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Experimental investigation of an FMS due-date scheduling problem: an evaluation of due-date assignment rules

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Abstract. This paper investigates the performance of due-date assignment rules in a flexible manufacturing system (FMS). Although emphasis is placed on a comparison of due-date assignment rules, machine and automated guided vehicle (AGV) scheduling rules are also evaluated under various experimental conditions using an FMS simulation model. The mean job tardiness is the measure of performance by which the rules are compared. The sensitivity to AGV workload, buffer capacity, and processing time distribution is also investigated to assess the robustness of the due-date assignment rules.

1. Introduction

Flexible manufacturing systems (FMSs) can be described as batch manufacturing systems which consist of a group of computer-controlled (CNC) machines connected by an automated materials handling system. These systems are used to process a wide variety of different parts with low to medium demand volume.

Even though the FMS concept was originated in the 1960s with an emphasis on the integration of standard machine tools, materials handling equipment, and computer systems (Ranky 1986), the number of FMS applications did not start to increase significantly until the early 1980s. By 1987, approximately 300 FMSs had been implemented around the world (Singhal *et al.* 1987). Today, FMSs seem to be a very promising technology for batch manufacturing companies. They possess the efficiency of dedicated transfer lines in mass production systems while retaining the flexibility of a job shop in batch manufacturing systems.

In many respects, an FMS can be viewed as an automated job shop. The major difference between an FMS and a conventional job shop is that the human functions are automated in the FMS. Moreover, an FMS is a highly integrated system with an automated materials handling system (usually an AGV system) which ties together the machining centres and has a significant impact on the system performance. Thus, scheduling problems of FMSs are more difficult than traditional job shop problems due to considerations of the additional resource constraints (materials handling, limited in-process buffer spaces, etc.).

The FMS scheduling literature also includes a number of studies and proposed solution approaches ranging from analytical techniques to simulation and artificial intelligence/expert systems (Sabuncuoglu and Hommertzheim 1989b, Ranky 1988, Kusiak and Chen 1988, Kusiak 1986, and Raman, Talbot and Rachamadugu 1986). This paper is primarily concerned with scheduling problems of an FMS with the objective of investigating the performances of due-date assignment rules against the mean tardiness criterion.

2. Relevant literature

An FMS survey made by Smith *et al.* (1986) showed that the most important criterion used in FMS scheduling is meeting due-dates. This is followed by the maximization of system utilization and the minimization of in-process inventory. While this limited survey (22 FMS installations), gives some insight as to which criteria are currently the most important, in general, the FMS scheduling problem is multi-objective, and the selection of a particular criterion depends upon various factors such as the state of the shop, characteristics of jobs, due-date tightness, the overall objectives of the company, etc.

The objective of due-date management is to achieve on-time delivery of the products to customers, but this is rarely accomplished in practice. Because of the complex and dynamic interactions in manufacturing environ-

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ments and unexpected interruptions, some orders are completed early while other orders are late. Each late delivery can cause a penalty cost or at least a loss of goodwill. Similarly, each early completion of jobs can increase the inventory cost because the customer may not be willing to accept early shipment due to its production and inventory policies.

Although meeting due-dates is very important, it is also a very difficult problem, since it is hard to find a compromise of due-date performances of the system from the wide variety of measures used in the industry. Some of these are as follows: mean tardiness, conditional tardiness, proportion of late orders, mean lateness, maximum lateness, etc.

In practice, due-dates are sometimes dictated by the customer and are called 'exogenous' due-date assignments. At other times, they are totally under the control of the company, which sets due-dates based on the expected completion time of orders. This type of due-date setting procedure is called an 'endogenous' due-date assignment. Actual systems usually operate somewhere between these two extremes. There may be situations where negotiation with customers is possible. Sometimes the management may even impose due-date restrictions based on targeted service levels or assembly, and master schedules may dictate the due-dates. This paper focuses on endogenous due-date assignment.

Due-date assignment is a critical task since it represents a delivery commitment of the system. Furthermore, the performance of the scheduling system, including the scheduling algorithms and rules, are highly dependent on the due-date information. Since it also serves as the basis for many production and inventory decisions in a company, the due-date assignment problem has been studied extensively in the literature.

Smith and Seidmann (1981) reviewed previous work related to the job-shop. In their study, they identified three basic categories for due-date assignment procedures: direct, heuristic, and analytical. According to their terminology, the direct procedure refers to simple procedures which utilize the current information about jobs or the state of the system. Heuristic procedures involve more complex methodologies to set the due-dates by using simulation runs, whereas analytical procedures are based on the results obtained from analytical investigations (see Baker and Scudder (1990) for summary of analytical work for static scheduling problems).

Since the due-date assignment problem cannot be isolated from the overall scheduling problem, the scheduling problem is very difficult to handle by analytical means. Because of this, the majority of previous work has focused on the investigation of direct and heuristic procedures. Furthermore, since heuristic procedures extensively utilize results obtained from direct procedures, the analyses of direct procedures have received extensive attention by many researchers (Baker 1984, Baker and Bertrand 1981, Miyazaki 1981). According to the above classification, this paper is concerned with the direct procedures.

A direct procedure is a simple rule which assigns a flow-time allowance to an arriving job by using the job characteristics and/or the current state of the system. In this context, the flow-allowance refers to the total time allocated to a job in the system for several activities such as processing, transportation, and waiting. The job characteristics refer to the processing times, the number of operations, etc. On the other hand, the state of the system can be defined by the number of jobs in the system, utilization rates, etc.

As reported by other researchers such as Kanet (1982), the flow-allowance (or lead time) has a quite different meaning to the flow-time. While the flow-allowance is a reasonable amount of time budgeted to perform all activities related to a job, the flow-time is the the actual time realized in the system (the time between job release and its completion). Since management has limited control over the flow-times, it directly results from the system performance and is a random variable. On the other hand, flow-allowances (or lead times) can be totally controlled and set by the management and are constants rather than a random variable. The relationship between the flow-allowance and flow-time is such that attainable

Table 1. Due-date assignment rules.

Symbol	Description
CON	Constant flow allowance
SLK	Flow-allowance is equal to the total processing time of the job plus a constant slack
TWK	Flow-allowance proportional to the total work (or processing time)
NOP	Flow-allowance proportional to the total number of operations
PPW	Flow-allowance equal to the processing time plus an estimate of waiting time

Table 2. Flow-allowance equations.

CON :	$A_i = k * ETWK$
SLK :	$A_i = P_j + (k-1) * ETWK$
TWK :	$A_i = k * P_j$
NOP :	$A_i = k * N_i * ETWK/ENOP$
PPW:	$A_i = P_j + (k-1) * N_i * ETWK/ENOP$

due-dates can be determined if the flow-time is fairly predictable. In this context, the expected flow-time is very useful in setting the allowances.

In this paper, five due-date assignment rules (or direct procedures) are considered (Table 1). Mathematical definitions of these due-date assignment are presented in Table 2.

The following notation is used in defining flow allowances:

i = job index
j = operation index
t = time at which the scheduling decision is being made
D_i = due-date of job i
R_i = ready time or arrival time of job i
A_i = original flow allowance for job i
C_i = completion time of job i
k = allowance factor or measure of due-date tightness
T_i = tardiness of job i
F_i = flow-time of job i
N_i = total number of operations of job i
P_j = total remaining operation time of job at its jth operation
$ETWK$ = estimated average total work content for all jobs
$ENOP$ = estimated average number of operations
$D_i = R_i + A_i$
$T_i = \max(0, C_i - D_i)$

In the above definition, $ETWK$ is determined from distribution functions which generate processing times and the number of operations.

The due-date which is set by using the procedures listed in Table 1 represents the job due-date. Operation due-dates can also be determined. For example, operation-based due-date assignment using TWK is

$$d_{i,j} = d_{i,j-1} + k \times p_{i,j}$$

where $d_{i,j}$ = due-date of job i for operation j and $p_{i,j}$ = operation time for jth operation of job i.

Thus, not only the job due-dates but also the operation due-dates can be used to schedule the jobs. While the job due-date represents the expected date that the job must be released from the system, the operation due-date represents the expected date that a job must complete a particular operation.

From earlier job-shop studies, there is some evidence that the relative performance of the due-date assignment rules change with scheduling rules. Therefore, scheduling rules are also considered in this paper. Since machine and materials handling aspects of FMSs are primarily under study, scheduling rules are further classified into (1) machine scheduling rules and (2) AGV scheduling rules. The machine scheduling rules are those which are used to select the next job from the input queue upon the availability of machine. On the other hand, AGV rules are used to select the best workcentre (machine) and job to be served upon the availability of an AGV. Machine scheduling rules for this study were selected from the recent FMS and job-shop literature and are listed in Table 3. For the AGV scheduling rules, the FCFS (first come first served) and LQS (largest queue size) rules were tested. FCFS has the ability to complement the machine scheduling rules by serving a workcentre with the earliest job completion. On the other hand, LQS uses information on queue level. This rule was found to be the best rule against the mean flow-time criterion in earlier studies (Sabuncuoglu and Hommertzheim 1989a, 1992). In addition, some of the machine due-date scheduling rules were also used as a part of AGV scheduling.

Due-date assignment rules here already been tested in job-shop environments (Baker 1984, Baker and Kanet 1984, Baker and Bertrand 1981, Kanet and Christy 1989). In these studies, TWK was found to be the best rule. In the FMS scheduling literature, there are relatively few simulation studies which address due-date scheduling.

Montazeri and Wasssenhowe (1989) investigated the performance of several slack-based due-date rules in a prospective FMS. Their conclusion was that S/OPN (smallest remaining slack per operation) performs better than other due-date scheduling rules. Choi and Malstrom (1988) have also tested FMS scheduling rules in a limited study based on a comparison of job-shop scheduling rules using a physical simulator. Their results indicated that SLK was the preferred due-date scheduling rule based on the varous measures. In the above studies, neither the due-date assignment was analysed nor was the AGV subsystem explicitly modelled. Ro and Kim (1990) developed a routeing algorithm for an FMS and compared it with the linear programming model using various scheduling criteria. In their study, they used TWK as the due-date assignment rule, but did not compare various methods of setting due-dates. Thus,

Table 3. List of machine due-date scheduling rules.

Symbol	Description
EDD	Earliest due-date
SLK	Smallest remaining slack
SCR	Smallest critical ratio
S/OPN	Smallest remaining slack per operation
MOD	Smallest modified operation due-date

there is a real need to test due-date assignment rules in an FMS environment.

3. System considerations, simulation model and assumptions

Figure 1 shows the layout of the hypothctical FMS studied in this research. This same system was used in Sabuncuoglu and Hommertzheim (1992, 1993). In this system, there are eight workstations, six of which are machining centres that perform a wide variety of operations, such as turning, milling and drilling. The two remaining stations are used for washing and inspection. Each workcentre has a limited input/output buffer at which parts can wait before and after an operation. In addition, there is an input/output carousel where parts are loaded and unloaded. There are also two central buffer areas at which parts are temporarily stored to prevent system blocking. Materials and parts are transferred in the system by an AGV. Each AGV moves a part between the workcentres along a predetermined path which is assumed to be unidirectional. Upon completion of a part transfer, an idle AGV either stays at the destination station or returns to the staging area for the next journey, depending upon the current operating policy. However, based on pilot simulation runs, the former method was used in the simulation experiments. Also, a 'direct access part retrieval design' is considered to be operational so that any part from the queue can be retrieved regardless of its position in the queue.

Each workcentre can handle at most one operation at a time and each machine and AGV is continuously operational without any breakdown. Pre-emption is not allowed and the setup time is included in the operation time. Whenever a machine and an AGV becomes idle, the next job in the queue is processed immediately (non-delay scheduling). An AGV transfers only one part at a time (the unit load is one). At intersections in the AGV path network (Figure 1), an AGV moving a part has priority over other AGVs travelling empty. In the case of a tie, the right of passing at the intersection is determined on a FCFS basis. Upon job completion at any workcentre, if there is more than one AGV available to transfer the part to the next station, the one closest to the workcentre which is demanding service is selected.

A discrete simulation model was developed to represent the hypothetical FMS described above. As a simulation modelling tool, SIMAN (Pegden 1986) was used. The purpose of this study is to analyse the FMS scheduling problem by taking into account the limited capacities of not only the machines but also the materials handling system and the in-process inventory. Therefore, the simulation model was developed in such a way that these three resources and their interactions were represented in detail.

Data for the simulation runs was generated as follows: the job interarrival time was exponentially distributed. Each job was processed by a series of workcentres. The number of operations was determined by a discrete uniform distribution between 1 and 6. Parts entered the system based on availability of machines and AGVs and

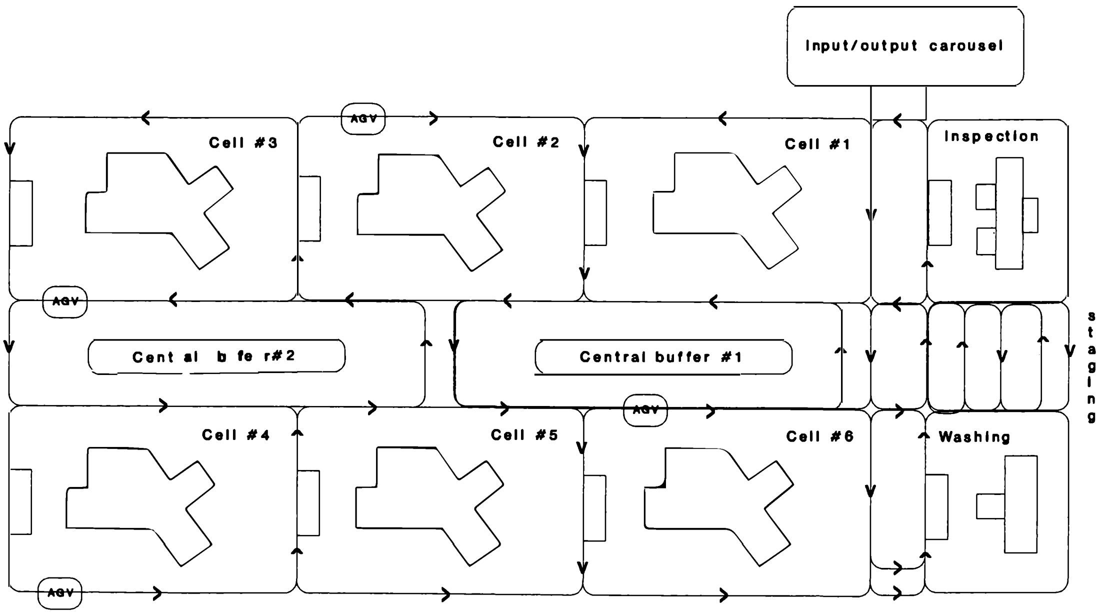

Figure 1. Schematic view of an FMS.

their earliest due-date priority. The machine assignment was random and no job was allowed to visit the same machine more than once. Besides the workcentres, all jobs visited the washing station. However, only 50% of the jobs were processed by the inspection station. The scheduling rules were tested under the following experimental conditions:

- varying levels of due-date allowances (tightnesses);
- different buffer (or queue) capacities;
- varying AGV speeds;
- different types of processing time distributions and their parameters (exponential and normal distributions).

The normal distribution is used because it is one of the distributions for which the variance is independent of mean. This allows the analyst to control the variance in the system.

Since the study objective is to measure the relative performance of alternative rules or operating policies, it is logical to compare them under identical conditions. Thus, a common random number (CRN) variance reduction technique (VRT) was utilized to provide the same experimental conditions (i.e. each job arrived at the same time and was assigned the same routeing and operation times for each case considered). Furthermore, in order to obtain consistent samples from the simulation model across the alternatives tested, a scheme suggested by Conway (1963) was utilized. This involved numbering the jobs in the order of their arrival. Based on some pilot runs, the statistics for the first 300 jobs were discarded and samples were collected for only the jobs numbered between 301 and 3300.

4. Analysis of simulation results

The mean tardiness performance of different due-date assignment rules was measured using both normally and exponentially distributed processing times. In the experiments, only the positive values are considered for the normally distributed operation times. First, the rules were compared under a set of standard experimental conditions and then the sensitivity of the results were measured by varying the conditions. Under the standard conditions, the queue (or the buffer) capacity at each workcentre was five and FCFS was used as the AGV rule for scheduling two AGVs. In addition, the average utilization rates of the machines and the AGV system was approximately 85 and 87·5%, respectively.

4.1. *Analysis of the due-date assignment rules under the standard experimental conditions*

This section presents the simulation results of five due-date assignment rules (given in Table 1). From earlier job-shop results, there was some evidence that the relative performance of the due-date assignment rules change with due-date scheduling rules at varying due-date allowances. Thus, simulation experiments were repeated with different due-date scheduling rules at varying due-date tightnesses. The flow-allowances were controlled by a flow-allowance (or due-date tightness) parameter, k, so that each due-date assignment rule produced the same average flow allowances.

As can be seen in Table 4, the performance of due-date assignment rules were slightly different for the lower values of the tightness parameter, but they became similar when the due-date tightness was reduced. The mean tardiness performance of the scheduling rules became better as the tightness decreased. Among the due-date assignment rules tested, none of the rules dominated. The relative performance of due-date assignment rules changed with the different scheduling rules at the varying levels of due-date tightness. PPW was the preferred rule when the due-date was tight ($k = 3$). In the

Table 4. Mean tardiness performance (in minutes) of the due-date assignment rules under the standard experimental conditions.

Flow-allowance parameter k	Due-date rules	Due-date assignment rules				
		CON	SLK	TWY	NOP	PPW
3	EDD	131·6	122·1	126·4	114·7	132·8
	SLK	124·1	114·8	137·8	111·4	131·5
	SCR	157·3	164·9	150·5	115·0	132·4
	MOD	102·5	130·7	99·0	96·2	80·5
	S/OPN	155·4	126·9	142·7	116·4	150·3
4	EDD	68·8	60·6	59·7	57·8	80·7
	SLK	61·3	54·5	37·4	71·5	44·0
	SCR	64·9	91·1	85·4	75·9	83·9
	MOD	70·7	64·8	51·0	50·4	50·6
	S/OPN	60·7	57·6	46·9	58·2	78·2
5	EDD	30·0	24·7	18·2	22·4	28·3
	SLK	25·8	23·1	26·8	30·8	23·1
	SCR	59·1	40·4	31·3	22·5	26·3
	MOD	39·9	62·6	29·2	36·9	36·9
	S/OPN	28·9	34·2	31·9	26·3	22·4
6	EDD	11·2	8·4	10·7	9·8	10·3
	SLK	10·5	9·9	21·0	13·3	10·7
	SCR	11·9	31·5	22·7	9·6	20·1
	MOD	19·9	28·9	17·3	21·8	14·4
	S/OPN	13·6	16·0	13·6	16·0	8·7

other conditions, the results were so mixed that it was not possible to identify the best due-date assignment rule.

The same type of crossover effect was also observed in the performance of scheduling rules. Again, none of the rules outperformed the others. The relative performance of due-date scheduling rules changed with the different due-date assignment rules at varying values of the tightness parameter. Except for the SLK due-date assignment rule, MOD performed slightly better than the other scheduling rules when the tightness parameter was small ($k=3$). In conclusion, neither the due-date assignment rules nor the scheduling rules provided substantially different mean tardiness performances.

From job-shop studies (Baker 1984, Kanet and Christy 1989), it is known that TWK and MOD are preferred due-date assignment and scheduling rules, respectively. However, from the results of the FMS simulated, there was no evidence indicating their superior performance. None of the rules clearly dominated in terms of due-date performance. This problem in discriminating the relative effectiveness of the rules can be due to one or more of the following reasons:

(1) A job which had the highest priority at a current station would not have the same degree of urgency at the other stations, because in the FMS model the job pool at any station was limited by the queue capacity.
(2) A job finishing the current operation could not be delivered to the next station immediately by the AGV system due to the FCFS AGV rule which was insensitive to due-date information.
(3) Variances of the processing times were low. Therefore, the due-date assignment rules which are based on the processing times with small variance would not yield significantly different due-date performances.

There might be some other reasons for this type of similar due-date performances of the rules. These possibilities will be explored as follows:

Case 1. Using different AGV scheduling rules

Under the standard experimental conditions, FCFS was used as the AGV rule. However, it is known that the FCFS rule does not use the due-date information in prioritizing the AGVs. The aim was to use the due-date rules to assign both machines and AGVs so that differences in the performances of rules could be identified. The experiments were repeated and the simulation results are displayed in Table 5.

Again, the results indicated that none of the due-date assignment rules dominated. The relative performances of scheduling rules were also quite mixed. Only MOD

Table 5. Mean tardiness performance (in minutes) of the due-date assignment rules using the due-date rules as machine and AGV scheduling rules.

Flow-allowance parameter k	Machine /AGV rules	Due-date assignment rules CON	SLK	TWK	NOP	PPW
	EDD	124·9	111·6	95·6	93·7	96·5
	SLK	132·9	118·0	103·9	113·3	122·1
3	SCR	143·4	126·8	108·8	137·0	104·6
	MOD	104·5	104·8	90·5	95·4	81·4
	S/OPN	134·9	138·2	94·6	107·6	133·7
	EDD	63·3	51·9	48·4	41·5	44·6
	SLK	69·6	56·1	39·6	48·1	46·5
4	SCR	58·5	67·3	61·9	57·6	53·9
	MOD	59·9	66·3	39·9	48·4	37·9
	S/OPN	67·4	48·3	54·2	42·2	54·5
	EDD	26·6	20·4	22·4	20·6	29·0
	SLK	31·6	23·4	38·2	15·1	21·0
5	SCR	20·9	27·4	24·9	19·5	25·1
	MOD	21·9	24·8	25·1	21·9	19·9
	S/OPN	31·8	28·3	21·9	21·8	24·1
	EDD	9·7	6·9	6·2	7·4	6·9
	SLK	13·3	8·4	9·5	5·2	6·1
6	SCR	14·5	18·0	15·2	7·5	7·4
	MOD	9·8	21·4	9·5	6·2	13·6
	S/OPN	19·5	23·2	19·1	15·2	18·9

was slightly better when the due-date was tight ($k=3$) due to its SPT (shortest processing time) characteristic. But at other values of k, neither the due-date assignment rules nor scheduling rules resulted in relatively better mean tardiness performances.

In the investigation of performance of AGV scheduling rules, LQS was found to be the best AGV rule against the mean flow-time measure (Sabuncuoglu and Hommertzheim 1992, 1989a). Thus, the performance of the date assignment and scheduling rules were also compared using LQS as the AGV rule.

As shown in Table 6, the resulting mean tardiness values were relatively small compared to the results obtained with the FCFS AGV rule (Table 4). This indicated that the better flow-time performance can lead to lower mean tardiness. But still their relative performance changed with the different combination of due-date scheduling rules. A similar crossover effect was also observed in the due-date scheduling rules.

From the simulation results discussed in the previous sections, there was not sufficient evidence of superior performance for any rule from either the due-date assignment or scheduling rule sets. Therefore, the performance of the due-date assignment rules were further analysed under new experimental conditions such as increasing the queue capacity, increasing the processing time variances, reducing the AGV load level, and applying all the

Table 6. Mean tardiness performance (in minutes) of the due-date assignment rules using LQS and the AGV rule.

Flow-allowance parameter k	Due-date rules	Due-date assignment rules: CON	SLK	TWK	NOP	PPW
3	EDD	97·3	94·2	83·1	82·7	83·5
	SLK	92·1	91·6	80·5	79·8	84·8
	SCR	99·5	89·2	90·7	85·5	85·4
	MOD	77·3	72·6	65·7	68·7	66·6
	S/OPN	99·7	92·8	81·9	87·3	86·2
4	EDD	43·0	41·9	37·2	38·6	33·9
	SLK	38·0	37·9	23·2	34·7	31·4
	SCR	44·0	35·6	27·5	38·4	34·6
	MOD	36·5	34·5	25·2	29·2	27·8
	S/OPN	36·0	37·0	25·6	28·0	29·1
5	EDD	15·7	16·0	10·5	10·1	10·3
	SLK	13·8	12·5	12·0	10·7	8·8
	SCR	14·0	15·3	13·0	13·0	10·7
	MOD	16·7	14·4	12·0	11·7	12·0
	S/OPN	34·6	22·3	11·2	10·5	9·0
6	EDD	5·1	5·3	4·1	5·5	4·2
	SLY	4·6	3·7	5·2	4·8	4·6
	SCR	6·6	5·1	6·6	3·9	3·2
	MOD	6·4	5·5	5·6	4·7	4·6
	S/OPN	5·7	3·4	5·6	5·1	4·7

first three changes simultaneously. Five due-date assignment rules were considered in the experiments. While FCFS was used as the AGV rule, EDD and MOD were taken as the machine scheduling rules. These two rules were selected due to the fact that EDD is a commonly used scheduling rule in practice and MOD was found to be the best rule in earlier job-shop studies. Each of the ten rule combinations (five due-date assignment and two due-date scheduling rules) were tested at varying levels of due-date tightness. Again, the flow-allowances were controlled by the due-date tightness parameter. As mentioned above, the due-date performances of rules were measured under four new experimental conditions. These are as follows:

Case 2. Increasing the queue capacity

The queue (or buffer) capacity was increased to ten from the original capacity of five. Here, the aim was to give the rules more decision opportunities by providing a larger number of jobs in the queue. Recall that when the queue capacity is increased, the job finishing the current operation can be delivered to the next station immediately as long as an AGV is available. Also, the possible interference or delay caused by limited queue capacities can be reduced. Therefore, it was expected that some of the due-date assignment rules would perform better under this type of less restrictive situation.

Table 7. Mean tardiness performance (in minutes) of the due-date assignment rules when queue capacity is ten.

Flow-allowance parameter k	Due-date rules	Due-date assignment rules: CON	SLK	TWK	NOP	PPW
3	EDD	92·0	91·5	74·5	82·2	79·9
	MOD	71·3	62·5	61·0	60·5	60·0
4	EDD	38·0	38·1	24·7	29·9	29·4
	MOD	32·6	27·7	20·4	22·9	22·0
5	EDD	11·7	11·9	6·1	7·4	5·6
	MOD	11·8	11·0	6·1	6·9	6·7
6	EDD	2·3	2·5	1·0	1·3	1·3
	MOD	2·6	4·2	1·4	1·3	1·2

As shown in Table 7, simulation results confirmed the initial expectations. The performance of the rules began to differ. Among the due-date assignment rules tested TWK, NOP, and PPW produced better mean tardiness than the CON and SLK rules. Similarly, the MOD scheduling rule was better than the EDD rule especially when k is small ($k = 3$ and 4). The differences in the performance of due-date assignment rules were greater with the EDD scheduling rule (Table 7). Also, the differences between the rules (both the due-date and scheduling rules) increased as the due-date tightness increased.

Case 3. Increasing the variance of processing times

It is known from job-shop studies that the variance of the processing time affects the relative performance of the scheduling rules. Most of the scheduling rules utilize operation time related information to prioritize the jobs. Moreover, some of the rules, such as MOD, are very sensitive to the variance of the processing time distribution. In the scheduling literature, the due-date assignment rules were not tested at varying levels of operation time variances; there was some expectation in this study that an increase in the variance of operation time distributions would affect the relative performances of due-date assignment rules.

To test the above conjecture, the variance of the processing time distribution was increased to 8·64 (40% of mean) from the original value of 6·48 (30% of the mean) and the simulation experiments were repeated under this new condition. Again, FCFS was used as the AGV rule. Utilization rates corresponding to the machines and the AGV system were 85 and 87·5%, respectively.

As shown in Table 8, the performances of due-date assignment rules were quite different under the high variability. Not only the due-date assignment rules differed but the due-date scheduling rules EDD and MOD produced different mean tardiness performances.

Table 8. Mean tardiness performance (in minutes) of the due-date assignment rules when the coefficient of variance is 40%.

Flow-allowance parameter k	Due-date rules	Due-date assignment rules: CON	SLK	TWK	NOP	PPX
3	EDD	240·2	165·2	128·0	172·3	149·1
	MOD	127·8	131·6	84·7	89·0	91·0
4	EDD	162·7	90·8	71·0	109·7	87·0
	MOD	75·3	68·1	64·1	67·1	64·8
5	EDD	101·7	44·3	35·2	67·8	44·9
	MOD	42·4	34·2	27·7	25·2	44·1
6	EDD	58·9	20·5	21·8	25·0	16·1
	MOD	22·3	13·9	13·3	13·7	12·6

Table 9. Mean tardiness performance (in minutes) of the due-date assignment rules at reduced AGV load level.

Flow-allowance parameter k	Due-date rules	Due-date assignment rules: CON	SLK	TWK	NOP	PPW
3	EDD	95·6	86·9	71·3	79·9	81·2
	MOD	59·3	53·8	50·3	53·5	51·5
4	EDD	40·3	33·9	22·8	27·9	25·9
	MOD	26·1	22·2	16·7	19·4	19·0
5	EDD	13·3	9·9	4·9	7·6	8·5
	MOD	8·7	7·8	4·4	5·4	5·3
6	EDD	3·2	1·8	1·2	1·5	1·0
	MOD	2·3	2·1	1·2	1·3	1·1

In general, TWK, NOP, and PPW were better due-date assignment rules than CON and SLK irrespective of the due-date scheduling rules. It is interesting to notice the crossover effect between TWK and PPW. While TWK was better than PPW at low values of flow allowances, PPW yielded slightly better mean tardiness than TWK at the loose due-dates. Between the two due-date scheduling rules tested, MOD always produced better mean tardiness performance. However, its superior performance over the EDD rule reduced as the due-date tightness decreased.

Case 4. Reducing the AGV load

Both the machines and AGV system control the material flow in an FMS. However, the degree of the control changes depending upon the current load levels of these subsystems. At one time machines may be highly loaded and therefore dominate the scheduling system. But at another time the AGVs may be a bottleneck and eventually drive the scheduling system. Thus, as the fourth condition, the AGV load was reduced to provide more opportunities for the machine scheduling rules (or due-date scheduling rules) to dominate the due-date performance of the system. It was expected that the performance of due-date assignment and scheduling rules would begin to differ. To accomplish this, the AGV speed was increased to 75 from 60 ft/min. The resulting average AGV utilization was approximately 82·5%.

As can be seen in Table 9, there was not much difference between the performance of the due-date assignment rules. Even though TWK, NOP, and PPW produced slightly better mean tardiness than SLK and CON at the tight due-date ($k=3$), their performances appeared to be very similar when the value of the due-date tightness parameter increased. Between the two due-date scheduling rules tested, MOD, which has SPT characteristics, resulted in a considerable mean tardiness improvement over the EDD rule when $k=3$. However, at the other values of tightness parameter, EDD performed competitively with the MOD rule. It produced the minimum mean tardiness with the CON and SLK due-date assignments rules.

Case 5. Simultaneously increasing the queue capacity and the variance of processing time, and reducing the AGV load

For the last case, all the changes discussed before were applied simultaneously. Recall that this experimental condition was derived from the standard condition by increasing the queue capacity and the variance of the processing time and reducing the AGV load. These changes were made to test the difference in the performance of due-date assignment rules.

As shown in Table 10, TWK, NOP, and PPW resulted in the better mean tardiness compared to CON and SLK, irrespective of the due-date scheduling rules. Furthermore, among these three rules, TWK minimized

Table 10. Mean tardiness performance (in minutes) of the due-date assignment rules at reduced AGV load level and increased queue capacity and variances of processing times.

Flow-allowance parameter k	Due-date rules	Due-date assignment rules: CON	SLK	TWK	NOP	PPW
3	EDD	93·0	99·6	87·2	85·6	92·3
	MOD	79·9	71·9	63·2	70·6	68·3
4	EDD	41·3	46·5	40·3	37·1	41·4
	MOD	63·5	38·6	36·9	35·8	39·6
5	EDD	15·2	18·1	13·0	16·8	10·6
	MOD	30·3	25·7	19·6	17·1	17·3
6	EDD	4·6	6·1	7·3	5·3	5·6
	MOD	12·2	16·9	9·5	9·6	9·3

the mean tardiness at varying levels of the tightness parameter. The resulting mean tardiness improvements by TWK were greatest when the tightness parameter (k) was small.

The relative performance of the due-date scheduling rules were also quite different. In general, MOD outperformed the EDD rule. Except for very loose due-dates ($k=6$), it provided a considerable mean tardiness improvement over EDD regardless of the due-date assignment rule and the tightness parameter used.

Table 11. Mean tardiness performance (in minutes) of different due-date assignment rules using FCFS as the AGV rule.

Flow-allowance parameter k	Due-date rules	Due-date assignment rules: CON	SLK	TWK	NOP	PPW
3	EDD	246·2	232·7	202·2	223·0	188·7
	SLK	243·2	285·5	195·5	244·7	263·1
	SCR	420·5	274·3	223·0	301·4	263·3
	MOD	80·6	65·9	70·7	66·1	58·1
	S/OPN	253·2	236·9	207·5	261·6	250·47
4	EDD	177·7	167·1	108·1	157·7	145·5
	SLK	174·3	214·9	124·5	186·6	165·1
	SCR	312·6	168·6	132·9	257·2	170·2
	MOD	53·3	40·2	37·2	48·4	37·7
	S/OPN	199·3	171·5	100·5	179·4	146·8
5	EDD	122·9	115·3	64·9	99·9	106·2
	SLK	119·1	157·8	78·0	103·5	89·9
	SCR	143·0	157·3	86·2	125·4	156·9
	MOD	33·6	33·0	28·3	31·4	26·5
	S/OPN	122·0	92·7	65·2	105·6	95·1
6	EDD	36·6	35·0	26·6	24·9	25·5
	SLK	35·7	32·6	21·9	38·2	32·2
	SCR	50·2	44·7	40·7	42·2	45·9
	MOD	17·8	14·0	9·9	17·0	13·6
	S/OPN	38·0	33·1	19·6	37·4	27·7

4.2. *Analysis of due-date assignment rules using exponentially distributed processing times*

In the previous sections, the normal distribution was used to generate the processing times. However, the exponential distribution is also a commonly used processing time distribution in the literature. In fact, most of the experimental studies which investigated the due-date performances of scheduling rules assumed exponentially distributed processing times (Baker 1984, Baker and Kanet 1984). In general, the exponential distribution possesses very large variability. It is known from the earlier studies on the job-shop and the results obtained in the previous sections that the relative performance of the rules are more significant under high variability. Thus, the objective of this section is to repeat the simulation experiments using the exponential distribution, and to observe the differences in the performance of the due-date assignment due to the increased variability.

Under the standard experimental conditions, the mean operation times and the AGV speed were determined in such a way that the average machine and AGV utilization rates were kept at 85 and 87·5%, respectively. However, during the initial simulation runs, the system was saturated for all rules under these conditions. The standard conditions were changed by reducing both the machine and AGV load. At the new conditions, the mean operation time was reduced from 20·60 to 19·03 min and the AGV speed was increased from 60 to 65 ft/min. This resulted in average machine and AGV utilizations of 75 and 82%, respectively.

The FMS system was simulated under these conditions. Again, five due-date assignment rules were compared at varying levels of flow-alowances (due-date tightness) by using the different due-date scheduling rules. Recall that the due-date scheduling rules refer to the machine scheduling rules in this study. FCFS was used as the AGV scheduling rule.

The relative performance of the rules against the mean tardiness measure are presented in Table 11. The results indicated that not only did the relative performance of the due-date assignment rules become more significant, but also mean tardiness increased with exponentially distributed processing times (refer to Figures 2 and 3 for comparison of normally and exponentially distributed cases). Recall that the system was lightly loaded in the exponential case but yielded higher mean tardiness than the normally distributed case. This is primarily due to the characteristics of the exponential distribution (high coefficient of variation).

In general, TWK outperformed the other due-date assignment rules irrespective of due-date tightness and the due-date scheduling rule. PPW produced the second best mean tardiness performances in most of the conditions tested. However, its relative performance, compared to SLK and NOP, changed with different combinations of the scheduling rules at varying levels of due-date tightness. CON performed poorly compared to the other rules.

Among the scheduling rules tested, MOD yielded the best tardiness performance. The superior performance of the MOD rule was due to its SPT characteristic under the tight due dates. While the SCR rule performed very poorly, the relative performance of SLK, EDD, and S/OPN changed with the due-date assignment rules at the varying levels of the due-date tightness.

The due-date assignment rules were further tested by using different AGV scheduling rules. First, LQS was used as the AGV rule. The simulation results (Table 12)

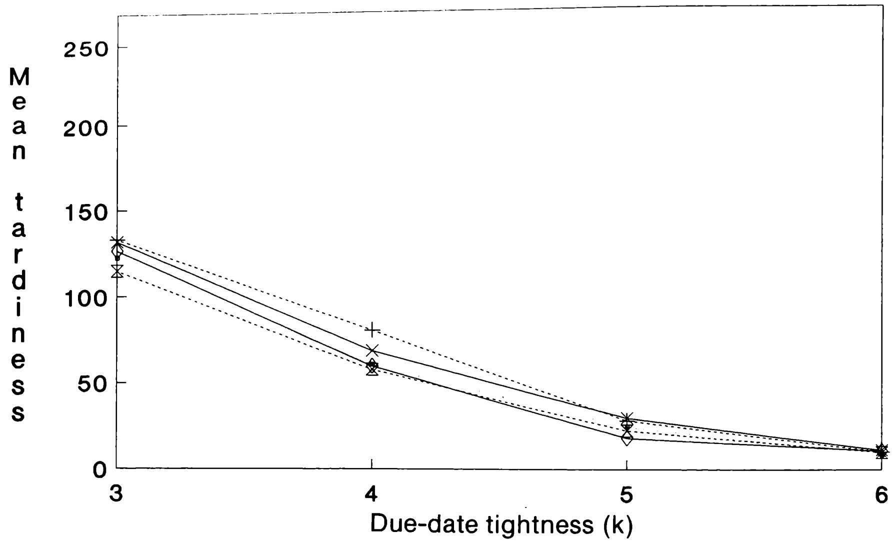

Figure 2. Mean tardiness performance of CON(×), SLK(·), TWK(◇), NOP(⧗) and PPW(+) with EDD machine scheduling rule (normally distributed case).

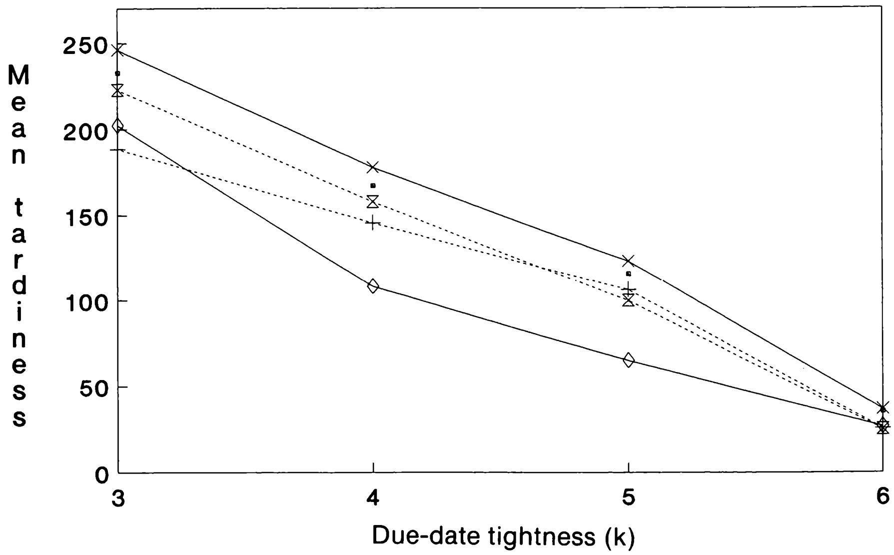

Figure 3. Mean tardiness performance of CON(×), SLK(·), TWK(◇), NOP(⧗) and PPW(+) with EDD machine scheduling rule (exponentially distributed case).

show that the mean tardiness performance of all the rules were improved with the LQS rule compared to FCFS (Table 11). Among the due-date assignment rules, TWK achieved the minimum tardiness in most of the conditions tested. PPW yielded the second best performance and this was followed by the NOP and SLK rules. The CON rule performed poorly compared to the other rules. On the other hand, MOD was still the best due-date scheduling rule since it improved the mean tardiness significantly. SCR performed poorly. The performance of the other scheduling rules, EDD, SLK, and S/OPN, changed with the different combinations of scheduling rules at the varying values of tightness.

Finally, the simulation experiments were repeated using the due-date scheduling rules as the AGV rules. Under this condition, the same due-date scheduling rule was used both for the machine and AGV scheduling rule. As shown in Table 13, TWK minimized the mean tardi-

Table 12. Mean tardiness performance (in minutes) of different due-date assignment rules using LQS as the AGV rule.

Flow-allowance parameter k	Due-date rules	Due-date assignment rules CON	SLK	TWK	NOP	PPW
3	EDD	170·2	158·9	116·3	160·5	141·1
	SLK	172·3	165·3	152·1	170·4	163·2
	SCR	196·5	181·7	155·8	199·4	189·6
	MOD	76·1	59·3	55·6	56·1	52·7
	S/OPN	188·7	171·6	137·2	173·0	157·3
4	EDD	110·3	101·7	70·3	92·7	105·5
	SLK	110·5	103·3	66·3	102·5	93·9
	SCR	154·4	121·9	94·3	128·1	109·5
	MOD	41·9	34·5	32·2	34·5	30·5
	S/OPN	121·4	103·7	62·2	106·3	99·7
5	EDD	66·0	65·9	35·1	53·6	43·5
	SLK	65·0	59·9	42·7	60·8	50·0
	SCR	90·0	73·2	53·5	66·2	72·5
	MOD	27·9	20·2	19·8	23·4	20·4
	S/OPN	64·2	54·0	33·5	56·2	62·4
6	EDD	36·6	35·0	26·6	24·9	25·5
	SLK	35·7	32·6	21·9	38·2	32·1
	SCR	50·2	44·7	40·6	42·2	45·8
	MOD	17·8	14·0	9·9	17·0	13·6
	S/OPN	37·9	33·1	19·6	37·4	27·7

Table 13. Mean tardiness performance (in minutes) of the due-date assignment rules using the due-date scheduling rules as the AGV rules.

Flow-allowance parameter k	Due-date rules	Due-date assignment rules CON	SLK	TWK	NOP	PPW
3	EDD	226·9	187·4	163·6	186·5	213·4
	SLK	230·0	225·2	188·6	208·2	225·3
	SCR	387·2	315·7	198·2	298·8	245·4
	MOD	71·5	60·8	56·2	60·0	57·0
	S/OPN	222·1	198·9	170·4	210·7	219·4
4	EDD	159·5	123·5	105·7	140·1	127·3
	SLK	160·2	155·9	114·5	164·3	130·2
	SCR	191·0	179·6	111·8	199·5	178·6
	MOD	45·9	37·6	29·5	37·7	31·2
	S/OPN	173·0	128·2	81·6	158·6	119·9
5	EDD	105·4	76·5	55·5	90·4	82·2
	SLK	105·3	101·4	54·9	91·9	80·2
	SCR	137·1	102·7	84·7	123·2	119·1
	MOD	27·0	19·0	21·0	24·5	16·7
	S/OPN	98·7	89·7	43·4	86·4	81·5
6	EDD	65·2	43·9	24·1	60·7	50·9
	SLK	66·4	62·8	40·4	57·8	48·5
	SCR	86·0	88·4	52·2	87·3	61·4
	MOD	15·2	11·8	9·6	19·6	10·6
	S/OPN	59·5	38·3	38·2	47·3	51·5

ness with any due-date scheduling rule at any value of due-date tightness parameter. Similarly, MOD outperformed any other due-date scheduling rule irrespective of the due-date assignment method and the value of tightness parameter. While the CON due-date assignment rule and the SCR due-date scheduling rule resulted in the poorest mean tardiness, the relative performances of the other rules changed with the level of due-date tightness. It appears that EDD performed well with the SLK due-date assignment rule. Also, PPW is a very effective due-date assignment method when used with the MOD scheduling rule.

5. Conclusions and directions for future research

In this paper, the performances of several due-date assignment rules and machine/AGV scheduling rules were studied using an FMS simulation model. The results indicate that none of the due-date assignment or due-date scheduling rules exhibited dominating performance with normally distributed processing times. As the variance of the processing time distribution or the queue capacity increased, or the AGV load was reduced, the relative performances of the rules differed.

In the exponential case, the TWK due-date assignment rule minimized the mean tardiness for most of the conditions tested. PPW produced the second best performance and this was followed by NOP and SLK. The CON rule was the worst of all the rules tested. The superior performance of TWK is quite reasonable since it is more sensitive to the mean and variance of the total processing time than the other due-date assignment methods. Accentuated differences for due-date performances of the due-date assignment and scheduling rules in the exponential case indicated that the variance of the operation time was the major factor in separating the performance of the rules.

The flow-allowance level (or due-date tightness) was also a very important factor in evaluating the rules. As the flow-allowance decreased, the differences among the performances of the rules became significant. There was also some evidence that improving the mean flow-time also improved due-date performance. This was noticed when LQS was used as the AGV rule. Moreover, with the tight due-dates, the rules which minimized the flow-time, also resulted in better due-date performances.

Among the machine due-date scheduling rules tested, MOD produced better mean tardiness. Among the AGV rules tested, LQS outperformed the other rules. Even though LQS did not use the due-date information, it produced the best results, indicating that the mean tardiness could be improved significantly by minimizing the mean flow-time.

The resulting performances of TWK due-date assignment rule and the MOD scheduling rule in the exponential case also confirmed the previous job-shop studies (Kanet and Christy 1988, Baker 1984, Baker and Kanet 1984).

While there are a number of other assignment and scheduling rules that could have been studied in this paper, those that were selected had been shown to be effective in other studies. The results presented in this paper are valid under the experimental conditions described. Hence there is a need for further research to develop new rules and continue to test the existing ones under different experimental conditions against the various criteria. Such research should address the impact of varying system parameters such as arrival rates, processing time parameters, and the different FMS configurations.

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