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Review for Scheduling Algorithms on a Fab Manufacturing System with Special Characteristics Called As Re-Entrant Flows

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ABSTRACT

Scheduling is very important issue in manufacturing systems such as large-scale complex manufacturing system. Especially, in semiconductor manufacturing system, the complexity of scheduling is very high since there are various constraints such as re-entrant flows, limited waiting time, equipment dedication and so on. There are many researches for scheduling algorithms or dispatching rules on the semiconductor manufacturing systems, however, there are few researches for the scheduling algorithms considering the above special characteristics such as re-entrant flows of lots, limited waiting time of lots, equipment dedication for operations of photolithography and so on. In this paper, we focus on and review the previous scheduling algorithms or dispatching rules for the re-entrant flowshops of various types in a semiconductor manufacturing system, and suggest the needed future research areas for the scheduling problems with special constraints in a semiconductor manufacturing system.

I. INTRODUCTION

In order to survive in today's business environment, which can be characterized by frequent technological changes, uncertain demands, and short life cycles of products [1], it is necessary to achieve high system performances in terms of throughput rate and service level by implementing efficient and effective planning and scheduling methods [2]. Particularly, in electronics industry, such operational decision are very important, since product variety and complexity of manufacturing process as well as capital expenses have increased due to the high degree of automation and versatility [3]. In fact, many traditional industries, such as textile and mirror industries, have manufacturing systems that can be regarded as re-entrant flowshops [4]. In addition, the re-entrant flowshops can be found in the electronics manufacturing systems like those for PCB (printed circuit board), TFT-LCD (thin film transistor liquid crystal display) and semiconductor manufacturing [2]. In this paper, we review the related existing researches for re-entrant flowshop scheduling problems.

Re-entrant flowshop can be considered as an extended form of flowshop, that is, re-entrant flowshop has a flow line like flowshop but there are reentrant flows [2]. In a typical flowshop, jobs are composed of m (number of machines) operations at most and each job visits each machine one time. However, in re-entrant flowshops, jobs should visit machines multiple times. In other words, jobs should go through multiple passes (L) of serial manufacturing processes. In the m-machine ($m \geq 2$) re-entrant flowshop, each job should be processed L (≥ 2) times on each machine, that is, one time or multiple times and hence each job is composed of Lm operations. Figure 1 shows a schematic view of a re-entrant flowshop.

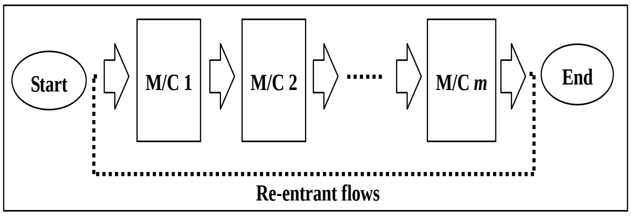

Fig 1. A schematic view of re-entrant flowshop [2]

II. RELATED PREVIOUS RESEARCHES

Not much progress has been made for re-entrant flowshop scheduling problems. However, the studies about re-entrant flowshops have been increasing in past one decade [2]. Pan and Chen [5] show that the re-entrant permutation flowshop scheduling problem with the objective of minimizing makespan is NP-hard in the strong sense even for the two-machine case, and give mixed integer programming formulations and heuristic algorithms for the problem, and Chen [6] suggests a branch and bound algorithm for the m-machine re-entrant permutation flow-shop scheduling problem. Choi and Kim [4, 7] suggest a branch and bound algorithm and some heuristic algorithms for the two-machine and m-machine re-entrant flowshop with the objective of minimizing makespan, respectively. Demirkol and Uzsoy [8] suggest decomposition methods for the objective of minimizing maximum lateness in a re-entrant flowshop with sequence dependent setup times, while Graves et al. [9] model a wafer fab as a re-entrant flowshop scheduling problem and give a simple and effective scheduling algorithm for the objective of minimizing average throughput time subject to meeting a given production rate.

There are several research results on more general problems, i.e., re-entrant job shop scheduling problems. Re-entrant job shops can be found in many production systems, especially in high-tech industries. For example, in semiconductor manufacturing, a process flow is highly re-entrant because wafers usually make multiple visits to an equipment group as successive circuit layers are added onto them [10]. The production control problem for certain re-entrant shops, especially those for VLSI (very large scale integrated circuit) wafer fabrication, has been addressed by several authors [11]. A second example is the manufacturing of printed circuit boards that require both surface-mounted devices and conventional pin-through-hole devices and a third example is parts go through the painting and baking divisions alternately for different coats of paint in a painting shop [12]. For re-entrant jobshop scheduling problems with the objective of minimizing makespan, Wang et al. [13] prove some properties that identify a specific class of optimal schedules, and then use these properties in designing an approximation algorithm and branch and bound type optimization algorithm. Hwang and Sun [14] develop dominance properties, and use these to develop a dynamic programming algorithm for a side frame press shop scheduling problems, which can be regarded as a re-entrant jobshop scheduling problem. Drobouchevitch and Strusevich [15] develop various heuristic algorithms for the two-machine re-entrant jobshop scheduling problems with minimizing makespan and analyze the worst case performance of the algorithms. Pan and Chen [16] present two binary integer programming optimization formulations for the re-entrant jobshop scheduling problems with the objective of minimizing makespan, and in the formulations, layer division procedures are developed and incorporated to improve the solution speed of the binary integer programming optimization formulations. Kubiak et al. [12] propose a dynamic programming algorithm and an approximation algorithm for the re-entrant job shop scheduling problems with the objective of minimizing mean flow time. In addition, for the cyclic job shop scheduling problem, which can be denoted as a type of re-entrant jobshop scheduling problems since a job or product may be processed at a machine repeatedly, Lee [17] develops an efficient algorithm, and Nicholas et al. [18] characterize the complexity of the scheduling problem for several types of job shops, and there are numerous other studies on cyclic job shop scheduling problems [19].

In the section III of this paper, we show the previous research results of Choi [4, 20, 21, 22] for of three types of re-entrant flowshop scheduling problems and algorithms for the problems.

III. THREE TYPICAL RE-ENTRANT FLOWSHOP SCHEDULING PROBLEM MODELS FOR REVIEWS

A. Review Model 1 (Two-machine Re-entrant flow Scheduling Problems in a Fab)

Choi [4, 7] suggested B&B (branch and bound) and heuristic algorithms for the two-machine re-entrant flowshop scheduling problems with the objective of makespan and total tardiness, respectively. In these researches, the re-entrant flowshop considered here, all jobs must be processed twice on each machine, that is, each job should be processed on machine 1, machine 2 and then machine 1 and machine 2 [4, 7]. Figure 2 shows a schematic view of a two-machine re-entrant flowshop.

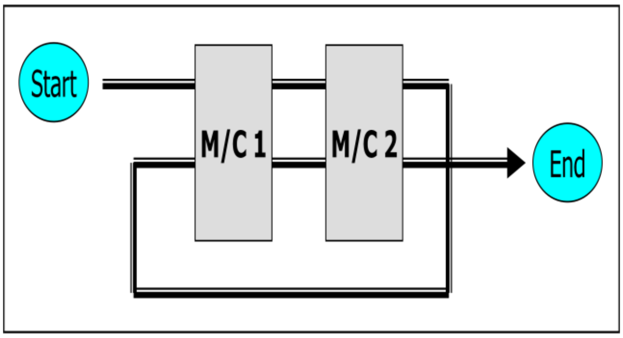

Fig 2. Two-machine re-entrant flowshop

In these researches, some dominance properties, lower bounds and heuristic algorithms were developed for the problems, and use these to develop a branch and bound algorithm. For evaluation of the performance of the algorithms, computational experiments are performed on randomly generated test problems. Results of the experiments show that the suggested branch and bound algorithm can solve problems with up to 200 jobs and 20 sub-jobs (10 jobs) for the problems with objective functions of the minimizing make span and total tardiness, respectively, in a reasonable amount of CPU time [4, 7]. In this paper, we show the performance results of only branch and bound algorithms.

For the objective function of minimizing makespan, processing times of the operations were generated from the discrete uniform distribution with a range of [1, 10R] at the two levels (1 and 10) for R, that is, a parameter for the range of processing times.

Table I. Performance of the B&B algorithm [4]

n	*R*=1			*R*=10		
	ACPUT†	MCPUT‡	NPNS#	ACPUT	MCPUT	NPNS
20	0.07	0.01	0	499.54	0.04	7
30	0.10	0.05	0	504.18	0.17	7
50	0.95	0.51	0	748.80	1.32	9
100	10.01	7.83	0	781.73	32.44	10
200	165.15	125.74	0	2782.11	2732.32	10

† Average CPU time or lower bound on the average CPU time, which was computed assuming that the CPU time for a problem that has not been solved in 3600 seconds is 3600 seconds

‡ Median of CPU time

Number of problems (among 50 problems) that have not been solved in 3600 seconds

For the objective function of minimizing total tardiness, 10 problems for each of all combinations of six levels for the number of sub-jobs (20, 24, 26, 28, 32 and 36) and four pairs of values for (T, R), which were (0.1, 1.8), (0.1, 1.4), (0.3, 1.4) and (0.3, 1.2).

Table II. Performance of the suggested B&B algorithm [7]

Number of sub-jobs	(*T*, *R*)	ACPUT†	MCPUT‡	NPNS#
16	(0.3, 1.4)	0.74	0.12	0
	(0.3, 1.2)	0.98	0.53	0
	(0.4, 1.2)	0.82	0.56	0
	(0.4, 1.0)	6.46	1.92	0
	(0.5, 1.0)	4.74	1.96	0
	(0.5, 0.8)	2.92	2.74	0
18	(0.3, 1.4)	29.98	8.98	0
	(0.3, 1.2)	12.33	3.43	0
	(0.4, 1.2)	19.86	14.01	0
	(0.4, 1.0)	76.88	29.51	0
	(0.5, 1.0)	90.71	84.37	0
	(0.5, 0.8)	54.22	31.41	0
20	(0.3, 1.4)	105.38	9.25	0
	(0.3, 1.2)	578.47	288.25	0
	(0.4, 1.2)	460.49	294.03	0
	(0.4, 1.0)	520.52	211.08	0
	(0.5, 1.0)	494.52	455.24	0
	(0.5, 0.8)	827.49	655.01	0
22	(0.3, 1.4)	1637.20	954.41	4
	(0.3, 1.2)	639.15	81.09	1
	(0.4, 1.2)	713.44	343.59	1
	(0.4, 1.0)	2092.44	2403.48	5
	(0.5, 1.0)	2448.71	3600.01	6
	(0.5, 0.8)	3020.27	3600.01	7

† See the footnote of Table 3.

‡ Median of CPU time

Number of problems (among 10 problems) that were not solved to the optimality in 3600 seconds

B. Review Model 2 (M-machine Re-entrant flow Scheduling Problems in a Fab)

Choi [21, 22] suggested various heuristic algorithms for the m-machine re-entrant flowshop scheduling problems with the objective of makespan and total tardiness, respectively. In this research, the m-machine re-entrant flowshop considered here, all jobs must be processed L(≥2) times on each machine (m machines), that is, each job should be processed on machine 1, machine 2,…., machine m. Figure 3 shows a schematic view of an m-machine re-entrant flowshop.

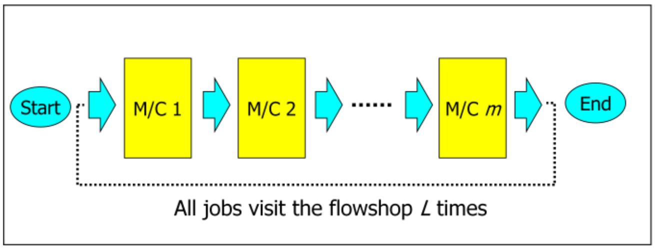

Fig 3. A m-machine re-entrant flowshop

In these researches, various heuristic algorithms and dist\patching rules were developed for the problems. For evaluation of the performance of the algorithms, computational experiments are performed on randomly generated test problems.

For the objective function of minimizing makespan, the below results of 60 problems were generated in the following way, 10 problems for each of the following problem sizes, i.e., the numbers of sub-jobs (number of jobs × number of passes) and machines: (25×4, 20), (50×4, 10), (50×4, 20) and (100×5, 20). Processing times of the sub-jobs were generated from the discrete uniform distribution with a range of [1, 99]. The details of the heuristics can be shown in the paper of Choi [21].

For the scheduling problems with the objective of minimizing total tardiness, to evaluate performance of the algorithms suggested in this chapter, Choi [22] performed a series of tests on randomly generated test problems. For this series of tests, the processing times of the operations were generated from the discrete uniform distribution with a range of [1, 100]. Then, due dates of the jobs are generated using two parameters, T (tardiness factor) and R (due date range). The due dates of the jobs are generated from a discrete uniform distribution [P(1－T－R/2), P(1－T + R/2)], where P is the sum of the processing times of all operations divided by 2 (the number of machines) [22]. We generated 540 problems randomly, 5 problems for each of all combinations of three levels (20, 50 and 100) for the number of jobs, three levels (2, 5 and 10) for the number of machines, three levels (2, 4 and 6) for the number of passes that should be made for each job and four levels for parameters used to generate due dates of jobs, where the selected pairs (T, R) were (0.2, 0.5), (0.2, 1), (0.5, 0.5) and (0.5, 1) [22]. The details of the heuristics can be shown in the paper of Choi [22].

Table III. Performance of the suggested algorithms [21]

Algorithms	(25×4, 5) †	(25×4, 10)	(25×4, 20)	(50×4, 10)	(50×4, 20)	(100×5, 20)
LBB+MN3	1.66, 7‡	8.03, 0	26.17, 0	3.07, 2	11.08, 0	1.38, 8
ITB+MN3	1.57, 7	7.81, 0	26.73, 0	3.05, 2	12.40, 0	1.21, 7
HLI1+MN3	1.61, 6	7.06, 0	26.37, 0	3.14, 1	12.38, 0	1.72, 6
HLI2+MN3	1.47, 7	7.82, 0	26.73, 0	2.93, 3	12.40, 0	1.00, 9
Random+MN3	1.68, 7	7.99, 0	26.17, 0	3.04, 2	12.01, 0	1.31, 7
LBB+MN3+SO	1.49, 7	6.59, 0	25.36, 0	2.73, 3	10.47, 0	1.19, 8
ITB+MN3+SO	1.39, 7	6.45, 0	24.24, 0	2.89, 3	11.08, 0	1.18, 8
HLI1+MN3+SO	1.32, 8	6.77, 0	23.02, 0	2.75, 4	11.12, 0	1.18, 8
HLI2+MN3+SO	1.11, 9	6.47, 0	24.24, 0	2.77, 4	11.08, 0	0.99, 9
Random+MN3+SO	1.51, 8	6.51, 0	24.67, 0	2.92, 3	11.24, 0	1.20, 8

† (n×L, m), where n, L and m denote the number of jobs, the number of passes required for each job, and the number of machines, respectively

‡ Average of percentage gaps of heuristic solutions from a lower bound and number of problems (out of 10 problems) for which the algorithm found solutions for which the percentage gap is less than 2%.

Table IV. Performance of the constructive or sub-improvement heuristic algorithms [22]

Algorithms	Percentage gap (%)†	Number of best solutions‡
MEDDp	0.51 (0.38)	52
MSLACKp	0.61 (0.39)	42
MMDDp	0.37 (0.30)	88
Random+MN1	0.56 (0.36)	45
MEDDp+MN1	0.47 (0.39)	69
MSLACKp+MN1	0.53 (0.37)	63
MMDDp+MN1	0.36 (0.32)	87
Random+MN2	0.46 (0.39)	54
MEDDp+MN2	0.32 (0.37)	95
MSLACKp+MN2	0.38 (0.38)	63
MMDDp+MN2	0.24 (0.22)	137

Random+MN3	0.21 (0.27)	188
MEDDp+MN3	0.16 (0.31)	226
MSLACKp+MN3	0.19 (0.34)	207
MMDDp+MN3	0.06 (0.18)	299
Random+MN1+SI	0.53 (0.39)	105
MEDDp+MN1+SI	0.36 (0.37)	164
MSLACKp+MN1+SI	0.32 (0.37)	117
MMDDp+MN1+SI	0.27 (0.24)	126
Random+ MN2+SI	0.38 (0.40)	117
MEDDp+MN2+SI	0.29 (0.37)	149
MSLACKp+MN2+SI	0.31 (0.39)	129
MMDDp+MN2+SI	0.29 (0.22)	131
Random+ MN3+SI	0.19 (0.27)	216
MEDDp+MN3+SI	0.15 (0.31)	231
MSLACKp+MN3+SI	0.17 (0.34)	212
MMDDp+MN3+SI	0.06 (0.18)	305
SA1	0.20 (0.26)	183
SA2	0.22 (0.14)	199

†Average (standard deviation in parenthesis) of relative deviation indexes (RDIs)

‡Number of problems (out of 540 problems) for which the algorithm found the best solutions

C. Review Model 3 (Hybrid Re-entrant flow Scheduling Problem in a Fab)

Choi [20] suggested various heuristic algorithms for the hybrid re-entrant flowshop scheduling problems with the objective of makespan. In the shop, there are one or more identical parallel machines at each stage, and each order is composed of several identical lots, and an order is specified by the product type associated with the order, the order size, i.e., the number of products to be processed for the order, and the due date [20]. Figure 5 shows a schematic view of a hybrid re-entrant flowshop. The details of the heuristics can be shown in the paper of Choi [20].

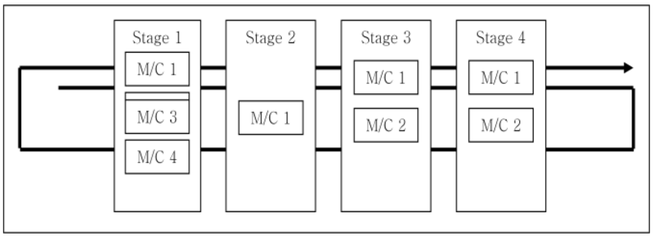

Fig 4. A schematic view of hybrid re-entrant flowshop

We generated 324 problem instances, 4 problems for each of all combinations of three levels for the number of orders (10, 15 and 20), three levels for the number of stages (4, 6 and 8), and nine levels for parameters used to generate due dates of orders. In the test problems, tightness of due dates are controlled by two parameters, T and R, called tardiness factor and due date range, respectively, and the nine selected pairs (T, R) were (0.1, 0.8), (0.1, 1.0), (0.1, 1.2), (0.1, 1.4), (0.1, 1.6), (0.3, 0.8), (0.3, 1.0), (0.3, 1.2) and (0.5, 0.8).

Table V. Performance of the algorithms [20]

Algorithms		Relative deviation index		NBS‡
		average	Std. dev.†	
List scheduling algorithms with priority rules	Random	0.986	0.064	0
	EDD	0.183	0.123	0
	SL1	0.239	0.151	1
	S/RMOP1	0.216	0.122	0
	S/RMWK1	0.325	0.169	0
	MDD1	0.137	0.106	7
	MOD1	0.144	0.115	4
	COVERT1	0.287	0.128	0
	ATC1	0.335	0.131	0
	SL2	0.170	0.120	0
	S/RMOP2	0.212	0.126	0
	S/RMWK2	0.225	0.128	0
	MDD2	0.171	0.117	1
	MOD2	0.178	0.121	0
	COVERT2	0.401	0.163	0
	ATC2	0.328	0.128	0
	SL3	0.395	0.198	0
	S/RMOP3	0.437	0.206	0
	S/RMWK3	0.514	0.193	0
	MDD3	0.471	0.240	1
	MOD3	0.506	0.205	0
	COVERT3	0.404	0.197	0
	ATC3	0.426	0.173	0
Lot-based algorithms	LMN1	0.303	0.162	0
	LMN2	0.123	0.084	7
Order-based algorithms	OMN1	0.010	0.033	218
	OMN2	0.037	0.061	91

† Standard deviation

‡ Number of problems (out of 324 problems) for which the algorithm found the best solutions

IV. CONCLUSION

In this paper, we review three topics on re-entrant flowshop scheduling with throughput and due date-related measures. All topics in this paper are motivated by scheduling problems in real manufacturing companies such as semiconductor manufacturing line. This topics or scheduling problems can be extended in the following several directions. In the previous researches, researchers developed various efficient optimal and heuristic algorithms to solve problems of practical sizes for re-entrant flowshop scheduling problems with the throughput and due date-related measures. Also, scheduling problems with m-machine re-entrant flowshop, that is the general case of two-machine re-entrant flowshop, can be considered when developing optimal solution algorithms, although solving the problem would be more difficult than that of two-machine re-entrant flowshop [3]. In addition, we needs to consider various characteristics of scheduling situation in real manufacturing systems to be used in real fab.

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