Priority assignment procedures in multi-level assembly job shop

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Priority Assignment Procedures in Multi-Level Assembly Job Shops

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Abstract: This paper deals with the design of priority rules for job shops that process multi-level assembly jobs. Specifically, it explores the means by which the structural complexity of jobs can be incorporated explicitly into priority rules to reduce job lead times. The job lead time is viewed as consisting of two components: flow time and job staging delays. The primary focus of the paper is on the development of a class of priority rules that is aimed at reducing the staging delay. The class of priority rules that is developed is then used in combination with rules that are effective for the flow time component. The combined rule results in the improvement of the lead time performance. The paper also includes experimental results on sets of jobs of varying degrees of complexity. These results provide a comparative perspective on the performance of priority rules that have been examined in the earlier research literature as well as the rules specifically developed in this paper.

■ In a typical manufacturing environment, one encounters job shops that process multi-level assembly jobs far more frequently than shops processing simple string type jobs. However, most of the past and current research literature related to job shops concentrates on facets of shops processing string type jobs. Even though these efforts have contributed insights into problems associated with job shops, there still are certain unique problems associated with scheduling assembly type jobs that do not arise when dealing with simple string type jobs. In this paper we report on the first phase of an ongoing study related to priority assignment procedures in job shops where multi-level assembly jobs are processed.

In order to review the existing research in this area we introduce some concepts that are central to the issues to be discussed.

An assembly type job consists of a set of segments that have to be assembled together after the processing of the segments is completed. Figure 1 shows three types of assembly jobs: single level (fan structure), two level, and three level assembly jobs. In a multi-level assembly job, a higher level segment cannot start its processing unless all lower level segments that precede it have been completely processed and assembled together. A multi-level job is considered complete when all of its highest level segments are fabricated and assembled together. This structural complexity associated with assembly type jobs introduces problems related to coordination and pacing that do not exist when dealing with string type jobs.

In jobs of the string type, the flow time of a job consists of the sum of the actual processing times of the operations that make up the job plus the time that the operations have to wait for a machine at work center queues. In multi-level assembly jobs, the lead time consists of a combination of 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. (The staging delay is the delay encountered by segments coming into an assembly point when they have to wait for one another before their assembly operation can start.)

Since this type of assembly environment requires attention to both coordination and pacing, a priority assignment procedure has to be judged on how well it succeeds in reducing

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Figure 1a
String Type Job

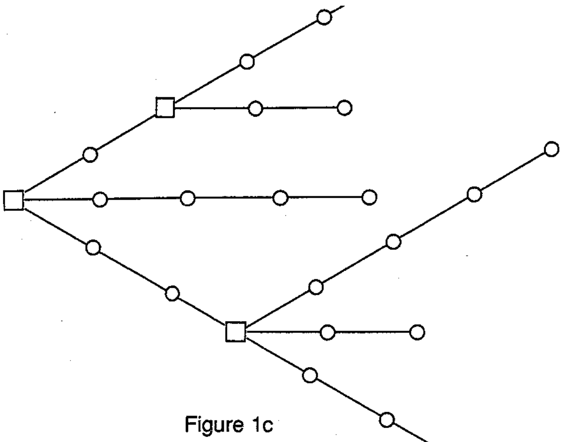


Figure 1c
2-levels,
8-segments job

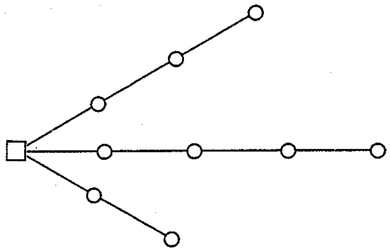


Figure 1b
1-level, 3-segments job

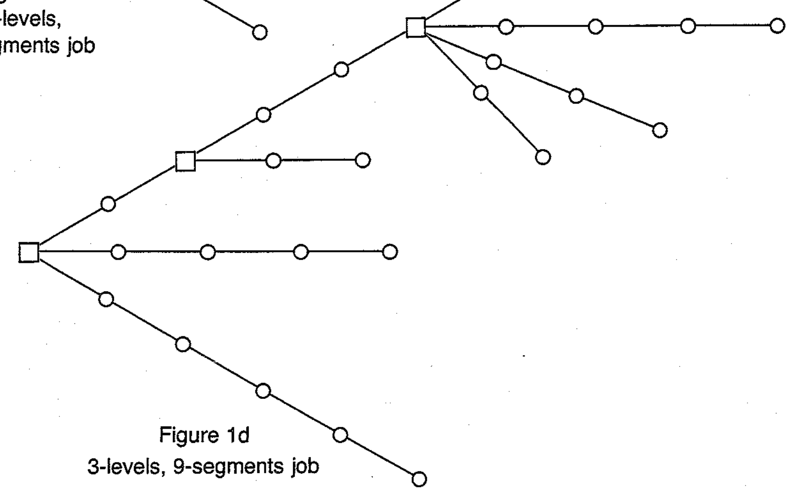


Figure 1d
3-levels, 9-segments job

the flow time of the segments and to what extent it can coordinate the processing of the different segments that belong to the same job.

The Scope of the Paper

This paper will focus on understanding the design of priority assignment procedures that include information related to the structural complexity of a job and the impact this type of information has on the job lead time performance measure.

As was pointed out previously, the average lead time of a set of multi-level assembly jobs consists of two components: the average flow time of the job segments and the average staging delay of the segments.

It would be useful to understand how a priority rule achieves its performance. That is, what part of the resulting average lead-time is made up of the flow time component and what part is contributed by the staging delay component. Examining the performance of various priority rules in terms of their lead time components would provide a means of combining the desirable characteristics of various priority rules that may have different strengths. This would result in the design of a rule with a superior lead time performance.

The experimental results of previous research are difficult to interpret in this regard (with the exception of single level assembly type jobs) due to the lack of a convenient expression that relates the average job flow time and the average job staging delay to the average job lead time of a set of jobs that have been processed.

In this paper we first develop a convenient additive expression for the average lead time of a set of general multi-level assembly jobs. This expression is in terms of the job's average flow time (the weighted average flow time of its segments) and the job's average staging delay (the weighted average staging delay of its segments). We then discuss approaches for designing priority assignment procedures that include information on the structural complexity of the jobs. Since staging delays appear to be the new major element in the transition from string type jobs to multi-level assembly type jobs, we decided to start with designing priority rules that focus on reducing staging delays thus, "pacing" the progress of related job segments.

The discussion in this paper is centered on priority rules, that do not utilize due date information rules. It is assumed that the average flow time, staging delay and lead time of a job are the primary performance measures. In testing such priority rules, a job arriving at the shop is assigned a due date according to the due date assignment procedure suggested by Maxwell [8]. (See the section on the simulation experiment.)

The problems and decisions related to due date assignment procedures are studied in the second phase of this research [2]. The interaction of due date assignment procedures with priority rules incorporating due date information and job structure complexity, are also considered in the second phase.

The emphasis in the first phase of the study reported in this paper, is on priority rules that focus on the staging delay.

Review of the Literature

Research related to shop performance where multi-level assembly jobs are considered has been very limited. Three studies were reported in the mid-and late sixties by Carroll [4], Maxwell and Mehra [9] and Maxwell [8] that have dealt with job structures of the assembly type. These were followed by Siegel [13], and more recently by Miller, *et al.,* [10], Rochette and Sadowski [11], Sculli [12], and Goodwin and Goodwin [7]. A brief discussion of the results relevant to priority assignment procedures in assembly job shops given in some of these research studies is presented next.

Maxwell and Mehra [9] used multi-level "symmetric tree structured" jobs in their experiments. They tested the performance of four basic priority rules and a variety of composite rules constructed from the four basic rules. The staging delay was not explicitly included as a measure in the comparison of the different priority rules. They observed a steady improvement in the performance of the shop as additional and increasingly complex information was incorporated into the composite priority rules.

Maxwell [8] utilized job shops where single-level assembly jobs were considered. Each job had the same number of segments. He tested the performance of several priority rules with respect to mean job lead time, mean flow time, and mean staging delay and other performance measures. Among the rules he tested the NUSEG priority rule (the imminent operation that belongs to the job with the fewest number of unfinished segments is processed first) had the best performance with respect to the mean staging delay. When combined with SPT (the operation with the shortest processing time is processed first) as a tie breaker, this rule resulted in an improved overall performance. He concluded that, further improvements in performance could be achieved by using a priority assignment procedure that incorporated the dynamic progress of the job segments as they proceed through the shop and also by making use of the SPT as a tie breaker.

Siegel [13] studied the performance of several priority rules using multi-level assembly jobs. His research was exploratory in nature and was aimed at identifying the major attributes of priority assignment procedures in this complex environment. In his study, he considered job segments that consisted only of a single operation. He found that the TWKR priority rule (the operation that belongs to the job with the least amount of total work remaining is processed first), was predominantly the best rule with respect to the mean lead time. However, he concluded that there was a need to develop better priority assignment procedures for multi-level job shops; and that these procedures should possess three attributes; pacing, structural dependence, and acceleration. Although his study articulated these attributes which are fundamental to multi-level assembly job shop scheduling, it did not attempt to synthesize better rules from these attributes.

Basic Definition and Concepts

Job Types

There are two basic job types that have been used in studying job shops: string and assembly type jobs. A "string" type job consists of a set of serial operations ordered in a linear sequence (See Figure 1-a). An assembly job consists of a set of segments that have to be assembled together after the processing of the segments is completed. A segment, in turn, consists of a set of serial operations ordered in a linear sequence. Figure 1 shows three types of assembly jobs: single level (fan structure (Figure 1-b), two level (Figure 1-c), and three level (Figure 1-d) assembly jobs.

The Average Job Lead Time, Average Flow Time and Average Staging Delay

In this section we develop a general expression for the average job lead time in terms of its components. In string type jobs, the lead time of a job is the sum of the flow time of the operations that make up the job, i.e., the sum of the actual processing times of the operations plus the time that operations have to wait for a machine at work center queues. In multi-level assembly type jobs, however, the lead time of a job consists of a combination of the flow time of its segments, the assembly time at each assembly point, the time that assembly operations have to wait at assembly centers, and the staging delay of each segment. The concept of staging delay will be illustrated using a one level assembly job (fan structure) shown in Figure 1-b.

Before the assembly operation can start, it is necessary that three assemblies be completed. The staging delay at this assembly node is given by:

$$[C_{[3]} - C_{[1]}] + [C_{[3]} - C_{[2]}]$$

where,

$C_{[1]}$ is the earliest time at which one of the three assemblies is completed, and

$C_{[3]}$ represents the time at which the last of the three assemblies is completed.

Thus, the average staging delay at the assembly operation would be

$$a_1 = (1/3)[(C_{[3]} - C_{[1]}) + (C_{[3]} - C_{[2]})].$$

In order to simplify the analysis, we assume a zero value for all assembly times. In addition, the assembly shop is assumed to have a large number of assemblers that are continuously available so that no queue would ever develop i.e., we assume zero waiting time at assembly centers.

Maxwell [8], developed a convenient expression for *single level* assembly jobs. The expression decomposes the lead time of a job into two additive components: the average flow time and the average staging delay associated with the segments of the job. The lead time expression takes the form:

$$\begin{aligned} LT_k &= \frac{1}{h_k}\sum_{i=1}^{hk} f_i + \frac{1}{h_k}\sum_{i=1}^{hk} a_i \\ &= F_k + a_k \end{aligned} \tag{1}$$

where LT_k = lead time of job k,
h_k = total number of assembly segments in job k,
f_i = flow time of the segment i,
a_i = staging delay of the segment i,
F_k = weighted flow time component of job k, and
a_k = weighted staging delay component of job k.

This expression is job specific. If one is interested in the status of the lead time in the shop, that is the average lead time, $\overline{LT}$, of a set of jobs that have been processed:

$$\begin{aligned} \overline{LT} &= \frac{1}{N}\sum_{k=1}^{N} LT_k \\ &= \frac{1}{N}\sum_{k=1}^{N}\frac{1}{h_k}\Sigma_{i\epsilon S(k)}(f_i + a_i) \end{aligned}$$

where N is the total number of jobs processed in the shop and $S(k)$ is the set of all segments in job k.

In the special case where all jobs are single level assembly jobs and have the same number of segments ($h_k = h$); the average lead time, $\overline{LT}$, can be obtained:

$$\begin{aligned} \overline{LT} &= \frac{1}{hN}\sum_{k=1}^{N}\Sigma_{i\epsilon S(k)} f_i + \frac{1}{hN}\sum_{k=1}^{N}\Sigma_{i\epsilon S(k)} a_i \\ \overline{LT} &= \overline{F} + \overline{a} \end{aligned} \tag{2}$$

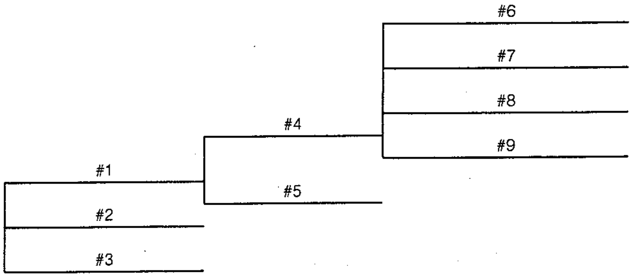
where the average lead time in the shop is conveniently expressed in terms of the average flow time, $\overline{F}$, and the average staging delay, $\overline{a}$, in the shop.

Conceptually, the general case for a single level assembly where the number of segments differ from job to job is not any more complicated than the case above. However, this is more cumbersome computationally because the flow times and staging delays of the segments of each job would have to be weighted by $\frac{1}{h_k}$ where h_k is job specific information. Therefore, we can still obtain the average lead time of the shop as a sum of the averages of its components as shown in (2).

As Siegel points out [13, p. 127], this lucid relationship between average lead time and its components is obscured in multi-level assembly jobs.

We will now show how this convenient relationship can be extended to multi-level assembly structures.

We recall that in the general single level assembly jobs where ($h_k \neq h$) the key was to weight the flow times and staging delays of the segments of job k by $\left(\frac{1}{h_k}\right)$. In multi-level job structures we would have to find the "appropriate weight" for a particular segment as related to the segment's position in the job structure. Consider the following job:



The weight to be associated with segment #6 at a sub-sub assembly level would be: $\frac{1}{4 \times 2 \times 3}$. The weight associated with segment #5 would be $\frac{1}{2 \times 3}$ and for segment #3 the weight would be $\frac{1}{3}$. Therefore if we let

Z_i = the product of the number of segments at each assembly junction of the job leading from the final assembly through the assembly junction of the segment i being considered,

then we can write the expression for the lead time of a multi-level job as follows:

$$LT_k = \Sigma_{i\epsilon S(k)}\frac{1}{Z_i}f_i + \Sigma_{i\epsilon S(k)}\frac{1}{Z_i}a_i.$$

If this type of "weighting" is done for every job processed in the shop then we would have the average lead time expression for the shop:

$$\begin{aligned} \overline{LT} &= \frac{1}{N}\sum_{n=1}^{N}\Sigma_{i\epsilon S(n)}\frac{1}{Z_i}f_i + \frac{1}{N}\sum_{n=1}^{N}\Sigma_{i\epsilon S(n)}\frac{1}{Z_i}a_i \\ \overline{LT} &= \overline{F} + \overline{a} \end{aligned}$$

The additional computational effort to strive to maintain this "lucid" relationship is worthwhile because it provides a convenient comparative measure of performance when different priority rules are simulated. The effectiveness of a priority rule can be quickly discerned: is the rule achieving its performance by reducing the average flow time in the shop or is the performance due to a reduction of the average staging delay or both.

We have used this relationship as the basis of the experimental comparisons.

Priority Assignment Procedure

In this paper we examine the design of a class of priority assignment procedures that has a focus on the staging delay component of the job lead time.

First we present a brief discussion of the three attributes which were identified by Siegel [13] as being fundamental to the design of effective priority assignment procedures in multi-level job shops.

Attributes for Designing Priority Rules

- *Pacing* is associated with the coordination of assembly components or segments. One form of pacing discussed by Siegel assigns all segments of a job the same priority value. This priority value may be constant throughout the processing of the job (such as in the case of the FASFS—first arrived at the system, first served — priority rule), or may change with time (such as in the case of the TWKR priority rule). We distinguish between this type of pacing and the case where an explicit attempt is made to keep the difference in the progress of related job segments to be as close to each other as possible. This second type of pacing or coordination can be achieved by assigning a priority value to a segment that is a function of the progress of that particular segment in relation to the progress of other immediately related segments. (The detailed design of priority assignment procedures which induce this kind of pacing is presented later in this section.)
- *Acceleration,* implies that segments which are close to completion (have few remaining operations or little remaining work) should have a high priority.

  The effect of acceleration was observed by Conway in his RAND study of the classical job shop (with string-type of jobs) [5]. He noted that the priority rule "fewest number of remaining operations," NOPR, resulted in a 12% decrease in mean flow time relative to RANDOM-sequencing. The experiments by Siegel demonstrate that this effect carries over to assembly jobs.
- *Structural dependence,* implies that certain aspects of the job structure influence the mean job lead time through "aggregate" structure related characteristics such as total number of operations, and total work. However, Seigel noted that the effects of the structure dependence attribute are significant to warrant separate investigation.

  Therefore, in order to explore some structure related aspects in greater detail, we develop a class of priority rules which specifically aim at taking advantage of information related to structural complexity and additional information that would induce pacing. We compare the performance of these rules with that of standard rules like FASFS and with the best rules known for reducing mean job lead time in the published literature.

Priority Rules That Induce Pacing By Using Structural Complexity Information

We now introduce the rationale for priority rules that focus on factors that relate to pacing and structural complexity.

A staging delay occurs if the segments that converge into an assembly operation are not completed at exactly the same time. The occurrence of such an event for a given job is related to the progress that each of its segments is making in the shop. If, for instance, segments of a job vary greatly with respect to the number of remaining operations, or with respect to the total remaining work on each segment, at a specific time, then there is a high probability that the completion times of these segments will differ significantly. We may conclude that the mean staging delay can be decreased by assigning priority values to the imminent operations of the segments of a job so as to equalize the "within" job progress of each segment. To our knowledge, the effect of this type of job pacing on the mean staging delay and the mean job lead time has not been investigated. We, therefore, have designed a class of priority rules that focus on this effect and investigate their performance with respect to the average staging delay and lead time of a job.

The priority assignment of the "within" job pacing rule is based on the assumption that the mean staging delay can be reduced, *if* the different segments of the job have the same number of remaining operations, or have the same amount of remaining work at any stage of the job that is in progress. Therefore, if a segment has many remaining operations or a greater amount of remaining work relative to other segments of the same job, it should be assigned a higher priority relative to other segments of the *same* job. Thus, the priority value of a segment that belongs to a given job should be calculated based on the difference between the average number of remaining operations (remaining work) per segment of that job and the number of remaining operations (remaining work), of the specific segment. We refer to these priority rules as the Relative Number of Remaining Operations (RRO) and Relative Remaining Processing Time (RRP). For a single level assembly job, the priority value of a segment or assembly i:

$$\mathrm{RRP}_i = \left(\frac{1}{J_O}\sum_{l=1}^{J_O} P_l\right) - P_i$$

where P_i is the processing time or the number of operations remaining on segment i and J_O is the number of assembly type segments in the job.

For segments of multi-level assembly jobs, the calculation of the RRO and RRP priority values is not so obvious. The extension of the above expression to the case of multi-level assembly jobs is discussed in Appendix A.

Combining the RRO and RRP With The TWKR

The class of pacing rules suggested in the previous section coordinates the segments "within" a job. If it were to be used "across" jobs, it would try to coordinate all the segments in the shop as if they belonged to one big job. Therefore, these rules should be used in conjunction with rules that have a strong "acceleration" component and are global in their perspective.

To this end, we have combined the RRO and RRP rules with TWKR. This combined rule would work as follows: examining the set of imminent operations in the queue, sorted in increasing TWKR sequence, if there is a tie in terms of the TWKR priority component, for imminent operations belong to the *same* job then the operation with the smallest value of RRO or RRP is chosen. Simulation experiments (see next section) were conducted to study the effectiveness of these rules using job configurations of varying complexity.

The Simulation Experiment

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 different priority assignment procedures and job structures in this study. The model was coded in SIMSCRIPT II.5 (See Appendix B for the validation of the model.)

The job shop in the simulation model consists of a given number of machine centers with a specific number of identical machines that are continuously available. The interarrival time of jobs are exponentially distributed with a mean chosen to yield the desired average utilization of the shop.

Job Types and Structure

An arriving job can consist only of assembly type segments, both assembly and sub-assembly, or assembly, sub-assembly and sub-sub-assembly type segments. The current simulation model allows up to four job classes corresponding to Figure 1a, b, c and d respectively. The class of an arriving job is determined from a pre-specified input probability distribution. For each job class, the number of assembly level 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 is determined from an input probability distribution.

The number of operations and the routing of a job segment is a function of the segment level within the job (assembly, sub-assembly, or sub-sub-assembly). For each segment level the number of segment types is determined from an input probability distribution. Wtihin a segment level, the routing of each segment type is assumed to be known with certainty. The processing time of an operation is a truncated exponentially distributed random variable whose mean is the same for each machine center (to achieve equal utilization across the machine centers) and its value is restricted to be less than 10 times the mean.

We experimented with nine different job configurations. These job configurations (number of assemblies per job, number of sub-assemblies per assembly segment, etc.) are summarized in Table 1.

Job Due Dates

Each arriving job is assigned a due date which is set internally to reflect an estimate of the job flow time through the shop. The due date assignment procedure is theh same as the one used by Maxwell [8]. Specifically, a job due date was computed as follows:

$$d_k = r_k + C \underset{i \in s(k)}{\text{Max}} \{g_i\}$$

where r_k is the arrival time of job k, $S(k)$, the set of segments on job k, and g_i the total number of operations on segment i. All results reported in this study use $C = 2.4$.

Priority Rules

The simulation model included several priority assignment procedures. A priority assignment procedure is classified as either static or dynamic. A static priority assignment procedure calls for assigning a priority to any segment whenever it joins a queue. Under dynamic priority assignment procedures, every time a machine is free, the priority values of all segments in that queue are reevaluated. Under both static and dynamic priority assignment procedures the segment with the lowest priority value is selected. The priority rules and the results are given in Table 2.

Output Analysis

Statistics were collected on the mean and standard deviation of the following performance measures:

1. The lead time of a job (LT)
2. The flow time of a job (FT)
3. The staging delay of a job (SD).

Table 1.

Job Configuration	# of assemblies	# of sub-assemblies per an assembly	# of sub-sub-assemblies per a sub-assembly	Average # of Segments per job
1	[2–10]	0	0	6.00
2	10	0	0	10.00
3	[2–3]	[4–6]	0	15.00
4	[4–6]	[2–3]	0	17.50
5	[7–9]	[4–5]	0	44.00
6	[2–3]	[2–3]	[3–5]	33.75
7	[2–3]	[3–5]	[2–3]	37.50
8	[3–5]	[2–3]	[2–3]	39.00
9	[7–9]	[2–3]	[2–3]	78.00

*[a–b] represents an integer uniform distribution between a and b.

Table 2: The sample mean and sample standard deviation of the sample mean for each performance measure under different priority rules

Job Config	Performance Measure	FASFS	NUSEG FCFS	NUSEG SPT	TWKR FCFS	NUSEG RRO	NUSEG RRP	TWKR RRO	TWKR RRP
1	Lead	85.69*	61.02	55.51	61.06	60.33	60.28	58.30	58.91
	Time	(12.01)**	(6.96)	(6.68)	(6.63)	(8.10)	(7.91)	(6.37)	(6.51)
	Flow	68.01	47.75	43.42	44.67	51.42	51.15	44.03	44.59
	Time	(10.48)	(6.57)	(6.30)	(5.71)	(7.87)	(7.68)	(5.53)	(5.61)
	Staging	17.70	13.27	12.10	16.41	8.93	9.15	14.29	14.34
	Delay	(1.54)	(0.40)	(0.39)	(0.94)	(.25)	(.26)	(0.85)	(0.91)
2	Lead	66.59	65.03	57.44	60.92	84.85	77.92	57.59	57.77
	Time	(5.28)	(5.23)	(4.65)	(4.45)	(10.98)	(9.33)	(4.42)	(4.52)
	Flow	48.37	49.83	43.09	42.57	79.04	71.98	42.63	43.00
	Time	(4.63)	(4.95)	(4.37)	(3.81)	(11.15)	(9.46)	(3.77)	(3.79)
	Staging	18.25	15.24	14.38	18.38	5.84	5.96	14.99	14.80
	Delay	(0.66)	(0.29)	(0.29)	(0.65)	(0.21)	(0.20)	(0.66)	(0.66)
3	Lead	104.07			88.84			88.95	84.88
	Time	(9.46)			(7.16)			(7.05)	(7.05)
	Flow	78.53			62.63			64.13	63.66
	Time	(8.23)			(5.93)			(6.13)	(5.83)
	Staging	25.57			26.23			20.85	21.25
	Delay	(1.26)			(1.25)			(1.17)	(1.23)
4	Lead	116.42			103.26			97.50	98.21
	Time	(13.55)			(10.21)			(9.87)	(10.04)
	Flow	88.78			74.94			75.39	75.81
	Time	(12.47)			(8.74)			(8.6)	(8.72)
	Staging	26.66			28.34			22.14	22.42
	Delay	(1.23)			(1.50)			(1.30)	(1.35)
5	Lead	168.85			153.35			138.71	140.33
	Time	(29.94)			(14.52)			(14.46)	(14.71)
	Flow	129.54			113.51			117.01	117.93
	Time	(18.29)			(12.65)			(12.82)	(13.01)
	Staging	39.35			39.89			22.74	22.44
	Delay	(2.72)			(1.92)			(1.70)	(1.77)
6	Lead	151.84			129.85			119.43	120.99
	Time	(13.95)			(11.94)			(11.82)	(11.68)
	Flow	115.35			92.56			95.22	95.93
	Time	(12.26)			(9.91)			(10.09)	(9.96)
	Staging	36.52			37.32			24.24	25.09
	Delay	(1.75)			(2.04)			(1.74)	(1.74)
7	Lead	201.05			168.84			156.75	157.80
	Time	(30.62)			(22.19)			(22.70)	(21.94)
	Flow	160.29			126.15			128.38	129.08
	Time	(27.51)			(18.78)			(19.20)	(18.78)
	Staging	40.79			42.73			28.39	28.76
	Delay	(3.18)			(3.44)			(3.22)	(3.18)
8	Lead	179.14			158.04			145.62	146.97
	Time	(20.25)			(15.81)			(15.69)	(15.80)
	Flow	140.73			116.91			119.41	120.05
	Time	(18.54)			(13.80)			(13.79)	(13.83)
	Staging	38.45			41.17			26.24	26.95
	Delay	(1.82)			(2.10)			(2.03)	(2.09)
9	Lead	234.50			217.05			193.53	196.20
	Time	(21.96)			(19.56)			(19.83)	(20.00)
	Flow	181.93			161.93			169.66	170.47
	Time	(19.56)			(17.38)			(17.95)	(18.02)
	Staging	52.62			55.17			23.93	25.78
	Delay	(2.86)			(2.35)			(2.17)	(2.20)

* Sample mean

**Sample standard deviation of the mean based on using 15 batch means

In each simulation run, observations of each of the performance measures were grouped into sets of batches (a set of batches for each performance measure). For a given performance measure, the size of a batch was set large enough so as to achieve approximate independence among the batch means of the particular performance measure (see for example, [1, 6]) For each of the measures LT, FT, and SD the mean value of a batch was then used as an observation in computing the corresponding grand mean and standard deviation of that mean (see Table 2). The same procedure was used in the analysis of variance (discussed below) performed in this study.

In order to compare the differences in the performance of the various priority rules, one must ensure that each priority rule is subject to the same input traffic (this is the primary intent of the "common random numbers" variance reduction technique [3]). This was accomplished in the following way:

- separate random number streams were assigned to generating job interarrival times, job structure (number of assemblies, number of subassemblies for each assembly, etc), and operation processing times;
- at the time a job arrives at the shop, its specific structure, and the actual processing time of each of its operations were generated; and each simulation experiment ran until a total of 99,450 segments had been processed; with the first 1,200 segments being used for warm-up purposes. Thus, when experimenting with configuration #2, for example, the simulation run length was set at 99450/10 = 9,945 completed jobs whereas the statistics on the first 1200/10 = 120 completed jobs were discarded and the statistics on the rest of the jobs 98250/10 = 9,825 were grouped into 15 batches each of size 9825/15 = 655 jobs.
- when collecting observations on each of the measures LT, FT, and SD; observations were grouped together in batches according to their arrival times rather than their completion times.

Multivariate Analysis of Variance was used to discern differences among the LT, FT and SD performance measures for the various priority rules when applied to each of the nine job configurations investigated in this study.

Discussion of Results

The following is a discussion of the results presented in Table 2.

Single Level Assemblies: Variable Number of Assemblies in Jobs

The use of RRO and RRP in combination with NUSEG reduces the average staging delay but at the expense of an increase in the average flow time. This is not surprising since pacing and not acceleration is the major attribute of the three priority rules: NUSEG, RRO, and RRP. The performance of TWKR-RRO and TWKR-RRP is not significantly different from NUSEG-SPT. Again, this follows from the similarity of the major attribute of the components of the three priority rules. Specifically, pacing is the major attribute of each of the NUSEG, RRO and RRP, while acceleration is the major attribute of SPT and TWKR. Thus for this configuration, the new rules are as good as the performance of the best rule cited in the literature.

Single Level Assemblies: Same Number Assemblies in Every Job (10)

Once again, if we combine RRO and RRP with NUSEG, the average staging delay is significantly better than NUSEG-SPT, but the increase in the average flow time component negates the improvement when we look at the lead time. The performance of TWKR-RRO and TWKR-RRP is as good as NUSEG-SPT in this case as well.

Two Level Assemblies

As the number of assembly level segments increase in relation to sub-assembly level segments, the average lead time and the standard deviation of the average lead time increase (compare cases 3, 4, and 5). The average staging delay for TWKR-FCFS increases as the number of assembly segments increases (compare cases 3 and 5). However, for TWKR-RRO and TWKR-RRP, the average staging delay appears to be invariant. In all three job sets, the average staging delay performance of TWKR-RRO and TWKR-RRP are significantly better than TWKR-FCFS.

Three Level Assemblies

Comparing job sets 8 and 9, we note that as the number of assemblies increases in relation to the number of sub and sub-sub assemblies, the average lead time increases. The average staging delay for TWKR-FCFS increases with this complexity. On the other hand, TWKR-RRO and TWKR-RRP do not exhibit an increase in the average staging delay. The performance of TWKR-RRO and TWKR-RRP with respect to average staging delay is significantly better than TWKR-FCFS in all cases for the three level assemblies.

Conclusion

This paper studies the explicit inclusion of job structure complexity in the design of priority assignment rules for job shops processing multi-level assemblies. We focused on the lead time as the major performance measure. A pacing rule was developed. This rule in conjunction with an acceleration rule such as TWKR provides improved performance on the staging delay component of the lead time.

In terms of performance for the two and three level assembly jobs, the new rules show a significant improvement over previous rules given in the literature with respect to average staging delays. For single level assemblies, the performance of the new rules is just as good as the best rule cited in the literature.

There appears to be no significant difference between the performance of RRO and RRP because the average processing time at each work station was assumed to be the same. If the average processing time at work centers were significantly different from each other, then the relative remaining processing time (RRP) would give a more exact representation than the relative remaining number of operators (RRO).

The improvement in the lead time performance of the new rules is obscured by the large variance of the flow time component. Thus, our multivariate ANOVA analysis showed that the average lead time under the new rules and the ones cited in the literature are not statistically different. However, if we were to apply the criterion used in earlier studies of looking at the relative change in the average lead time, the lead times resulting from the use of the new rules are 5–15% more effective. The improvements in the average staging delay performance are 20–60% better.

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Appendix A

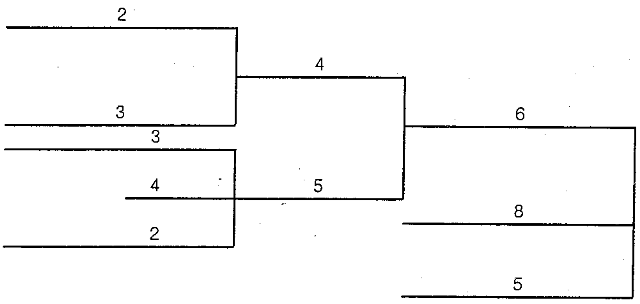
The Basis for the "Relative Remaining" Index

The basic idea of the "relative remaining" number of operations or processing time index is to transmit the structural complexity in terms of a relevant factor such as remaining processing time or remaining number of operations to the imminent operations of a multi-level assembly job.

The index paces the various segments of the job so that staging delays are as small as possible. The index highlights those segments that are falling behind and gives them a high priority.

We first illustrate the index with a numerical example and then formalize it in terms of algebraic expressions.

Consider the following three level assembly job: (suppose that the numbers represent remaining processing time or operations on each segment)



We first compute the remaining processing time of the job *aggregated* at the assembly level segments:

First Assembly:	$(2 + 3) + (3 + 4 + 2) + (4) + (5) + (6)$	$= 29$
Second Assembly:	(8)	$= 8$
Third Assembly:	(5)	$= 5$

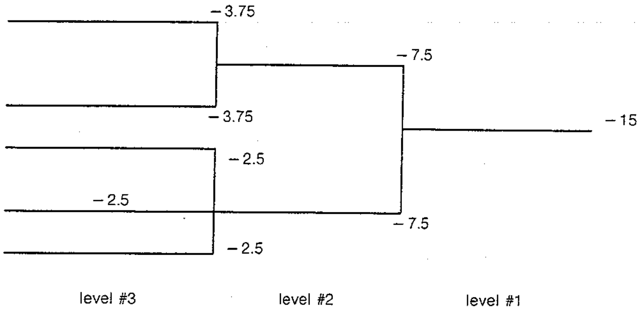
We then calculate a property of this aggregated job structure: the average processing time remaining per aggregated assembly segment: $1/3(42) = 14$.

We then define the relative remaining processing time as the difference between the average and the aggregate processing time of each assembly segment:

$$14 - 29 = -15; 14 - 8 = 6 \quad \text{and} \quad 14 - 5 = 9.$$

Even at this aggregate level, the index suggests that assembly one should receive a higher priority. If one ignores this fact, and processing proceeds on assembly two and three, the wait for the completion of assembly one would result in a large staging delay.

Since the imminent operations of the first assembly are at the sub-sub-assembly level, the contribution of the relative remaining processing time on the aggregated assembly segments have to be transmitted to lower assembly junctions:

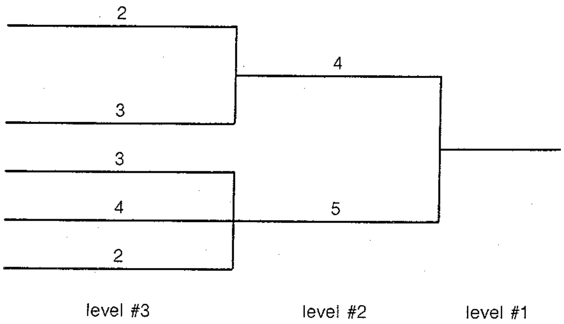


The assignment of (−7.5) to each of the two subassembly segments transmits the relative measure of incompleteness of the first assembly but assumes that each lower level segment is equally critical.

The assumption made here is that work will proceed in parallel on these subassembly segments. It is for this reason that the aggregate index is subdivided equally at a junction.

We wish to disaggregate this measure even further to reflect the structure of the lowest junction.

The values transmitted to the lowest junction have to be further adjusted to reflect the exact structure at level #2 of the assembly component.



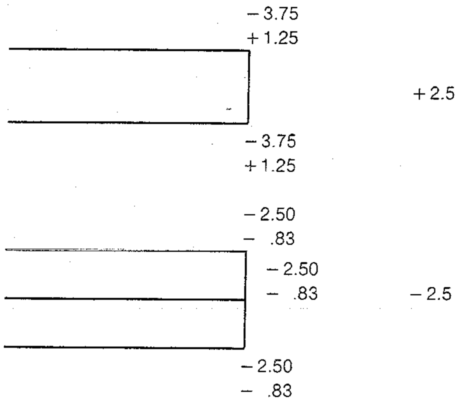
Excluding the processing time of the assembly segment at level #1, we can compute the index for the aggregate level #2 and #3:

Assembly one:

Subassembly 1:	(2 + 3) + 4 = 9
Subassembly 2:	(3 + 4 + 2) + 5 = 14

The average per segment = 11.5 and the relative remaining index values are 2.5 and −2.5.

Now we transmit these values to the lowest level junction:



We have to reflect the structure of level #3 at the lowest level segments

Assembly 1, Subassembly 1

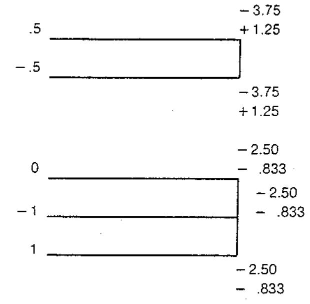
Subsubassembly 1: 2
Subsubassembly 2: 3.

The average = 1/2(2 + 5) = 2.5

The index value of each sub subassembly of sub-assembly 1 independent of any higher level components: 2.5 − 2 = .5 2.5 − 3 = −.5.

Similarly for sub-subassemblies of subassembly 2 of assembly 1 the index valued would be 0, −1, and 1.

Thus now including the transmitted relative effects of the higher level segments:



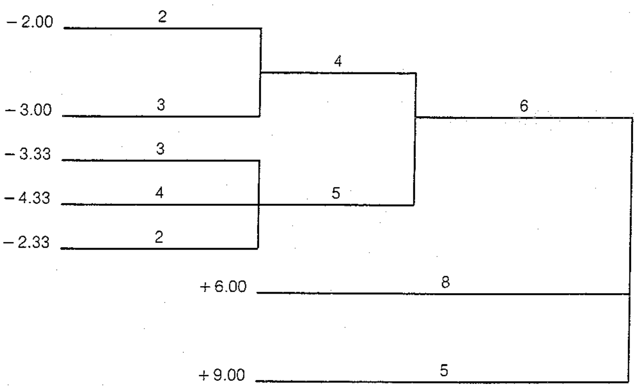
RRP = −3.75 + 1.25 + .5 = −2.0

RRP = −3.75 + 1.25 − .5 = −3.0
= −2.50 − .833 − 0 = −3.33
= 2.50 − .833 − 1 = −4.33

= 2.00 − .833 + 1 = − 2.33
−15 ≅ −14.99

what we have accomplished is the distribution of the aggregate urgency of the first assembly segment and other intermediate structural elements all the way to the imminent operations of the job reflecting the structural complexity.

Completing the calculations, the relative remaining processing time index on the imminent operations of the job would be as follows:



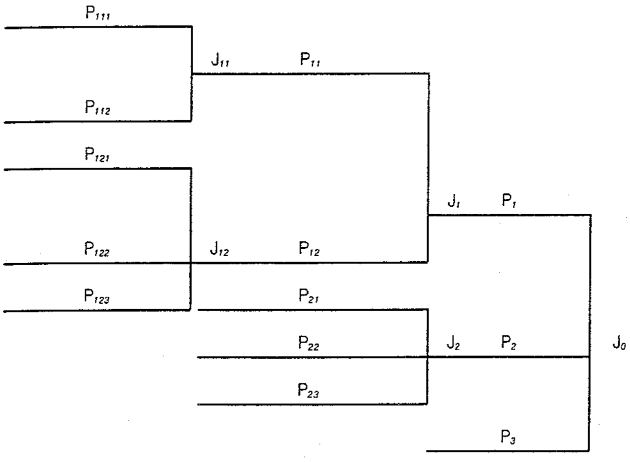
(Note: The sum of all RRP's of imminent operations equals zero.)

As the processing of the job progresses, the index would be updated dynamically. One could also use the number of remaining operations instead of remaining processing time as a factor for the index.

General Formulation of The Index

The intuitive approach presented in the previous numerical example will now be generalized and presented in a more compact form.

Three Level Job Structures



Using the same line of reasoning as used for the example discussed above, the RRP index for the *n*th subsubassembly of the *m*th subassembly of the *l*th assembly:

$$\mathrm{RRP}_{lmn} =$$

$$\frac{1}{J_{(l)m}J_m J_O}\left[\sum_{i\epsilon S(K1)} P_i + \sum_{i\epsilon S(K1)}\sum_{j\epsilon S(K_2^i)} P_{ij} + \sum_{i\epsilon S(K1)}\sum_{j\epsilon S(K_2^i)}\sum_{K\epsilon S(K_3^{ij})} P_{ijk}\right]$$

$$-\frac{1}{J_{(l)m}J_l}P_l - \frac{1}{J_{(l)m}}P_{lm} - P_{lmn}$$

where, $J_{(l)m}$ = total number of subsubassemblies in the *m*th subassembly of the *l*th assembly.
J_{li} = number of subassemblies in *l*th assembly of the job.
$S(K_{ij})$ = the set of subassembly segments that are on the *i*th assembly.
$S(K_3)$ = the set of sub-sub assembly segments that are on the *j*th subassembly of assembly i.

The RRP index for those subassemblies that have no subsubassemblies:

$$\mathrm{RRP}_{lm} =$$

$$\frac{1}{J_l J_O}\left[\sum_{i\epsilon S(K1)} P_i + \sum_{i\epsilon S(K1)}\sum_{j\epsilon S(K_2^i)} P_{ij} + \sum_{i\epsilon S(K1)}\sum_{j\epsilon S(K_2^i)}\sum_{K\epsilon S(K_3^{ij})} P_{ijk}\right]$$

$$-\frac{P_l}{J_l} - P_{lm}.$$

The RRP index for those assemblies, in a three level job structure that have no subassemblies (therefore no subsubassemblies):

$$\mathrm{RRP}_l =$$

$$\frac{1}{J_O}\left[\sum_{i\epsilon S(K1)} P_i + \sum_{i\epsilon S(K1)}\sum_{j\epsilon S(K_2^i)} P_{ij} + \sum_{i\epsilon S(K1)}\sum_{j\epsilon S(K_2^i)}\sum_{K\epsilon S(K_3^{ij})} P_{ijk}\right] - P_l.$$

Appendix B

Validation of the Simulation Model

We carried out the validation as follows:

(i) Most recent studies on this topic, explicitly or implicitly, have used Maxwell's study as a benchmark [8]. We therefore, chose Maxwell's results as a basis for validating our simulation model.

In his study, Maxwell generated the number of operations per segment from a geometric distribution with a mean of 9 operations and used randomized routings where a segment was equally likely to start at any machine center.

The probability of having a segment of type *t* is (0.11118) $(0.88882)^{t-1}$ with a segment of type *t* having *t* operation except segments of type 18, 19 and 20 which would have 20, 24, and 39 operations respectively. The routings were constructed in such a way that operations of all assembly types were equally distributed among machine centers.

The validation experiments were performed for 2 segment single level assembly jobs using 8 different priority rules that were selected from Maxwell's study. These rules were considered relevant to the focus of our paper. Statistics were kept on jobs 226 through 4725, i.e. a total of 4500 completed jobs. Each rule was tested against the same set of jobs. The results of the validation experiments are given in Table B.1. In order to readily show the degree of correspondence between Maxwell's results and ours we normalized both results by dividing the value of each performance measure by the corresponding average processing time of an operation.

For all measures of performance and under all priority rules, except NUSEG, there is, in general, a very close degree of correspondence between Maxwell's results and ours. The difference may be due to approximating the geometric distribution for the number of operations per segment. However, we could not explain the difference between our results and those of Maxwell's when using the NUSEG priority rule. We believe that our results are in line with what one would expect since there is no obvious reason for the NUSEG to have a negative effect on the average flow time. It was also difficult to explain why this negative effect of the NUSEG, as observed by Maxwell, did not carry over to the NUSEG-SPT case.

(ii) To validate the procedural detailed steps in the SIMSCRIPT model, a GPSS simulation model for a three level assembly job shop was constructed and used to simulate a deterministic three level assembly structure. The results of the GPSS and SIMSCRIPT runs were identical.

Table B.1

Performance measure Priority rule	Lead Time Mean		Flow Time Mean		Staging Delay Mean		% Tardy		Tardiness Mean	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
FCFS	159.93	149.28	104.17	100.71	52.77	48.57	60.95	59.89	75.97	64.46
SPT	74.4	73.80	45.47	45.01	28.93	28.79	10.80	11.09	155.9	139.65
FASFS	121.2	121.13	98.7	98.66	22.47	22.47	52.58	51.62	59.17	50.66
NUSEG (Dynamic)	111.13	154.13	99.17	150.18	11.93	3.95	24.73	42.65	150.6	168.28
MAXNRD (Static)	147.53	202.63	115.6	141.78	31.93	60.85	36.70	51.72	163.33	216.29
MAXNRD (Dynamic)	124.1	NA	107.83	NA	16.27	NA	26.65	NA	163.87	NA
MAXNRD-SPT (Dynamic)	64.37	69.67	63.2	62.67	6.17	7.00	9.27	9.57	133.4	127.63
NUSEG-SPT (Dynamic)	70.37	72.31	54.77	61.99	10.6	10.32	11.27	11.50	95.87	92.82

(1) The ratio of the performance measure to the average processing time — based on our experiments
(2) The ratio of the performance measure to the average processing time — based on Maxwell's experiments
NA — No results are available for this case.

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