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A Simulation-Based Study of Dispatching Rules in a Dynamic Job Shop Scheduling Problem with Batch Release and Extended Technical Precedence Constraints

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Highlights

- A DJSP model with batch release and extended technical precedence constraints aiming at the mould & die manufacturing industry is proposed.
- The disjunctive graph model of the JSP with extended technical precedence constraints is presented.
- Four new dispatching rules are developed with the aim to perform well under tardiness-related performance measures.
- The effectiveness of the new proposed rule is validated, and the influences of the model parameters on dispatching rules are investigated.

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A Simulation-Based Study of Dispatching Rules in a Dynamic Job Shop Scheduling Problem with Batch Release and Extended Technical Precedence Constraints

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Abstract: This paper considers a simulation-based analysis of dispatching rules for scheduling in a dynamic job shop with batch release taking into account the extended technical precedence constraint which is a new term defined as the extension of conventional routing-based technical precedence constraint in our paper. With respect to tardiness-related measures, the relative performances of some widely-used dispatching rules as well as four new ones proposed in our paper are evaluated for different settings of the model parameters. The results of the simulation study demonstrate the effectiveness of the four new proposed dispatching rules, and also reveal that the relative performance of dispatching rules can be affected by some model parameters. For the standard job shop scheduling problem model, where there are no extended technical precedence constraints between jobs, as well as for the models taking into account the extended technical precedence constraint, it is shown that for minimizing the total tardiness and the percentage of tardy jobs, the four new proposed dispatching rules are very effective under relatively loose due date. With respect to tardiness-related objectives, the relative performance of the analyzed dispatching rules can be affected by changing not only the levels of the extended technical precedence constraint, but also the due date tightness.

Key words: dynamic job shop scheduling problem; dispatching rules; simulation scheduling; extended technical precedence constraint; due date tightness

1. Introduction

The job-shop scheduling problem (JSP) has been extensively studied over the last several decades and it attracts the attention of researchers and practitioners equally. The classical JSP is usually defined as: there are *n* jobs, each consisting of a specific set of operations which have to be processed by *m* machines or work stations within a given time period according to a given technical precedence order, a schedule need to be made to minimize a measure (or multiple measures) of performance. Obviously, the classical JSP is a static scheduling problem, in which all information for the *n* jobs is pre-known, and with the description of “a given technical precedence order”, it usually means conventional routing-based precedence constraints, i.e., all operations belonging to the same job must be processed in a specified order and no gap need to be considered between one operation’s finishing and its immediate successor’s starting (Cheng, Gen, and Tsujimura, 1996; Shakhlevich, Sotskov, and Werner, 2000).

However, these conditions may not always hold in many scheduling problems in realistic manufacturing systems. For example, in mould & die manufacturing industry, the manufacture systems of which are typically make-to-order, this means that almost all of their processing tasks (usually moulds or dies comprising of some jobs) come from orders. The manufacturers get orders randomly over time, resulting in jobs releasing to the shop batch by batch intermittently. It can be regarded as the dynamic job-shop scheduling problem (DJSP), in which the jobs released to the shop intermittently and are included in the current scheduling procedure. In the process of mould and/or die manufacturing, there are usually some kinds of technical precedence, apart from conventional routing-based precedence, occur.

For example, in electrical discharge machining, a commonly encountered situation when processing mould & die parts is that the electrode must be completed before a part, e.g., a female die to be processed with the electrode. Another case is the assembly operation, the only one operation belonging to the mould & die (not any of a part) which can be considered as a special job, can start its processing only after all of its composing parts have been completed. Obviously, these precedence constraints arise between two or more different jobs. Actually, the unconventional technical precedence may also occur between two operations of the same job when they have not only a sequence relationship but also a time gap between their processing. A familiar case appears in the casting process. When a casting operation finishes, the next machining operation can be carried out only after an aging treatment finished even if the needed machine is available at that time.

Based on the context of mould & die manufacturing systems and the understandings mentioned above, we put forward the definition of extended technical precedence constraints relative to the conventional routing-based precedence constraints, with specific concepts and illustrations given in section 3. Moreover, we also propose a DJSP with batch release and extended technical precedence constraints (DJSP_B&E), where jobs are released to the shop in batches, and technical precedence order between different jobs and non-zero gap conventional routing-based precedence constraints which are defined as extended technical precedence constraints in our paper, are taken into account. As it has been proven that the classical JSP with the objective of makespan minimization is one of the hardest NP-complete combinatorial optimization problems (Garey, Johnson and Sethi, 1976; Lenstra, Rinnooy Kan and Brucker, 1977; Brucker, Sotskov and Werner, 2007), the model studied here, which may be classified as a general shop scheduling problem, i.e. an extension of JSP with more realistic situations taken into account, is an NP-complete problem as well. And Garey, Johnson and Sethi (1976) suggested that for larger and more complicated scheduling problems, the best approach may well be to seek heuristics which will guarantee near-optimal results. Therefore, the dispatching rule, which is a widely used heuristics in complicated scheduling environment, because of their ease of implementation and low time complexity, was adopted to solve the problem concerned in our study.

2. Literature review

The JSP can be classified into static model and dynamic model according to the nature of the job arrivals at the shop and the properties of disturbances occurring during the whole scheduling process. For dynamic model where jobs arrive at the shop intermittently and in succession over time, which is defined as DJSP by Ramasesh (1990) and Qiu and Lau (2013), many researches are focusing on those problems in which jobs are released one by one.

Ramasesh (1990) presented a survey on simulation research of DJSP, he indicated that most preceding studies usually assume that the arrival of jobs to the shop follows a Poisson distribution, an Erlang distribution, a uniform distribution, a geometric distribution, a binomial distribution, or an empirical distribution. The Poisson distribution is the most commonly used one for modeling the job arrival process, and the corresponding models can largely be seen in studies by e.g., Holthaus and Rajendran (1997a), Vinod and Sridharan (2008, 2011), Adibi, Zandieh and Amiri (2009), and Scholz-Reiter, Hildebrandt and Tan (2013), among others. Apparently, whether in Poisson distribution, Erlang distribution, or others, the arrival of jobs to the shop is in the manner of one by one separately, and there is no correlation among them. However, in practical manufacturing system, such as in mould & die manufacturing industry as we mentioned above, jobs are usually released to shop in the manner of batch by batch. Researches on the scheduling problem with batch consideration usually focusing on the mode the machine processing the jobs, and they can be categorized into two types, i.e., parallel batch scheduling problem and serial batch scheduling problem, which can be referred in Cheng, Lin and Toker (2000), Yuan, Yang, and Cheng (2004), Mosheiov and Oron (2005), Mosheiov and Oron (2008), Zhang and Gu (2009), and Cheng, Lin and Toker (2000), Yuan, Yang, and Cheng (2004), Mosheiov and Oron (2005), Mosheiov and Oron (2008), Zhang and Gu (2009) respectively. However, little research work on jobs releasing to shop batch by batch, which conforms to the model considered in our paper concerning with the mould & die manufacturing industry, has been done.

In addition, there are some more precedence constraints existed in mould & die manufacturing environment, making it different from the constraints in conventional DJSP model. As for the studies regarding the precedence constraints of the DJSP in literatures, several assumptions were relaxed with practical conditions considered. For instance, most studies on job-shop scheduling assume that jobs are independent and that no assembly operations exist, then some researchers take into account the dependent jobs with assembly operations or assembly environment, which is often referred as assembly job shop scheduling problem (AJSP). In AJSP, the shop involves both processing and assembly operations, this means that the shop contains precedence relations not only between operations but also between jobs. For the job shop with assembly operations, Sculli (1980) studied the priority dispatching rules for a job shop with assembly operations, and the results indicated that job status information was in favor of improving the performance of rules. Thiagarajan and Rajendran (2005) addressed the AJSP with the consideration of jobs having different earliness, tardiness and holding costs, and their relative costs were incorporated in the form of scalar weights to present dispatching rules. The results of the simulation study demonstrate the effectiveness of the proposed rules in minimizing the mean and maximum values of the measures of performance. Pathumnakul and Egbelu (2006) investigated the problem of minimizing the weighted earliness penalty in assembly job shops where a job (corresponding to an actual product) in the shop was assumed to have a tree product structure consisting of components (corresponding to jobs in our paper) and subassemblies. An effective heuristic was developed to solve the problem by decomposing the problem into several single machine problems, and solutions to the single machine problem were used to construct the solution to the original problem. Chan, Wong and Chan (2008) presented AJSP which started with classical JSP and appended an assembly stage to the completed jobs. Lot streaming technique was adopted in their study to combine with AJSP, and an efficient algorithm was proposed using genetic algorithms and dispatching rules to resolve the problem. Then an evolutionary algorithm with genetic algorithm was developed to solve AJSP (Chan, Wong and Chan 2009). A similar problem, resource-constrained AJSP with lot streaming technique, was then proposed in Wong, Chan, and Chan (2009), and was resolved by proposing an innovative approach with genetic algorithm. These researchers investigated the AJSP with the consideration of some practical scheduling situations or objectives which made the model more applicable to practical production, and some of them also presented several heuristics or dispatching rules incorporating the scheduling attribute information, which were found to be effective for the objective under that circumstance.

The scenario of assembly operation in mould & die manufacturing systems, where precedence constraints existed between two or more different jobs, is similar to the assembly environment in AJSP. However, the unconventional technical precedence constraints occurring between two operations of the same job when they have not only a sequence relationship but also a time gap between their processing, which is an important distinction in mould & die manufacturing systems, were not taken into account in AJSP. Literatures regarding the time gap between operation processing can be seen in studies with the consideration of separable sequence-dependent setup times in DJSP.

For example, Rossi (2014) investigated the FJSP with sequence-dependent setup and transportation times, because most studies often assume that the operation setup and job transportation times are negligible or part of the processing time; the system considered that an operation was subjected to two kinds of lag times, i.e., sequence-dependent and sequence-independent setup times, corresponding to the previous operation processed on the resource and in the job routing respectively. The study concluded that the experimental results and statistical tests show that the proposed system was able to work to the best, and the system faced quite well the job shop scheduling with sequence-dependent and sequence-independent setup times. Other research that investigated the separable sequence-dependent setup times in shop scheduling problems can be referred in Allahverdi, Gupta, and Aldowaisan (2008), Hurink and Knust (2005), Ivens and Lambrecht (1996), Rossi and Dini (2001), Gedik, et al., (2016), Ciavotta, Minella and Ruiz (2013). These studies dealing with the separable setup and transportation time in different ways, and developed various promising methods to solve it, resulting in reduced transportation time, more effective system and improved performance.

The experimental researches concerning the additional precedence constraints mentioned above dealing with mainly these two kinds, i.e., precedence relations existing between jobs and between operations, and sequence-dependent setup and transportation times. However, there appears to be little research work has been done on the DJSP in which the extended technical precedence, that can be regarded as the definition including both these two kinds of constrains as we defined above, was depicted or formulated. Besides, the simplified assumptions and analysis will affect the solution quality for practical application in mould & die manufacturing industry in which explicit treatment of such precedence is required. And the system model with these precedence constraints into account would make it more practical for real scheduling environment in mould & die manufacturing industry. These findings and applications motivated us to do the current work.

As the general job shop scheduling problem is computationally intensive to solve, most researchers focus their efforts on developing efficient heuristics that generate near-optimal solution at a reasonable computation time. The heuristic algorithm based on dispatching rules, adopted also in our study, is popularly used solutions in solving complicated, dynamic and large-sized scheduling problems in practical production as they are readily implemented, being computationally efficient, and robust to variability and uncertainty in a job shop (Qiu and Lau, 2013). According to Gere (1966), the definition of dispatching rule refers to the combination of one or more of the priority rules, as well as the combination of one or more of the heuristic rules. Dispatching rule is a special case of priority rules (Haupt, 1989), which is used to select jobs for machines. It assigns priority value to the jobs waiting in queue when the machine gets available, which is based on the attribute information about jobs, machines or the shop, then select the job with the highest priority value for the machine to process. Panwalkar and Iskander (1977) summarized 113 rules and made a systematic generalization and summarization. Haupt (1989) listed 26 basic dispatching rules and their priority value expression, with detailed illustrations of their definitions.

Many dispatching rules have been proposed using different methods or taking into account some practical situations over the past several decades (Holthaus, 1997, 1999; Holthaus and Rajendran, 1997b; Ferrell et al., 2000; Chan, et al., 2003; Jayamohan and Rajendran, 2004; Parthanadee and Buddhakulsomsiri, 2010; Pickardt, et al., 2012; Chen and Matis, 2013; Branke and Pickardt, 2011), and most of them had achieved relatively good results in experimental scenarios. In our experimental investigation, some existing rules widely used in literatures are selected as benchmark rules, and several rules aiming at the scheduling problem addressed in our study are proposed.

The organization of the remaining sections of this paper is as follows: In section 3, the model of DJSP_B&E is characterized in detail. Section 4 gives the scheduling procedure and a representative selection of dispatching rules including not only some widely used existing scheduling rules but also four new proposed ones. Section 5 presents a simulation study describing the design of the experiment and some important aspects of the results of the experimental investigation. The performance of dispatching rules and the influences of model parameters on dispatching rules are evaluated and analyzed in section 6. Finally, some concluding remarks and directions for future work are given out in section 7.

3. Problem formulation

In this section, the definition and some illustrations about the extended technical precedence constraint is presented first, followed by the description of the DJSP with extended technical precedence constraint.

3.1 The extended technical precedence constraints

For the technical precedence in shop scheduling problems, it is a customary practice for researchers to define that $O_{i,j+1}$ cannot be started until O_{ij} is completed, where $j = 1,2,\cdots,n_i - 1$; and there are no precedence constraints existing among operations of different jobs. The definition means that the technical precedence only exists in the interior of a job and no time gap needs to be taken into account. However, this does not hold well in many practical conditions. Some typical exceptions occur in the mould & die manufacturing system as we mentioned above. Here in this paper, we present some generalized definitions and statements for the extended technical precedence constraints. In general, they can be categorized into the following four types:

$t_{i'j'}^{ij}$=SS: means that $O_{i'j'}$ can be started only after O_{ij} has been started for a certain period of $g_{i'j'}^{ij}$;

$t_{i'j'}^{ij}$=SC: means that $O_{i'j'}$ can be started only after O_{ij} had been completed for a certain period of $g_{i'j'}^{ij}$;

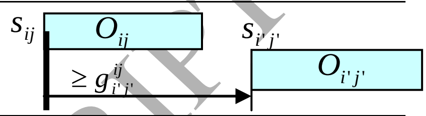
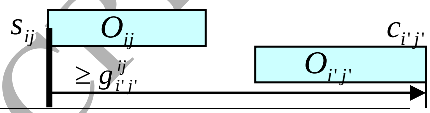
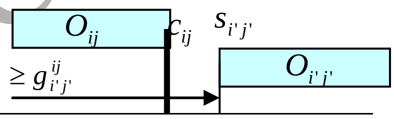
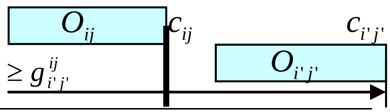
$t_{i'j'}^{ij}$=CS: means that $O_{i'j'}$ can be completed only after O_{ij} has been started for a certain period of $g_{i'j'}^{ij}$;

$t_{i'j'}^{ij}$=CC: means that $O_{i'j'}$ can be completed only after O_{ij} had been completed a certain period of $g_{i'j'}^{ij}$.

The $t_{i'j'}^{ij}$ represents the type of extended technical precedence between O_{ij} and $O_{i'j'}$, and $g_{i'j'}^{ij}$ is the time gap between processing O_{ij} and $O_{i'j'}$ with respect to their extended technical precedence. The four types can also be expressed in inequations and illustrations as shown in Table 1.

In the inequations, s_{ij} is the start time of O_{ij}. Obviously, the conventional technical precedence is a special case of $R_{i'j'}^{ij}(\mathrm{CS}, g_{i'j'}^{ij})$ when $i' = i$, $j' = j+1$ and $g_{i'j'}^{ij} = 0$. The four types of extended technical precedence can be transformed from one to another. As $R_{i'j'}^{ij}(\mathrm{CS}, g_{i'j'}^{ij})$ may be the most commonly used type, here we give the transformations from the others to this type.

Table 1 Expressions of extended technical precedence

$R_{i'j'}^{ij}$	inequations	illustrations
(SS, $g_{i'j'}^{ij}$)	$s_{i'j'} \geq s_{ij} + g_{i'j'}^{ij}$	
(SC, $g_{i'j'}^{ij}$)	$c_{i'j'} \geq s_{ij} + g_{i'j'}^{ij}$	
(CS, $g_{i'j'}^{ij}$)	$s_{i'j'} \geq c_{ij} + g_{i'j'}^{ij}$	
(CC, $g_{i'j'}^{ij}$)	$c_{i'j'} \geq c_{ij} + g_{i'j'}^{ij}$	

For $R_{i'j'}^{ij}(\mathrm{SS}, g_{i'j'}^{ij})$, we have

$$s_{i'j'} \geq s_{ij} + g_{i'j'}^{ij} \quad \Rightarrow \quad s_{i'j'} \geq s_{ij} + p_{ij} - p_{ij} + g_{i'j'}^{ij} = c_{ij} + (g_{i'j'}^{ij} - p_{ij})$$

this means that $R_{i'j'}^{ij}(\mathrm{SS}, g_{i'j'}^{ij})$ is equivalent to $R_{i'j'}^{ij}(\mathrm{CS}, (g_{i'j'}^{ij} - p_{ij}))$. Here we express them as follows:

$$R_{i'j'}^{ij}(\mathrm{SS}, g_{i'j'}^{ij}) \Leftrightarrow R_{i'j'}^{ij}(\mathrm{CS}, (g_{i'j'}^{ij} - p_{ij})) \tag{1}$$

In the same way, we may also have

$$R_{i'j'}^{ij}(\mathrm{SC}, g_{i'j'}^{ij}) \Leftrightarrow R_{i'j'}^{ij}(\mathrm{CS}, (g_{i'j'}^{ij} - p_{ij} - p_{i'j'})) \tag{2}$$

$$R_{i'j'}^{ij}(\mathrm{CC}, g_{i'j'}^{ij}) \Leftrightarrow R_{i'j'}^{ij}(\mathrm{CS}, (g_{i'j'}^{ij} - p_{i'j'})) \tag{3}$$

3.2 The job shop scheduling problem with the extended technical precedence

The problem can be described as follows. There is a set of jobs J continuously arriving at the shop over time and a set of machines M in the shop. Associated with each job J_i are a release time r_i and a due date d_i. Each job J_i has n_i operations to be processed satisfying the extended technical precedence constraints. Each operation O_{ij} is assigned a specified machine M_k for processing and associated with a processing time

p_{ij}. Each machine M_k has an initial available time a_k for processing its first operation O_k^1. No preemption is allowed in all the processing procedure. No overlap processing time is permitted on the same machine.

As the disjunctive graph representation is becoming a standard model for describing instances of the job shop scheduling problem, and it offers a scheme for problem models (such as sequence-dependent setup times by Brucker and Thiele, 1996 and flexible job shop scheduling problem by Dauzère-Pérès and Paulli, 1997) similar to the model proposed in our paper, we also present the representation and notes of the disjunctive graph model of the problem below.

A disjunctive graph is usually described to be a directed graph $G=(V, C \bigcup D)$. *V* denotes a set of nodes corresponding to operations of all jobs under consideration and two additional nodes, a source (denoted by 0) and a sink (denoted by *) which represent the start and the end of a schedule respectively. The source and the sink nodes can be regarded as two dummy operations for which the processing time is zero. *C* is a set of conjunctive arcs which represent conventional technical precedence constraints. *D* is a set of undirected disjunctive edges connecting mutually unordered operations which require the same machine for their processing. Each conjunctive arc is labeled with the positive weight equal to the processing time of the operation where the arc begins.

To illustrate the extended technical precedence constraints in the disjunctive graph model, we define the disjunctive graph as $G=(V, C \bigcup D \bigcup R)$, where *V*, *C* and *D* are the same as described above, and *R*, a set of additional conjunctive arcs represented by directed dashed arcs, expresses the extended technical precedence constraints. Each directed dashed arc is assigned a nonnegative number (placed into a rectangle to distinguish it from processing times) equal to the time gap $g_{i'j'}^{ij}$. Fig. 1 presents an example of the disjunctive graph integrating the extended technical precedence constraints. There are 3 machines and 3 jobs in the case. Two extended technical precedence constraints, i.e., $R_{32}^{11}(\mathrm{CS},2)$ and $R_{31}^{21}(\mathrm{CS},3)$, exist among the 3 jobs.

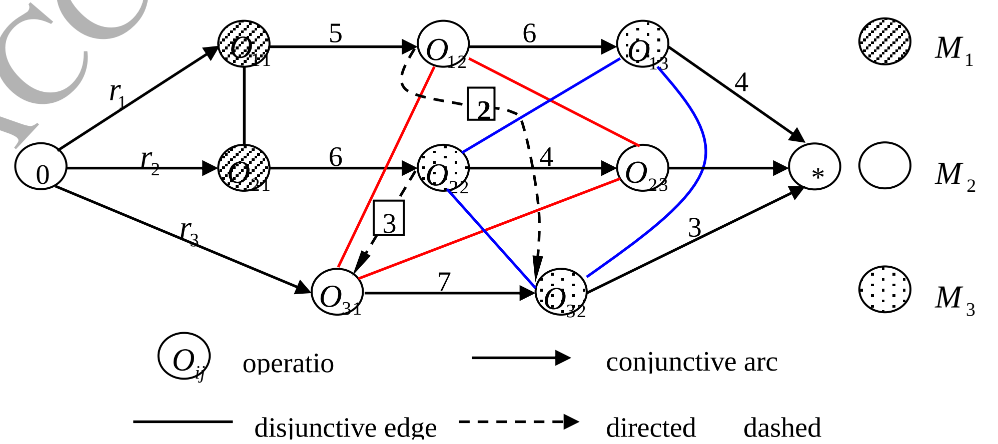


Fig.1. The disjunctive graph integrating the extended technical precedence constraints

It should be noted that circuits are not allowed among the conjunctive arcs and directed dashed arcs, otherwise, order conflicts will occur. For instance, if we add a precedence $R_{21}^{31} = (\mathrm{SS},2)$ to the above example, a circuit will appear as shown in Fig.2. Apparently, a feasible schedule, according to Fig.2, must satisfy $s_{31} \geq c_{21} + 3$ (corresponding to $R_{31}^{21}(\mathrm{CS},3)$) and $s_{21} \geq s_{31} + 3$ (corresponding to $R_{21}^{31} = (\mathrm{SS},2)$). Then we have: $s_{21} \geq s_{31} + 2 \geq c_{21} + 3 + 2 = s_{21} + 6 + 3 + 3 = s_{21} + 12$, this is obviously a paradox. So we stressed that there should be no circuits existed among the conjunctive arcs and directed dashed arcs.

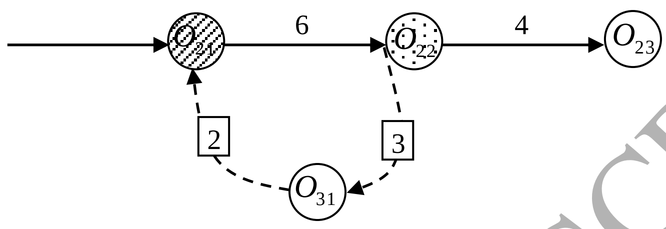


Fig.2. An example of circuit causing order conflict

The disjunctive graph model described above is an alternative representation of the job shop scheduling problem with extended technical precedence constraints. As Blazewice, Domschke and Pesch (1996) state that the diagraph model is becoming the standard model for scheduling applications because it is more efficient than Gantt diagrams to describe knowledge for optimization search techniques, it may be used for solving the general shop scheduling problem.

4. Proposed solution approach

In this section, some definitions will be presented first, and then the scheduling procedure is described. Finally, some existing dispatching rules and four new developed ones used for the following simulation study are addressed.

Definition 1. Fore-relative operation and hind-relative operation. For an extended technical precedence constraint $R_{i'j'}^{ij}(t_{i'j'}^{ij}, g_{i'j'}^{ij})$, we define O_{ij} as the fore-relative operation and $O_{i'j'}$ the hind-relative operation.

Definition 2. Schedulable operation and unschedulable operation. Let t_q be the current time at which the dispatching decision is to be made. An operation O_{ij} is schedulable at t_q if it is not a hind-relative operation or all its fore-relative operation(s) has/have been scheduled before t_q.

If O_{ij} is schedulable at t_q, we denote it as $\vec{O}_{ij}^{t_q}$. Otherwise, it is a unschedulable operation, which is denoted by $\tilde{O}_{ij}^{t_q}$.

Definition 3. Schedulable operation set and unschedulable operation set. The schedulable operation set, denoted by A_{t_q}, and the unscheduled operation set, denoted by U_{t_q}, are the sets comprising all schedulable operations and all the unschedulable operations at t_q, i.e., $A_{t_q} = \{\vec{O}_{ij}^{t_q}\}$ and $U_{t_q} = \{\tilde{O}_{ij}^{t_q}\}$ respectively.

4.1 The scheduling procedure

The scheduling is carried out according to the following steps.

***Step 1*:** Transform all extended technical precedence constraints into the type of CS according to Eqs. (1) ~ (3);

***Step2*:** Compute initial r_{ij} and d_{ij} of O_{ij} (for $j = 1,2,\cdots,n_i$ of all jobs including in the current scheduling horizon). For convenience, we introduce two dummy operations O_{i0} and $O_{i(n_i+1)}$, corresponding to the source node and the sink node in the disjunctive graph respectively. Obviously, we have $p_{i0} = p_{i(n_i+1)} = 0$, $r_{i0} = r_i$, and $d_{i(n_i+1)} = d_i$, then

$$r_{ij} = \max\{ r_{i(j-1)} + p_{i(j-1)}, \max_{\rho_{ij}^{mn}=1}(r_{mn} + p_{mn} + g_{ij}^{mn})\} \tag{4}$$

$$d_{ij} = d_{i(j+1)} - p_{i(j+1)} \tag{5}$$

***Step 3*:** Compute the priority index Z_{ij} for all operations included in A_{t_q};

***Step 4*:** Schedule operation $O_{i*j*} \in A_{t_q}$, where O_{i*j*} is the operation which has the highest priority with respect to the given dispatching rules, hence we get s_{i*j*} and c_{i*j*};

***Step 5*:** Update A_{t_q} and U_{t_q} to generate $A_{t_{q+1}}$ and $U_{t_{q+1}}$ as follows:

$$A_{t_{q+1}} = A_{t_q} - O_{i*j*} + \left\{O_{ij} \mid \tilde{O}_{ij}^{t_q} \wedge \vec{O}_{ij}^{t_q}\right\}; \tag{6}$$

$$U_{t_{q+1}} = U_{t_q} - \left\{O_{ij} \mid \tilde{O}_{ij}^{t_q} \wedge \vec{O}_{ij}^{t_q}\right\}. \tag{7}$$

Step 6: Update r_{ij} for all operations that are affected by O_{i*j*}. We denote those operations as $O_{\overline{i*j*}}$. Then we have:

$$r_{\overline{i*j*}} := r_{\overline{i*j*}} + (s_{i*j*} - r_{i*j*}) \tag{8}$$

Step 7: If $A_{t_{q+1}} = \Phi$ and $U_{t_{q+1}} = \Phi$, go to *Step 8*; otherwise, let $t_q := t_{q+1}$, $A_{t_q} := A_{t_{q+1}}$, and $U_{t_q} := U_{t_{q+1}}$, repeat from *step 3* to *step 6* ;

Step 8: Finish the scheduling procedure.

4.2 Selection of existing dispatching rules and development of new dispatching rules

Some existing widely used rules in literatures are selected as benchmarks for comparative study in our investigation. A famous simple dispatching rule, SPT (shortest processing time), is reported to be an effective rule in minimizing the mean flow time, mean tardiness and the number of tardy jobs, hence we will take it as a benchmark rule in our study. SL/OPN (slack per remaining operation) is often used as a benchmark for evaluating the rules with respect to the tardiness-related performance measures. The well-known EDD (earliest due date) appears to be either an optimal rule or an accurate heuristic in many scheduling problems involving due dates (Mosheiov and Oron, 2004). MDD (modified due date) is demonstrated to function effectively in both tight and loose conditions and show considerable promise for application in complex production systems (Baker and Bertrand, 1982; Naidu, 2003), and this rule is also proved to be the best when an operational due date is considered (Parthanadee and Buddhakulsomsiri, 2010). ODD (earliest operation due date) performs well in scheduling with operation due-dates (Kanet and Hayya, 1982). WINQ (total work-content of jobs in the queen of the next operation of a job) is reported to be a widely used rule for evaluating tardiness-related measures (Rajendran and Holthaus, 1999). By comprehensively considering processing time, slack, and waiting time for the next operation, RR shows dynamic and global characteristics, and demonstrates to have superior performance in flow time and tardiness related measures (Raghu and Rajendran, 1993). A comparative study by Rajendran and Holthaus (1999) also concluded that RR and a combinatorial dispatching rule PT+WINQ+SL, perform well with respect to the tardiness-related performance measures. Based on these studies and conclusions, the above mentioned eight rules were considered in our simulation study as benchmark rules.

In addition, a investigation conducted by Jayamohan and Rajendran (2004) found that the PT+PW+ODD rule performs best with the objective of weighted mean tardiness, followed by the PT+PW. And when the objective is the percentage of tardy jobs, the PT+PW rule was reported to be the best for this objective under the conditions of high utilization level and relatively tight due-date setting. Furthermore, in the paper the concept FDD (flow due-date) was put forward with the attempts to yield minimum value for flow time-related measure, here in our investigation the additive function was used to combine the PT+PW with FDD, i.e. the PT+PW+FDD rule, to test its performance in our scheduling environment. Moreover, the rule LBE+LBT+LBF, proposed by Thiagarajan and Rajendran (2005) for the problem of scheduling in dynamic assembly job-shops, which computed the lower bounds on the earliness cost, the tardiness cost and the holding cost, was demonstrated to be effective in dynamic assembly job shops, especially in job-shop-like flat manufacturing systems in minimizing the mean and maximum values of performance measures. Here we use the LBF+LBT, as the earliness was not taken into account in our investigation, to compete with other popular rules.

Apart from the twelve selected rules, we also propose four new ones, which are all based on the slack of operation (SOP), aiming at the DJSP_B&E model with the objective of tardiness-related performance measures. Kutanoglu and Sabuncuoglu (1999) concluded that the priority rules which make use of operational information such as operation due-dates and operation processing times perform consistently better than their job-based counterparts, so we put forward the concept of the slack of an operation based on the slack of a job. The definition of the SOP is given first as follows.

Definition 4. *Slack of operation*. Just like the definition of the slack of a job, the slack of an operation can be defined as the due date of the operation minus its earliest finish time with respect to the current decision time. So the slack of O_{ij}, denoted by sl_{ij}, is given by

$$sl_{ij} = d_{ij} - (t_q + p_{ij}). \tag{9}$$

Based on the definition of the slack of operation, it is obvious that the operation with the smallest priority value is the most urgent one. As a result, it should have the highest priority so that could be processed first with the aim of reducing tardiness.

Proposed rule 1 **(SOP rule)**: It is reasonable that the smaller the slack of an operation is, the more urgent the operation is, so the operation with the least slack should be given priority to load for processing. Hence, the priority index of this rule is given by

$$Z_{ij} = sl_{ij} = d_{ij} - (t_q + p_{ij}). \tag{10}$$

Proposed rule 2 **(MSOP rule)**: This rule is based on the nonnegative slack of operation, and its priority index is given as follows:

$$Z_{ij} = \max\{0, d_{ij} - (t_q + p_{ij})\} \tag{11}$$

In view of the outstanding performance of the RR rule regarding the tardiness-related measures, we attempt to combine it with the new proposed rules above to get better performance. As for the combination form, because the dynamic ratio-type could result in misbehavior when the value becomes negative according to Adam and Surkis (1980), so the additive function is often adopted. Here we also use this combination form to develop two combinational rules which are presented as follows, with the intent to behave well under tardiness-related performance measures.

Proposed rule 3 **(RR+SOP rule)**: The priority index of this rule is defined as follows:

$$Z_{ij} = (sl_i \times \exp(-\eta) \times p_{ij}) / \sum_{h=j}^{n_i} p_{ih} + \exp(\eta) \times p_{ij} + w_{i(j+1)}^{t_q} + d_{ij} - (t_q + p_{ij}). \tag{12}$$

Proposed rule 4 **(RR+MSOP rule)**: The priority index of this rule is calculated by:

$$Z_{ij} = (sl_i \times \exp(-\eta) \times p_{ij}) / \sum_{h=j}^{n_i} p_{ih} + \exp(\eta) \times p_{ij} + w_{i(j+1)}^{t_q} + \max\{0, d_{ij} - (t_q + p_{ij})\}. \quad (13)$$

For the above four rules, the job with the minimum priority value is chosen for processing. In addition, the RR rule is combined with PT+PW, PT+PW+ODD, PT+PW+FDD and LBF+LBT respectively, with the intent to have a possibly improved performance.

5. Experimental design and results of the simulation study

Blackstone, Philips and Hogg (1982) mentions that the study of job shops by analytic techniques, such as queuing theory, becomes extremely complex even for small problems. Therefore, the use of simulation for analyzing dispatching rules is inevitable. Due to the same difficulties in studying the dispatching rules for solving DJSP_B&E, we also rely on simulation to study the rules' effectiveness. In order to evaluate the performance of the above mentioned dispatching rules for DJSP_B&E, an experiment of simulation scheduling with some cases is conducted in our study.

5.1 Design of the experiment

In the experiment, some typical standard assumptions, e.g., no reentry, no preemption, no alternative routing of jobs, and no breakdowns of machines, are made, with the exceptions of no assembly of jobs, no release times, and no due dates. Ten machines are considered in the shop to which jobs intermittently released in batches over time. The batch size (the number of jobs in a batch), denoted by s_b, is obtained from a discrete uniform distribution DU[10,50]. Each job in a batch has a series of operations need to be processed in a specified routing. The routing of each job is generated randomly, with every machine having an equal probability of being chosen. The number of operations for each job is drawn from a discrete uniform distribution DU[3,6]. The processing times of operations are generated from a uniform distribution U[5,15]. Extended technical precedence constraints are considered in our experimental cases. The jobs (or the job couples) with extended technical precedence constraints and their operations are selected randomly with no conflict (i.e., no circuit in the corresponding disjunctive graph) occurring. For the convertibility of the types of extended technical precedence constraint, we only consider the type of $R_{i'j'}^{ij}(\mathrm{CS}, g_{i'j'}^{ij})$ in which the time gap $g_{i'j'}^{ij}$ is got from a uniform distribution U[5,10]. As the number of jobs with extended technical precedence constraints may be a parameter influencing the performances of rules, we introduce E_c to denote the percentage of jobs with extended technical precedence constraints on the total number of jobs under scheduling consideration. Three levels of E_c, 0%, 3%, and 5%, are investigated in our experiment.

The release time of jobs is commonly determined in accordance with the shop utilization level U_g (Holthaus, 1999; Rajendran and Holthaus, 1999). For jobs released in batches in DJSP_B&E, U_g is computed as follows:

$$U_g = \frac{s_b \cdot \bar{n} \cdot \bar{p}}{m \cdot \bar{t}_v} \times 100\%,$$

where $\bar{n}$ denotes the mean number of operations of a job and $\bar{p}$ the mean processing time of an operation (here $\bar{n}$ =4.5 and $\bar{p}$ =10 time units), $\bar{t}_v$ is the mean inter-arrival time between job-batches. Giving an utilization level of U_g, the inter-arrival times can be derived by the exponential distribution $\mathrm{E}(1/\bar{t}_v)$. Without loss of generality, we assume that the release time of the first batch is zero, and then the release times for other batches can be obtained according to the inter-arrival times.

The total work content (TWK) method (Blackstone, Philips and Hogg, 1982) is used to set the due date of jobs in our study. Four levels of allowance factor c were set in the experimental investigation according to the percentage of tardy jobs, which might be a reasonable index measuring the tightness of due date.

The experiment is conducted under three levels of E_c and four values of c with the shop utilization level of 90%, thus there are a total number of 12 parameter sets. For each parameter set, we conduct simulation scheduling to observe the values of total tardiness and percentage of tardy jobs, denoted by of T_Σ and $\%T$, respectively. Each simulation scheduling starts with the shop in an empty and idle condition and the jobs continuously arrive at the shop in batches. In order to overcome the initial bias in sampling, the shop steady states are tested in our study by simulation scheduling. It has been found that the shop reaches steady state after the release of about 20 batches of jobs for all parameter sets, so the data are collected from the 21st batch. The run length of simulation scheduling is set as 80 batches of jobs, i.e., about 2400 (80×30) jobs (Holthaus, 1999; Rajendran and Holthaus, 1999). In order to avoid truncation error, the shop is continuously loaded with jobs in batches, until the 80th batch jobs have completed their processing. Ten independent runs are conducted under each parameter set and the mean value of T_Σ and $\%T$, denoted by $\overline{T_\Sigma}$ and $\overline{\%T}$ respectively, are collected to evaluate the performances of the 20 rules. As for the statistical analysis of the experimental data, one-way ANOVA with block design and Duncan's Multiple Range Test are conducted to test the homogeneity of the rules.

5.2 Results of the simulation scheduling experiment

The simulation scheduling system was implemented using JBuilder, running on a 2.70 GHz PC with 4 GB

RAM. The experimental results, i.e., $\overline{T_\Sigma}$ and $\overline{\%T}$ of all the 20 rules under different experimental parameter sets, are presented from Table 2 to Table 4. In the tables, the superscript letters (e.g., a, b and c) express the levels and the homogeneity of $\overline{T_\Sigma}$ and $\overline{\%T}$. For instance, "a" means that the corresponding rule(s) has/have the best performance, "b" means the next best rule(s), and so on (only the top 3 levels are marked in the tables). All the rules corresponding to the same letter belong to a homogeneous subset by Duncan's Multiple Range Test.

Table 2 $\overline{T_\Sigma}$ and $\overline{\%T}$ of rules for $E_c = 0\%$

Rule	C =10		C =14		C =18		C =22	
	$\overline{T_\Sigma}$	$\overline{\%T}$	$\overline{T_\Sigma}$	$\overline{\%T}$	$\overline{T_\Sigma}$	$\overline{\%T}$	$\overline{T_\Sigma}$	$\overline{\%T}$
SPT	714105	19.01	646114	15.33	589690	13.05	541034	11.24
SL/OPN	199680	43.78	36676^{a}	15.88	911^{a}	1.74^{a}	0^{a}	0.00^{a}
EDD	186717	46.50	59042	22.48	10540	6.96	5839	0.53^{c}
MDD	204984	22.41	79251	8.95^{a}	20597	2.69^{b}	6122	0.52^{c}
ODD	186413	46.92	56672	22.41	8950	6.74	5291	0.46^{b}
WINQ	350818	31.72	250789	22.80	179774	16.44	128997	12.04
RR	198424	31.42	103114	19.43	45921	10.27	18617	4.12
PT+WINQ+SL	378736	21.66	310463	14.75	261369	11.00	223948	8.44
PT+PW	1307032	17.03	1244878	14.83	1189412	13.34	1138518	12.48
PT+PW+ODD	765386	12.50^{a}	673311	10.14^{b}	619603	8.85	563888	8.04
PT+PW+FDD	1514810	32.32	1405503	26.64	1312019	23.15	1229622	20.46
LBF+LBT	173044^{c}	47.53	47500^{b}	23.11	5763^{b}	7.55	220^{c}	0.80
SOP	188583	47.30	57845	22.47	7629^{c}	6.48	2^{b}	0.01^{a}
MSOP	259707	45.57	74890	20.94	9091	5.29	2^{b}	0.01^{a}
RR+SOP	163480^{b}	25.22	65827	10.08^{ab}	17058	2.89^{c}	2317	0.45^{b}
RR+MSOP	153210^{a}	39.96	48772	17.36	8423	4.75	548	0.54
RR+ PT+PW	975066	13.54^{bc}	927235	11.67^{c}	885544	10.49	856548	9.84
RR+ PT+PW+ODD	419076	13.96^{c}	401092	10.65^{c}	384174	8.73	358606	7.54
RR+ PT+PW+FDD	284423	35.44	182773	26.54	108312	18.58	62169	12.37
RR-(LBF+LBT)	154481^{a}	40.02	48004^{c}	17.19	9068	4.98	471	0.44^{b}

Table 3 $\overline{T_\Sigma}$ and $\overline{\%T}$ of rules for $E_c = 3\%$

Rule	C =10		C =14		C =18		C =22	
	$\overline{T_\Sigma}$	$\overline{\%T}$	$\overline{T_\Sigma}$	$\overline{\%T}$	$\overline{T_\Sigma}$	$\overline{\%T}$	$\overline{T_\Sigma}$	$\overline{\%T}$
SPT	602715	17.95^{c}	538818	14.42	486640	12.06	442264	10.42
SL/OPN	243172^{c}	27.46	153270^{a}	7.55^{b}	138417^{a}	1.72^{a}	131397^{a}	1.68^{a}
EDD	252009	33.64	170957	13.26	142590^{b}	3.10	138776	1.99
MDD	270201	16.82^{b}	187786	6.70^{a}	151693	2.26^{b}	146431	1.99
ODD	249279	33.86	169661^{c}	12.88	142370^{b}	3.09^{c}	138345	1.95

WINQ	376472	27.60	293462	18.28	237815	12.70	199137	8.95
RR	264757	25.85	190780	13.29	155067	6.21	138282	3.37
PT+WINQ+SL	384245	19.77	322888	13.16	280155	9.56	248258	7.35
PT+PW	1041723	16.36[b]	983366	13.89	931937	12.37	885200	11.44
PT+PW+ODD	719925	12.89[a]	656398	10.58	587861	9.29	537001	8.29
PT+PW+FDD	1124292	28.82	1028635	23.16	949140	19.72	879789	17.23
LBF+LBT	236767[b]	33.52	160022[b]	12.44	141443[b]	3.57	133745[b]	1.76
SOP	252311	34.03	171940	13.01	144557	3.14	137257	1.70[b]
MSOP	292209	32.77	180292	12.06	145548	2.92[c]	137441	1.70[b]
RR+SOP	243308[c]	19.62	174865	7.17[b]	145787	2.69[c]	136108[c]	1.76
RR+MSOP	233787[a]	28.45	166358[c]	10.11	143562[c]	3.07[c]	136091[c]	1.76
RR+ PT+PW	823746	13.14[a]	778695	11.20	734931	10.03	703988	9.08
RR+ PT+PW+ODD	448614	14.01[a]	430295	10.93	399281	9.05	384091	8.01
RR+ PT+PW+FDD	337431	30.79	253524	21.24	196020	13.88	159094	8.65
RR-(LBF+LBT)	231427[a]	28.21	165112[c]	9.71[c]	143632[c]	3.10	135894[c]	1.72[c]

Table 4 $\overline{T_\Sigma}$ and $\overline{\%T}$ of rules for $E_c = 5\%$

Rule	C =10		C =14		C =18		C =22	
	$\overline{T_\Sigma}$	$\overline{\%T}$	$\overline{T_\Sigma}$	$\overline{\%T}$	$\overline{T_\Sigma}$	$\overline{\%T}$	$\overline{T_\Sigma}$	$\overline{\%T}$
SPT	956522	20.72	882248	16.95	819831	14.62	765982	12.88
SL/OPN	429100[c]	42.11	288695[a]	11.40[a]	259481[a]	3.85[a]	246006[a]	2.88[a]
EDD	443940	44.93	315793	22.73	26813[b]	5.95	255894	3.30[c]
MDD	510027	22.63	374827	11.65[a]	305552	4.55[b]	286200	3.24[c]
ODD	441684	45.60	310494[b]	21.25	267577[b]	5.77	255441	3.23[c]
WINQ	604729	30.62	508909	21.96	438994	16.52	385753	13.05
RR	467769	30.66	366035	19.89	307524	12.47	267256	7.50
PT+WINQ+SL	654800	21.50	585306	15.57	533136	12.05	491046	10.07
PT+PW	1477203	18.27[c]	1411253	15.94	1352641	14.38	1298490	13.40
PT+PW+ODD	1077200	15.26[ab]	984723	12.95[b]	909797	11.47	843079	10.65
PT+PW+FDD	1839409	33.94	1723974	28.38	1624197	24.78	1534900	22.34
LBF+LBT	421729[b]	46.69	301260[ab]	21.57	263902[a]	6.79	249961[b]	3.90
SOP	444356	45.77	314345	21.16	269782[b]	5.60[c]	255444	3.10[b]
MSOP	523600	44.88	341473	19.27	277344	5.37[c]	257468	3.06[b]
RR+SOP	431172	25.48	332919	12.30[b]	275941	5.24[c]	254794[c]	3.37
RR+MSOP	417601[a]	38.17	312839[c]	18.59	270007[c]	5.97	253560[c]	3.51
RR+ PT+PW	1229604	14.97[a]	1164743	12.86[b]	1134186	11.69	1077105	11.01
RR+ PT+PW+ODD	690276	16.35[b]	677189	13.20[c]	649023	11.15	619302	10.19
RR+ PT+PW+FDD	526550	34.62	430046	25.88	358523	19.15	305319	13.84
RR-(LBF+LBT)	420047[b]	39.06	310792[b]	18.31	270048[c]	5.96	253633[c]	3.45

6. Analysis and discussion of experimental results

This section reports and analyses the experimental results for testing the new proposed dispatching rules in the model of DJSP_B&E, and also trying to figure out the influences of different model parameters on the performance of dispatching rules.

6.1 Evaluation of the proposed dispatching rules

In order to analyze the relative performance of the dispatching rules with respect to the minimization of T_{Σ} and the minimization of $\%T$ in dependence of the due date tightness, four different levels of c are investigated. For these experiments E_c =0% is chosen to represent the situation without consideration of the extended technical precedence constraints. We have presented only these typical results in figures because a graphical representation of all results will result in too many figures, making the article too lengthy. In all figures, the bars in sequential order denote the rules in the order as they appear in the tables above.

6.1.1 The total tardiness

Fig. 3 shows the total tardiness results of dispatching rules on different levels of due date tightness. The results indicate that SOP, MSOP, RR+SOP, RR+MSOP, LBF+LBT, SL/OPN and RR-(LBF+LBT) emerge as outstanding rulers in minimizing the total tardiness in all cases, regardless of changing the level of the due date tightness of the problem instances, so they are effective in both tight and loose conditions. The performances of MDD, EDD and ODD are slightly inferior, but still behave very well under the measure of total tardiness time. The reason is that they both concentrates on the due date which resulting in better performance with due date-based objectives. The RR rule also performs relatively well, as it has been proved to have good performance with respect to the tardiness measures for a large number of different values of the model parameters (Holthaus, 1999). Besides, the SPT rule behaves badly in minimizing the total tardiness. This verifies that SPT is good at minimization of mean flow time while is weak in due date-based objectives (Conway, 1965; Ramasesh, 1990; Rochette and Sadowski, 1976). The WINQ and PT+WINQ+SL perform relatively well; this is because PT+WINQ+SL minimize the maximum tardiness and the variance of tardiness of jobs (Holthaus and Rajendran, 1997a).

In addition, the results indicate that the four new rules have good performance both in tight and loose due date environment, and they can be more effective when the due dates become looser regarding the total tardiness objectives. And it is to be noted that SOP and MSOP's performance are improved under tight due date tightness while deteriorated in loose due date settings when combined with RR. Among these rules, the PT+PW+FDD rule is the worst in minimizing the total tardiness. The PT+PW and RR+PT+PW rule ranks second and third in the worst performance list, as they were put forward with the attempt to minimize flow time-related measures. However, the PT+PW+ODD rule, which was also presented by Jayamohan and Rajendran (2004), performs much better than PT+PW and PT+PW+FDD, although cannot compete with the rules proposed in our paper. This is because with the addition of ODD, the purpose is to maintain the tardiness of different jobs at low levels, thereby minimizing the weighted mean tardiness, and the results of our investigation coincides with the conclusions. These rules were demonstrated to be good in Jayamohan and Rajendran (2004) where different weights or penalties relating the flow time and tardiness of different jobs were considered, for which model parameters the rules can make full use of, while the model of our investigation assume all jobs have the same weight as it concentrates on the extended technical precedence constraints. And the three rules' performance improved a lot when combined with RR while LBF+LBT's efficiency was weakened after combining with RR. Overall, the four new proposed rules have good performance in all cases, and they are excellent when the due date is loose.

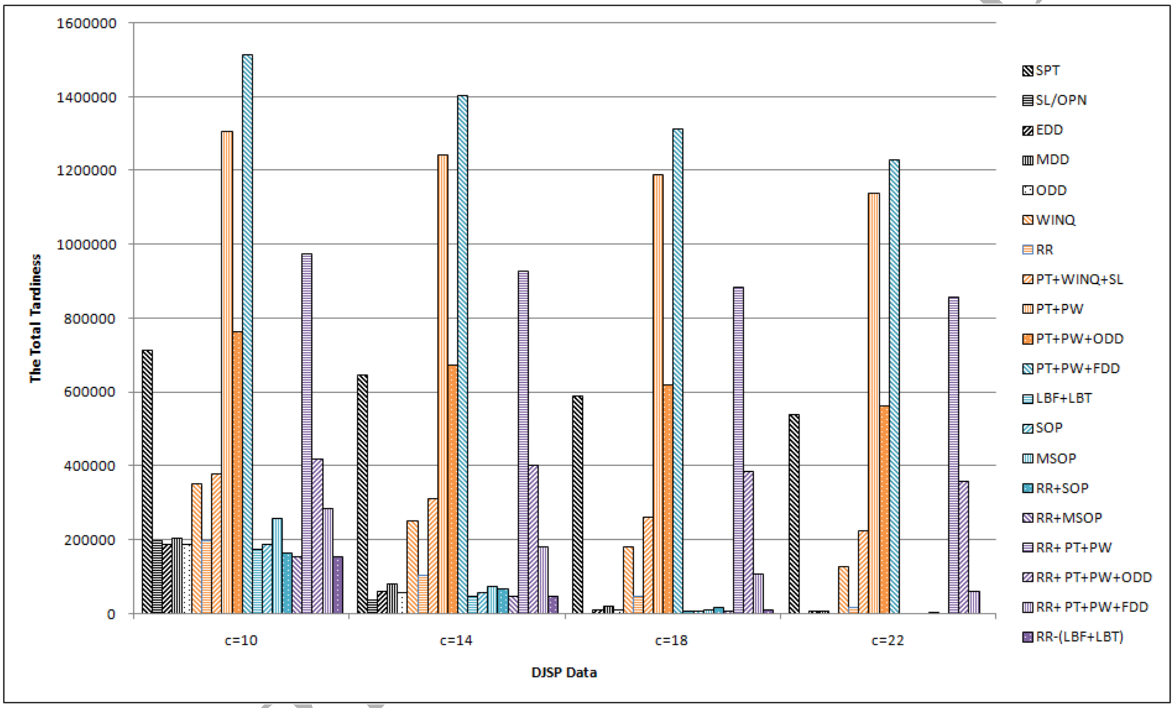


Fig.3. Comparing the total tardiness of dispatching rules on different due date tightness

6.1.2 The percentage of tardy jobs

Fig. 4 compares the percentage of tardy jobs of dispatching rules on different due date tightness. We can see that SPT and PT+WINQ+SL share the same tendency. They are both excellent under tight conditions, but get bad results when the due date is loose. The performance of SPT coincides with the existing conclusion (Holthaus and Rajendran, 1997a), which is that for minimizing the percentage of tardy jobs the SPT rule is effective when the shop utilization is high 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 (Blackstone, Philips and Hogg, 1982; Russell, Dar-El and Taylor, 1987). Contrarily, the four new proposed rules' performance is bad when the due date is tight, and become very effective when the due date is loose regarding the objective of the percentage of tardy jobs. The LBF+LBT, SL/OPN and RR-(LBF+LBT) share the same tendency.

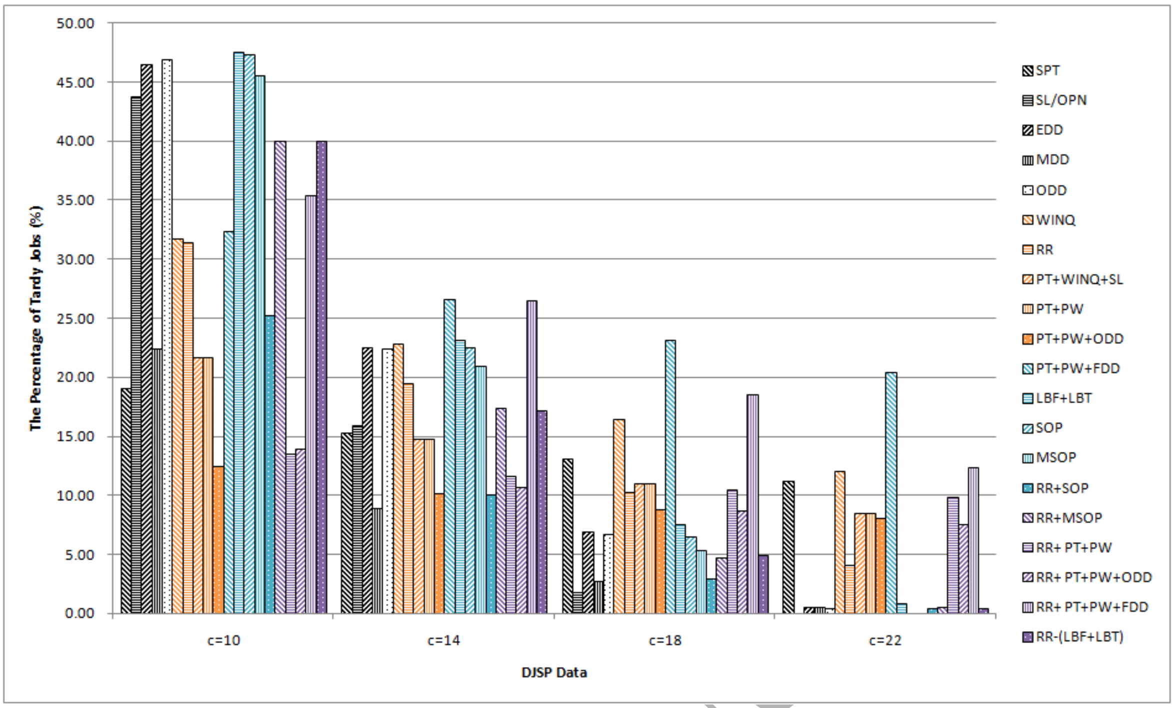


Fig.4. Comparing the percentage of tardy jobs of dispatching rules on different due date tightness

The three due date-based rules, EDD, MDD and ODD, have bad performance under tight due date conditions and can get good results when the due date is loose. And it is obvious that MDD is still the best rule among these three regarding the objective of the percentage of tardy jobs. The PT+PW, PT+PW+ODD and PT+PW+FDD are relatively effective under tight due date, but they are bad when the due date is loose, especially the PT+PW+FDD. And the PT+PW rule is more effective for the objective of the percentage of tardy jobs under the conditions of high utilization level and relatively tight due-date setting. In addition, the WINQ rule has bad performance both in tight and loose conditions. The RR rule fares better under loose due date settings. Holthaus and Rajendran (1997a) pointed out the reason is that for highly loaded conditions with tight due-date settings, the slack component of the RR rule is dominant and it loses its contribution as the allowance factor increases. Overall, the performance of the existing rules coincides with the conclusions drawn in previous works. It is clear to see that the four new proposed rules can achieve very good results when the due date is relatively loose regarding the objective of the percentage of tardy jobs. It is noteworthy that after combined with RR, the rule SOP and MSOP can achieve better results. The same phenomenon is suitable for PT+PW, PT+PW+ODD and PT+PW+FDD when the due date is relatively loose, as RR fares better under loose due date settings.

The performance of dispatching rules under E_c =3% and 5% are also observed, and the same conclusion can be drawn, i.e. the four new proposed rules are very effective under relatively loose due date settings with the objective of the minimization of T_Σ and the minimization of $\%T$. To sum up, the overall experimental results indicate that the performance of the new proposed rules is very effective in relatively loose due date conditions for tardiness-related measures, so they are promising to apply to solve the DJSPs.

6.2 The influences of the model parameters on dispatching rules

The model of the DJSP in our paper considers different levels of E_c and c, this section will analyze the influences of these model parameters on the performance of dispatching rules.

6.2.1 The extended technical precedence constraints

In order to analysis the effects of E_c to the performances of dispatching rules, three different levels are investigated. For these experiments, the allowance factors represent a loose due date tightness is chosen. Fig. 5 below shows the overall performance of dispatching rules using the function of the above mentioned two performance measures on different E_c. The two kinds of data were added with the weight of 0.5 after normalization processing, and the results are presented below. We can see that for the majority of the rules, the objective value of the function increases with the increase of E_c, which means that the performance of dispatching rules become worse. The reason for this tendency is obvious, that is, the higher the level of the extended technical precedence is, the more constraints exist, thus making the scheduling become more complex due to the consideration of these precedence constraints.

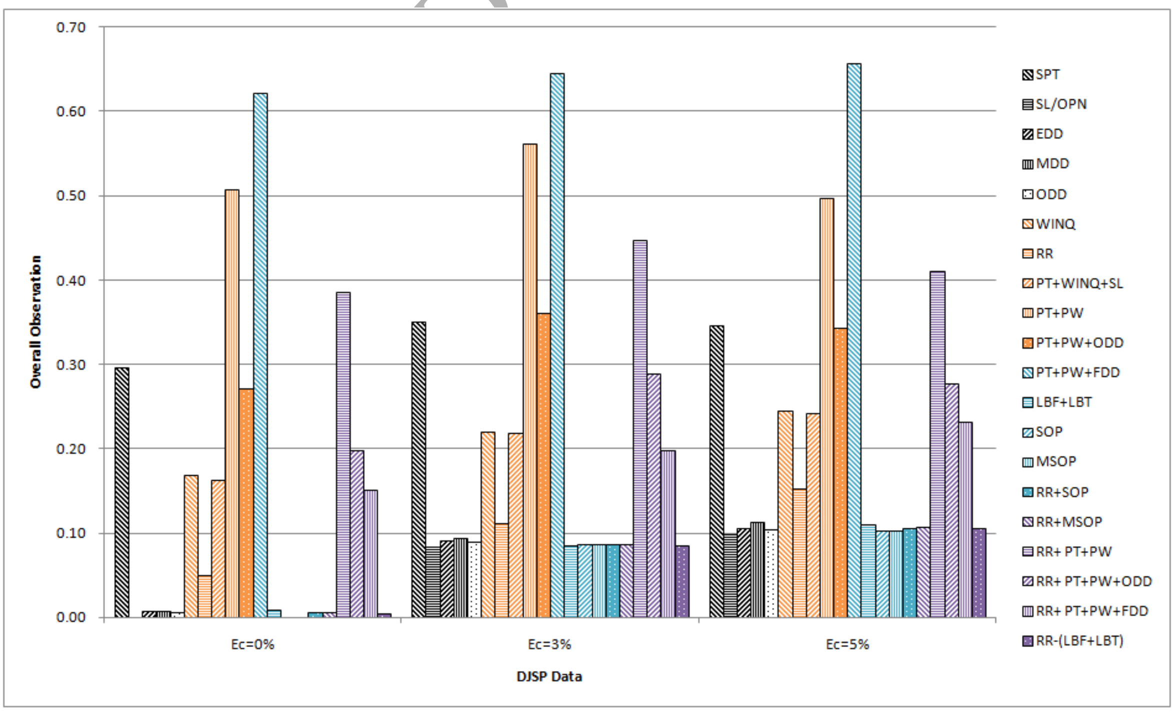


Fig.5. Comparing overall observation of dispatching rules on DJSP data with different E_c

6.2.2 The allowance factor

The influences that the due date tightness on the performances of dispatching rules can be seen in Fig.3 and Fig.4. With the increase of the allowance factor, the value of tardiness-related measures of dispatching rules decreases. This means that the dispatching rules perform better when the due dates become loose. This tendency is obvious as the looser the due date tightness is, the less the chance for the jobs to be tardy, it is just that the influence level the allowance factor to different rules differs in the degree.

For rules like SPT, PT+PW+FDD and RR-(PT+PW+FDD), their performance is worse compared with others when the allowance factor getting larger, although the objective values decrease. This demonstrates that these rules can be more effective in tight due date environment. Contrarily, the new proposed rules and LBF+LBT are versus to that tendency. The SOP, MSOP, RR+SOP, RR+MSOP and LBF+LBT can achieve very good results in relatively loose due date settings while having general performance in tight due date environment. This indicates that the allowance factor can influence the dispatching rules' performance, and there is need to distinguish different rules' effectiveness in different due date tightness. And it can be seen that if the rule incorporates due date information in the scheduling process, its tardiness-related performance can be improved a lot with the increase of the allowance factor. Fig.6 presents the overall observation of dispatching rules using the function of the two performance measures on different due date tightness, and it is clear to see their influences to the performances of dispatching rules.

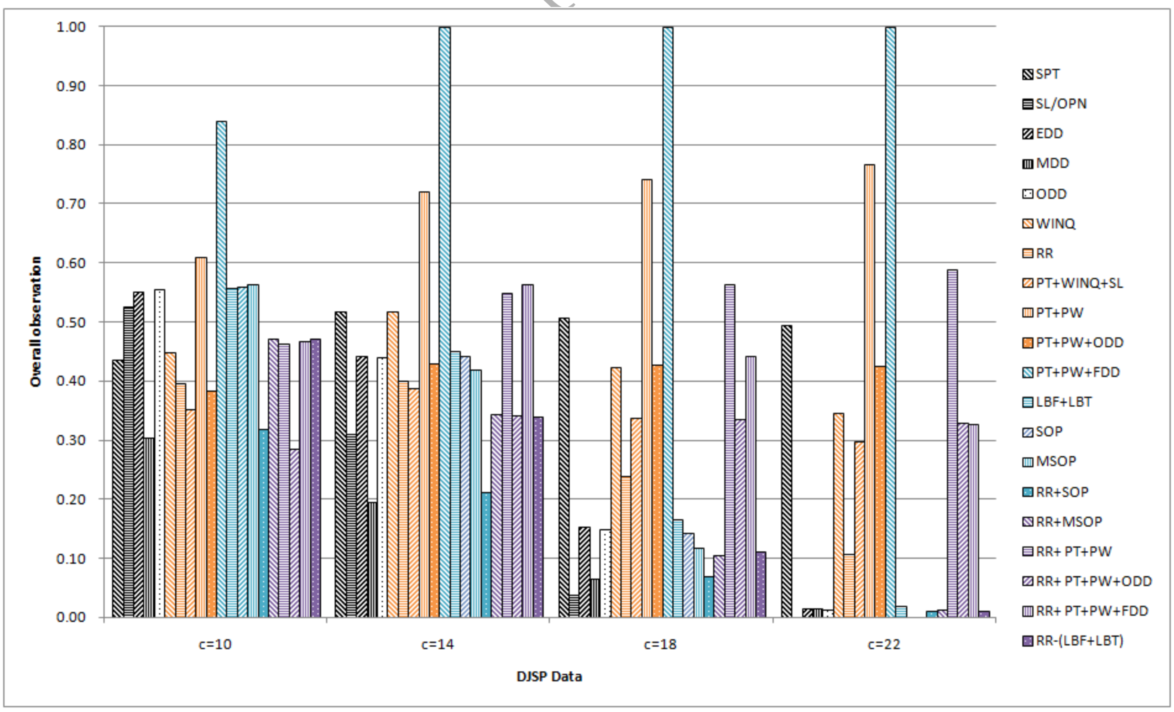


Fig.6. Comparing overall observation of dispatching rules on DJSP data with different due date tightness

Summing up the analysis of the results of the tardiness-related performance measure, the relative performance of dispatching rules can be affected by both the level of the extended technical precedence constraints and the due date tightness. In addition, we had also set the shop utilization to other levels, attempting to find out whether the influences the model parameters to the performance of the dispatching rules are the same at different shop utilization levels. The data showed the tendency is similar at different shop utilization level in general.

7. Conclusions and future works

In this paper, a dynamic job shop scheduling problem with the consideration of extended technical precedence constraints and the due date tightness is presented, four new dispatching rules have been proposed and the relative performance of dispatching rules with respect to tardiness-related objectives have been analyzed, studying the influences of different levels of the model parameters on the performance of dispatching rules.

The experimental results of the existing rules validate the conclusions drawn in previous literatures. The results of the experimental evaluation also demonstrate the effectiveness of the four new proposed dispatching rules, showing that they are very excellent when the due date is relatively loose. This demonstrates that they are effective and promising to apply to solve the real word DJSPs. In addition, the influences of the model parameters on dispatching rules are studied, the results reveal that the relative performance of dispatching rules can be affected by both the level of the extended technical precedence constraints and the due date tightness.

Several possible extensions of this study can be developed. Firstly, future research could be directed towards the development of rules that include more information about the scheduling environment, and more kinds of combinations of the information, so as to overcome the short-sighted nature of dispatching rules and optimize as many measures of performance as possible simultaneously. And it should be noted that there is a trade-off between the complexity of the rule and its simplicity nature in structure. Secondly, different shop utilization levels could be considered as a model parameter in the experimental investigation to analysis its influence on the performance of dispatching rules, and distinguish the conditions dispatching rules perform well under light or load conditions. Thirdly, other performance measures could be used as the objective function and other scheduling scenarios which consider more practical situations could be investigated to evaluate the effectiveness of the dispatching rules so as to improve their performances and robustness.

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