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Scheduling in job shops with machine breakdowns: an experimental study

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Abstract

This paper considers the simulation-based analysis of dispatching rules for scheduling in dynamic job shops taking into account interruptions on the shop floor. With respect to flowtime and due date-based objectives, the relative performance of well-known, recently proposed as well as some new dispatching rules is evaluated for different settings of the model parameters. The results of the simulation study reveal that the relative performance of scheduling rules can be affected by changing the levels of the breakdown parameters. For the standard model, where all machines are continuously available, as well as for the models taking into account breakdowns of machines, it is shown that for minimizing mean flowtime the performance of one recently proposed rule (PT + WINQ) is significantly better than the performance of all other rules. Analogously it is shown that for minimizing maximum flowtime, and for minimizing variance of flowtime, one new rule (AT − RPT) is superior to all other rules. With respect to due date-based objectives the relative performance of the analyzed scheduling rules is more sensitive to the percentage of time the machines have failures and the mean time to repair.

Keywords: Job shop scheduling; Machine breakdowns; Dispatching rules; Simulation

1. Introduction

The dynamic job shop scheduling problem may be characterized as follows: in a manufacturing system which comprises M machines (work stations) the jobs arrive

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continuously in time. Each job consists of a specified set of operations which have to be performed in a specified sequence (routing) on the machines. Schedules for processing the jobs on each of the M machines have to be found which are best solutions with respect to given flowtime or due date-based objectives. Because of the constrained information horizon (the arrival times, routings and processing times of the jobs arriving in future are not known in advance) only for those jobs currently in the shop processing sequences on the various machines can be determined. The decision as to which job is to be loaded on a machine, when the machine becomes free, is normally made with the help of a dispatching (scheduling) rule. Over the last four decades, many dispatching rules have been proposed and studied by many researchers [5,9,16]. Although there exists a variety of simulation-based studies of dispatching rules [16], the number of papers taking into account interruptions on the shop floor (machine breakdowns) is very small [4,19]. Moreover, up to now there does not exist any study analyzing the effect of breakdown parameters on the relative performance of dispatching rules with respect to flowtime and due date-based objectives.

This paper considers the simulation-based analysis of dispatching rules for scheduling in dynamic job shops with machine breakdowns. For evaluating the relative performance of the scheduling rules the mean and maximum flowtime, variance of flowtime, mean and maximum tardiness, percentage of tardy jobs and variance of tardiness criteria have been chosen. In the simulation study different values of the breakdown parameters (breakdown level and mean breakdown time) are used to analyze their effect on the relative performance of the rules.

The organization of the remaining sections of this paper is as follows: In Section 2 the dynamic job shop scheduling problem is characterized in detail. Section 3 gives a representative selection of dispatching rules including not only some recently proposed scheduling rules but also three new ones. Section 4 presents a simulation study describing the design of the experiments and the important aspects of the results of the experimental investigation. The essential results of this paper are summarized in Section 5.

2. The job shop scheduling problem with machine breakdowns

N jobs arrive continuously in time in a shop consisting of M machines $m = 1, \ldots, M$. Job i $(1 \leq i \leq N)$ has the due date d_i, e.g. the promised delivery date and comprises k_i operations $q = 1, \ldots, k_i$, which have to be performed on the machines according to the routing of job i which is given by $\tilde{m}_i = (\tilde{m}_{i1}, \ldots, \tilde{m}_{ik_i})$. The operation q of job i, which has to be performed on machine $\tilde{m}_{iq}$, requires the processing time p_{iq}. The arrival time, due date, routing and processing times of a job are not known until the job arrives in the shop.

The aim of the scheduling process is to find sequences for processing the jobs on each of the machines which are best orders with respect to the given objectives. In the following objectives based on flowtime and due dates are considered, chosen as substitudes for economic goals [5,9]. Flowtime-based objectives are oriented by the basic aim of short manufacturing times necessary to complete the jobs. If r_i denotes the arrival time (release time) of job i and C_i the completion time, the amount of time job i spends in the shop is given by the flowtime $F_i = C_i - r_i$. Flowtime-based objectives are

- the minimization of mean flowtime $\bar{F} = 1/N \sum_{i=1}^{N} F_i$,
- the minimization of maximum flowtime $F_{\max} = \max\{F_i | 1 \leq i \leq N\}$ and
- the minimization of variance of flowtime $\sigma_F^2 = 1/N \sum_{i=1}^{N} (F_i - \bar{F})^2$.

Due date-based objectives are oriented by the basic aim of completing the jobs in due time. If the completion time of job i exceeds its due date, job i is tardy. $T_i = \max\{0, C_i - d_i\}$ is called the tardiness of job i. Due date-based objectives are

- the minimization of percentage of tardy jobs $\%T = 100 \cdot |\{i | T_i > 0, 1 \leq i \leq N\}|/N$,
- the minimization of mean tardiness $\bar{T} = 1/N \sum_{i=1}^{N} T_i$,
- the minimization of maximum tardiness $T_{\max} = \max\{T_i | 1 \leq i \leq N\}$ and
- the minimization of variance of tardiness $\sigma_T^2 = 1/N \sum_{i=1}^{N} (T_i - \bar{T})^2$.

The model for the job shop scheduling problem is based upon the following assumptions [1,5,6,9,16]:

Each machine can perform only one operation at a time on any job. Each job can be processed only by one machine at a time. A job, once taken up for processing, should be completed before another job can be taken up. An operation on any job cannot be performed until all previous operations on the job are completed. No two successive operations on a job can be performed on the same machine ($\tilde{m}_{iq} \neq \tilde{m}_{i,q} + 1$, $q = 1, \ldots, k_i - 1$). The processing times are independent of the job orders on the machines. Set-up times are included in the processing times, transportation times are negligible.

In contrast to the standard assumption of no interruptions on the shop floor [9,16], in the model considered in this paper the machines are not continuously available. If a machine breaks down, e.g. a stochastic breakdown or irregular interruption for maintenance, no operation can be performed until the end of the time to repair (breakdown time). An operation currently performed on the machine is interrupted and restarted until the end of the breakdown time. If a machine m breaks down at the instant t, the assumption is made, that at instant t the *time to repair* is known. At instant t + *time to repair* machine m restarts the processing of the interrupted job, which now requires the remaining processing time. Besides the release times, routings and processing times of the jobs the breakdown times and interbreakdown times (times between failures) of the machines are stochastic parameters, for which the probability distributions and their parameters (e.g. mean value and variance) are known.

3. Dispatching rules for job shop scheduling

Using a dispatching rule, for each of the M machines the jobs to be processed are scheduled as follows. As soon as a machine m becomes free, it has to be decided which of the waiting jobs (if there is any in the queue of machine m) is to be loaded on the machine. For making this decision a priority rule is used to assign to each of the waiting jobs a priority value. The job having the highest priority, which is defined by either the smallest or the largest priority value, is selected for processing next. In the following a representative selection of the large set of priority rules proposed over the last 40 years [5,9,14,16], is given. These rules include not only well-known scheduling rules but also recently proposed ones. For their description the following notations are used:

m: Index of the machine, for which the job to be processed next has to be selected.
t: Time at which the priority values are calculated.
$t_{\hat{m}}$: Time at which the next job can be loaded on machine $\hat{m}$ ($\hat{m}=1, \ldots, M$; $t_m = t$).
i: Index of the job, for which the priority value is calculated.
r_i^m: Arrival time of job i at machine m.
j: Index of the operation, job i is waiting for at machine $\tilde{m}$ ($\hat{m}_{ij}=m$).
j_h: Index of operations of a job h ($j_h=1, \ldots, k_h$).
c_{hj_h}: Completion time of operation j_h of job h.
N_m^t: Set of jobs waiting for processing in the queue of machine m at time t.
s_i^t: Slack of job i at time; $s_i^t = d_i - t - \sum_{q=j}^{k_i} p_{iq}$.
$\tilde{N}_m^t$: Set of all operations, machine m has finished until time t;$\tilde{N}_m^t = \{(h,j_h)|\tilde{m}_{hj_h} = m$ and $c_{hj_h} \leq t\}$.
Z_i^t: Priority value of job i at time t.

Well-known dispatching rules are for instance [5,9]:

FIFO (first in, first out): $Z_i^t := r_i^m$, where the highest priority is given to the job i^* with $Z_{i*}^t = \min\{Z_i^t | i \in N_m^t\}$. Using the FIFO rule the jobs are processed in the order they arrive at the machine.
AT (arrival time): $Z_i^t := r_i$, where the highest priority is given to the job i^* with $Z_{i^*}^t = \min\{Z_i^t | i \in N_m^t\}$. Using the AT rule the jobs are processed in the order they arrive in the shop.
TIS (time in system): $Z_i^t := t - r_i$, where the highest priority is given to the job i^* with $Z_{i^*}^t = \max\{Z_i^t | i \in N_m^t\}$. Since the instant t is equal for all jobs $i \in N_m^t$ the rules AT and TIS are equivalent, i.e. they generate the same job orders.
SPT (shortest processing time): $Z_i^t := p_{ij}$, where the highest priority is given to the job i^* with $Z_{i^*}^t = \min\{Z_i^t | i \in N_m^t\}$, i.e. the job with the shortest processing time is selected.
WINQ (work in the queue of its next operation):

$$Z_i^t := 0, \quad \text{if } j = k_i$$

$$Z_i^t := (t_{\tilde{m}_{i,j+1}} - t) + \sum_{h \in N^t_{\tilde{m}_{i,j+1}}} p_{hj_h}, \quad \text{if } j < k_i,$$

where the highest priority is given to the job i^* with $Z_{i^*}^t = \min\{Z_i^t | i \in N_m^t\}$. If the number of operations remaining of job i is greater than 1 ($j < k_i$) the priority value of this job is defined by the sum of the total work-content of jobs in the queue for the next operation and the time interval between the time at which the next job can be loaded on the subsequent machine and the present instant. If the subsequent machine $\tilde{m}_{i,j+1}$ is not interrupted at time t, the interval $(t_{\tilde{m}_{i,j+1}} - t)$ equals the remaining processing time of the job currently being processed on machine $\tilde{m}_{i,j+1}$. However, if there is a failure at machine $\tilde{m}_{i,j+1}$ then the interval $(t_{\tilde{m}_{i,j+1}} - t)$ includes the remaining processing time of the interrupted job as well as the remaining time to repair. If the term $(t_{\tilde{m}_{i,j+1}} - t)$ is omitted in the definition of the priority value the resulting rule is equivalent to the standard WINQ rule without taking into account interruptions on the shop floor [9].

Recently proposed dispatching rules are for instance [11,15]:

RR (rule by Raghu and Rajendran):

$$Z_i^t := \left(s_i^t \Big/ \sum_{q=j}^{k_i} p_{iq} \right) e^{-\eta_m^t} p_{ij} + e^{\eta_m^t} p_{ij}, \quad \text{if } j = k_i$$

$$Z_i^t := \left(s_i^t \Big/ \sum_{q=j}^{k_i} p_{iq} \right) e^{-\eta_m^t} p_{ij} + e^{\eta_m^t} p_{ij} + \hat{w}_{i,j+1}^t, \quad \text{if } j < k_i,$$

where the highest priority is given to the job i^* with $Z_{i^*}^t = \min\{Z_i^t | i \in N_m^t\}$. $\eta_m^t = (\sum_{(h,j_h) \in \tilde{N}_m^t} p_{hj_h})/t$ denotes the utilization level of machine m with respect to the interval $[0, t]$ and $\hat{w}_{i,j+1}^t$ the expected waiting time of the subsequent operation at time t. Let $t' = \max\{t + p_{ij}, t_{\tilde{m}_{i,j+1}}\}$, then $\hat{w}_{i,j+1}^t$ equals the sum of processing times of all the jobs in the queue of machine $\tilde{m}_{i,j+1}$ which have at time t' a higher priority (according to the RR rule) than job i.

PT + WINQ (processing time plus work in the queue of its next operation):

$$Z_i^t := p_{ij}, \quad \text{if } j = k_i$$

$$Z_i^t := p_{ij} + (t_{\tilde{m}_{i,j+1}} - t) + \sum_{h \in N_{\tilde{m}_{i,j+1}}^t} p_{hj_h}, \quad \text{if } j < k_i,$$

where the highest priority is given to the job i^* with $Z_{i^*}^t = \min\{Z_i^t | i \in N_m^t\}$. This dispatching rule is based upon a simple additive combination of the rules SPT and WINQ. The priority value is defined by the processing time on machine m plus the total work-content of jobs in the queue for the next operation including the interval between the time at which the next job can be loaded on the subsequent machine and the present instant.

PT + WINQ + SL (processing time plus work in the queue of its next operation plus slack):

$$Z_i^t := p_{ij} + \min\{s_i^t, 0\}, \quad \text{if } j = k_i$$

$$Z_i^t := p_{ij} + (t_{\tilde{m}_{i,j+1}} - t) + \sum_{h \in N_{\tilde{m}_{i,j+1}}^t} p_{hj_h} + \min\{s_i^t, 0\}, \quad \text{if } j < k_i,$$

where the highest priority is given to the job i^* with $Z_{i^*}^t = \min\{Z_i^t | i \in N_m^t\}$. This rule combines the PT + WINQ rule with a slack component in order to incorporate due date information in the calculation of the priority value.

Using simulation models the relative performance of dispatching rules can be analyzed with respect to a given objective. Although there is the difficulty, that one finds in the literature conflicting evidence on the relative performance of scheduling rules caused by different values of the model parameters, in the following some of the essential results of the various studies are shortly summarized. With respect to the minimization of mean flowtime in a large number of studies the SPT rule is the best (e.g. see Refs. [7,8,16–18]). However, there are new studies [10,11,15] showing that the recently proposed rules RR and PT + WINQ are superior to the SPT rule for minimizing mean flowtime. In addition, the relative performance of the PT + WINQ rule compared to the SPT rule increases significantly with increasing load level of the shop [10]. With respect to the minimization of maximum flowtime and the minimization of variance of flowtime the rules FIFO and AT (TIS, respectively) are efficient [18]. For minimizing the percentage of tardy jobs the SPT rule is effective, when the shop utilization is high or/and the due dates are tight. However, at lower levels of shop utilization or with loose due dates, dispatching rules which incorporate due date information in the scheduling process perform better than the SPT rule (e.g. see Ref. [2,3,5,15,16,18]). With respect to the minimization of mean tardiness the RR-rule has the best performance, which is proved for a large number of different values of the model parameters [11,15]. For minimizing maximum tardiness and variance of tardiness the rules RR and PT + WINQ + SL had been found to outperform other rules [11].

Besides the seven known rules FIFO, AT (TIS), SPT, WINQ, RR, PT + WINQ and PT + WINQ + SL three new rules are considered in the simulation study. These dispatching rules are:

AT − RPT (arrival time minus remaining processing time): $Z_i^t{:=}r_i - \sum_{q=j}^{k_i} f_{ij}$,where the highest priority is given to the job i^* with $Z_{i^*}^t = \min\{Z_i^t | i \in N_m^t\}$. Since the remaining processing time of a job is incorporated in the priority value calculation, this rule should outperform the rules FIFO and AT with respect to the minimization of maximum flowtime and variance of flowtime.

PT/TIS (ratio of processing time and time in system): $Z_i^t := p_{ij}/(t - r_i)$, where the highest priority is given to the job i^* with $Z_{i^*}^t = \min\{Z_i^t | i \in N_m^t\}$. This rule is a simple combination of the rules SPT and TIS which should give good results not only for minimizing mean flowtime but also for minimizing maximum and variance of flowtime.

(PT + WINQ)/TIS (ratio of processing time plus work in the queue of its next operation and time in system):

$$Z_i^t{:=}p_{ij}/(t - r_i), \quad \text{if } j = k_i$$

$$Z_i^t{:=}\left(p_{ij} + (t_{\tilde{m}_{i,j+1}} - t) + \sum_{h \in N^t_{\tilde{m}_{i,j+1}}} p_{hj_h}\right) \Big/ (t - r_i), \quad \text{if } j<k_i,$$

where the highest priority is given to the job i^* with $Z^t_{i^*} = \min\{Z^t_i | i \in N^t_m\}$. The motivation for the design of the combination rule (PT + WINQ)/TIS is the fact, that the PT + WINQ rule performs very well for minimizing mean flowtime but performs poorly with respect to the measures maximum flowtime and variance of flowtime. Using the ratio of PT + WINQ and TIS should result in small values of mean flowtime as well as small values of maximum flowtime and variance of flowtime.

4. Experimental evaluation of the dispatching rules

4.1. Design of the experiments

For the experimental evaluation of the dispatching rules presented in Section 3 a job shop consisting of $M = 10$ machines is chosen. The number of operations for each job is generated uniformly distributed between 2 and 14. The routing for each job is generated randomly, with every machine having an equal probability of being chosen. The processing times are drawn from a rectangular distribution with the range [1,49]. Thus the mean processing time of an operation is $\bar{p} = 25$ time units. The interarrival times of the jobs are distributed exponentially, where the mean interarrival time λ controls the shop utilization U_g. If $\bar{P}$ denotes the mean total processing time of a job ($\bar{P} = 8 \cdot \bar{p} = 200$ time units), the shop utilization is defined as $U_g = \bar{P}/(M \cdot \lambda)$. Choosing $\lambda = 200/9$ time units results in an utilization level of 90% ($U_g = 0.90$). For fixing the due date of an arriving job h the total processing time of job h is weighted with a due date factor c ($d_h = r_h + c \cdot \sum_{q=1}^{k_h} p_{hq}$ [3]). For the tardiness-based analysis of the dispatching rules the due date factors $c = 4$ and $c = 8$ are used, where $c = 4$ represents tight due dates and $c = 8$ loose due dates.

The breakdown times (times to repair) and interbreakdown times (times between failures) are exponentially distributed, where MTTR denotes the mean time to repair and MTBF the mean time between failures. All M machines have the same mean values MTTR and MTBF. $A_g = \text{MTTR}/(\text{MTBF} + \text{MTTR})$ denotes the breakdown level of the shop, viz. the percentage of time the machines have failures. For instance, for $A_g = 0.05$ and MTTR = 125 time units ($5 \cdot \bar{p}$) follows $\text{MTBF} = \text{MTTR}/A_g - \text{MTTR} = 125/0.05 - 125 = 2375$. Thus, on an average of 2375 time units a machine is available and then breaks down with a mean time to repair of 125 time units. For evaluating the effect of the breakdown level A_g and the effect of the mean time to repair MTTR on the relative performance of the dispatching rules, values for $A_g \in \{0, 0.025, 0.05\}$ and for $MTTR \in \{\bar{p}, 5\bar{p}, 10\bar{p}\}$ are investigated, where $A_g = 0$ represents the standard model without taking into account interruptions on the shop floor.

In each simulation run the shop is continuously loaded with jobs, that are numbered on arrival. In order to ascertain when the system reaches a steady-state, the utilization level and breakdown level of the machines as well as the mean flowtime of jobs have been observed. It has been found that the shop reaches a steady-state after the arrival of about 500 jobs. Therefore, data have been collected from the jobs numbered from 501 to 2500, and the shop is still loaded with jobs, until these $N = 2000$ numbered jobs are completed. For each combination of a dispatching rule and fixed values of the model parameters 30 independent simulation runs have been performed. The statistical analysis of the experimental data is based upon a singlefactor ANOVA with block design (common random numbers for one block) and Duncan's multiple range test [12,13] showing that the chosen sample size yields a variance which results in a Type I error of at most 1%.

4.2. Results of the experimental evaluation

4.2.1. Flowtime-based analysis

In order to analyze the relative performance of the scheduling rules with respect to the flowtime-based objectives minimization of mean flowtime $\bar{F}$, minimization of maximum flowtime $F_{\max}$ and minimization of variance of flowtime σ_F^2 in dependence of the percentage of time the machines have failures, three different values for the breakdown level A_g (0, 2.5 and 5%) are investigated. For these experiments the mean breakdown time $\mathrm{MTTR} = 5\bar{p}$ is chosen representing a medium mean time to repair.

Table 1 presents the relative percentage increase (RPI) in mean flowtime $\bar{F}$ for the 10 dispatching rules relative to the best performing rule in dependence of the breakdown level A_g. If SR denotes the set of the 10 dispatching rules and $\bar{F}(X)$ the mean flowtime for rule $X \in SR$ (mean value over the 30 replications), the relative percentage increase in mean flowtime for rule X is defined as follows:

$$\mathrm{RPI}(\bar{F}) = 100 \cdot (\bar{F}(X) - \min\{\bar{F}(Y) | Y \in SR\}) / \min\{\bar{F}(Y) | Y \in SR\} \; [\%].$$

In Table 1 the dispatching rules are ranked according to nondecreasing $\mathrm{RPI}(\bar{F})$ values marking those values with the same letter (e.g. a, b and c) for which the statistical analysis has not shown any significant differences between the corresponding mean values. For minimizing mean flowtime the performance of the PT + WINQ rule is significantly better than the performance of all other rules. This holds for the standard model without interruptions on the shop floor ($A_g = 0$) as well as for the models with positive breakdown levels. Although the

Table 1
$\mathrm{RPI}(\bar{F})$ of rules for $A_g = 0$, 0.025 and 0.05

$A_g = 0$		$A_g = 0.025$		$A_g = 0.05$	
Rule	$\mathrm{RPI}(\bar{F})$	Rule	$\mathrm{RPI}(\bar{F})$	Rule	$\mathrm{RPI}(\bar{F})$
PT + WINQ	0.0	PT + WINQ	0.0	PT + WINQ	0.0
RR	3.2	(PT + WINQ)/TIS	9.5[a]	(PT + WINQ)/TIS	6.3
SPT	7.5[a]	RR	10.3[a]	RR	13.2[a]
(PT + WINQ)/TIS	8.5[a]	SPT	11.7[a]	SPT	16.2[b,a]
PT + WINQ + SL	10.5	WINQ	18.1[b]	WINQ	16.6[b]
WINQ	14.9	PT + WINQ + SL	19.5[b]	PT/TIS	19.3[b]
PT/TIS	19.4	PT/TIS	21.7	PT + WINQ + SL	20.1[b]
AT	46.2	AT	50.2[c]	AT	45.8
AT – RPT	48.0	AT – RPT	51.2[c]	AT – RPT	47.1
FIFO	55.1	FIFO	61.4	FIFO	60.2

relative performance of the PT + WINQ rule is not affected by the breakdown level, the relative performance of the other dispatching rules can be affected if the breakdown level is varied. Whereas for $A_g = 0$ the RR rule performs significantly better than the SPT and (PT + WINQ)/TIS rules, for $A_g = 0.025$ any significant differences are not detected and for $A_g = 0.05$ the (PT + WINQ)/TIS rule is more effective than RR and SPT. Fig. 1 shows the $\bar{F}$-values (absolute mean values over the 30 replications) of the first seven rules in dependence of A_g, excluding the rules AT, AT − RPT and FIFO because of their large mean flowtimes. This figure illustrates not only the effect of the breakdown level on the relative performance of the analyzed rules, but also its effect on the absolute $\bar{F}$-values, which increase with increasing percentage of time the machines have failures.

Table 2 presents the relative percentage increase in maximum flowtime RPI(F_{max}) for all rules in dependence of the breakdown level A_g, where RPI(F_{max}) has been calculated analogously to RPI($\bar{F}$). The 10 priority rules are ranked in the order of nondecreasing *RPI*(F_{max})-values, where those values are marked with the same letter for which there is not any significant difference between the corresponding mean F_{max}-values. For minimizing maximum flowtime the dispatching rule AT − RPT is significantly the best rule, followed by the AT rule. Next in rank are the rules PT/TIS and PT + WINQ + SL. While for $A_g = 0$ there is no significant difference between the mean values of PT/TIS and PT + WINQ + SL, for $A_g = 0.025$ and $A_g = 0.05$ PT + WINQ + SL performs better than PT/TIS. The performance of the RR rule is also affected by the breakdown level. If the machines are continuously available the F_{max}-values of the RR rule are significantly smaller than the F_{max}-values of FIFO. For $A_g = 0.025$ any significant difference is not detected, while for $A_g = 0.05$ the RR rule is outperformed by the FIFO rule. Although the performance of the best rule is not affected by the breakdown level A_g, with respect to the minimization of maximum flowtime the relative performance of the dispatching rules can vary with changing breakdown level. Fig. 2 shows the F_{max}-values of the first seven rules in dependence of A_g, excluding the rules SPT, WINQ and PT + WINQ because of their large maximum flowtimes. With increasing breakdown level the F_{max}-values

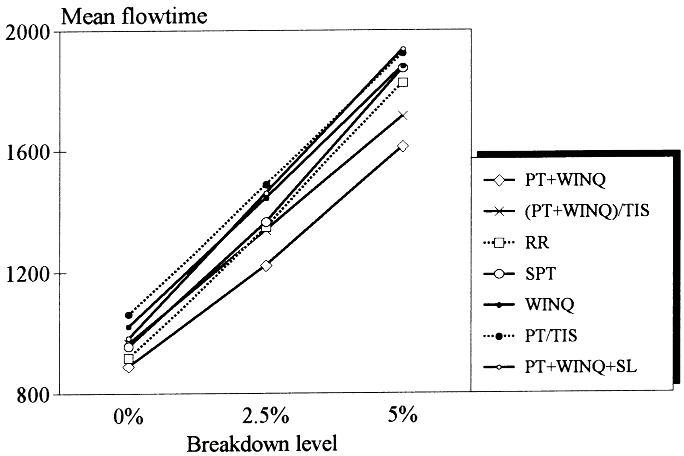

Fig. 1. $\bar{F}$ in dependence of A_g.

Table 2
RPI(F_{max}) of rules for $A_g = 0$, 0.025 and 0.05

$A_g = 0$		$A_g = 0.025$		$A_g = 0.05$	
Rule	RPI(F_{max})	Rule	RPI(F_{max})	Rule	RPI(F_{max})
AT – RPT	0.0	AT – RPT	0.0	AT – RPT	0.0
AT	8.4	AT	3.6	AT	2.3
PT/TIS	18.2[a]	PT + WINQ + SL	9.8	PT + WINQ + SL	9.8
PT + WINQ + SL	18.9[a]	PT/TIS	14.4	PT/TIS	15.9
(PT + WINQ)/TIS	46.5[b]	(PT + WINQ)/TIS	48.9	(PT + WINQ)/TIS	55.5
RR	54.3[b]	RR	89.7[a]	FIFO	108.9
FIFO	101.7	FIFO	101.5[a]	RR	168.7
PT + WINQ	303.3[c]	PT + WINQ	309.4[b]	WINQ	408.2[a]
WINQ	335.9[c]	WINQ	356.9[b]	PT + WINQ	415.0[a]
SPT	609.4	SPT	760.9	SPT	892.8

increase, where the maximum flowtime yielded by the RR rule is more affected by A_g than the F_{max}-values of the other rules.

Table 3 presents the relative percentage increase in variance of flowtime RPI(σ_F^2) for all rules in dependence of A_g. With respect to the minimization of σ_F^2 the AT – RPT rule has the best performance followed by the AT and PT/TIS rules. Whereas for $A_g = 0$ the (PT + WINQ)/TIS rule performs slightly better than the PT + WINQ + SL rule, where the difference between the mean values is not significant, for $A_g = 0.025$ and $A_g = 0.05$ the PT + WINQ + SL rule is significantly better than the (PT + WINQ)/TIS rule. Although there is no large variation in the relative performance of the investigated dispatching rules when the breakdown level is changed, these experiments show, that for minimizing σ_F^2 the relative performance of some dispatching rules can be affected if the machines are not continuously available.

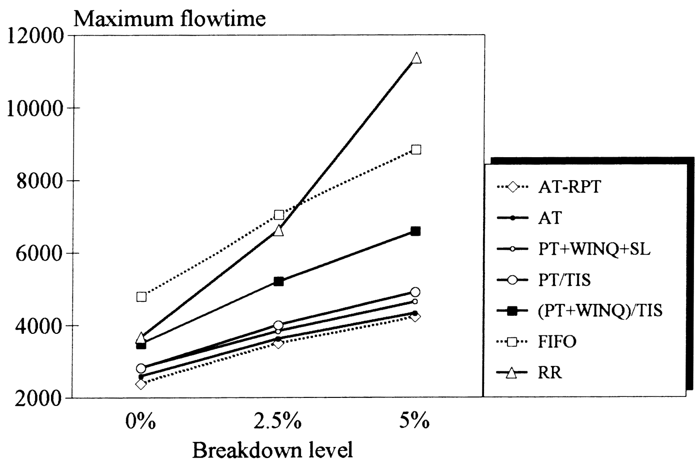

Fig. 2. F_{max} in dependence of A_g.

Table 3
RPI(σ_F^2) of rules for $A_g = 0$, 0.025 and 0.05

$A_g = 0$		$A_g = 0.025$		$A_g = 0.05$	
Rule	RPI(σ_F^2)	Rule	RPI(σ_F^2)	Rule	RPI(σ_F^2)
AT − RPT	0.0	AT − RPT	0.0	AT − RPT	0.0
AT	17.9	AT	13.1	AT	9.8
PT/TIS	26.9	PT/TIS	23.9	PT/TIS	28.0
(PT + WINQ)/TIS	70.1[a]	PT + WINQ + SL	54.9	PT + WINQ + SL	49.8
PT + WINQ + SL	78.7[a]	(PT + WINQ)/TIS	88.2	(PT + WINQ)/TIS	101.9
RR	96.9	RR	128.0	RR	238.5
FIFO	274.3	FIFO	281.7	FIFO	317.1
PT + WINQ	336.9	PT + WINQ	409.4	PT + WINQ	629.7[a]
WINQ	424.9	WINQ	566.2	WINQ	723.2[a]
SPT	938.4	SPT	1413.1	SPT	2240.2

The analysis of the $\bar{F}$-, $F_{\max}$- and σ_F^2-values yielded by the 10 dispatching rules for the three investigated breakdown levels has shown that the relative performance of a scheduling rule with respect to a flowtime-based objective can be affected by the percentage of time the machines have failures. For these experiments a mean time to repair of MTTR $= 5\bar{p}$ has been chosen. In the following the effect of the parameter MTTR on the relative performance of the dispatching rules is studied fixing the breakdown level with $A_g = 2.5\%$. For MTTR the three levels $1\bar{p}$, $5\bar{p}$ and $10\bar{p}$ are investigated representing a small, medium and large mean time to repair, respectively. Table 4 gives the relative percentage increase in mean flowtime $\bar{F}$ for all rules in dependence of the mean time to repair. For minimizing $\bar{F}$ the PT + WINQ rule has the best performance which is not affected by the mean breakdown time. Considering the rules SPT, RR and (PT + WINQ)/TIS, the ranking of these rules depends on MTTR. For MTTR $= \bar{p}$

Table 4
RPI($\bar{F}$) of rules for MTTR $= \bar{p}$, $5\bar{p}$ and $10\bar{p}$

MTTR $= \bar{p}$		MTTR $= 5\bar{p}$		MTTR $= 10\bar{p}$	
Rule	RPI($\bar{F}$)	Rule	RPI($\bar{F}$)	Rule	RPI($\bar{F}$)
PT + WINQ	0.0	PT + WINQ	0.0	PT + WINQ	0.0
RR	6.4	(PT + WINQ)/TIS	9.5[a]	(PT + WINQ)/TIS	8.3[a]
(PT + WINQ)/TIS	9.7[a]	RR	10.3[a]	SPT	10.3[a]
SPT	10.6[a]	SPT	11.7[a]	RR	16.1[d]
PT + WINQ + SL	15.6[b]	WINQ	18.1[b]	WINQ	18.9[b,d]
WINQ	16.7[b]	PT + WINQ + SL	19.5[b]	PT/TIS	20.8[b,e]
PT/TIS	21.7	PT/TIS	21.7	PT + WINQ + SL	22.4[e]
AT	49.7[c]	AT	50.2[c]	AT	48.2[c]
AT − RPT	50.8[c]	AT − RPT	51.2[c]	AT − RPT	48.9[c]
FIFO	60.7	FIFO	61.4	FIFO	60.0

the $\bar{F}$-value of the RR rule is significantly smaller than the $\bar{F}$-values of (PT + WINQ)/TIS and SPT. For MTTR = $5\bar{p}$ there are no significant differences between the three mean values, whereas for MTTR = $10\bar{p}$ the SPT and (PT + WINQ)/TIS rules perform significantly better than the RR rule. Fig. 3 shows the mean flowtimes yielded by the 10 rules in dependence of MTTR. This figure illustrates that with respect to the minimization of mean flowtime the relative performance of dispatching rules can be affected by the mean time to repair and that the $\bar{F}$-values increase with increasing MTTR. Although for MTTR = 25, 125 and 250, the breakdown level A_g is the same (only the mean interbreakdown times are different), a larger mean time to repair results in larger mean flowtimes compared to a smaller mean time to repair. This phenomenon can be explained by the bottleneck-character of a machine which is broken down. If a machine has a failure with a long time to repair, this machine becomes a large bottleneck, increasing the waiting time and thus the flowtime of each of the waiting jobs by the long breakdown time.

Table 5 presents the relative percentage increase in maximum flowtime for all scheduling rules in dependence of the mean breakdown time. With respect to the minimization of F_{max} the performance of the AT − RPT rule is significantly better than the performance of all other rules. Although a large variation in the relative performance of the dispatching rules could not be observed when the mean time to repair is changed, for the rules FIFO and RR there are some changes. For MTTR = $\bar{p}$ the RR rule performs significantly better than FIFO, whereas for MTTR = $5\bar{p}$ and $10\bar{p}$, any significant differences between the mean F_{max}-values of the FIFO and RR rules are not detected. The maximum flowtimes of the first seven dispatching rules in dependence of MTTR are shown in Fig. 4, where the rules SPT, WINQ and PT + WINQ have been excluded because of their large F_{max}-values. This figure illustrates the variation in the relative performance of the rules FIFO and RR when MTTR is changed and also the effect of the mean time to repair on the absolute F_{max}-values, which increase with increasing mean breakdown time.

The relative percentage increase in variance of flowtime for all rules in dependence of MTTR is given in Table 6. For minimizing σ_F^2 the relative performance of the 10 scheduling rules is

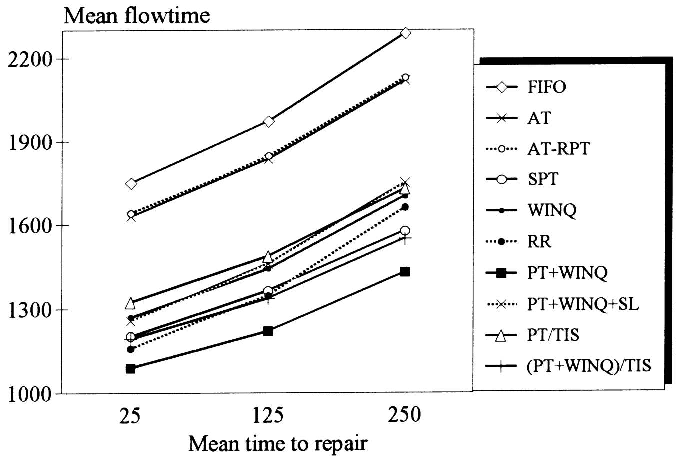

Fig. 3. $\bar{F}$ in dependence of MTTR.

Table 5
RPI(F_{max}) of rules for MTTR = $\bar{p}$, 5$\bar{p}$ and 10$\bar{p}$

MTTR = $\bar{p}$		MTTR = 5$\bar{p}$		MTTR = 10$\bar{p}$	
Rule	RPI(F_{max})	Rule	RPI(F_{max})	Rule	RPI(F_{max})
AT – RPT	0.0	AT – RPT	0.0	AT – RPT	0.0
AT	6.2	AT	3.6	AT	3.7
PT + WINQ + SL	16.6[a]	PT + WINQ + SL	9.8	PT + WINQ + SL	8.1
PT/TIS	19.3[a]	PT/TIS	14.4	PT/TIS	14.5
(PT + WINQ)/TIS	55.0[b]	(PT + WINQ)/TIS	48.9	(PT + WINQ)/TIS	59.2
RR	58.7[b]	RR	89.7[a]	FIFO	96.9[a]
FIFO	109.3	FIFO	101.5[a]	RR	111.6[a]
PT + WINQ	345.2[c]	PT + WINQ	309.4[b]	PT + WINQ	327.7[b]
WINQ	367.9[c]	WINQ	356.9[b]	WINQ	375.2[b]
SPT	749.8	SPT	760.9	SPT	654.5

not affected by the mean time to repair. The AT – RPT rule is significantly the best one, followed by the AT rule and the PT/TIS rule.

With respect to the flowtime-based objectives minimization of $\bar{F}$, minimization of F_{max} and minimization of σ_F^2 the proposed rules PT/TIS and (PT + WINQ)/TIS generate compromise solutions. Considering the (PT + WINQ)/TIS rule, the mean flowtime is not significantly higher than the mean flowtime yielded by the SPT rule and the maximum flowtime as well as the variance of flowtime are significantly smaller than those values generated by the FIFO rule. This behavior of (PT + WINQ)/TIS has been observed using not only the standard model, where all machines are continuously available, but also the model taking into account interruptions on the shop floor. Compared to the (PT + WINQ)/TIS rule the PT/TIS rule still reduces the maximum flowtime and variance of flowtime but increases the mean flowtime.

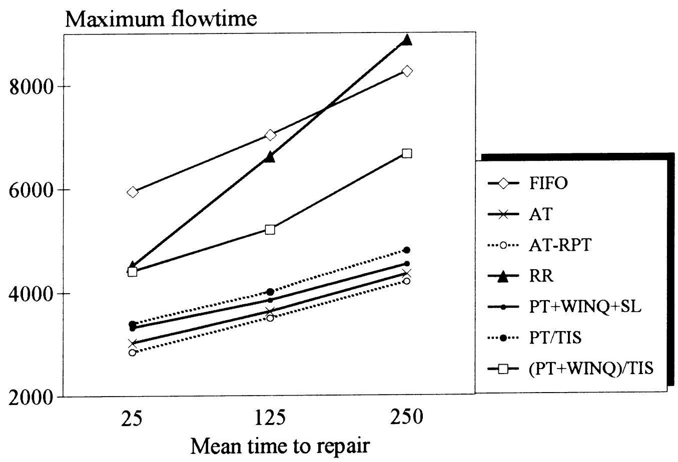

Fig. 4. F_{max} in dependence of MTTR.

Table 6
RPI(σ_F^2) of rules for MTTR = $\bar{p}$, $5\bar{p}$ and $10\bar{p}$

MTTR = $\bar{p}$		MTTR = $5\bar{p}$		MTTR = $10\bar{p}$	
Rule	RPI(σ_F^2)	Rule	RPI($\sigma_F^{)}$	Rule	RPI(σ_F^2)
AT − RPT	0.0	AT − RPT	0.0	AT − RPT	0.0
AT	14.9	AT	13.1	AT	11.2
PT/TIS	30.6	PT/TIS	23.9	PT/TIS	24.1
PT + WINQ + SL	71.1	PT + WINQ + SL	54.9	PT + WINQ + SL	47.1
(PT + WINQ)/TIS	91.5	(PT + WINQ)/TIS	88.2	(PT + WINQ)/TIS	96.1
RR	118.2	RR	128.0	RR	168.5
FIFO	312.2	FIFO	281.7	FIFO	251.4
PT + WINQ	439.3	PT + WINQ	409.4	PT + WINQ	427.2
WINQ	550.9	WINQ	566.2	WINQ	652.3
SPT	1386.8	SPT	1413.1	SPT	1235.1

Table 7
%T of rules for A_g = 0, 0.025 and 0.05

$A_g = 0$		$A_g = 0.025$		$A_g = 0.05$	
Rule	%T	Rule	%T	Rule	%T
$c = 4$					
SPT	28.5	SPT	39.9	SPT	49.4
PT + WINQ	35.7	PT + WINQ	49.4	PT + WINQ	60.5
WINQ	46.2	WINQ	60.0	WINQ	70.2
RR	54.7[a]	(PT + WINQ)/TIS	75.9	(PT + WINQ)/TIS	86.6
(PT + WINQ)/TIS	57.1[a]	RR	81.6	RR	91.9
PT + WINQ + SL	67.3	PT + WINQ + SL	87.4	PT + WINQ + SL	94.8
PT/TIS	71.5	PT/TIS	89.8	PT/TIS	96.6[a]
FIFO	83.2	FIFO	93.4	FIFO	97.1[a]
AT − RPT	84.8[b]	AT	95.8[a]	AT	98.6[b]
AT	85.3[b]	AT − RPT	95.9[a]	AT − RPT	98.7[b]
$c = 8$					
RR	1.4	RR	16.4[a]	SPT	24.4
PT + WINQ	10.3[a]	SPT	17.4[a]	PT + WINQ	29.0
SPT	10.5[a]	PT + WINQ	19.7	WINQ	39.1[a]
(PT + WINQ)/TIS	15.3[b]	WINQ	27.7	RR	40.3[a]
PT + WINQ + SL	15.6[b]	(PT + WINQ)/TIS	31.0	(PT + WINQ)/TIS	47.1
WINQ	16.2[b]	PT + WINQ + SL	36.1	PT + WINQ + SL	56.6
PT/TIS	20.9	PT/TIS	42.7	PT/TIS	63.6
FIFO	33.0[c]	AT	60.6[b]	AT − RPT	79.3[b]
AT	34.6[c]	AT − RPT	60.9[b]	AT	79.3[b]
AT − RPT	36.9	FIFO	61.6[b]	FIFO	80.3[b]

The flowtime-based analysis has shown in all that with respect to a flowtime-oriented objective the relative performance of a scheduling rule can be affected if the breakdown level A_g or the mean time to repair MTTR is varied. For minimizing mean flowtime the PT + WINQ rule is significantly superior to all other rules investigated in the experimental study. This holds not only for the standard model, where all machines are continuously available, but also for the analyzed models taking into account breakdowns of machines. For minimizing maximum flowtime and for minimizing variance of flowtime the performance of the proposed rule AT − RPT is significantly better than the performance of all other rules. For each combination of the investigated levels of the parameters A_g and MTTR the AT − RPT rule has generated the smallest $F_{\max}$- and σ_F^2-values.

4.2.2. Tardiness-based analysis

In this subsection the relative performance of the 10 dispatching rules with respect to the tardiness-based objectives minimization of the percentage of tardy jobs $\%T$, minimization of mean tardiness $\bar{T}$, minimization of maximum tardiness $T_{\max}$ and minimization of variance of tardiness σ_T^2 is analyzed investigating different values for the breakdown parameters and two levels of due date tightness. In the following three values for the breakdown level A_g (0, 2.5 and 5%) are studied fixing the mean time to repair with $\mathrm{MTTR} = 5\bar{p}$.

Table 7 presents the percentage of tardy jobs (absolute mean values over 30 simulation runs) yielded by the 10 dispatching rules in dependence of the breakdown level A_g for tight due dates ($c = 4$) as well as for loose due dates ($c = 8$). With tight due dates SPT is significantly the best rule for minimizing the percentage of tardy jobs followed by the PT + WINQ rule. If the due dates are loose and all machines are continuously available, the RR rule performs better than

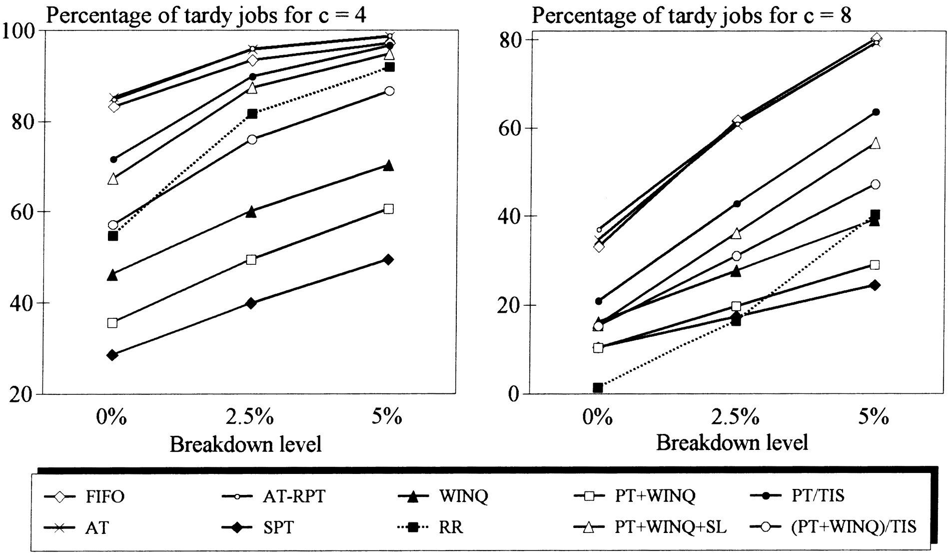

Fig. 5. $\%T$ in dependence of A_g.

all other rules. However, taking into account interruptions on the shop floor for $A_g = 2.5\%$ there is no significant difference between the mean values of SPT and RR and for $A_g = 5\%$ the performance of the rules SPT and PT + WINQ is significantly better than the performance of the RR rule. In contrast to the small variation in the relative performance for tight due dates, with loose due dates the relative performance of the rules is significantly affected by the breakdown level. For both levels of due date tightness Fig. 5 shows the $\%T$-values yielded by the 10 scheduling rules in dependence of the percentage of time the machines have failures. For loose due dates as well as for tight due dates the percentages of tardy jobs increase with increasing breakdown level.

Table 8 gives the relative percentage increase (RPI) in mean tardiness $\bar{F}$ for the 10 rules relative to the best performing rule in dependence of the breakdown level A_g. With due dates which are loose for all breakdown levels the RR rule has significantly the best performance with respect to the minimization of mean tardiness. Next in rank are the rules PT + WINQ + SL and (PT + WINQ)/TIS. With tight due dates the RR rule is effective if all machines are continuously available. For $A_g = 2.5\%$ the PT + WINQ rule is also effective, where the mean values of PT + WINQ and RR are not significantly different. However, for

Table 8
RPI($\bar{T}$) of rules for $A_g = 0$, 0.025 and 0.05

$A_g = 0$		$A_g = 0.025$		$A_g = 0.05$	
Rule	RPI($\bar{T}$)	Rule	RPI($\bar{T}$)	Rule	RPI($\bar{T}$)
$c = 4$					
RR	0.0	PT + WINQ	0.0[a]	PT + WINQ	0.0[a]
PT + WINQ + SL	40.1[a]	RR	4.8[a,b]	(PT + WINQ)/TIS	4.3[a]
PT + WINQ	41.7[a]	(PT + WINQ)/TIS	7.6[b]	RR	15.1
(PT + WINQ)/TIS	42.4[a]	PT + WINQ + SL	25.9[c]	PT/TIS	25.7[b]
PT/TIS	73.6	PT/TIS	29.8[c]	PT + WINQ + SL	27.5[b]
SPT	91.5[b]	SPT	31.3[c,d]	WINQ	27.6[b]
WINQ	97.5[b]	WINQ	35.9[d]	SPT	32.1[b]
AT	185.3	AT	91.9[e]	AT	73.1[c]
AT – RPT	197.0	AT – RPT	94.4[e]	AT – RPT	75.4[c]
FIFO	227.3	FIFO	117.8	FIFO	99.2
$c = 8$					
RR	0.0	RR	0.0	RR	0.0
PT + WINQ + SL	1666.7	PT + WINQ + SL	162.8	PT + WINQ + SL	52.7
(PT + WINQ)/TIS	3349.1	(PT + WINQ)/TIS	326.7	(PT + WINQ)/TIS	104.7
PT/TIS	3706.3	PT/TIS	369.1	PT/TIS	139.5[a]
PT + WINQ	5177.6	PT + WINQ	441.9	PT + WINQ	152.7[a]
WINQ	8332.9[a]	WINQ	713.2	WINQ	240.5
FIFO	8463.3[a]	AT	797.3[a]	AT	302.5[b]
AT	8496.6[a]	AT – RPT	846.2[a]	AT – RPT	316.2[b]
AT – RPT	9939.5[b]	SPT	846.3[a]	SPT	317.3[b]
SPT	10631.9[b]	FIFO	977.9	FIFO	404.1

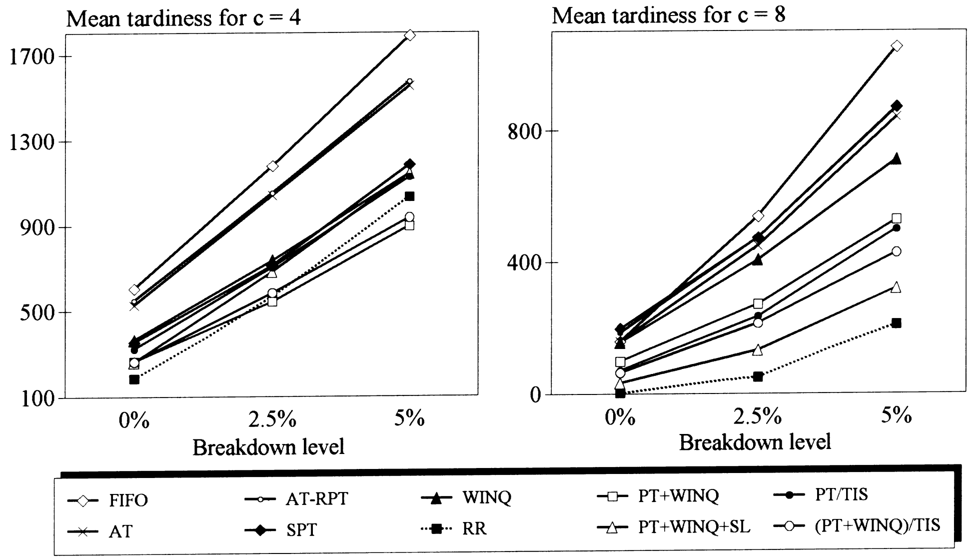

Fig. 6. $\bar{T}$ in dependence of A_g.

$A_g = 5\%$ the rules PT + WINQ and (PT + WINQ)/TIS are superior to the RR rule. The absolute $\bar{T}$-values are shown in Fig. 6. This figure illustrates for both levels of due date tightness that the relative performance of the dispatching rules is affected if the breakdown level is varied.

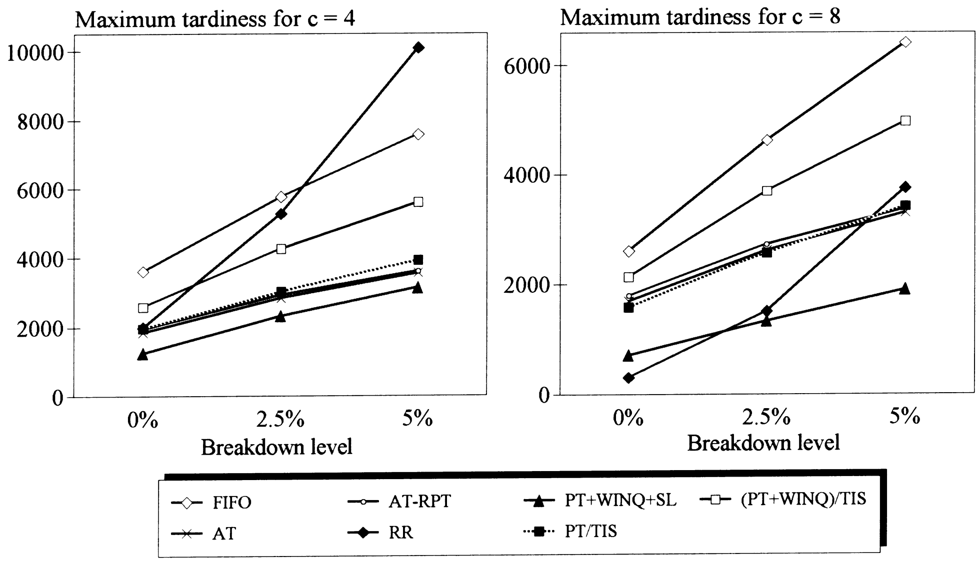

Fig. 7. $T_{\max}$ in dependence of A_g.

Table 9
RPI(T_{max}) of rules for $A_g = 0$, 0.025 and 0.05

$A_g = 0$		$A_g = 0.025$		$A_g = 0.05$	
Rule	RPI(T_{max})	Rule	RPI(T_{max})	Rule	RPI(T_{max})
$c = 4$					
PT + WINQ + SL	0.0	PT + WINQ + SL	0.0	PT + WINQ + SL	0.0
AT	48.3[a]	AT	22.6[a]	AT	13.4[a]
AT − RPT	55.7[a]	AT − RPT	26.3[a]	AT − RPT	15.0[a]
PT/TIS	57.1[a]	PT/TIS	30.1[a]	PT/TIS	25.1
RR	58.9[a]	(PT + WINQ)/TIS	83.7	(PT + WINQ)/TIS	78.9
(PT + WINQ)/TIS	106.5	RR	127.3[b]	FIFO	141.7
FIFO	188.8	FIFO	148.5[b]	RR	222.3
PT + WINQ	575.4[b]	PT + WINQ	464.0[c]	WINQ	551.7[b]
WINQ	642.2[b]	WINQ	540.6[c]	PT + WINQ	554.1[b]
SPT	1161.3	SPT	1146.6	SPT	1205.8
$c = 8$					
RR	0.0	PT + WINQ + SL	0.0[a]	PT + WINQ + SL	0.0
PT + WINQ + SL	136.0	RR	13.1[a]	AT	73.7[a]
PT/TIS	421.7	PT/TIS	92.6[b]	AT − RPT	77.5[a]
AT	457.1	AT	96.2[b]	PT/TIS	79.6[a]
AT − RPT	489.2	AT − RPT	104.7[b]	RR	97.2[a]
(PT + WINQ)/TIS	601.1	(PT + WINQ)/TIS	177.4	(PT + WINQ)/TIS	161.5
FIFO	756.4	FIFO	247.3	FIFO	236.9
PT + WINQ	2359.4[a]	PT + WINQ	800.8[c]	PT + WINQ	910.0[b]
WINQ	2615.2[a]	WINQ	936.9[c]	WINQ	920.5[b]
SPT	4744.9	SPT	1988.0	SPT	1992.4

The relative percentage increase in maximum tardiness for the rules in dependence of the breakdown level A_g is given in Table 9. With due dates which are tight the performance of the PT + WINQ + SL rule is significantly better with respect to the minimization of T_{max} than the performance of all other rules. This holds not only for $A_g = 0\%$ but also for $A_g = 2.5\%$ and $A_g = 5\%$. With loose due dates and for $A_g = 0\%$ the RR rule is superior to all other rules. For $A_g = 2.5\%$ the rules PT + WINQ + SL and RR generate the smallest T_{max}-values, where there is no significant difference between the corresponding mean values. However, for $A_g = 5\%$ the PT + WINQ + SL rule is significantly the best rule with respect to the minimization of maximum tardiness. Fig. 7 presents the absolute T_{max}-values of the first seven dispatching rules, excluding PT + WINQ, WINQ and SPT because of their large mean values. For both levels of due date tightness Fig. 7 illustrates the variation in the relative performance of the rules changing the percentage of time the machines have failures.

Table 10 presents the relative percentage increase in variance of tardiness in dependence of A_g. With tight due dates the PT + WINQ + SL rule is superior to all other rules for minimizing σ_T^2. Whereas for $A_g = 0\%$ RR is the rule next in rank, for $A_g = 2.5\%$ and $A_g = 5\%$ the rules PT/TIS, AT and AT − RPT are significantly better than the RR rule. With due dates which are loose for $A_g = 0\%$ and $A_g = 2.5\%$ the RR rule has the best performance. For $A_g = 5\%$ the

Table 10
RPI(σ_T^2) of rules for $A_g = 0$, 0.025 and 0.05

$A_g = 0$		$A_g = 0.025$		$A_g = 0.05$	
Rule	RPI(σ_T^2)	Rule	RPI(σ_T^2)	Rule	RPI(σ_T^2)
$c = 4$					
PT + WINQ + SL	0.0	PT + WINQ + SL	0.0	PT + WINQ + SL	0.0
RR	30.7	PT/TIS	25.6	AT	12.3[a]
PT/TIS	76.6	AT	40.9[a]	AT – RPT	12.5[a]
AT	132.8[a]	AT – RPT	43.1[a]	PT/TIS	14.7[a]
(PT + WINQ)/TIS	141.8[a]	RR	83.1[b]	(PT + WINQ)/TIS	83.0
AT – RPT	151.6[a]	(PT + WINQ)/TIS	95.1[b]	RR	202.6[b]
FIFO	467.6	FIFO	306.7	FIFO	283.9[b]
PT + WINQ	739.8	PT + WINQ	527.1	PT + WINQ	673.9[c]
WINQ	1052.4	WINQ	804.9	WINQ	808.1[c]
SPT	2574.6	SPT	2207.4	SPT	2752.2
$c = 8$					
RR	0.0	RR	0.0	PT + WINQ + SL	0.0[a]
PT + WINQ + SL	1269.1	PT + WINQ + SL	50.1	RR	71.9[a,b]
PT/TIS	5720.8	PT/TIS	391.2	PT/TIS	143.8[b]
(PT + WINQ)/TIS	7790.7	AT	686.2[a]	AT	224.7[c]
AT	12313.4	(PT + WINQ)/TIS	691.9[a]	AT – RPT	244.8[c]
AT – RPT	14965.9[a]	AT – RPT	749.7[a]	(PT + WINQ)/TIS	283.1[c]
FIFO	16249.6[a]	FIFO	1462.3	FIFO	697.0
PT + WINQ	42634.0	PT + WINQ	3293.9	PT + WINQ	2037.1[d]
WINQ	68293.9	WINQ	5351.9	WINQ	2488.6[d]
SPT	187489.9	SPT	15606.9	SPT	8956.9

PT + WINQ + SL rule performs slightly better than RR, although the difference between the mean σ_T^2-values of both rules is not significant.

The analysis of the $\%T$-, $\bar{T}$-, $T_{\max}$- and σ_T^2-values generated by the 10 scheduling rules for the three breakdown levels has shown that the relative performance of the dispatching rules with respect to a due date-based objective can be affected by the percentage of time the machines have failures. This holds for due dates which are tight as well as for those which are loose. In the following, the effect of the mean time to repair on the relative performance of the rules is analyzed fixing the breakdown level with $A_g = 2.5\%$. Analogously to the flowtime-based analysis for the parameter MTTR three levels ($\bar{p}$, $5\bar{p}$, $10\bar{p}$) are studied.

Table 11 presents the percentage of tardy jobs for each rule in dependence of the mean time to repair for both levels of due date tightness. With due dates which are tight for minimizing $\%T$ the relative performance of the 10 rules is not affected by MTTR. The SPT rule has the best performance followed by PT + WINQ and WINQ. However, if the due dates are loose the parameter MTTR significantly affects the relative performance of the rules. With a small mean time to repair the RR rule performs better than all other rules. Whereas for a medium mean time to repair the rules RR and SPT are effective, where the mean values of both rules are not significantly different, for the large mean breakdown time MTTR $= 10\bar{p}$ the rule SPT has

Table 11
$\%T$ of rules for $\mathrm{MTTR}=\bar{p}$, $5\bar{p}$ and $10\bar{p}$

$\mathrm{MTTR}=\bar{p}$		$\mathrm{MTTR}=5\bar{p}$		$\mathrm{MTTR}=10\bar{p}$	
Rule	$\%T$	Rule	$\%T$	Rule	$\%T$
$c=4$					
SPT	35.1	SPT	39.9	SPT	44.2
PT + WINQ	45.3	PT + WINQ	49.4	PT + WINQ	53.5
WINQ	56.7	WINQ	60.0	WINQ	62.8
(PT + WINQ)/TIS	71.6	(PT + WINQ)/TIS	75.9	(PT + WINQ)/TIS	79.1
RR	74.8	RR	81.6	RR	85.8
PT + WINQ + SL	82.3	PT + WINQ + SL	87.4	PT + WINQ + SL	89.5
PT/TIS	85.7	PT/TIS	89.8	PT/TIS	92.3
FIFO	91.4	FIFO	93.4	FIFO	94.1
AT − RPT	93.3[a]	AT	95.8[a]	AT	96.5[a]
AT	93.9[a]	AT − RPT	95.9[a]	AT − RPT	96.6[a]
$c=8$					
RR	7.3	RR	16.4[a]	SPT	21.3
SPT	14.7[a]	SPT	17.4[a]	PT + WINQ	25.0
PT + WINQ	15.6[a]	PT + WINQ	19.7	WINQ	32.8[a]
WINQ	23.5[b]	WINQ	27.7	RR	34.2[a]
(PT + WINQ)/TIS	24.9[b]	(PT + WINQ)/TIS	31.0	(PT + WINQ)/TIS	39.1
PT + WINQ + SL	27.0	PT + WINQ + SL	36.1	PT + WINQ + SL	50.1
PT/TIS	34.5	PT/TIS	42.7	PT/TIS	53.5
AT	51.3[c]	AT	60.6[b]	FIFO	70.1[b]
AT − RPT	52.3[c]	AT − RPT	60.9[b]	AT − RPT	70.6[b]
FIFO	52.5[c]	FIFO	61.6[b]	AT	70.7[b]

significantly the best performance, followed by the PT + WINQ rule. Fig. 8 shows the $\%T$-values of the 10 dispatching rules for both levels of due date tightness. This figure illustrates not only the variation in the relative performance of the rules for loose due dates changing the mean time to repair, but also the increment of the $\%T$-values with increasing MTTR.

For each dispatching rule the relative percentage increase in mean tardiness in dependence of MTTR is given in Table 12. With loose due dates the RR rule is superior to all other rules for minimizing $\bar{T}$. Next in rank are the rules PT + WINQ + SL and (PT + WINQ)/TIS. Although there is no large variation in the relative performance of the rules, for SPT and AT there are some changes. For $\mathrm{MTTR}=\bar{p}$ the AT rule performs significantly better than SPT. Whereas for $\mathrm{MTTR}=5\bar{p}$ there is no significant difference between the $\bar{T}$-values of SPT and AT, for $\mathrm{MTTR}=10\bar{p}$ AT performs significantly worse than SPT. With due dates which are tight the relative performance of the rules is sensitive to MTTR. For $\mathrm{MTTR}=\bar{p}$ the RR rule is most efficient. For $\mathrm{MTTR}=5\bar{p}$ the rules PT + WINQ and RR are efficient, where the difference between the mean values of both rules is not significant. However, for the large mean time to repair $\mathrm{MTTR}=10\bar{p}$ the PT + WINQ rule is significantly the best rule, followed by (PT + WINQ)/TIS. Fig. 9 presents the absolute $\bar{T}$-values of the 10 rules in dependence of MTTR illustrating the variation in the relative performance of the rules changing the mean

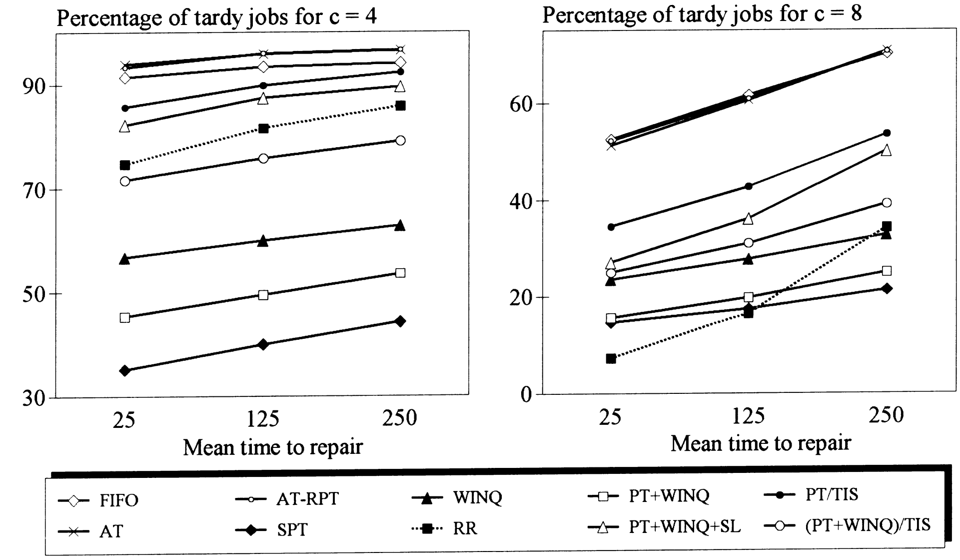

Fig. 8. $\%T$ in dependence of $MTTR$.

time to repair. Fig. 9 also shows that a larger mean time to repair results in larger $\bar{T}$-values compared to a smaller mean time to repair, although the percentage of time the machines have failures is the same. The flowtime-based analysis has shown, that the mean flowtimes increase with increasing MTTR. Since the due date factor is fixed, the $\bar{T}$- and $\%T$-values are also increased.

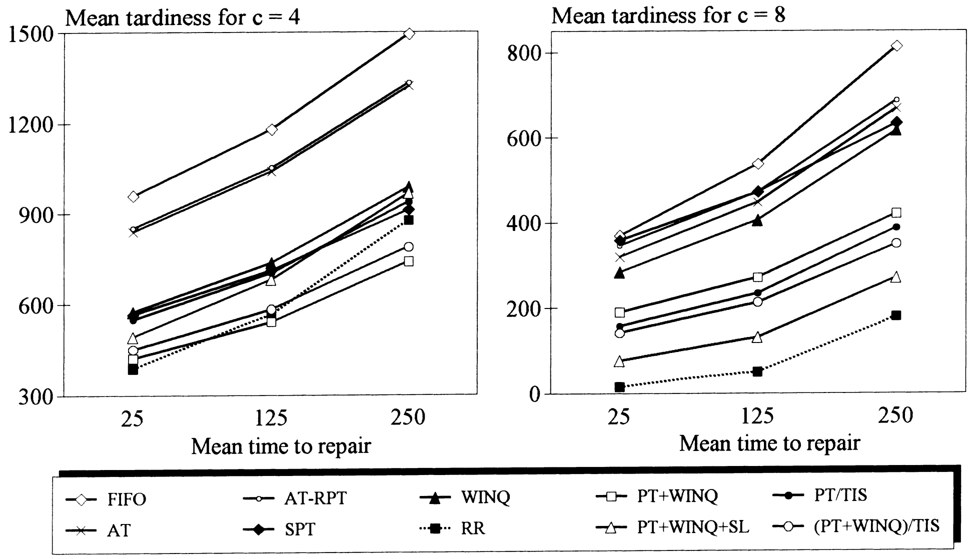

Fig. 9. $\bar{T}$ in dependence of $MTTR$.

Table 12
RPI($\bar{T}$) of rules for MTTR = $\bar{p}$, 5$\bar{p}$ and 10$\bar{p}$

MTTR = $\bar{p}$		MTTR = 5$\bar{p}$		MTTR = 10$\bar{p}$	
Rule	RPI($\bar{T}$)	Rule	RPI($\bar{T}$)	Rule	RPI($\bar{T}$)
$c = 4$					
RR	0.0	PT + WINQ	0.0[a]	PT + WINQ	0.0
PT + WINQ	8.5	RR	4.8[a,b]	(PT + WINQ)/TIS	6.5
(PT + WINQ)/TIS	16.2	(PT + WINQ)/TIS	7.6[b]	RR	18.5[a]
PT + WINQ + SL	26.9	PT + WINQ + SL	25.9[c]	SPT	23.2[a,b]
PT/TIS	41.7[a]	PT/TIS	29.8[c]	PT/TIS	26.9[b]
SPT	46.0[a]	SPT	31.3[c,d]	PT + WINQ + SL	30.8[c,b]
WINQ	48.2[a]	WINQ	35.9[d]	WINQ	33.6[c]
AT	116.4[b]	AT	91.9[e]	AT	78.7[d]
AT − RPT	119.9[b]	AT − RPT	94.4[e]	AT − RPT	80.2[d]
FIFO	147.6	FIFO	117.8	FIFO	102.0
$c = 8$					
RR	0.0	RR	0.0	RR	0.0
PT + WINQ + SL	376.1	PT + WINQ + SL	162.8	PT + WINQ + SL	50.1
(PT + WINQ)/TIS	781.5	(PT + WINQ)/TIS	326.7	(PT + WINQ)/TIS	94.4
PT/TIS	880.7	PT/TIS	369.1	PT/TIS	114.9
PT + WINQ	1079.4	PT + WINQ	441.9	PT + WINQ	134.0
WINQ	1662.9	WINQ	713.2	WINQ	242.7[a]
AT	1882.9	AT	797.3[a]	SPT	252.4[a]
AT − RPT	2052.2[a]	AT − RPT	846.2[a]	AT	270.9[b]
SPT	2129.3[a]	SPT	846.3[a]	AT − RPT	281.8[b]
FIFO	2198.8[a]	FIFO	977.9	FIFO	352.4

Table 13 presents the relative percentage increase in maximum tardiness for the 10 rules. With tight due dates the PT + WINQ + SL rule has significantly the best performance for minimizing $T_{\max}$. Next in rank are the rules AT, AT − RPT and PT/TIS, respectively. Although there is no large variation in the relative performance of the rules when MTTR is varied, for RR and FIFO there are some changes. For MTTR = $\bar{p}$ RR performs significantly better than FIFO, while for MTTR = 5$\bar{p}$ and MTTR = 10$\bar{p}$ there is no significant difference between the $T_{\max}$-values of the two rules. With loose due dates the relative performance of the rules is more sensitive to MTTR compared to tight due dates. For MTTR = $\bar{p}$ and MTTR = 5$\bar{p}$ RR and PT + WINQ + SL are the most efficient rules for minimizing maximum tardiness, where there is no significant difference between the corresponding $T_{\max}$-values. For MTTR = 10$\bar{p}$ the performance of the PT + WINQ + SL rule is significantly better than the performance of the RR rule. The absolute $T_{\max}$-values of the first seven rules are shown in Fig. 10, excluding the rules PT + WINQ, WINQ and SPT because of their large maximum tardiness. The variation in the relative performance of the rules changing the mean time to repair is illustrated and also the increment of maximum tardiness when the parameter MTTR is increased.

Table 13
RPI(T_{max}) of rules for MTTR = $\bar{p}$, 5$\bar{p}$ and 10$\bar{p}$

MTTR = $\bar{p}$		MTTR = 5$\bar{p}$		MTTR = 10$\bar{p}$	
Rule	RPI(T_{max})	Rule	RPI(T_{max})	Rule	RPI(T_{max})
$c = 4$					
PT + WINQ + SL	0.0	PT + WINQ + SL	0.0	PT + WINQ + SL	0.0
AT	32.8[a]	AT	22.6[a]	AT	11.7[a]
AT – RPT	38.2[a]	AT – RPT	26.3[a]	AT – RPT	11.9[a]
PT/TIS	43.8[a]	PT/TIS	30.1[a]	PT/TIS	21.8
RR	66.3	(PT + WINQ)/TIS	83.7	(PT + WINQ)/TIS	81.8
(PT + WINQ)/TIS	100.3	RR	127.3[b]	FIFO	123.4[b]
FIFO	167.6	FIFO	148.5[b]	RR	143.7[b]
PT + WINQ	559.5[b]	PT + WINQ	464.0[c]	PT + WINQ	436.4[c]
WINQ	608.3[b]	WINQ	540.6[c]	WINQ	508.3[c]
SPT	1222.0	SPT	1146.6	SPT	880.9
$c = 8$					
RR	0.0[a]	PT + WINQ + SL	0.0[a]	PT + WINQ + SL	0.0
PT + WINQ + SL	10.3[a]	RR	13.1[a]	RR	48.5[a]
PT/TIS	159.7[b]	PT/TIS	92.6[b]	AT	58.3[a]
AT	165.8[b]	AT	96.2[b]	AT – RPT	63.1[a]
AT – RPT	178.7	AT – RPT	104.7[b]	PT/TIS	64.3[a]
(PT + WINQ)/TIS	260.3	(PT + WINQ)/TIS	177.4	(PT + WINQ)/TIS	149.1
FIFO	333.6	FIFO	247.3	FIFO	186.4
PT + WINQ	1172.4[c]	PT + WINQ	800.8[c]	PT + WINQ	676.1[b]
WINQ	1304.6[c]	WINQ	936.9[c]	WINQ	802.9[b]
SPT	2598.8	SPT	1988.0	SPT	1372.3

Table 14 gives the relative percentage increase in variance of tardiness for all rules in dependence of MTTR. With tight due dates the PT + WINQ + SL performs significantly better than all other rules. Considering RR and AT, the relative performance for minimizing σ_T^2 is affected by the mean time to repair. Whereas for MTTR = $\bar{p}$ the AT rule performs significantly worse than the RR rule, for MTTR = 5$\bar{p}$ and MTTR = 10$\bar{p}$ the performance of AT is significantly better than the performance of RR. With due dates which are loose for MTTR = $\bar{p}$ and MTTR = 5$\bar{p}$ RR is the most efficient rule. For the large mean time to repair MTTR = 10$\bar{p}$ the PT + WINQ + SL rule is slightly better than the RR rule, although the difference between the mean σ_T^2-values is not significant.

Summing up the results of the tardiness-based analysis, with respect to a due date-oriented objective the relative performance of the scheduling rules is affected when the breakdown level A_g or the mean time to repair MTTR is varied. This holds for due dates which are tight as well as for those which are loose. With tight due dates, the SPT rule is still the most effective rule for minimizing the percentage of tardy jobs. However, if the due dates are loose and all machines are continuously available or the breakdown level and the mean time to repair are small, the RR rule is superior to the SPT rule. With loose due dates the RR rule has the best performance for minimizing mean tardiness. With tight due dates the RR rule is only effective if the levels of the breakdown parameters are small. If the percentage of time the machines

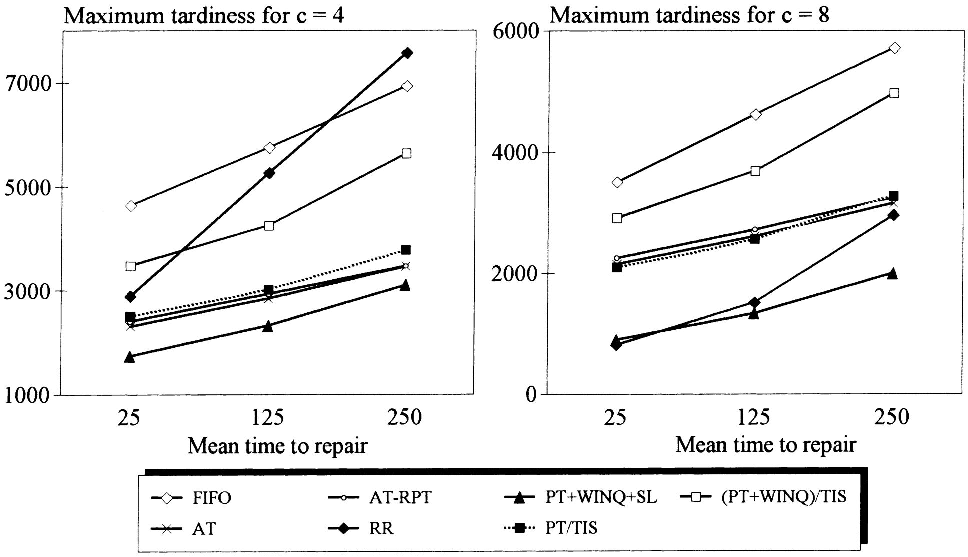

Fig. 10. T_{max} in dependence of MTTR.

have failures is high and/or the mean time to repair is large, the processing time-based rule PT + WINQ becomes superior to the RR rule. With respect to the minimization of maximum tardiness and variance of tardiness the PT + WINQ + SL rule performs better than all other rules if the due dates are tight. With loose due dates and small or medium levels of the breakdown parameters the RR rule has the best performance.

5. Summary

In this paper the relative performance of dispatching rules with respect to flowtime and due date-based objectives has been analyzed studying the effect of different levels of the breakdown parameters. The results of the experimental evaluation reveal that the relative performance of scheduling rules is sensitive to the breakdown level as well as to the mean time to repair.

For minimizing mean flowtime the dispatching rule PT + WINQ has the best performance. The effectiveness of this rule has been proved not only for the standard model without interruptions on the shop floor but also for the investigated models taking into account breakdowns of machines. With respect to the minimization of maximum flowtime and variance of flowtime the AT − RPT rule proposed in this paper is most efficient. This holds for the case where all machines are continuously available as well as for the studied settings of the breakdown parameters. In contrast to the superiority of the rules PT + WINQ for minimizing mean flowtime and AT − RPT for minimizing maximum flowtime and variance of flowtime, with respect to the due date-based objectives, the relative performance of the scheduling rules is more affected by the breakdown level and the mean time to repair. With respect to the minimization of the percentage of tardy jobs, the SPT rule is most efficient if the due dates are

Table 14
RPI(σ_T^2) of rules for MTTR = $\bar{p}$, $5\bar{p}$ and $10\bar{p}$

MTTR = $\bar{p}$		MTTR = $5\bar{p}$		MTTR = $10\bar{p}$	
Rule	RPI(σ_T^2)	Rule	RPI(σ_T^2)	Rule	RPI(σ_T^2)
$c=4$					
PT + WINQ + SL	0.0	PT + WINQ + SL	0.0	PT + WINQ + SL	0.0
PT/TIS	43.1[a]	PT/TIS	25.6	PT/TIS	16.1[a]
RR	50.3[a]	AT	40.9[a]	AT – RPT	16.3[a]
AT	65.4[b]	AT – RPT	43.1[a]	AT	17.5[a]
AT – RPT	72.7[b]	RR	83.1[b]	(PT + WINQ)/TIS	87.9[b]
(PT + WINQ)/TIS	114.1	(PT + WINQ)/TIS	95.1[b]	RR	136.5[b]
FIFO	372.9	FIFO	306.7	FIFO	241.7
PT + WINQ	653.7	PT + WINQ	527.1	PT + WINQ	483.5
WINQ	891.9	WINQ	804.9	WINQ	819.4
SPT	2491.8	SPT	2207.4	SPT	1619.0
$c=8$					
RR	0.0	RR	0.0	PT + WINQ + SL	0.0[a]
PT + WINQ + SL	172.9	PT + WINQ + SL	50.1	RR	45.3[a]
PT/TIS	1067.1	PT/TIS	391.2	PT/TIS	136.4
(PT + WINQ)/TIS	1648.5	AT	686.2[a]	AT	218.9
AT	1948.6	(PT + WINQ)/TIS	691.9[a]	AT – RPT	233.5[b]
AT – RPT	2220.8	AT – RPT	749.7[a]	(PT + WINQ)/TIS	301.2[b]
FIFO	3471.6	FIFO	1462.3	FIFO	603.1
PT + WINQ	8756.9	PT + WINQ	3293.9	PT + WINQ	1498.6
WINQ	12644.2	WINQ	5351.9	WINQ	2687.7
SPT	38248.3	SPT	15606.9	SPT	5406.1

tight. With loose due dates the RR rule is mostly superior to the SPT rule. For minimizing mean tardiness the RR rule has the best performance if the due dates are loose. With due dates which are tight the PT + WINQ rule is mostly more effective than the RR rule. For minimizing maximum tardiness and variance of tardiness the PT + WINQ + SL rule has the best performance with tight due dates. If the due dates are loose the RR rule often outperforms the other rules.

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