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FLEXIBLE JOB SHOP SCHEDULING PROBLEM WITH PARALLEL BATCH PROCESSING MACHINE

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ABSTRACT

A flexible job-shop scheduling problem (FJSP) with parallel batch processing machine (PBM) is studied. First, mixed integer programming (MIP) formulation is proposed. In order to address a NP-hard structure of this problem, we relax the model to *selectively* include jobs into the model. There are thousands of jobs in a floor, but we are mostly interested in priority jobs because special customers promise a significant amount of financial compensation in exchange of an expedited delivery. This relaxation could allow non-priority jobs remain unscheduled, but it expedites the discovery of solutions. We then turn job-dependent processing time into machine-dependent by assuming a machine has an equal processing time on different jobs. This assumption is acceptable for the sake of the reduced computational time. This further relaxed model significantly reduces a computational time compared to the original one when tested on a set of common problem instances from a paper in the literature.

1 INTRODUCTION

In semiconductor industry, researchers have exploited a performance of each production areas such as lithography, diffusion, etch, and implanter for the last decades by using advanced scheduling/dispatching systems. Now, there is a growing need of orchestrating a whole factory to seek a global optimization. While flexible job shop scheduling problem (FJSP) with 6000-job (assuming 150K monthly wafers output and 30 days cycle time), thousands of machine, hundreds of steps, and several dozens of products is unlikely to be solved in reasonable time, linking and orchestrating multiple consecutive steps seem to be tractable.

One of applications is wet-diffusion area scheduling problem which has 2-4 consecutive steps with parallel batching machines (Bixby *et al*. 2006; Yugma *et al.* 2012; Jung *et al.* 2014). Another application is to schedule jobs having a time constraints between consecutive process steps (Sun *et al*. 2005; Ham *et al*. 2011; Klemmt and Mönch 2012; Sadeghi *et al*. 2015). Last application which has yet been studied in the literature is to schedule a priority jobs in order to meet a pre-determined due date. It is a common business practice of foundry industry. They call it priority job scheduler (PJS). Due to non-preemptive nature of machines in semiconductor manufacturing, a floor supervisor often takes an extreme measure letting some ports of machine empty as a priority jobs are approaching from an upstream steps which results in a productivity loss. We tackle the problem in the context of FJSP with batching.

1.1 FJSP

The classical job shop scheduling problem (JSP) schedules a set of jobs on a set of machines with the objective to minimize a maximum completion time over all jobs (*Cmax*), subjected to the constraint that each job has an ordered set of operations, each of which must be processed on a predefined machine, whereas FJSP allows an operation to be processed on a machine out of a set of alternatives, which adds another dimension of complexity.

Researchers have addressed the FJSP mostly using heuristics. Despite the fact that those heuristics may generate fast and effective solutions, they are usually tailor-made. Moreover, the efficiency of these techniques strongly depends on the proper implementation and fine tuning of parameters since they combine the problem representation and the solution strategy into the same framework. In contrast, mathematical modelling approach divides the problem representation and the solution strategy in an exact MIP model and solving mechanics respectively (Kopanos *et al.* 2010). Furthermore, as computer hardware and solvers have improved, practitioners have been able to formulate increasingly detailed and complex problems. Therefore, we explorer a mathematical modelling approach.

Table 1 shows an overview of FJSP mathematical models in the literature. The overview table created by Demir and İşleyen (2013) is slightly modified. A vast number of researches have addressed FJSP and its variants such as plan flexibility, setup, overlapping, preventive maintenance, etc. However, to the best of our knowledge to date, no published work has dealt with the FJSP with batching.

Table 1: The articles related FJSP mathematical models.

References	Highlights	Journal
Liu and MacCarty 1997	with sequence dependent setup times	Eur. J. Oper. Res.
Kim and Egbelu 1999	with process plan flexibility	Int. J. Prod. Res.
Thomalla 2001	with alternative process plan	Int. J. Prod. Eco.
Low 2001	with sequence dependent setup times	Int. J. Prod. Res.
Tamaki *et al.* 2001	with sequence dependent setup times	IEEE Symposium
Lee *et al.* 2002	with process plan flexibility	Comput. Ind. Eng.
Torabi *et al.* 2005	with homogenous machines	Int. J. Prod. Eco.
Imanipour 2006	with sequence dependent setup times	IEEE conference
Low *et al.* 2006	with sequence independent setup times	Comput. Oper. Res.
Gao *et al.* 2006	with flexible preventive maintenance	J. Intell. Manuf.
Fattahi *et al.* 2007	-	J. Intell. Manuf.
Mehrabad and Fattahi 2007	with sequence dependent setup times	Int. J. Adv. Manuf. Technol.
Zhang *et al.* 2009	-	Comput. Ind. Eng.
Lin and Jia-zhen 2009	with sequence independent setup times	Systems Eng. theory practice
Fattahi *et al.* 2009	with overlapping	Appl. Math. Modell.
Özgüven *et al.* 2010	with process plan flexibility	Appl. Math. Modell.
Fattahi and Fallahi 2010	with disturbances	J. Manuf. Sci. Technol.
Ham *et al.* 2011	-	Int. J. Prod. Res.
Moradi *et al.* 2011	with preventive maintenance	Expert Syst. Appl.
Zhang *et al.* 2012	with transportation constraints	Comput. Oper. Res.
Demir and İşleyen 2013	evaluation of MIP models	Appl. Math. Modell.
Jalilvand-Nejad and Fattahi 2015	with sequence dependent setup times	J. Intell. Manuf.

1.2 Priority Job Scheduler

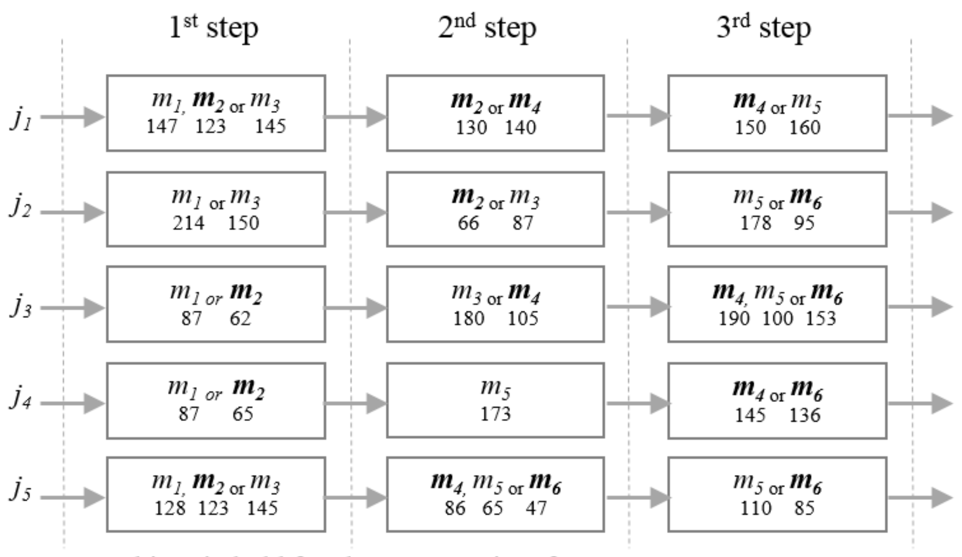
Business requirements drive the need for a small number of jobs to be run through the factory as fast as possible. Various manual and automated schemes have been tried to keep the priority jobs from "queuing at the machine". These schemes involve idling tools ahead of the arrival of priority jobs and trading machine utilization for priority jobs cycle time (Bixby *et al.* 2006). We tackle this PJS problem in the context of FJSP with batching.

The main contributions of this paper can be summarized as follows. We propose a mathematical formulation of FJSP with batching constraint for the first time and make a practical modification in order to implement the theory into the practice.

2 PROBLEM DESCRIPTION & FORMULATION

2.1 FJSP with Batching

The FJSP with batch processing machine inherits every complexity of the original FJSP. In addition, it has a set of parallel batch processing machines. Each job has to be processed on one machine out of a set of given compatible machines as it visits a pre-determined series of steps. The batching allows multiple jobs to be simultaneously processed as long as the total size of the batch does not exceed machine capacity. The processing time of a batch is dependent on the individual jobs in the batch, which is the maximum of individual processing times. Figure 1 represents a FJSP instance of 5-job, 6-machine, and 3-step with batching.


1st step
2nd step
3rd step
j_1
m_1, $\mathbf{m_2}$ or m_3 147 123 145
$\mathbf{m_2}$ or $\mathbf{m_4}$ 130 140
$\mathbf{m_4}$ or m_5 150 160
j_2
m_1 or m_3 214 150
$\mathbf{m_2}$ or m_3 66 87
m_5 or $\mathbf{m_6}$ 178 95
j_3
m_1 or $\mathbf{m_2}$ 87 62
m_3 or $\mathbf{m_4}$ 180 105
$\mathbf{m_4}$, m_5 or $\mathbf{m_6}$ 190 100 153
j_4
m_1 or $\mathbf{m_2}$ 87 65
m_5 173
$\mathbf{m_4}$ or $\mathbf{m_6}$ 145 136
j_5
m_1, $\mathbf{m_2}$ or m_3 128 123 145
$\mathbf{m_4}$, m_5 or $\mathbf{m_6}$ 86 65 47
m_5 or $\mathbf{m_6}$ 110 85

Note: Machines in bold font have a capacity of two.
Numbers under each machine represent a processing time at steps.
Batching requirement is added to original instance MFJS1 by Fattahi *et al.* 2007

Figure 1: FJSP instance of 5-job, 6-machine, and 3-step with batching.

In this problem, we assume all machines and jobs are available at time 0. We also assume that batch processing machine can process different products simultaneously (compatible job families). The notation used in this paper is summarized in the following:

Sets:		Decision variables:	
J	jobs (j)	X_{jsmk}	1 if job j occupies sequence k in the permutation sequence on machine m at step s; 0 otherwise
S	steps (s)		
M	machines (m)		
$K(\|J\| \times \|S\|)$	permutation sequences (k)		

Parameters:		Resultant variables:	
$par_{j,s,m}^{ptime}$	processing time	$J_{j,s}^{arrival}$	arrival time to step *s* of job *j*
par_{m}^{capa}	capacity of machine *m*	$M_{m,k}^{start}$	start time of sequence *k* on machine m
M	$max\left\{\sum_{j,s,m} par_{j,s,m}^{ptime}\right\}$	$M_{m,k}^{complete}$	completion time of sequence *k* on machine m
		$M_{m,k}^{ptime}$	processing time of sequence *k* on machine *m*
		C_{max}	makespan

We name the following model $FJSP^{+Batching}$.

Routing	$\sum_{m,k} X_{jsmk} = 1 \quad \forall j,s$	(1.1)
	$\sum_{j,s}(X_{jsmk}) \leq par_{m}^{capa} \quad \forall k,m$	(1.2)
Scheduling	$M_{m,k}^{ptime} \geq \left(par_{j,s,m}^{ptime}\right)X_{jsmk} \ \forall j,s,m,k$	(1.3)
	$J_{j,s}^{arrival} = par_{j}^{release} \ \forall j, s = 1$	(1.4)
	$M_{m,k}^{start} \geq J_{j,s}^{arrival} + M\left(X_{jsmk} - 1\right) \ \forall j,s,m,k$	(1.5)
	$M_{m,k}^{complete} = M_{m,k}^{start} + M_{m,k}^{ptime} \quad \forall m,k$	(1.6)
	$J_{j,s+1}^{Arrival} \geq M_{m,k}^{complete} + M\left(X_{jsmk} - 1\right) \quad \forall j,m,k : s < \lvert S\rvert$	(1.7)
	$M_{m,k+1}^{start} \geq M_{m,k}^{complete} \ \forall m : k < \lvert K\rvert$	(1.8)
Measuring	$Cmax \geq M_{m,k}^{complete} + M\left(X_{jsmk} - 1\right) \forall j,s,m,k$	(1.9)
	$Minimize\ CMAX$	(1.10)

Constraint (1.1) ensures that jobs are assigned to one of the available slots. Machine capacity is taken into consideration in Constraint (1.2). Then, Constraint (1.3) defines the processing time of a batch on a machine, which is represented by the longest time of all jobs in the batch. Constraint (1.4) considers the release time of a job. Constraint (1.5) ensures that a batch cannot start its processing until all jobs assigned to the corresponding batch become ready. Constraint (1.6) determines the completion time of a batch. Constraint (1.7) ensures that the available time of a job is greater than or equal to the completion time at the very previous step. Constraint (1.8) ensures the precedence relationship between batches at the same machine. Finally, Constraint (1.9) determines the makespan and Objective (1.10) minimizes it.

Figure 2 represents an optimal solution for the FJSP instance of 5-job, 6-machine, and 3-step when batching is not considered or the capacity of machine is set to 1. The values in rectangle show a job schedule, for instance, *j3s1m1p87* indicates job 3 is scheduled to machine 1 at step 1 with a processing time of 87.

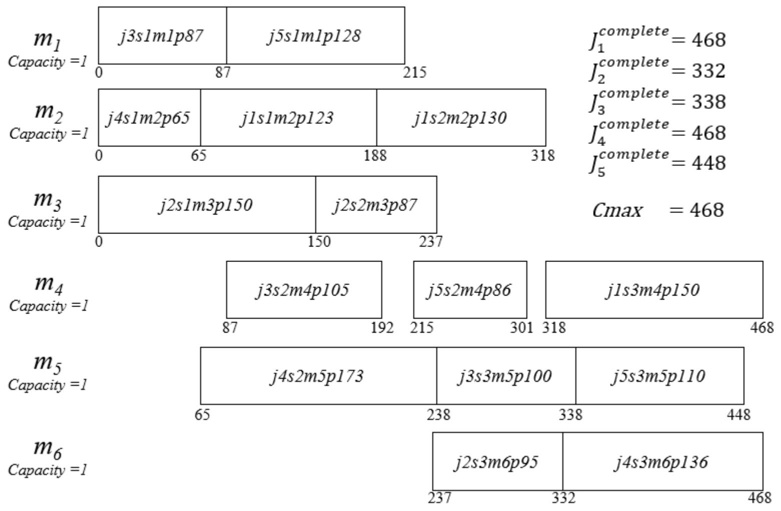


Figure 2: An optimal solution for the 5-job, 6-machine, and 3-step without batching.

On the other hand, Figure 3 represents an optimal solution for the same instance when batching is considered.

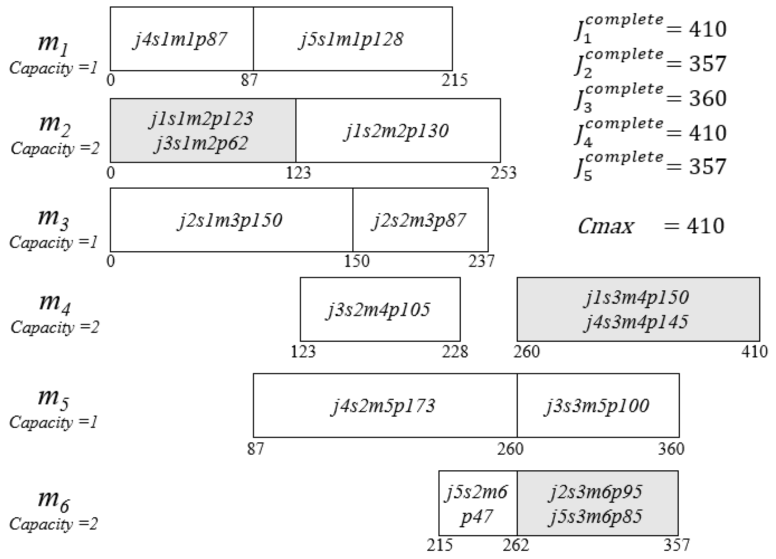


Figure 3: An optimal solution for the 5-job, 6-machine, and 3-step with batching.

2.2 FJSP with Batching Applied to Priority Job Scheduling

During a preliminary experimentation, we found that the $FJSP^{+Batching}$ model can not generate an effective solution for a large instances after several hours of computational time so we explorer an opportunity of practical modification. An interview with an industry subject matter expert (SME) provides two key insights:

a) One key insight is about a selective job scheduling. There are thousands of jobs in floor, but we are mostly interested in priority jobs because special customers promise a significant amount of financial compensation in exchange of an expedited delivery. To take advantage of this compromise, the proposed model has come under close scrutiny. The model uses lots of binary variables (X_{jsmk}). One of set indexes which caught our eye is k, permutation sequence, whose size is currently set to $|J| \times |S|$

assuming all operations could be scheduled to a single machine. This size can be dramatically decreased owing to the compromise which allows some jobs remain unscheduled. The unscheduled jobs are scheduled at the next run. Now, the routing Constraint (1.1) which forces all jobs to be assigned is not valid any more so we change the constraint as follows:

$$\sum_{m,k} X_{jsmk} \leq 1 \quad \forall j, s \tag{2.1}$$

Constraint (2.2) is added in order to force a job to complete all operations once it is selected for schedule.

$$\sum_{mk} X_{jsmk} = \sum_{mk} X_{j,s+1,m,k} \; \forall j : s < |S| \tag{2.2}$$

Unfortunately, this change on the routing constraint drives a solver to make undesirable results. Namely, a solver drops all jobs from a schedule to minimize *Cmax*. In order to prevent this side effect, Objective (2.3) rewards each job schedule with a large compensation, *M,* which is the theoretical upper bound of *Cmax*.

$$Maximize \sum_{j,s,m,k} (M) X_{jsmk} \tag{2.3}$$

We then calculate a completion time of a job and use it to calculate the makespan as melted into Constraints (2.4) and (2.5), which replace Constraint (1.9).

$$J_j^{complete} \geq M_{m,k}^{complete} + M\left(X_{jsmk} - 1\right) \; \forall jsmk \tag{2.4}$$

$$CMAX \geq J_j^{complete} \quad \forall j \tag{2.5}$$

This change reduces a number of nodes in branch-and-bound algorithm owing to smaller |*K*|. This variant is named $FJSP_{Selective}^{+Batching}$.

b) Another insight is about a processing time. Although there are minor variations of processing times, a machine has an equal processing time on different jobs in general. This compromise is acceptable for the sake of a reduced computational time. The proposed model has again come under close scrutiny. We modify $FJSP^{+Batching}$ model as follows. Let par_m^{ptime} be the processing time of machine *m*. Then, Constraint (1.6) can be replaced by Constraint (2.6) and Constraint (1.3) can be removed. This modification tightens the formulation and vastly improves CPLEX run-time performance. We discuss it in computational study section.

$$M_{m,k}^{complete} = M_{m,k}^{start} + par_m^{ptime} \quad \forall m, k \tag{2.6}$$

Hereby, new objectives are to maximize a total count of jobs scheduled while minimizing the last completion time.

3 COMPUTATIONAL STUDY

In this section, we test the effectiveness of our proposed models. We first compare $FJSP^{+Batching}$ with $FJSP_{Selective}^{+Batching}$ in order to understand a computational advantage of the proposed method. Then, we repeat a similar study with the assumption of machine-dependent processing time.

MIP models are generated by IBM OPL and solved by CPLEX 12.6.3 on a personal computer with an Intel Core i5-3470 @ 3.2 Ghz processor and 16 GB RAM.

3.1 Small-Size Test Instances

To test our model, we borrow the same test problems instances created by Fattahi *et al.* 2007. They randomly generated a total of 20 FJSP instances. The instances are divided to two categories: small size problems (SFJS1:10) and medium and large size problems (MFJS1:10). The instances however do not have a batching requirement so we simply assume even (odd) numbered machines have a capacity of two (one). Another change is made to support the machine-dependent processing time assumption. The processing time of machine (par_m^{ptime}) is calculated as follows: $min\left\{par_{j,s,m}^{ptime} \ \forall m\right\}$.

In this study, we make sure $FJSP_{Selective}^{+Batching}$ to schedule every jobs for a fair comparison with $FJSP^{+Batching}$. This is made by setting |K| value to six and confirmed during a study.

3.2 Results of Small-Size Test Instances

Table 2 summarizes the computational results. Column 1 shows the name of instances used by Fattahi *et al*. 2007. Columns 2–5 contain the best solutions generated by $FJSP^{+Batching}$ and $FJSP_{Selective}^{+Batching}$ which are reported within 300 seconds. The $FJSP_{Selective}^{+Batching}$ finds an optimal solutions of 11 instances out of 20 within 300 seconds compared to 9 out of 20 by $FJSP^{+Batching}$ which demonstrates a reduction of computational time. Another finding is that there is a significant difference in *Cmax* values for the large instances of MFJS 8, 9 and 10, which suggests a superiority of $FJSP_{Selective}^{+Batching}$ for an industry-scale problem instance.

Table 2: Comparison of two different models with the assumption of job-dependent processing time.

	$FJSP^{+Batching}$		$FJSP_{Selective}^{+Batching}$	
Problem	*Cmax*	CPU	*Cmax*	CPU
SFJS1	**66**	0.05	**66**	0.08
SFJS2	**107**	0.05	**107**	0.05
SFJS3	**208**	0.31	**208**	0.20
SFJS4	**272**	0.06	**272**	0.05
SFJS5	**100**	0.14	**100**	0.39
SFJS6	**320**	12.29	**320**	1.37
SFJS7	**397**	9.77	**397**	1.00
SFJS8	**216**	5.34	**216**	6.46
SFJS9	**210**	2.95	**210**	0.87
SFJS10	516	300	**516**	91.96
MFJS1	410	300	410	300
MFJS2	410	300	410	300
MFJS3	420	300	420	300
MFJS4	506	300	506	300
MFJS5	488	300	488	300
MFJS6	631	300	**614**	42.43
MFJS7	916	300	863	300
MFJS8	896	300	808	300

MFJS9	nf	300	955	300
MFJS10	3418	300	1215	300

* Optimal values in bold.

Table 3 summarizes the computational results based on the assumption of machine-dependent processing time. Under this assumption, both $FJSP^{+Batching}$and $FJSP^{+Batching}_{Selective}$ find an optimal solutions of 16 instances out of 20 within 300 seconds which demonstrates a reduction of computational time by tightening the formulation. We also find a significant differences in *Cmax* values for the large instances of MFJS8, 9 and 10.

Table 3: Comparison of two different models with the assumption of machine-dependent processing time.

	$FJSP^{+Batching}$		$FJSP^{+Batching}_{Selective}$	
Problem	*Cmax*	CPU	*Cmax*	CPU
SFJS1	**48**	0.03	**48**	0.03
SFJS2	**63**	0.01	**63**	0.03
SFJS3	**106**	0.03	**106**	0.03
SFJS4	**126**	0.03	**126**	0.03
SFJS5	**42**	0.02	**42**	0.03
SFJS6	**134**	0.09	**134**	0.12
SFJS7	**194**	0.08	**194**	0.17
SFJS8	**100**	0.11	**100**	0.17
SFJS9	**84**	0.16	**84**	0.25
SFJS10	**314**	0.22	**314**	0.28
MFJS1	**236**	1.00	**236**	4.38
MFJS2	**236**	2.28	**236**	6.58
MFJS3	**250**	4.06	**250**	12.34
MFJS4	**251**	26.43	**251**	71.57
MFJS5	**251**	17.91	**251**	29.44
MFJS6	**254**	23.71	**254**	51.29
MFJS7	325	300	325	300
MFJS8	980	300	344	300
MFJS9	1160	300	435	300
MFJS10	1036	300	457	300

* Optimal values in bold.

4 CONCLUSION AND FUTURE WORKS

Encountered at semiconductor manufacturing, a flexible job-shop scheduling problem (FJSP) with parallel batch processing machine (PBM) is studied as there is a growing need of orchestrating a whole factory to seek a global optimization. We establish a baseline by composing a mixed integer programming (MIP) formulation for the first time. Owing to two critical insights we found during an interview with industry SME, an original mathematical formulation is relaxed to cope with an industry-size instances. The first insight is about a selective job scheduling. Although there are thousands of jobs in a floor, industry is mostly interested in priority jobs because special customers promise a significant amount of financial compensation in exchange of an expedited delivery. The priority jobs must be included into a schedule whereas normal jobs could be selectively scheduled as much as possible to maximize a production output, but it is still optional. The second insight is about the machine-dependent processing time. There are minor variations of processing times depending on recipes, but a machine has a similar processing time on different jobs in general. This compromise is acceptable for the sake of a reduced computational time. This modification tightens the formulation and vastly improves CPLEX run-time performance.

This research can be further extended by considering a relatively new approach, constraint programming (CP), which is designed to cope with a complex scheduling problems such as TSP, JSP, and FJSP. Another extension is to improve the proposed MIP model. We can also look into application side as we previously discussed in the introduction section.

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