{\omega(UB - Z_{LR(SPP)}(u))}{\sum_{t=1}^{T}\left(1 - \sum_{i=1}^{N}\sum_{k=1}^{K_i} a_{i,t}^{(k)} x_i^{(k)}\right)^2}$$

The scalar ω is initialized at 1.5 and halved whenever the lower bound has failed to increase for some fixed number of iterations. The initial upper bound (UB) is given by the best known solution to DLSP so far (see Section 2.2). During the subgradient optimization procedure new lower bounds are obtained from LR(SPP). Note that solving LR(SPP) can be done by simple inspection, using the rule:

$$x_i^{(k)} = \begin{cases} 1 & \text{if } \min_\ell\{c_i^{(\ell)} - \sum_{t=1}^{T} a_{i,t}^{(\ell)} u_t\} < M \text{ and} \\ & \text{this minimum is obtained for } \ell = k. \\ 0 & \text{otherwise.} \end{cases}$$

and $s_i = 1$ if $x_i^{(k)} = 0$ for all $k = 1,..,K_i$ and $s_i = 0$ otherwise.

The Dual Ascent Column Generation Procedure (DACGP) can now be summarized as follows:

Dual Ascent Column Generation Procedure (DACGP):

Step 1: Generate for each item a number of feasible production schedules, using (randomization) heuristics. Set $u_t = 0$ for $t = 1,..,T$.

Step 2: Use the Dual Ascent Procedure to update dual variables u, starting with dual variables u obtained in the preceding iteration. Then apply 100 iterations of the subgradient optimization. Pass on the (approximately optimal) dual variables u to the subproblems $DLSP_i(u)$.

Step 3: Generate one new production schedule by solving $DLSP_i(u)$ for each item i and consider this schedule in further computations if it prices out. If no production schedule prices out, then *STOP*. Otherwise go to step 2.

2.2 Search for feasible solutions

The question that remains to be answered is how to find *feasible* solutions to DLSP, or equivalently, how to generate strong upper bounds (UB). If we use PCGP or DCGP, every integer solution to LP(SPP) is clearly an upper bound. However, although the columns obtained by PCGP or DCGP may contain an integer solution, it is not necessarily found by the simplex algorithm. To overcome this difficulty, a limited branch and bound search is performed after termination of the column generation procedure. (Note that this procedure does still not guarantee that an integer feasible is found if one exists, since the integer program only contains the columns generated by PCGP or DCGP (i.e. a subset of all possible columns). Therefore, although the DLSP at hand may be feasible, the SPP defined on the columns generated by PCGP or DCGP may very well contain no integer feasible solution.)

A search for feasible solutions to DLSP when using DACGP is done in two different ways. First, in step 2 an integer solution to LR(SPP) may be found in which $s_i = 0$ for all $i = 1,..,N$ and (8) is not violated. Clearly, this solution is also feasible to DLSP. Second, we try to find feasible solutions among the columns generated so far, by solving SPP using the enumeration algorithm of Garfinkel and Nemhauser (1969). In our experiments we have executed this algorithm every *ten* iterations *after step 3* of DACGP.

In case of **zero setup times**, we have extended each of the heuristics with an effective upper bounding procedure developed by Fleischmann (1990), which guarantees a feasible starting solution. This procedure generates production plans for all items by sequentially solving single item problems, in such a way that the overall (multi-item) production problem remains feasible. To demonstrate this procedure in more detail, suppose we have generated production plans for items $1,..,i-1$. When determining production for item i in period t, it suffices to check whether period t is not used for production by any other item $1,..,i-1$ and the feasibility rule $\sum_{\tau=1}^{t} y_{i,\tau} \leq t - \sum_{j \neq i} D_{j,t}$ is not violated.
Proceeding in this way for items $i+1,..,N$ ultimately leads to a feasible multi-item starting solution.

Remark: When setup times are nonzero, the existence of a simple feasibility rule is unlikely (remember that generating feasible schedules in presence of nonzero setup times is NP-Complete) and Fleischmann's procedure cannot be used anymore. Therefore we were forced to test other procedures. We have chosen for the column generation approach, since this technique has the appealing property that the probability of generating a feasible solution is rather high (see Ryan and Falkner 1988).

3 Computational results

The heuristics PCGP, DCGP and DACGP were programmed in FORTRAN and implemented on an IBM-PS 2 Model 80 with mathematical co-processor 80386. Test problems were generated using a problem generator which is available from the authors upon request. We considered variations in the following problem parameters:

- The problem dimensions, as represented by the number of items N and the number of periods T.

- The setup times, which are either constant or generated at random from a discrete uniform (DU) distribution.
- The (approximate) EOQ-based time between ordering for item i, (TBO_i), which is randomly generated from a discrete uniform distribution.
- The (approximate) capacity utilization ρ and demand $d_{i,t}$, so that:

$$Prob\ \{\ d_{i,t} = 1\ \} = \frac{\rho}{N}\ \left(1 - \frac{a_i}{TBO_i}\right)$$

  Demand for item i in period t is set equal to one whenever $U \leq Prob\{\ d_{i,t} = 1\ \}$ and set equal to zero otherwise. (Here, U is generated randomly from a uniform $U(0,1)$ distribution.) During the generation of demand for period t it is checked whether $D_{i,t} \leq C_{i,t}$ holds for $i = 1,..,N$. If this *rough cut capacity check* is violated for some item i, demand for period t is regenerated for all items.

Two sets of test problems have been generated. The first set consists of 45 problems with **zero** setup times, while the second set contains 420 problems with **nonzero** setup times. For both sets of test problems, the following parameters have been fixed: the holding cost $h_i = 1$, the production cost $p_{i,t} = 0$ ($t = 1,..,T$) and the setup cost $S_i = \dfrac{D_{i,T} \times TBO_i^2}{2T \times \max(a_i, 1)}$ for $i = 1,..,N$.

Problems with zero setup time.

This set of test problems consists of 60 period problems with $N = 2$, $N = 4$ and $N = 6$ items, respectively. For each item-period combination we consider low (L) capacitated problems ($\rho \leq 0.55$), medium (M) capacitated problems ($0.55 < \rho \leq 0.75$) and high (H) capacitated problems ($\rho > 0.75$) with $TBO_i \sim DU(12, 20)$ for $i = 1,..,N$. Per (N, ρ) combination five problems were generated, resulting in $(3 \times 3) \times 5 = 45$ problems. All problems in this set were solved using four solution procedures: Fleischmann's heuristic (before entering the branch and bound phase), PCGP, DCGP and DACGP.

Table 1 shows the results for the first set of test problems. Here, the quality of the solutions is represented by the gap $\overline{\Delta Z}$, which is the average relative deviation (in percent) between upper bound (UB) and lower bound (LB), computed as: $\overline{\Delta Z} = 100\% \times (UB - LB)/LB$ over all solutions within each (N, ρ) combination. Furthermore, for each combination the total number of problems solved to *optimality* ($\overline{\Delta Z} = 0$) is denoted by O and the number of problems with a *positive gap* ($\overline{\Delta Z} > 0$) is denoted by G. The average CPU time (in seconds) is denoted by $\overline{CPU}$.

Evaluating the results, it can be seen that Fleischmann's heuristic finds an optimal solution for 24 out of 45 problems (53%), while this percentage is 80%, 82%, and 87% for PCGP, DCGP, and DACGP respectively. The average gap ($\overline{\Delta Z}$) for the solutions found by Fleischmann's heuristic amounts to 0.37%, while for PCGP, DCGP and DACGP the gap is 0.46%, 0.27%, and 0.08% respectively. Computation times for Fleischmann and for DACGP increase in most (but not all) cases when capacity utilization increases and when the number of items grows larger. The CPU-time required to solve problems using PCGP and DCGP grows rapidly when capacity utilization increases, because degeneracy makes the number of columns generated very large.

Table 1: Problems with zero setup time ($T = 60$).

	N	2			4			6		
	ρ	L	M	H	L	M	H	L	M	H
Fleischmann	ΔZ	0.13	0.11	0.33	0.40	0.42	0.24	0.50	0.58	0.62
	O	4	4	3	3	3	3	3	0	1
	G	1	1	2	2	2	2	2	5	4
	$\overline{CPU}$	< 1.0	2.6	< 1.0	1.6	3.4	5.6	2.0	7.8	5.8
PCGP	ΔZ	0.00	0.00	0.81	0.00	0.22	0.12	0.00	1.85	1.16
	O	5	5	3	5	3	4	5	2	4
	G	0	0	2	0	2	1	0	3	1
	$\overline{CPU}$	16.4	40.8	179.2	16.0	57.5	174.0	28.4	92.3	114.6
DCGP	ΔZ	0.55	0.00	0.14	0.00	0.11	0.12	0.00	0.91	0.60
	O	4	5	4	5	3	4	5	3	4
	G	1	0	1	0	2	1	0	2	1
	$\overline{CPU}$	18.4	53.8	177.2	15.4	74.4	441.2	20.6	171.6	257.6
DACGP	ΔZ	0.40	0.00	0.04	0.00	0.07	0.10	0.00	0.14	0.00
	O	4	5	4	5	3	4	5	4	5
	G	1	0	1	0	2	1	0	1	0
	$\overline{CPU}$	7.0	20.2	17.0	21.6	39.6	106.0	38.2	77.0	92.6

Computation times for the column generation based heuristics PCGP, DCGP and DACGP turn out to be rather large compared to Fleischmann's heuristic. This is caused by the fact that PCGP, DCGP and DACGP were developed for problems with nonzero setup times, and therefore consist of effective, but time and memory consuming procedures for finding feasible production schedules. These procedures obviously do not fully exploit the structure of problems with zero setup times as Fleischmann's procedure does.

Problems with setup times.

Our second set of test problems consists of the following item-period combinations: $\{(N,T) \mid (2,20), (2,40), (2,60), (4,40), (4,60), (6,60)\}$. Setup time for item i is generated as $a_i \sim DU(0,2)$ and time between ordering is either low (L) ($TBO_i \sim DU(8,16)$), medium (M) ($TBO_i \sim DU(12,20)$) or high (H) ($TBO_i \sim DU(20,30)$). For 20-period problems only low TBO's are considered and for 40-period problems high TBO's are left out. For each item-period combination we have again generated low (L), medium (M) and high (H) capacitated problems. In total we consider 42 different (N,T,TBO,ρ) combinations. For each of these combinations 10 different data sets were generated, yielding a total of 420 problems. Since the first set of test problems shows that DACGP largely outperforms PCGP and DCGP with respect to computation times, results for the second set of test problems relate to DACGP only, unless stated otherwise. (The slow convergence of the simplex methods in case of degeneracy agrees with results obtained in similar studies by e.g. Cattrysse and Van Wassenhove, 1989.)

Furthermore, because computational results for different TBO classes differ only slightly, we aggregate results over all TBO's. (The latter causes an unequal number of problems within each (N,T,ρ) class.)
Computational results are given in tables 2 and 3.

Table 2: Problems with nonzero setup times (DACGP).

		$T=20$				$T=40$				$T=60$			
N	ρ	$\overline{\Delta Z}$	O	G	I	$\overline{\Delta Z}$	O	G	I	$\overline{\Delta Z}$	O	G	I
	L	0.00	10	0	0	0.09	19	1	0	0.17	25	3	2
2	M	0.29	7	1	2	0.06	15	1	4	0.20	21	2	7
	H	0.86	5	1	4	0.01	13	1	6	1.22	10	10	10
	L					0.00	19	0	1	0.15	23	4	3
4	M					0.15	12	3	(¹ 5	0.47	19	5	6
	H					0.96	7	4	9	1.43	14	5	(² 11
	L									0.13	26	3	1
6	M									0.70	13	7	(¹ 10
	H									0.99	11	9	10

(¹: Feasible integer solution found by PCGP for one problem instance.
(²: LP-relaxation is feasible but no integer solution found by PCGP for one problem instance.

The notation in Table 2 is analogous to the one used in Table 1, except that gap ($\overline{\Delta Z}$) is computed over all **feasible** solutions within each (N,T,ρ) combination. In addition, the number of problems for which no feasible integer solution is found by DACGP is denoted by I. If no feasible integer solution for a particular problem instance is found by DACGP, an attempt is made to solve the problem by PCGP. If a feasible integer solution is found by PCGP, this is denoted by (¹. Problems for which the LP-relaxation of SPP (LP(SPP)) is feasible, but for which no feasible integer solution is found are denoted by (². These problems may or may not have a feasible integer solution. All other problem instances in the category I turn out to be infeasible with respect to LP(SPP).

Examination of the computational results shows that $\overline{\Delta Z}$ tends to increase when capacity utilization increases and when the number of periods increases. For low capacitated problems $\overline{\Delta Z}$ ranges from 0% to 0.17% while for high capacitated problems the gap turns out to be lower than 1.43%. This demonstrates that lower bounds obtained by fast heuristic methods like dual ascent and subgradient optimization are rather tight for the SPP formulation of DLSP. Considering the low capacitated problems it can be seen that only 11 out of 133 feasible problems have a gap, while for the medium and high capacitated problems these numbers are 19 out of 106 and 30 out of 90 respectively. It is remarkable that only for 3 out of 329 feasible problem instances no integer solution was found by DACGP, while it did find an optimal solution to 269 problems. This demonstrates that the upper bounding procedures are quite effective, especially for the relatively easy low capacitated problems.

Table 3 shows CPU-times (in seconds) for each (N, T, ρ) combination. Here, F is the average time (over all LP-feasible problems) required to find the first integer solution, B is the average time (again, over all LP-feasible problems) after which the best integer solution is found and R is the average time (over all problems) required for DACGP. In addition, Table 3 shows the average number of columns generated (C) (including *eight* starting columns per item, obtained by the heuristics), and the average number of times the master problem is solved (M).

Table 3: Problems with nonzero setup times (DACGP).

		$T=20$					$T=40$					$T=60$				
N	ρ	F	B	R	C	M	F	B	R	C	M	F	B	R	C	M
2	L	0.3	0.9	1.9	22.1	4.3	1.1	4.7	8.6	26.9	13.5	4.1	12.8	25.8	34.1	10.3
	M	0.3	1.8	2.4	21.8	4.4	6.8	14.7	20.4	38.7	26.1	13.9	36.2	76.3	56.8	22.3
	H	0.8	5.1	8.8	33.6	10.8	22.7	65.6	93.6	77.8	32.9	69.5	188.6	274.9	115.7	51.8
4	L						2.8	9.7	15.9	54.8	8.0	9.1	30.6	38.9	66.5	10.8
	M						8.9	25.7	37.8	72.6	14.3	68.4	107.1	120.8	112.8	23.0
	H						48.7	61.8	79.5	114.4	24.9	178.4	231.8	268.7	176.2	39.6
6	L											17.6	38.8	56.2	95.7	10.9
	M											95.7	144.9	264.9	162.9	23.0
	H											142.7	209.5	274.1	205.6	44.2

As can be seen from the results in Table 3, computation times grow with problem size, which can be explained by the fact that solving N single item subproblems takes $O(\sum_{i=1}^{N} a_i D_{i,T} T)$ per iteration. Furthermore, computation times increase when capacity utilization increases. The reason for this is that for high capacitated problems more columns have to be generated on average (and consequently, the master problem has to be solved more often) in order to obtain a feasible solution. Also, it follows that solving SPP by the enumeration algorithm of Garfinkel and Nemhauser takes longer. Nevertheless, considering the complexity of problems with nonzero setup times, computation times are fairly modest. Small problems (2 items and 20 periods) are solved in a few seconds, while medium sized problems (6 items and 60 periods) are solved within five minutes (on average).

4 Summary and conclusions

In this paper column generation heuristics were presented for the Discrete Lotsizing and Scheduling Problem (DLSP) with setup times. These heuristics represent one of the very few efforts at solving lot sizing problems with setup times. Computational results on a set of 420 test problems show that for some 82% of these problems an optimal solution is found, while in most other cases feasible solutions are found whose deviation from optimality is no more than 1.5% (on average). Furthermore, for medium sized problems (6 items and 60 periods) solutions are obtained on a personal computer within 5 minutes of CPU-time.

From a computational comparison between Fleischmann's heuristic, and the column generation heuristics on a set of 45 test problems with zero setup times it appears that Fleischmann's heuristic largely outperforms the column generation heuristics in computational speed, but that solutions obtained by the dual ascent column generation heuristic are slightly better in quality.

Note that Fleischmann's special purpose algorithm takes advantage of the structure of the problem without setup times, while ours does not. This explains the differences in computational requirements.

Our results are encouraging when compared to computational results obtained for other capacitated lotsizing models with setup times (like The Capacitated Lotsizing Problem, considered by Trigeiro et al. 1989). The reasons for this are twofold: First, DLSP is one of the few multi-item capacitated lotsizing problem formulations for which the capacitated single item subproblems resulting from relaxation of the multi-item capacity constraints are polynomially solvable and second, the lower bounds obtained in this way turn out to be rather tight for most problem instances. For generating upper bounds, application of a column generation heuristic in combination with the fast enumeration algorithm of Garfinkel and Nemhauser performs quite satisfactorily, since the probability of finding feasible (integer) solutions to DLSP turns out to be rather high.

Our future research in this area includes extensions of our heuristics to problems with sequence-dependent setup times and costs. Furthermore, the heuristics can be embedded in a branch and bound routine to guarantee optimal solutions.[1]

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