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Theory and Methodology

Due date assignment procedures with dynamically updated coefficients for multi-level assembly job shops

Nabil R. Adam
Rutgers Graduate School of Management, The State University of New Jersey, Newark, NJ 07102, USA

J. Will M. Bertrand
University of Technology, Eindhoven, Netherlands

Diane C. Morehead and Julius Surkis
Rutgers Graduate School of Management, The State University of New Jersey, Newark, NJ 07102, USA

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Abstract: This paper presents a study of due date assignment procedures in job shop environments where multi-level assembly jobs are processed and due dates are internally assigned. Most of the reported studies in the literature have focused on string type jobs. We propose a dynamic update approach (which makes use of Little's Law) to obtain the coefficients used in the traditional due date assignment procedures of constant allowance (CON), total work content (TWK) and critical path processing time (CPPT). The coefficient assigned to a given job reflects both the *state of the shop* at the time the job is processed and the *characteristics of the job*. The approach also provides the shop management with the ability to control the average job lateness. In the simulation experiments conducted in this study, we set the average lateness at zero. The analysis of simulation results shows that the proposed dynamic procedures provide overall better shop performance than their static counterparts, especially for less complex assembly job structures. A procedure for determining job due dates that extends the critical path concept of the CPPT procedure to critical path *flow time* (CPFT) is also proposed. Unlike the others, this procedure does not need the determination of any coefficients. The procedure uses estimates of waiting times at work centers that are determined *dynamically* based on shop work load information. In this paper, an adaptive adjustment approach is also suggested to bring average lateness for the CPFT procedure to a target value. Results of the simulation experiments show that the CPFT combined with the adaptive adjustment approach (CPFT-ADJ) provides overall improved performance compared to the dynamic and static versions of the CON, TWK, and CPPT procedures for less complex job structures. For more complex assembly job structures and string jobs the CPFT-ADJ procedure results in comparable performance to the dynamic versions of the CON, TWK, and CPPT procedures. The paper also

Correspondence to: N.R. Adam, Rutgers Graduate School of Management, The State University of New Jersey, Newark, NJ 07102, USA.

provides an investigation of the interaction between the the two priority rules: *earliest job due date* (JDD) and the *earliest operation due date* (OPNDD) and the four due date procedures: CON, TWK, CPPT, and CPFT-ADJ. In general, for multi-level assembly job structures JDD outperforms OPNDD in terms of average job lead time and tardiness.

Keywords: Multilevel job shops; Due date assignment procedures; Lead time allowance; Job shop scheduling

1. Introduction

Various procedures for assigning due dates to jobs arriving at a job shop have been discussed in the literature. Some of these studies have dealt with an environment where the arriving jobs had pre-assigned due dates and the objective was to devise priority rules to attain acceptable due date performance. Other studies have considered a job shop where the due dates of arriving jobs were set internally, and jobs had to be scheduled to meet the assigned due dates. In this paper, we shall be concerned with the latter environment.

The due date of a job is the sum of its arrival time and an estimate of its *lead time*, which we will call the lead time allowance. The determination of this *allowance* is the factor that gives rise to various due date assignment procedures. The procedures that have been discussed in the literature may be classified into three categories:

(a) the allowance of individual jobs is set equal to a constant (CON) representing the average lead time of a job in the shop;

(b) the allowance of a job is in proportion to its total processing time (TWK) or in proportion to its number of operations (NOP); and

(c) an allowance in proportion to the work content of the job and the *work load in the shop*.

For (c), two of the most common approaches that are used as surrogates for the work load in the shop are: the average waiting time of a job in the shop, and the number of jobs waiting for processing at the work center where the job is to be processed. For all of these procedures, there are coefficients that have to be estimated. In the literature, these coefficients were estimated by an 'a priori' pilot simulation study and they remain *static* throughout the experiments.

Several studies (e.g. [3,4,9,10]) have compared the performance of the different due date assignment procedures, in a job shop environment where string type jobs are processed. There is overwhelming evidence that, for string type jobs, the TWK method outperforms both the CON and the NOP methods (see, for example, [5,8]). Moreover, several studies (e.g., [6,9,21,23]) have reported an improved performance of the shop when the due date assignment method included information about the work load in the shop.

In this paper we propose a *dynamic* approach for determining the necessary coefficients for the CON, TWK, and CPPT procedures. The approach utilizes Little's result [17] to estimate lead time by observing the current value of the average number of jobs in the shop (it is also possible to use the instantaneous value of the number of jobs). We refer to this approach as the 'aggregate' approach, since it utilizes aggregate information related to the work load in the shop. The revised procedures are referred to as the CON-DYN, TWK-DYN, and CPPT-DYN. The procedures are compared to their respective *static* counter parts, i.e. CON-STAT, TWK-STAT, and CPPT-STAT.

An approach for determining job due dates that extends the critical path concept of the CPPT procedure is also proposed. According to this new procedure (referred to hereafter as CPFT: critical path flow time) a job's allowance is based on the flow time (processing time + expected waiting time at work centers) of the critical path. The CPFT procedure provides a means of estimating expected waiting times. In this paper, a method is proposed for obtaining waiting times that are *dynamically* estimated based on shop work load information. Thus, the estimate of expected waiting times at work centers does not depend on the results of *a priori pilot* experiments. The proposed method utilizes Little's result, but differs from the 'aggregate' approach mentioned above; it will be referred to as the 'micro' approach. The 'micro' approach obtains estimates of waiting times at each work center from the current value of the number of jobs waiting at each work center where an operation on the critical path is to be processed. Thus, the 'micro' approach uses more detailed information about the characteristics of the job and the work load in the shop. In this paper, an adaptive adjustment approach is also suggested to bring the average lateness under the CPFT procedure to a target value of zero. The due date assignment procedure which combines the CPFT and adaptive adjustment concepts will be referred to as the CPFT-ADJ procedure.

This paper also addresses the issue of interaction between priority rules and the due date assignment procedures. The due date assignment procedures and their interaction with the *earliest job due date* (JDD) and the *earliest operation due date* (OPNDD) priority rules are studied in *multi-level assembly* job shop environments.

Multi-level assembly jobs consist of a set of segments which have to be assembled together after their processing is complete. A segment, in turn, consists of a set of serial operations ordered in a linear sequence. For a multi-level assembly job, a higher level segment cannot be processed until all lower level segments have been processed and assembled together. The processing of such a job is complete when all of its highest level segments have been processed and assembled together.

The structural complexity of assembly jobs introduces an additional dimension to the problem of setting job due dates, since the lead time of a job consists of a combination of the following: the flow time of its segments, the assembly time, the time that the assembly operations have to wait at assembly centers, and the staging delay at various assembly points in the job. Unlike a queueing delay, which occurs due to resource limitations, a staging delay occurs whenever an assembly operation has to wait for the completion of all segments coming into the assembly point.

The current literature on assigning job due dates related to multi-level assembly job shops is presented in Section 2. In Section 3 a discussion of the approaches to due date assignment are presented. Section 4 includes a discussion on the interaction between the due date procedures and the priority rules. The performance study and the analysis of the results are included in Section 5. Our conclusions are presented in Section 6.

2. Literature review

In the literature, the focus of research related to multi-level assembly jobs has concentrated mainly on priority assignment rules and not on due date assignment procedures. We will now briefly review the due date assignment procedures used in various studies.

In general, the due date of a job k arriving at the shop at time r_k is:

$$d_k = r_k + A_k \tag{1}$$

where A_k represents the allowance for the expected lead time. A_k takes on a different form depending on the procedure used.

Maxwell and Mehra [19] experimental with multi-level 'symmetric tree structured' jobs. The due date, d_k, of job k, arriving at the shop at time r_k was determined as a function of the processing time on the critical path of the job and was computed in the following way:

$$d_k = r_k + C_1 \times (\text{sum of the processing times of operations on the critical path}). \tag{2}$$

The due date of an operation was given by:

$$(\text{Due date of the successor operation}) - C_2 \times (\text{processing time of the succeeding operation})$$

where the values of the coefficients C_1 and C_2 were determined *empirically* and were set at 13 and 2, respectively. We will refer to this procedure as CPPT. Maxwell and Mehra did not compare the CPPT procedure to other due date procedures. The purpose of their research was to compare the performance of different priority rules under the CPPT due date assignment procedure.

Research reported by Maxwell [18] concerns single level assembly jobs. He assigned due dates to arriving jobs using the following expression:

$$d_k = r_k + (\text{maximum total processing time among the segments})$$
$$+ C_3 \times (\text{maximum number of operations of a segment among all the segments}).$$

The value of C_3 was set such that the percentage of late jobs was approximately 50% using two segment assembly jobs under the FASFS priority rule (first arrived in system, first served). This procedure can be viewed as another form of the CPPT procedure.

Siegel [22] assigns due dates using a procedure relying on the total work content of a job (TWK):

$$d_k = r_k + C_4 \times (\text{sum of the processing times of all operations}). \qquad (3)$$

Based on the results of an initial study, Siegel set the value of C_4 at 1.4.

Goodwin and Goodwin [13] studied due date assignment procedures for multi-level assembly jobs. They used the total work content (TWK) and the predetermined constant lead time allowance (CON) procedures for setting job due dates. The appropriate values of the coefficient, C_4, in the total work content method, and the value of C for the constant method were determined *experimentally* and were *static* coefficients. Their results showed that the total work content method performed better.

The due date assignment procedures cited above have one common feature: the coefficients are determined *a priori by a pilot study* and are used throughout the experimental studies as *static* fixed values. This may have been adequate in the framework of the cited research since the focus was on the priority rule performance and not on due date assignment procedures. In a practical setting, this type of a *fixed coefficient* would be difficult to obtain due to the changing nature of job shops both in terms of job type and the dynamics of the shop.

Recently, Fry, Philipoom and Markland [11] studied the performance of seven due date assignment procedures that determined the lead time allowance of an incoming job according to the following:

1. TWK, see (3).
2. CPPT, see (2).
3. $C_5 \times$ (sum of the total work at all work centers).
4. $C_6 \times$ (sum of the processing times of all operations) + $C_7 \times$ (sum of the total work at all work centers).
5. $C_8 \times$ (sum of the processing times of operations on the critical path) + $C_9 \times$ (sum of the total work at all work centers).
6. ($C_{10} \times$ (sum of the processing times of all operations)) $\times$ ($C_{11} \times$ (sum of the total work at all work centers)).
7. ($C_{10} \times$ (sum of the processing times of operations on the critical path)) $\times$ ($C_{11} \times$ (sum of the total work at all work centers)).

Regression analysis was used to determine the appropriate values of the coefficients C_1, C_4, C_5, through C_{11}. Their results show that due date assignment procedures that incorporate shop work load information with or without job characteristic information provide improved tardiness and lateness performance, and that lead time performance is not significantly influenced by the information used in the due date procedure. The shop work load information was represented by the total amount of work in the shop.

The work by Fry et al. [11] presents a methodology (in this case regression analysis) for determining appropriate values for the relevant coefficients. Their methodology, however, does not go far enough in terms of being *dynamic* and being able to take into consideration the characteristics of the specific incoming job and the state of the shop at the time the job is processed. The regression methodology relies on *historical* data and updating the model for each incoming job would be impractical.

3. Dynamic due date assignment procedures

The following is a discussion of the proposed methodology for arriving at appropriate values of the coefficients used in the CON-DYN, TWK-DYN, and CPPT-DYN procedures. The proposed methodology ensures that the coefficients assigned to a given job reflects both the state of the shop at the time the job is processed and the characteristics of that job. A discussion of the CPFT procedure which does not require the use of any coefficients is also included in this section.

3.1. Calculation of the coefficients

The coefficients for the CON-DYN, TWK-DYN, and CPPT-DYN procedures will be based on estimates of expected job lead time. For a given job k arriving to the shop at time t its expected lead time, $\widehat{\mathrm{LT}}_k$, can be determined by applying Little's result [17] and Section 11.3 of Heyman and Sobel [14]: $N = \lambda \times \mathrm{LT}$.

According to this equation, in order to find the lead time of a job, LT, it suffices to know the work-in-process inventory, N, and the arrival rate at the shop, λ.

When applying the above equation in a production environment the following question arises: should be estimate LT *directly or indirectly*, i.e. by using estimates of N and λ? According to the work by Glynn and Whitt [12], the direct and indirect estimation of LT are equal in their statistical efficiency when an estimate of (rather than the actual) λ is used (as it is the case in our situation). Furthermore, Nozari and Whitt [20] recommend applying the indirect estimation of LT in a production environment where it is easier to count N:

$$\widehat{\mathrm{LT}}_k = \hat{N}_t / \hat{\lambda}_t \tag{4}$$

where

$\hat{\lambda}_t$ = An estimate, as of time t, of the average arrival rate of jobs to the shop,

$\hat{N}_t$ = An estimate, as of time t, of the average number of jobs in the shop. This estimate could be either the *time-average*, or *current* values (see [20]). Based on the results of a pilot experiment, we use *current* estimates in the performance study reported in Section 5.

For the CPFT procedure, estimates of waiting times, $\hat{w}_{tm}$ at the various work centers are needed. Little's equation, rewritten as follows, is used to estimate the waiting times:

$$\hat{w}_{tm} = N_{tm} / \hat{\lambda}_{tm} \tag{5}$$

where

N_{tm} = The number of jobs waiting for processing at work center m at time t.

$\hat{\lambda}_{tm}$ = An estimate, as of time t, of the average arrival rate of jobs to work center m.

Again, in this study, N_{tm} is the *current* value, instead of the time-average value. The use of Little's Law in the aggregate approach versus its use in the micro approach has several properties which may not be immediately obvious. Some of these properties are presented below.

1. Average lateness for the CON, TWK, and CPPT procedures, which is based on the 'aggregate' approach, will be zero, because average allowance equals average lead time.
2. Average lead time will be the same for all due date procedures, if the priority of the jobs is independent of the job's due date.
3. The average lead time estimate obtained from using the CPFT-ADJ procedure (which is based on the 'micro' approach) to determine average work center waiting times is equivalent to the average lead time estimate obtained from the 'aggregate' approach, only if the job structure is of the string type. This holds only for string type jobs because there is only one path, the critical path. In other words, lead time estimates at each work center are not biased by the lead time of operations not on the critical path, as is the case for assembly type jobs. Furthermore, job lead time estimates determined directly from the average number of jobs in the shop are equivalent to estimates determined from the

average number of jobs at each work center. Thus, for string type jobs, average lateness will also be zero for the CPFT-ADJ due date assignment procedure.

4. For assembly type jobs, the use of average work center waiting times obtained from the 'micro' approach to estimate lead times under the CPFT-ADJ procedure does not have to equal the average lead time estimated by the 'aggregate' approach or the average lead time of the jobs that have gone through the shop. Thus, for assembly structure jobs, average lateness may not be zero.

The following sections describe the CON-DYN, TWK-DYN, CPPT-DYN, and CPFT procedures with emphasis on how the aggregate and micro approaches are used.

3.2. The CON-DYN

Under the CON-DYN procedure, each job is given an allowance based on the average lead time of the jobs that have gone through the shop. The allowance given to job k arriving at the shop at time t is given by

$$A_k = \widehat{\mathrm{LT}}_k \tag{6}$$

where $\widehat{\mathrm{LT}}_k$ is the expected lead time of job k (see (4)).

3.3. The TWK-DYN

Under the TWK-DYN procedure, the allowance given to job k is based on the total processing time of the job, see (3). The coefficient, C_4, represents the ratio of the average lead time of the jobs that have been through the shop up-to the arrival time of job k and the average total processing time of these jobs. That is,

$$C_4 = \mathrm{AV\hat{G}LT}_t / \mathrm{AVG\hat{T}WK}_t \tag{7}$$

$\mathrm{AVG\hat{T}WK}_t$ = An estimate of average total processing time of jobs that have been processed by time t, and

$\mathrm{AV\hat{G}LT}_t$ = An estimate of average lead time of jobs that have been processed by time t.

$\mathrm{AVG\hat{T}WK}_t$ can be obtained directly from the jobs that have completed their processing at time t. The $\mathrm{AV\hat{G}LT}_t$, on the other hand, can be obtained using (4).

The allowance for a job k is given by $A_k = C_4 \times \mathrm{TWK}_k$ where TWK_k = total processing time of job k.

3.4. The CPPT-DYN

Under the CPPT-DYN procedure, the allowance given to a job k is based on the critical path processing time of the job. The coefficient, C_1, represents the ratio of the average lead time of the jobs that have been through the shop and the average critical path processing time of these jobs. That is,

$$C_1 = \mathrm{AV\hat{G}LT}_t / \mathrm{AVG\hat{C}PPT}_t \tag{8}$$

where

$\mathrm{AVG\hat{C}PT}_t$ = An estimate of average critical path processing time of jobs that have been processed by time t, and

$\mathrm{AV\hat{G}LT}_t$ = An estimate of average lead time of jobs that have been processed by time t.

$\mathrm{AVG\hat{C}PPT}_t$ can be obtained directly from the jobs that have completed their processing at time t. The $\mathrm{AV\hat{G}LT}_t$, on the other hand, can be obtained using (4).

The allowance for a job k is given by $A_k = C_1 \times \mathrm{CPPT}_k$ where CPPT_k = critical path processing time of job k.

3.5. *The CPFT due date assignment procedure*

For the CPFT procedure, the allowance given to job k is the maximum flow time of the different paths of job k, where a path encompasses assembly, and if applicable, sub-assembly and sub-sub-assembly segments. That is, the allowance for a job k is

$$A_k = F_k, \tag{9}$$

and

$$F_k = \max\{f_i\}, \quad i \in G(l), \quad l = 1, 2, \ldots, L, \tag{10}$$

$$f_i = \sum_{j \approx S(i)} P_{ij} + \sum_{m \in W(i)} w_{tm} + F_{l-1} \tag{11}$$

where

L = Number of levels of assembly.
$G(l)$ = Set of segments coming into an assembly junction at level l.
P_{ij} = Processing time of operation j on segment i.
$S(i)$ = Set of operations on segment i.
$W(i)$ = Set of work centers visited by operations on segment i.
$\hat{w}_{tm}$ = Expected waiting time at work center m calculated at time t (see (5)).

The flow time for a given segment i, f_i, at level l is the sum of the processing times of the operations on segment i, added to the sum of the waiting times of these operations at work centers, added to the maximum flow time of the segments at level $l-1$ that feed into segment i. Thus, F_k is the maximum flow time of the segments at the highest assembly level or the segments that feed into the final assembly junction, and thus represents the expected lead time allowance for job k, A_k.

Unlike, the CON-DYN, TWK-DYN, and CPPT-DYN, the allowance so far obtained through the CPFT procedure is not guaranteed to result in a zero average lateness. Thus, A_k needs to be *adjusted upward or downward* depending on the average lateness that exists in the system at the time the due date of a newly arrived job is calculated. The adjusted allowance, A^*_k, is calculated as follows:

$$A_k^* = A_k \times (1 + \mathrm{ADJ}_t) \tag{12}$$

where

$$\mathrm{ADJ}_t = \begin{cases} \max\left(\dfrac{\widehat{\mathrm{LATE}}_t}{\widehat{\mathrm{LT}}_t - \widehat{\mathrm{LATE}}_t}, \mathrm{AVGADJ}_{t'} \right) & \text{if } \dfrac{\widehat{\mathrm{LATE}}_t}{\widehat{\mathrm{LT}}_t - \widehat{\mathrm{LATE}}_t} > 0, \\ \min\left(\dfrac{\widehat{\mathrm{LATE}}_t}{\widehat{\mathrm{LT}}_t - \widehat{\mathrm{LATE}}_t}, \mathrm{AVGADJ}_{t'} \right) & \text{if } \dfrac{\widehat{\mathrm{LATE}}_t}{\widehat{\mathrm{LT}}_t - \widehat{\mathrm{LATE}}_t} < 0, \\ \mathrm{AVGADJ}_{t'} & \text{otherwise,} \end{cases}$$

$\widehat{\mathrm{LATE}}_t$ = average job lateness as of time t,
$\widehat{\mathrm{LT}}_t$ = average job lead time as of time t,
$\mathrm{AVGADJ}_{t'}$ = average adjustment made during the time period t'.

We notice here that the purpose of the adjustment ADJ is to obtain an average lateness of zero. The ratio, $\widehat{\mathrm{LATE}}_t/(\widehat{\mathrm{LT}}_t - \widehat{\mathrm{LATE}}_t)$ is used to accomplish this purpose, since it represents the percent of allowance by which the lead times of the preceding jobs were under or over compensated. *Negative* LATE_t values indicates that allowances were *over*estimated, and *positive* values indicate that allowance were *under*estimated.

We present below the specific steps for calculating the value of ADJ_t:

Step 0. Initially, set $\mathrm{AVGADJ}_{t'} = 0$.

Step 1. Calculate both the average job lateness, $\widehat{\mathrm{LATE}}_t$, and the average job lead time $\widehat{\mathrm{LT}}_t$, as of time t.

Step 2. If $\widehat{\mathrm{LATE}}_t/(\widehat{\mathrm{LT}}_t - \widehat{\mathrm{LATE}}_t) \neq 0$, then

$$\mathrm{ADJ}_t = \begin{cases} \max\left(\dfrac{\widehat{\mathrm{LATE}}_t}{\widehat{\mathrm{LT}}_t - \widehat{\mathrm{LATE}}_t}, \mathrm{AVGADJ}_{t'} \right) & \text{if } \dfrac{\widehat{\mathrm{LATE}}_t}{\widehat{\mathrm{LT}}_t - \widehat{\mathrm{LATE}}_t} > 0, \\ \min\left(\dfrac{\widehat{\mathrm{LATE}}_t}{\widehat{\mathrm{LT}}_t - \widehat{\mathrm{LATE}}_t}, \mathrm{AVGADJ}_{t'} \right) & \text{if } \dfrac{\widehat{\mathrm{LATE}}_t}{\widehat{\mathrm{LT}}_t - \widehat{\mathrm{LATE}}_t} < 0. \end{cases}$$

We *also* keep track of the average adjustment given to jobs arriving during the time period t' *to* t, AVGADJ_t;
Else, (i.e., $\widehat{\mathrm{LATE}}_t/(\widehat{\mathrm{LT}}_t - \widehat{\mathrm{LATE}}_t)$ *is approximately* 0),
stop computing AVGADJ_t and for each incoming job, let $\mathrm{ADJ}_t = \mathrm{AVGADJ}_t$

Step 3. As soon as the ratio $\widehat{\mathrm{LATE}}_t/(\widehat{\mathrm{LT}}_t - \widehat{\mathrm{LATE}}_t)$ starts to move away from zero, let $\mathrm{AVGADJ}_{t'} = \mathrm{AVGADJ}_t$, $t' = t$, and go to Step 1.

Initially, the adjustment given to incoming jobs is based on the ratio $\widehat{\mathrm{LATE}}_t/(\widehat{\mathrm{LT}}_t - \widehat{\mathrm{LATE}}_t)$. However, when this ratio approaches our target value of zero (approximately), the average adjustment that was used to get the ratio to zero should then be used as the adjustment factor for newly arriving jobs. If the ratio starts to move away from zero, then the current AVGADJ_t is no longer adequate. When the ratio starts becoming positive (negative), the adjustment factor becomes the larger (smaller) of the ratio and $\mathrm{AVGADJ}_{t'}$ values. The value that is larger (smaller) for positive (negative) ratios is used to bring average lateness back to zero quicker. When average lateness approaches zero again, a new AVGADJ_t value is calculated based on the adjustments made from the time the ratio started moving away from zero until the current time.

When the ratio starts to move away from zero, the $\widehat{\mathrm{LATE}}_t$ and $\widehat{\mathrm{LT}}_t$ values are reset to represent the current time period. That is, these values are based on jobs in the shop from this point in time forward. Also, the average value of the adjustment given to jobs from this point in time forward is tracked so that it would be used as the new AVGADJ when the ratio starts approaching zero again.

4. Interaction of priority rules and due date assignment procedures

The performance of each of the due date assignment procedures will be studied under two priority rules, the earliest job due date rule and the earliest operation due date rule. Under the JDD rule, the job with the earliest job due date is given priority over the other jobs in the queue. Under the OPNDD rule, the job with the earliest operation due date is given priority. The job due dates are determined according to the procedures described in the preceding section. However, procedures have to be developed to determine the operation due dates from the job due dates.

To compute the due date of each operation that belongs to a given job we need a methodology for allocating the job lead time allowance, A_k, to each segment i, then allocating each segment lead time allowance, A_i, to each operation, j on that segment. The due dates for each segment and each operation are determined by back-scheduling from the job's due date. A due date for a segment i at level l is calculated as follows:

$$d_{l_i} = d_{l_i+1} - a_{l_i+1} \tag{13}$$

where
d_{l_i+1} = Due date of the segment at the next higher level $l+1$ that segment i feeds into.
a_{l_i+1} = Allowance for the segment at the next higher level $l+1$ that segment i feeds into.

The due date for the highest segments, that is, at level L, equals the due date of the job as determined from the due date assignment procedure (i.e., $d_L \equiv d_k$). The due date of the last operation of segment i at level l, where the number of operations on the segment is n_{l_i}, equals the due date of the segment. That is, $d_{l_i, n_{l_i}} = d_{l_i}$. The due date of preceding operations on segment i equals the due date of the succeeding operation less an allowance for succeeding operation. That is, $d_{l_i,j} = d_{l_i,j+1} - a_{l_i,j+1}$ where $a_{l_i,j+1}$ is the allowance for operation $j+1$ on segment i at level l.

The allowance to each operation is based on the rationale used for determining the entire job's allowance (that is, the due date assignment procedure being used). The CPPT, and CPFT due date procedures use critical path information to determine a job's allowance. Thus, for the CPPT and CPFT procedures we have, respectively,

$$a_{l_i,j+1} = C_1 \times P_{ij} \text{ and } a_{l_i,j+1} = P_{ij} + w_{tm}.$$

Since the CON and TWK procedures do not use critical path information, the allowance allocated to each operation under these procedures is not as straightforward. Goodwin and Goodwin [13] studied the operation due date priority rule with the TWK and CON due date assignment procedures for multi-level assembly jobs. They determined operation due dates by allocating the total allowance for the job to each individual operation in proportion to the processing time of each segment. However, in the Goodwin and Goodwin study [13], each segment had only one operation. We propose a rationale similar to that of Goodwin and Goodwin by determining an operation's allowance based on the operation's processing time and by allocating the job's total allowance in proportion to processing time.

We determine a waiting time allowance factor for each operation by allocating the job's total allowance in proportion to the processing time of the segments [21]. That is, for the CON and TWK procedure we have

$$a_{l_i,j+1} = P_{i,j+1} \times \left(\frac{A_k \times \dfrac{\sum\limits_{b \in G(l)} \sum\limits_{c \in S(b)} P_{ab}}{\sum\limits_{l=1}^{L} \left(\sum\limits_{b \in g(l)} \sum\limits_{c \in S(b)} P_{ab} \right)} \times U_l}{\sum\limits_{b \in g(l)} \sum\limits_{c \in S(b)} P_{ab}} \right) \tag{14}$$

where U_l = number of segments at level l.

The factor by which $P_{i,j+1}$ is multiplied represents how much waiting time allowance is built into the job's allowance per unit of processing time. Since the determination of a job's due date under the CON and TWK procedures is not based on critical path information, the due date for an operation may be a negative value. Negative operation due date would indicate that these operations are more critical and will receive higher priority.

5. Performance study

5.1. The job shop simulator

A simulation model of a multi-level assembly job shop was developed and used as the basis for the experiments in investigating the performance of the various due date assignment procedures under the

Table 1

Job structure	No. of assemblies	No. of sub-assemblies per assembly	No of sub-sub-assemblies per sub-assembly	Average No. of segments per job
1	1	0	0	1.00
2	[2–10] [a]	0	0	6.00
3	10	0	0	10.00
4	[2–3]	[4–6]	0	15.00
5	[4–6]	[2–3]	0	17.50
6	[4–6]	[4–6]	0	30.00
7	[2–3]	[2–3]	[3–5]	33.75
8	[2–3]	[3–5]	[2–3]	37.50
9	[3–5]	[2–3]	[2–3]	39.00

[a] $[a-b]$ represents an integer uniform distribution between a and b.

JDD and OPNDD priority rules for different job structures. The model was coded in SIMSCRIPT II.5. See [2] for the validation of the model.

The simulated job shop consists of six work centers with a specific number of identical machines that are continuously available. The interarrival time of jobs are exponentially distributed with a mean value chosen to yield an average utilization of the shop of approximately 90%. The processing time of an operation at a work center is a truncated exponentially distributed random variable whose mean is the same for each work center (to achieve equal average utilization across the work centers).

Jobs arriving at the shop may consist of one segment, several assembly type segments, both assembly and sub-assembly segments, or assembly, sub-assembly, and sub-sub-assembly segments. We experimented with nine different job structures (see Table 1).

For each job class, the number of assembly segments, the number of sub-assembly segments coming into an assembly type segment, and the number of sub-sub-assembly segments per sub-assembly segment are determined from input probability distributions. There are many different jobs that can be generated for each job structure.

The number of operations and the routing of a job segment is a function of the segment level within the job. For each segment level, the number of segment types can be represented as a probability distribution. For each segment level, we use twenty different types of segments to represent different standard components or features that a customer requests. Additionally, the routing of each segment type is known with certainty. A segment may have anywhere from one to thirty-nine operations. We use known routings because in practice the routing for producing different components of a job are typically known.

The simulation collects statistics on the following performance measures: lead time, lateness, conditional tardiness, and percent tardy.

Since the simulation does not start out in steady state, statistics on some of the initial observations are discarded. Welch's [24] approach for estimating steady state was used to determine the warm-up number of observations for each simulation run. Each experiment ran for a total of 102 450 segments, with the first 1200 segments being used for warm-up purposes.

In each simulation run, observations of each of the performance measures were grouped into sets of batches to reduce the autocorrelation that exists between observations of a simulation run, resulting in realistic confidence intervals. An appropriate batch size was determined by running a pilot experiment and employing the batch means method described in [1]. The mean of the batches and the standard deviation of the mean were calculated for each performance measure.

In order to compare differences in the due date assignment procedures under the different priority rules for the different job structures, we ensured that each procedure is subject to the same exact *operating environment*. This was accomplished by

1) employing the variance reduction technique of common random numbers [7], by using separate random number streams for generating job interarrival times, job structure (i.e. number of assemblies, sub-assemblies per assembly, and sub-sub-assemblies per sub-assembly), and operation processing time;
2) generating a job's specific structure and the actual processing times of each of its operations at the time a job arrives at the shop;
3) grouping observations, on each of the measures, together in batches according to their arrival times rather than their completion times.

Since common random numbers are used in this study, correlations exist between observations generated from the different simulations runs. Thus, the use of well-known multiple comparison tests, such as the Tukey, Duncan, and Scheffe tests, to perform statistical comparisons between the different due date assignment and priority assignment procedures is not appropriate. However, the robustness of the t statistic enables the Bonferroni multiple comparison test to be used [16,21]. Thus, the t statistic and the Bonferroni inequality were used to perform statistical analysis for the data obtained in this study.

5.2. *Discussion of results*

Tables 2 and 3 show the results of the simulation experiments conducted in the study to analyze the performance of the due date assignment procedures discussed in this paper.

It is important to note that the *average lateness* is statistically *zero* for all job structures under all due date assignment procedures. The following are some general observations that apply to *all* job types.

- The dynamic versions of CON, CPPT, and TWK provide results that are either statistically *superior* or statistically *equivalent* to their respective static versions.
- For *multi-level assembly* type jobs, JDD *outperforms* OPNDD. Consistent with previous research results [15], for *string* type jobs the OPNDD priority rule *outperforms* JDD in lead time and tardiness.
- The dynamic versions of CON, TWK, and CPPT have lower lateness and tardiness variability as compared to their static counterparts. CPFT-ADJ has a larger variability as compared to the other dynamic procedures.
- Under more complex job structures and with the OPNDD priority rule, CPFT-ADJ results in *longer* lead times than the dynamic versions of CON, TWK, and CPPT, without any improvement in tardiness.

Next we discuss results in terms of the complexity of the job structure.

5.2.1. *String type jobs*

- The *dynamic* versions of CON, TWK, and CPPT procedures are statistically *superior* to their *static* counterparts with respect to the tardiness measure.
- Consistent with the results of previous research [5,8], TWK and CPPT *outperform* the CON procedure. Furthermore, the CPFT-ADJ procedure performs *as well as* the dynamic versions of CPPT and TWK.

5.2.2. *Single-level assembly jobs*

- The CPFT-ADJ procedure provides *better* overall performance especially with respect to the tardiness, and % of tardy measures.
- The *dynamic* versions of CON, TWK, and CPPT procedures perform *better* than their *static* counterparts with significantly lower lateness variability, lower average tardiness, and lower tardiness variability.
- There seem to be no significant difference among the CON, CPPT, and TWK procedures. When exceptions exist, the CPPT procedure is slightly better than the other two.
- In comparing the performance of the priority rules JDD versus OPNDD, where differences exist, the JDD *outperforms* OPNDD especially with respect to the lead time and tardiness measures.

Table 2
Performance of due date procedures under JDD priority rule

Job structure	Due date rule	Lead time	Lateness	Tardiness	% Tardy
No. 1	CON-DYN	32.4 (2.0)	0.0 (0.2)	9.7 (0.3)	57.9 (0.8)
	CON-STAT	32.5 (2.1)	0.1 (2.0)	14.8 (1.8)	48.1 (3.7)
	TWK-DYN	29.1 (1.4)	0.0 (0.1)	5.5 (0.1)	43.1 (0.8)
	TWK-STAT	29.4 (1.7)	0.4 (1.7)	10.4 (1.2)	40.3 (4.7)
	CPPT-DYN	29.1 (1.4)	0.0 (0.1)	5.5 (0.1)	43.1 (0.8)
	CPPT-STAT	29.4 (1.7)	0.4 (1.7)	10.4 (1.2)	40.3 (4.7)
	CPFT-ADJ	30.0 (1.4)	0.2 (0.2)	7.2 (0.3)	43.5 (1.4)
No. 2	CON-DYN	56.0 (2.6)	0.6 (0.5)	9.2 (0.2)	53.2 (1.2)
	CON-STAT	55.9 (2.7)	0.0 (3.4)	24.6 (2.5)	42.5 (4.1)
	TWK-DYN	46.2 (2.0)	0.2 (0.3)	6.9 (0.2)	51.3 (1.5)
	TWK-STAT	48.2 (2.4)	2.3 (3.1)	23.2 (2.4)	41.2 (4.3)
	CPPT-DYN	50.2 (2.2)	0.5 (0.4)	7.6 (0.2)	52.5 (1.3)
	CPPT-STAT	52.0 (2.5)	1.7 (3.3)	24.3 (2.3)	41.2 (4.4)
	CPFT-ADJ	50.5 (1.6)	−10.2 (7.8)	5.7 (0.2)	20.4 (1.2)
No. 3	CON-DYN	69.1 (2.5)	0.4 (0.4)	8.4 (0.2)	51.9 (1.6)
	CON-STAT	69.0 (2.5)	−0.1 (4.0)	30.4 (4.1)	44.2 (4.1)
	TWK-DYN	65.8 (2.3)	−0.1 (0.4)	7.7 (0.2)	52.2 (1.4)
	TWK-STAT	66.8 (2.4)	0.8 (3.7)	30.2 (2.2)	43.7 (4.1)
	CPPT-DYN	66.6 (2.5)	0.3 (0.4)	8.1 (0.2)	53.7 (1.6)
	CPPT-STAT	68.0 (2.4)	1.8 (3.7)	30.0 (2.2)	44.9 (4.0)
	CPFT-ADJ	65.2 (3.5)	−6.8 (8.4)	6.7 (0.3)	21.8 (2.8)
No. 4	CON-DYN	113.4 (5.8)	1.8 (0.7)	11.9 (0.3)	54.9 (1.7)
	CON-STAT	113.6 (5.8)	0.2 (5.8)	44.6 (5.1)	37.5 (4.9)
	TWK-DYN	106.7 (5.6)	0.6 (0.7)	11.4 (0.5)	54.4 (1.8)
	TWK-STAT	108.1 (5.7)	2.4 (5.6)	43.5 (4.9)	37.4 (4.8)
	CPPT-DYN	110.9 (5.7)	1.2 (1.7)	12.8 (0.7)	55.8 (1.9)
	CPPT-STAT	112.7 (5.9)	2.2 (5.7)	42.6 (4.8)	37.0 (4.5)
	CPFT-ADJ	118.9 (9.0)	−15.2 (9.9)	18.7 (5.7)	21.8 (3.9)
No. 5	CON-DYN	125.3 (7.6)	1.2 (1.1)	12.7 (0.3)	53.5 (2.6)
	CON-STAT	125.5 (7.8)	0.2 (7.8)	54.4 (6.8)	42.3 (6.3)
	TWK-DYN	118.7 (7.3)	0.5 (1.1)	12.0 (0.3)	54.2 (2.6)
	TWK-STAT	120.6 (7.6)	2.9 (7.4)	54.6 (7.1)	42.5 (6.2)
	CPPT-DYN	121.5 (7.3)	1.7 (1.1)	13.2 (0.4)	57.7 (2.6)
	CPPT-STAT	124.1 (7.5)	2.5 (7.3)	55.7 (7.8)	41.9 (6.2)
	CPFT-ADJ	129.9 (7.7)	−0.9 (9.9)	20.4 (7.1)	26.3 (4.2)
No. 6	CON-DYN	171.2 (13.6)	5.2 (3.8)	16.4 (0.8)	57.6 (3.1)
	CON-STAT	171.4 (13.6)	0.0 (13.6)	71.6 (10.3)	33.5 (7.1)
	TWK-DYN	165.8 (13.2)	2.0 (3.0)	15.7 (1.1)	52.8 (2.1)
	TWK-STAT	164.9 (13.5)	−0.1 (13.3)	67.8 (10.9)	33.0 (7.9)
	CPPT-DYN	168.2 (13.3)	5.0 (3.5)	17.9 (1.3)	57.9 (2.8)
	CPPT-STAT	170.3 (13.2)	2.0 (9.2)	69.2 (9.2)	33.4 (7.8)
	CPFT-ADJ	208.9 (18.8)	9.2 (13.7)	29.8 (8.6)	41.9 (4.6)
No. 7	CON-DYN	137.4 (7.6)	4.2 (3.1)	17.7 (0.4)	54.4 (2.2)
	CON-STAT	138.0 (7.9)	0.4 (9.2)	57.3 (8.5)	33.1 (5.9)
	TWK-DYN	130.5 (7.1)	0.4 (2.1)	15.3 (.3)	50.6 (1.9)
	TWK-STAT	130.8 (7.5)	−0.1 (8.5)	54.5 (7.8)	30.9 (6.3)
	CPPT-DYN	134.9 (7.4)	3.9 (2.8)	18.4 (0.3)	55.8 (2.2)
	CPPT-STAT	136.3 (7.6)	1.7 (8.7)	56.7 (8.2)	32.0 (6.2)
	CPFT-ADJ	184.7 (15.9)	7.6 (13.6)	27.0 (8.4)	41.6 (4.6)
No. 8	CON-DYN	176.5 (15.8)	−1.9 (3.7)	19.8 (1.0)	47.3 (2.7)
	CON-STAT	178.2 (15.8)	4.7 (15.8)	48.2 (12.4)	21.6 (6.5)
	TWK-DYN	167.4 (15.0)	−5.2 (5.6)	16.2 (0.7)	44.2 (2.1)
	TWK-STAT	166.7 (15.1)	−5.6 (15.8)	43.0 (12.9)	20.2 (6.5)
	CPPT-DYN	171.9 (15.4)	−4.3 (3.9)	18.6 (0.8)	48.6 (2.7)
	CPPT-STAT	175.3 (15.3)	5.0 (15.8)	49.0 (12.5)	21.5 (6.6)
	CPFT-ADJ	234.1 (18.7)	8.6 (18.5)	25.5 (15.7)	40.6 (3.5)

Table 2 (continued)

Job structure	Due date rule	Lead time	Lateness	Tardiness	% Tardy
No. 9	CON-DYN	219.1 (16.2)	2.0 (1.7)	20.1 (1.0)	52.4 (3.0)
	CON-STAT	218.8 (16.3)	−3.1 (19.1)	88.7 (18.2)	31.5 (7.2)
	TWK-DYN	209.7 (16.3)	1.1 (2.2)	19.3 (1.3)	52.3 (2.3)
	TWK-STAT	208.6 (16.9)	−1.6 (18.4)	81.2 (17.6)	31.4 (7.1)
	CPPT-DYN	215.2 (16.1)	1.7 (2.1)	18.5 (1.1)	53.2 (2.5)
	CPPT-STAT	215.0 (16.4)	−2.1 (16.9)	85.1 (17.7)	31.6 (7.0)
	CPFT-ADJ	302.4 (20.5)	11.4 (18.8)	27.8 (14.4)	42.9 (5.4)

- Interaction effects between due date assignment procedures and priority rules exist for lead time, tardiness and % tardy. The differences are more pronounced under OPNDD.
- The job structure is a factor in tardiness performance among due date assignment procedures where there is greater variability in the number of assemblies in the structure.

5.2.3. *Two-level assembly jobs*

- The *dynamic* versions of CON, TWK, and CPPT procedures are *superior* to their *static* counterparts, *except* with respect to the % tardy for job structures with more variability at the subassembly level.
- The CPPT procedure *outperforms* CON in lead time and tardiness measures under OPNDD for all job structures.
- The CPFT-ADJ procedure is a *good* performer with respect to all measures, especially the % tardy.
- Where statistical differences exist between the JDD and OPNDD priority rules, JDD *outperforms* OPNDD. The differences mainly occur in the lead time measure under the CON, TWK, and CPFT-ADJ due date procedures, and in tardiness performance under the CON and TWK procedures. The specific job structure does not influence the priority rule performance.
- Interaction effects are prevalent between due date procedures and priority rules. The performance measures influenced are lead time and tardiness.
- Overall, the specific job structure influences *all* performances measures, *except* tardiness. The dynamic versions seem to provide better performance for jobs with less variability at the subassembly level, while the CPFT-ADJ procedure provides better performance for jobs with more variability at the assembly level.

5.2.4. *Three-level assembly jobs*

- Even at this level of complexity, we find no significant difference among the performance of CON, TWK, and CPPT. Therefore, utilizing the simplest of these due date assignment procedures such as CON would ensure superior performance if lateness is the performance of choice.
- CPFT-ADJ would be chosen if tardiness performances is of importance.
- Under CPFT-ADJ, the only instance where there is a statistically significant difference in the performance of JDD and OPNDD priority rules is in the measure of the average lead time (JDD outperforms OPNDD).

Once again, there is interaction between complexity of structure, and due date assignment procedures, but it is difficult to make any clear generalization.

6. Conclusions

This paper introduces dynamically updated due date assignments where the appropriate coefficients are continually updated to reflect the changing job mix, work load and resources of a job shop processing multi-level assemblies. This dynamic updating based on average job lead time information reduces the

Table 3
Performance of due date procedures under OPNDD priority rule

Job structure	Due date rule	Lead time	Lateness	Tardiness	% Tardy
No. 1	CON-DYN	32.0 (1.8)	0.0 (0.2)	9.3 (0.2)	57.5 (0.7)
	CON-STAT	32.1 (1.9)	0.1 (2.0)	14.3 (1.6)	48.1 (3.6)
	TWK-DYN	22.2 (1.3)	0.0 (0.1)	2.7 (0.1)	51.8 (1.4)
	TWK-STAT	23.3 (1.6)	1.0 (1.5)	8.6 (1.2)	43.8 (4.8)
	CPPT-DYN	22.2 (1.3)	0.0 (0.1)	2.7 (0.2)	51.8 (1.4)
	CPPT-STAT	23.3 (1.6)	1.0 (1.5)	8.6 (1.2)	43.8 (4.8)
	CPFT-ADJ	25.4 (1.4)	−0.5 (0.5)	3.4 (0.3)	47.6 (4.8)
No. 2	CON-DYN	70.0 (4.4)	0.7 (0.5)	11.8 (0.4)	56.9 (1.7)
	CON-STAT	66.6 (3.2)	−3.4 (3.8)	26.9 (2.6)	42.4 (4.3)
	TWK-DYN	58.7 (3.5)	0.1 (0.4)	9.2 (0.4)	57.3 (1.8)
	TWK-STAT	57.2 (2.9)	−1.5 (3.3)	24.3 (2.6)	41.7 (4.5)
	CPPT-DYN	49.2 (2.6)	0.5 (0.4)	5.6 (0.2)	56.4 (2.3)
	CPPT-STAT	48.8 (2.3)	−0.1 (3.0)	21.9 (2.3)	39.8 (4.6)
	CPFT-ADJ	63.4 (2.9)	−12.1 (8.4)	4.9 (0.2)	16.2 (1.0)
No. 3	CON-DYN	90.4 (4.3)	0.9 (0.6)	13.7 (0.4)	56.3 (1.3)
	CON-STAT	86.5 (3.1)	−3.8 (4.7)	33.8 (2.2)	44.6 (4.4)
	TWK-DYN	86.2 (4.0)	−0.1 (0.6)	12.2 (0.3)	55.1 (1.6)
	TWK-STAT	82.5 (3.0)	−3.1 (4.5)	33.8 (2.2)	43.8 (4.5)
	CPPT-DYN	65.5 (2.7)	0.3 (0.4)	6.1 (0.2)	56.8 (2.1)
	CPPT-STAT	64.8 (2.2)	−0.5 (3.7)	27.2 (2.1)	42.7 (4.3)
	CPFT-ADJ	82.9 (5.6)	−9.7 (9.8)	6.0 (0.2)	16.5 (2.1)
No. 4	CON-DYN	158.4 (7.5)	2.9 (1.6)	21.4 (2.0)	56.7 (2.3)
	CON-STAT	152.0 (7.0)	−6.4 (7.0)	50.9 (6.1)	37.0 (4.6)
	TWK-DYN	149.3 (6.9)	0.9 (1.8)	18.7 (1.5)	55.2 (2.9)
	TWK-STAT	143.3 (7.0)	−8.3 (7.1)	47.9 (6.2)	35.4 (4.7)
	CPPT-DYN	126.6 (7.6)	1.2 (1.1)	11.6 (0.9)	56.2 (3.5)
	CPPT-STAT	123.5 (6.2)	−2.5 (5.4)	40.5 (5.0)	35.5 (4.7)
	CPFT-ADJ	190.6 (12.5)	−13.6 (10.1)	17.7 (6.7)	18.2 (4.9)
No. 5	CON-DYN	171.7 (9.1)	2.1 (2.1)	20.9 (0.9)	58.5 (3.7)
	CON-STAT	166.2 (8.0)	−5.6 (8.1)	59.1 (6.9)	44.1 (5.7)
	TWK-DYN	164.5 (8.6)	0.7 (2.0)	18.7 (0.8)	57.7 (3.6)
	TWK-STAT	158.2 (8.2)	−7.6 (8.1)	58.1 (8.1)	42.1 (5.6)
	CPPT-DYN	134.9 (8.5)	1.9 (1.4)	12.7 (0.6)	59.9 (3.7)
	CPPT-STAT	133.1 (7.6)	−2.0 (6.3)	52.7 (8.5)	42.3 (6.3)
	CPFT-ADJ	186.7 (15.7)	−12.4 (12.6)	19.2 (7.2)	23.6 (4.6)
No. 6	CON-DYN	261.1 (14.7)	6.9 (5.4)	37.9 (4.0)	58.5 (2.8)
	CON-STAT	258.8 (12.8)	−8.1 (12.9)	99.0 (14.9)	35.8 (7.0)
	TWK-DYN	248.3 (15.3)	2.1 (3.6)	33.8 (3.7)	54.4 (2.5)
	TWK-STAT	244.1 (11.4)	−15.6 (13.7)	93.3 (15.6)	35.6 (7.2)
	CPPT-DYN	203.3 (15.2)	5.3 (4.7)	19.5 (2.3)	60.0 (3.6)
	CPPT-STAT	203.2 (12.9)	0.3 (12.9)	75.4 (12.5)	34.6 (7.5)
	CPFT-ADJ	292.3 (16.3)	7.6 (13.4)	29.3 (8.9)	39.5 (5.3)
No. 7	CON-DYN	192.6 (12.7)	5.3 (3.9)	31.4 (1.4)	57.9 (2.0)
	CON-STAT	202.9 (9.7)	4.4 (11.3)	75.6 (9.8)	42.2 (4.9)
	TWK-DYN	187.4 (12.3)	0.3 (2.5)	26.1 (1.3)	54.5 (1.9)
	TWK-STAT	192.2 (9.7)	0.3 (10.9)	73.1 (10.9)	39.6 (5.2)
	CPPT-DYN	158.3 (9.7)	4.3 (2.9)	19.3 (0.8)	58.5 (2.3)
	CPPT-STAT	169.4 (8.1)	6.4 (10.2)	59.7 (9.3)	39.2 (5.2)
	CPFT-ADJ	256.6 (17.3)	5.7 (12.9)	25.5 (9.0)	39.3 (5.4)
No. 8	CON-DYN	263.3 (16.3)	−2.7 (4.2)	36.5 (2.5)	53.2 (2.7)
	CON-STAT	279.1 (17.1)	6.8 (18.1)	84.1 (13.9)	31.8 (6.3)
	TWK-DYN	252.8 (18.1)	−5.8 (5.9)	28.8 (1.8)	50.2 (2.1)
	TWK-STAT	262.7 (18.3)	4.2 (18.2)	76.1 (13.3)	30.6 (6.5)
	CPPT-DYN	211.9 (16.1)	−4.7 (4.1)	19.5 (0.9)	51.5 (3.2)
	CPPT-STAT	231.4 (15.4)	6.9 (16.6)	57.4 (11.5)	27.4 (6.6)
	CPFT-ADJ	307.0 (20.2)	7.1 (17.9)	19.9 (16.2)	38.9 (4.6)

Table 3 (continued)

Job structure	Due date rule	Lead time	Lateness	Tardiness	% Tardy
No. 9	CON-DYN	315.5 (18.3)	1.7 (5.0)	36.8 (2.8)	56.4 (3.5)
	CON-STAT	314.5 (16.1)	−2.8 (16.1)	97.1 (20.3)	38.1 (6.5)
	TWK-DYN	303.9 (16.8)	1.5 (4.3)	33.1 (2.0)	55.1 (3.1)
	TWK-STAT	301.3 (15.8)	−3.9 (15.1)	91.4 (19.4)	37.7 (6.6)
	CPPT-DYN	257.8 (13.7)	1.7 (2.7)	24.5 (1.9)	55.6 (3.8)
	CPPT-STAT	257.4 (14.1)	−0.2 (14.5)	88.1 (18.9)	34.4 (6.7)
	CPFT-ADJ	398.4 (21.6)	10.2 (17.9)	22.8 (15.8)	40.2 (6.0)

differences in performance between CON, TWK and CPPT. Thus, one could choose the dynamic CON procedure which is the simplest of the three procedures. Previous researchers using the static versions with constant coefficients found that the TWK procedure outperformed CON and CPPT.

The CPFT procedure introduced in this paper results in improved tardiness performance for multi-level assembly jobs. This procedure includes waiting time estimates at the various work centers. The *adaptive adjusted* version of CPFT results in a reduction of the negative lateness (with a mean set at zero) while retaining the desirable improved tardiness performance.

It should also be noted that in the experiments, the average job lateness was targeted at zero. The proposed procedure, however, provides shop management with the *ability to set* the average lateness at any *desired* level. Depending upon management's emphasis, the average job lateness may be set at zero, positive, or negative value. For example, if management wants to stress lower tardiness and lower percent tardy, the average lateness could be targeted at a slightly negative value.

Significant differences in the performance of the JDD and OPNDD priority rules exist for some performance measures under certain due date procedures. For string type jobs, where significance exists, the OPNDD priority rule outperforms the JDD priority rule. For multi-level assembly jobs, where significance exists, the JDD priority rule outperforms the OPNDD priority rule in average lead time and average conditional tardiness. One reason for the difference in results for string and assembly type jobs may be that when the more complex assembly structure is added to jobs, operation due dates, especially for operations not on the critical path, are not as meaningful. Another reason may be the approach (Orkin's) used to allocate the allowance to the operations. The performance measure that is most influenced by the choice of priority rule is average lead time. The average lateness and average conditional tardiness measures are also influenced for some job structures and under certain due date procedures. The due date procedures that most influence the performance of the priority rules is the CPFT-ADJ procedure. Furthermore, significant differences between the priority rules seem to be more prevalent for more complex job structures.

In this paper, the shop work load information used to obtain waiting time estimates for job due date determination is the average number of jobs waiting at a work center. Further research is in progress to study the performance of due date assignment procedures that utilize different shop work load information to estimate waiting times, for string and multi-level assembly jobs, where coefficients are not necessary. The intent is to determine how the use of different types of shop work load information influence performance, and if the influence varies depending on the complexity of the job structure. Thus, guidelines will be provided on what information to use in due date assignment for different job structures to provide improved shop performance.

The performance of due date based priority rules, the earliest job due date and earliest operation due date priority rules, were studied in this research for multi-level assembly jobs. The performance of these due date assignment procedures with respect to other priority rules, especially non-due date based priority rules [2], such as the total work remaining (TWKR) rule, the shortest processing time (SPT) rule, the cost over tardiness (COVERT) rule, etc., needs to be investigated for multilevel assembly jobs. Furthermore, the sensitivity of the performance of due date procedures under different priority rules should also be investigated.

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