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Book I

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Economic lead time determination in hierarchically controlled production systems

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Abstract

In practice decisions regarding customer order lead time quotation and customer order processing are taken in different parts of the organization. Definite lead times are quoted by the marketing and sales department and job flow control decisions are taken by the production department. This split up of decision responsibilities is in accordance with the differences in scope and control areas in complex organizations like job-shops or engineer-to-order firms. Production management often complaints that the marketing and sales department quotes unrealistic short lead times, whereas the marketing and sales department often complaints that the manufacturing flow times are too long and unreliable. In this paper we present a simple economic model of this situation for a job shop. The production department aims at realizing the jobs by using its capacity to perform the operations. The sales department uses a model of the performance of the shop and quotes a lead time to each customer order to maximize the expected profit, given that a penalty is put on quoting long lead times and tardy deliveries. Analysis of the model shows that for certain combinations of penalty functions and job flow time distributions, it is optimal for the marketing and sales department to quote very short (unrealistic) customer order lead times. If the job flow times are short and very reliable it becomes more attractive for the sales department to quote reliable lead times. In practice we often observe that the job flow times are long and have a high variance. The results of the research presented in this paper show why this often stimulates the sales department to quote short and unreliable lead time. Under a wide range of economic circumstances a short and reliable job flow time seems to be a necessary condition for quoting realistic lead times.

1. Introduction.

In practice decisions regarding customer order lead time quotation and customer order processing are taken in different parts of the organization. Definite lead times are quoted by the marketing and sales department and job flow control decisions are taken by the production department. This split up of decision responsibilities is in accordance with the functional structuring of the organization. Production management often complains that the marketing and sales department quotes unrealistic short lead times, whereas the marketing and sales department often complains that the manufacturing flow times

are unreliable and too long.
In this paper we study the assignment of optimal due dates to customer orders that arrive at a job shop. We study the situation where orders arrive dynamically over time, are assigned a due date, are released to the shop floor and, after processing in the shop, are completed. The job shop consists of a number of functionally organized work centers and each job requires a number of operations in different work centers. The due dates are assigned by a due date assignment system. The processing of the orders is controlled by a shop floor control system which may take the assigned due dates into account. When assigning due dates, the due date assigning system may take into account the characteristics of the job and the conditions of the shop which may affect the throughput time of the job. Thus the control system is hierarchically organized. Both the shop floor control problem and the due date assignment problem for job shops have been seperately studied. For a review of the literature we refer to Cheng and Gupta (1989). Also the interaction between due date assignment rules and shop floor control rules has been studied (see for instance Baker 1984, Cheng 1988, Salegna 1990). In most of this research the performance is measured in terms of due date performance i.e. the job tardiness or the mean and variance of the job lateness.
In this research we study the due date assignment problem in an economic setting. We study the situation where on the one hand a cost penalty is incurred as a function of the length of the job lead time and on the other hand, also a cost penalty is incurred as a function of the tardiness of the job. This assumes that the firm in some way or another is rewarded for assigning short job lead times; a reward which is lost by assigning long lead times. Also it is assumed that the firm is punished for late deliveries. Given the amount of research that has been done on due date assignment and shop floor control related to due date performance we may assume that firms in practice are confronted with such a reward and penalty structure.
In this paper we study the situation where this reward and penalty structure can be modelled with simple piecewise lineair functions. We derive optimal due date policies for various instances of the reward and penalty function under a simplifying assumption regarding the job flow time distribution. The results of this analysis are verified for a symmetrical job shop (all work centers have the same characteristics and all transition probabilities are equal), using systematic computer simulation. The remainder of this paper is organized as follows. In Section 2 we give an overview of recent relevant research and work out the research question in more detail. In Section 3 we present the formal model of the problem and derive the theoretical results. Section 4 presents the simulation study, the simulation results and the conclusions from these results. Finally in Section 5 the conclusions of the paper and some directions for future research are given.

2. Literature review.

As has already been mentioned in section 1 much research has been done on both due date assignment and shop floor control. In this section we discuss recent research which is focussed on economic oriented performance measures.
Prabhu et al. (1990) examines the problem of assigning due dates to a given set of jobs and sequencing them on a single machine in order to minimize the cost of quoting long due dates and that of missing the quoted due dates. They establish solution properties for the problem and identify special cases which can be solved easily. Their research is restricted to the static single machine case.
Vig and Dooley (1993) do not consider the cost aspect, but they develop a flow time estimate that improves average lateness and fraction tardy jobs.
Li and Lee (1994) provide a framework to measure the market impact of improvements in responsiveness in conjunction with other decisions such as price, quality and technology. They present a method for deriving the market share or demand rate for each firm as a function of the firms' decisions on price, quality and processing speed. They do not consider the problem for individual firms of optimizing their profit in situations where on the one hand the price a customer is willing to

pay depends on the quoted lead time and on the other hand there are costs for missed due dates. Lawrence (1994) presents a methodology for negotiating due dates between customers and producers in complex manufacturing environments. This is accomplished by modelling the setting of due dates as a lead time forecasting problem, and using the empirical distribution of forecast errors as the basis for negotiating and setting due dates with customers. It allows the construction of trade-off curves between customer due dates and several altenative performance measures including cost and service level measures. The method assumes that work center flow times have been tracked over time and that sufficient data have been accumulated to estimate flow time distributions for jobs as they arrive. There is no trade-off between the proceeds of promising small short lead times and the (expected) tardiness cost.

Enns (1994) gives a method for setting due dates in manner which allows the percentage of tardy jobs delivered to be controlled. It is based on a dynamic method of estimating prediction error variance. However, the price customers are willing to pay given a certain lead time is not taken into account.

Enns (1995) presents a forecasting approach to flowtime prediction in a job shop. The flowtime prediction relationship developed considers both job characteristics and shop loading information. The estimated distribution of forecast error is used to set delivery safety allowances which are based on a desired level of delivery performance. However, again lead time related prices are not taken into account.

Duenya and Hopp (1995) consider production situations where the proportion of customers that actually place an order depends on the quoted lead time. They use SMDP (Semi Markov Decision Process) theory and prove the optimality of different forms of control limit policies. Although there is a penalty for late deliveries the price does not depend on the quoted lead time.

Duenya (1995) adresses the case where there are several customer classes with different price and lead time preferences with regard to a single product. The intention of the paper is to demonstrate the importance of considering customer preference information in setting due dates and to develop a framework for utilizing this information when available.

Van Ackere (1995) uses a queueing model to analyse the effects of different load control methods on optimal utilization and pricing. It also discusses the impact of the availability of information about the existing backlog on the manager's optimal strategy. Although the pricing strategy is being considered, it is not lead time related and there is no trade-off between price and tardiness cost.

3. An economic performance model.

In this section we present and analyze an economic performance model of the customer order lead times (due dates) in relation to the order flow times (shop floor control). Often customers value short lead times over long lead times. In this research we assume that quoting short lead times leads to economic benefits, for instance by getting more customers, better customers (with higher margins), etc. In this study this has been modelled as a lineair price function. This function declines with an increase in quoted lead time. On the other hand we assume that there is a penalty for late deliveries. For every order that is delivered beyond its delivery date we lose a fixed amount of money.

We therefore study the following model:

- jobs arrive according to a Poisson process and are processed in a symmetrical job shop
- upon arrival at the shop a job **j** is assigned a lead time $\mathbf{l_j}$
- at each machine jobs are processed in order of arrival (the FCFS sequencing rule)
- customers value short lead times over long lead times; we assume that this preference materializes in different prices for jobs depending on the quoted job lead time. We model this prices component as a lineair function:

  $p(l_j) = a \qquad\qquad 0 \leq l_j \leq m$

  $p(l_j) = a - b(l_j - m), \qquad l_j \geq m$

with l_j : quoted lead time of job **j**

$p(.)$: the part of the job price that depends on the quoted lead time

m : the lead time that is generally accepted by the market; lower lead times do not lead to more profit

a,b : constants

Without loss of generality we set m equal to 0.

- if a job finishes later than the due date, the job is tardy and a tardiness cost is incurred. We assume that a constant tardiness cost **c** is incurred on each tardiness occurrence

The job-shop model we used consists of five work centers (as in many research, for example see Conway). Order routings are determined upon arrival. The routings are generated in such a way that each work center has an equal probability of being selected as the first work center. After the first operation the probabilities of going to any of the other work centers are equal and depend on the probability of leaving the shop, which in turn depends on the average routing length. We used an average routing length of 5, so the probability of leaving the shop equals 0.2, thus the work center transition probabilities all equal 0.8/4=0.2.

The utilization rate we use is 90%, which implies that the mean value of the order inter-arrival time has to be equal to 10/9.

At each work center processing times are generated from a negative exponential probability density function with a mean value of 1 time unit. Set-up times and transportation times are considered to be zero. The sequencing rule we will use is first-come-first-serve.

From earlier research (see Eilon and Chowdhurry [1976] and Bertrand [1983]) it can be concluded that it is important to distinghuish between the expected completion date **ĉ** and the due date **d**. The expected completion date is used in determining dispatch priorities and is based on predicted flowtimes. The due date is the delivery date quoted to the customer and is equal to the arrival time **r** of the customer order plus the lead time **l** quoted to the customer order. The time difference between the completion date and the due date is a safety allowance that can be adjusted according to the delivery performance desired.

If for order i
$$\hat{c}_i = r_i + F_i$$
$$d_i = r_i + l_i$$

where r_i: arrival time of order i
F_i: predicted flowtime

then the expected profit quoting a lead time l to order i equals

$$a - b \times l - c \times p(tardy \mid lead\ time = l) \qquad l \geq 0$$

Maximizing the profit is then equal to minimizing

$$b \times l + c \times p(tardy \mid lead\ time = l) \qquad l \geq 0$$

or minimizing

$$b \times l - c \times G(l) \qquad l \geq 0$$

where G(.) is the probability density function of the throughput time.
From this it follows that l has to be such that

$$b - c \times g(l) = 0 \qquad l \geq 0$$

where g(.) is the probability density function of the throughput time.

The question now is how to determine l. We will analyze this problem for a fixed lead time policy and for a work order dependent lead time policy.

<u>Fixed lead time.</u>
If a fixed lead time policy is followed then each order is given the same lead time. In that situation the lateness probability density function and the throughput time probability density function are similar (shifted over the fixed leadtime used).
We suppose that the throughput time has a negative exponential probability density function in case the fixed lead time policy is followed. This is supported by the research of Shantikumar (1984) and the results of some simulation experiments that have been carried out by the authors. In that situation there is maximum for the profit if l is equal to l_o, where l_o is found from the following equation:

$$b - c \times \frac{1}{F} \times e^{-\frac{1}{F} \times l} = 0 \qquad l \geq 0$$

So for c>bF we have a maximum if

$$l = F \times \ln \frac{c}{b \times F} \qquad (1)$$

Since we do not know if we have a global or a local maximum we have to compare a-bl_o-cp(tardy|l_o) (the profit in case l=l_o) with a-c (the profit in case l=0). If the profit for l equal to l_o is less then a-c we have to set l equal to 0, otherwise the economic optimal value of l is l_o.

If c ≤ bF we have to set l equal to 0. Every unit increase of l leads to a decrease of the expected tardiness costs that is less than the decrease of the price the customer is willing to pay. So, in this situation the profit decreases by an increase of l.

<u>Example:</u>
To illustrate the effects of the use of the economic lead time determination model we will use the earlier described job-shop. Often lead times are given such a value that a certain delivery reliability is obtained (we will call this the *conventional approach*). For instance to obtain a delivery reliability of 95% in our example the (fixed) lead time has to be set equal to 50+1.645*50=132.25. That leads to the following expected profits:
a=1000, b=5, c=100 : 1000-132.25*5-100*0.05 = 333.75
a=1000, b=5, c=500 : 1000-132.25*5-500*0.05 = 313.75
a=1000, b=5, c=1000: 1000-132.25*5-1000*0.05 = 288.75

If the *economic lead time determination method* is used we get the following results:
a=1000, b=5 and c=100 : the optimal value of l equals 0. The expected profit of an order is then a-c=900.
a=1000, b=5 and c=500 : the optimal value of l equals 36. Then the expected profit of an order is a-36b-$ce^{(-36/43)}$ = 605.
a=1000, b=5 and c=1000: the optimal value of l is equal to 66. In that case the expected profit of an order is a-66b-$ce^{(-66/43)}$ = 450.

Work order dependent lead time.

As has been shown by Bertrand (1983) and Enns (1994) using job information and shop status information can be very usefull for improving the delivery performance. In this paper we restrict ourselves to job information. In that situation we use the following completion time estimator:

$$\hat{c}_j = r_i + \sum_l p_{j,l} + \beta g_j \qquad (1)$$

where r_j : arrival time of order j
$p_{j,l}$: the processing time of operation l of job j
g_j : the number of operations of job j
β : the expected long term work center waiting time.

To obtain a certain due date reliability the due date d_i has to be set equal to c_i plus a safety time that depends on the required due date reliability. Since we use estimated completion times that are based on the number of operations it seems obvious to use also safety times that depend on the number of operations. Therefore the due date d is set equal to $\hat{c} + \Delta_g$, where g is the number of operations of the order we consider.

The results of Enns (1995) supports the assumption that in this situation the lateness has a normal distribution function. Therefore we get a maximum for the profit if l is equal to l_o, where l_o is such that:

$$b - \frac{c}{\sqrt{2\pi}\,.\sigma_{g,L}}.e^{-\frac{1}{2}\left(\frac{l_o - F - \mu_L}{\sigma_{g,L}}\right)^2} = 0$$

where $\sigma_{g,L}$ = the standard deviation of the lateness of the orders with g operations.

Taking the second derivative we find in case $c = b\sqrt{2\pi}\sigma_{g,L}$ that there is a bending point if l_o equals $F+\mu_{g,L}$. In that case we find a maximum for the profit by setting l equal to zero.

For $c > b.\sqrt{2\pi}.\sigma_{g,L}$ there is a maximum if l_o is equal to

$$F + \mu_{g,L} + \sigma_{g,L}.\sqrt{\log\left(\frac{c}{b.\sqrt{2\pi}\,\sigma_{g,L}}\right)^2}$$

For $c < b.\sqrt{2\pi}.\sigma_{g,L}$ the expected profit has a maximum by taking l equal to zero. Each increment of the lead time leads to a decrease of the price that is smaller than the decrease of the expected tardiness costs.

Since we do not know whether the maximum is a global of a local maximum we have to compare the profit if l is equal to l_o (a-bl_o-cp(tardy|l_o)) with a-c (the profit in case l=0). If the highest value is given by a-c we have to set l equal to 0. Otherwise the economic optimal value of l is given by l_o.

Example:

For the example we need to have the values of the standard deviation of the lateness for the different categories. Therefore we performed a simulation study using the job-shop described earlier in this section. Based on the data from this simulation we get the following results for an order consisting of *five operations*.

Conventional policy:

a=1000, b=5, c=100 : 1000-(43+1.645*28)*5-100*0.05 = 550

a=1000, b=5, c=500 : 1000-(43+1.645*28)*5-500*0.05 = 530

a=1000, b=5, c=1000: 1000-(43+1.645*28)*5-1000*0.05 = 505

If the *economic lead time determination method* is used we get the following results:

a=1000, b=5 and c=100 : the optimal value of l equals 0. The expected profit of an order is then a-c=900.

a=1000, b=5 and c=500 : the optimal value of l equals 67. Then the expected profit of an order is a-67b-(1-ϕ((67-43)/28))c = 567,55.

a=1000, b=5 and c=1000: the optimal value of l is equal to 80. In that case the expected profit of an order is a-80b-(1-ϕ((80-43)/28))c = 506,60.

The remaining question is how to determine the standard deviation of the lateness. If a constant **c**, that is independent of order characteristics, is used for determining the internal due date we can use Shantikumar (1984) for determining the standard deviation of the lateness since this is equal to the standard deviation of the flowtimes.

However, if job information information is used to determine customer order lead times the standard deviation of the lateness is not equal to the standard deviation of the flowtime and therefore we cannot use Shantikumar (1984) for determining $\sigma_{g,L}$. If the long term utilization level of the shop is stationary the standard deviation of the lateness that results from using job and shop load dependent due date rules is stationary over time and can be estimated from real life data. Therefore we assume that in practice a reliable estimate of the lateness distribution is available. These real life data can be used in the equation for the economic lead time as derived earlier.

5. Conclusions and directions for future research.

In this paper we derived a method for determining the optimal value for the customer lead time from an economic point of view. For this method we need to know the distribution of the lateness. In the situation where fixed lead times are used the lateness distribution has the same kind of distribution as the throughput time; it is only shifted in time. Assuming the throughput time has a negative exponential distribution and using long term behaviour data with respect to the parameter of the lateness distribution it appeared that our method always resulted in the highest expected profit.

In the situation where the lead time is based upon work order characteristics we used the normal distribution function as distribution function for the lateness with a standard deviation of the lateness that depends on the number of operations and parameter values based upon long term behaviour. Again our method outperformed other methods of assigning work order dependent lead times.

From the results it can be concluded that for certain combinations of penalty functions and job flow time distributions, it is optimal for the marketing and sales department to quote very short (zero), unrealistic, customer order lead times. This explains why in practice often unrealistic lead times are agreed upon with the customer. Dependent upon the ratio between the cost penalty with regard to the length of the lead time and the cost penalty with regard to tardiness it might be optimal to quote very short lead times, even if they are unrealistic.

In deriving the equation for the economic optimal lead time we assumed that the lateness has a normal distribution and that this distribution can be derived from real life data or by using some formulae assuming that we have a steady state situation. For practical purposes we only want to use a limited number of data (for instance due to the dynamics in the production environment) and therefore the question is how much data do we need to get reliable estimates, are these estimates more or less stationary over time and has the lateness a normal probability density function? This needs further investigation.

Furthermore we want to investigate the influence of using the Earliest Due Date sequencing rule instead of the FCFS rule. As is known from past research this sequencing rule leads to a small variance in lateness which, as can be derived from our formula, stimulates the Sales department to quote reliable lead times. In this situation not only the order acceptance function tries to optimize its lead time performance by quoting economic optimal lead times, but also the order realization function tries to optimaze its lead time performance by improving the throughput time reliability. However using the EDD rule, interactions effects occur which influence the lateness distribution which is used in determining economic lead times. Here we encounter a modelling problem.

In this study we used constant costs for tardy deliveries. So the costs were independent of the tardiness value. However, often there are costs associated with each unit of time that orders are finished too late. Therefore we need to investigate how this can be incorporated in our model.

Finally, in practice the customer order arrival pattern is influenced by quoting long lead times and/or late deliveries. So there is an interaction between the customer behaviour and the lead times quoted. This interaction needs to be investigated and our model needs to be adjusted for this ustomer behaviour) interaction effect.

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