

Incorporating Customer Responsiveness When Solving Blocking Flowshop Scheduling Problems

Amy Cohn and Selin Kurnaz
University of Michigan



Michigan**Engineering**
Industrial and Operations Engineering



Motivation

- Vast literature on scheduling in blocking flowshops
 - ◆ Fundamental structure underlying much of manufacturing
 - ◆ Combinatorially very challenging
 - ◆ Terrible LP relaxations
- Also significant criticism of this literature
 - ◆ Overly simplistic models
 - ◆ Lots of real-world complexity that isn't addressed
- Our interest stems from reconfigurable manufacturing, and issues of customer change

Background: Blocking Flowshop

- Group of products
- Series of production stages
- Each product spends different times at each stage

Example:

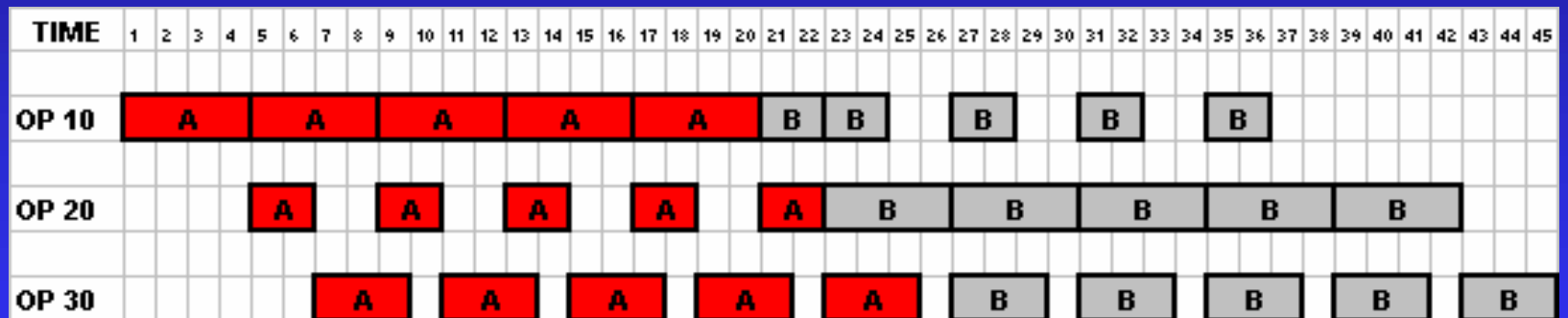
Products	Stage 1	Stage 2	Stage 3	Demand
A	4	2	3	5
B	2	4	3	5
Total				10

Computing Makespan

- The *makespan* is the time it takes for all products in an order (e.g. 5 A's and 5 B's) to move through the system
- Differences in production time by product and stage can create bottlenecks
- Order in which products are produced impacts makespan

Makespan Example

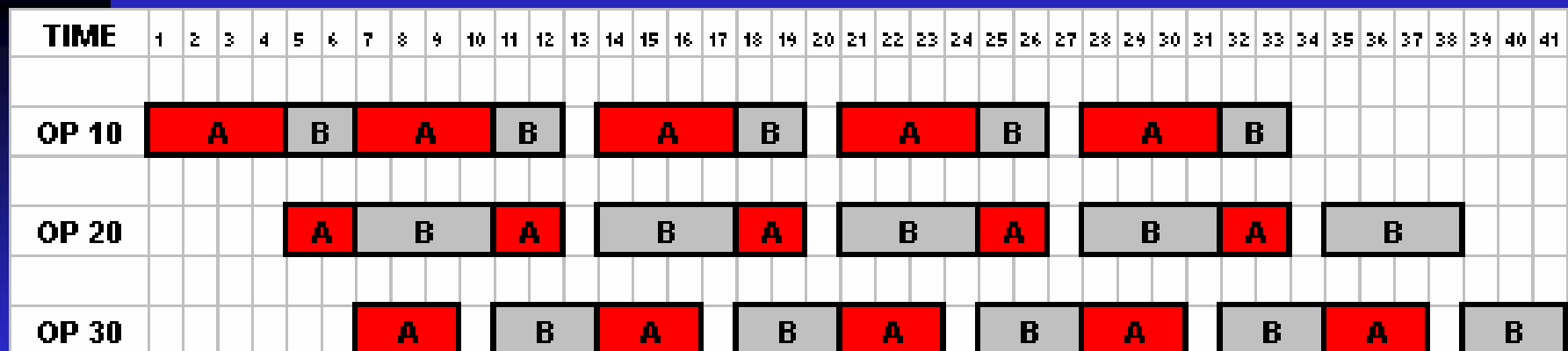
If we first produce all of product A, then all of product B, the makespan will be 45:



Makespan Example, cont.

Makespan depends directly on the sequence.

Here, alternating one unit of A with one unit of B leads to a makespan of 41:



Makespan Example, cont.

Optimal sequence is B A A B A B A B A B with a makespan of 40

[illegible]

Project Goal

- The typical objective in the literature is to sequence products so as to minimize *makespan* (i.e. time-to-completion)
- Our goal is to extend the definition of “optimality” to begin incorporating issues of *customer responsiveness*

Customer Responsiveness

- Customer responsiveness is loosely defined as “providing the customer with what they want when they want it”
 - ◆ Recognition of decreasing lead times and growing power of the customer
 - ◆ Order changes are often permitted without penalty, sometimes even beyond the point when production has begun

Simple Example

- Initial order for 100 units of A, 100 units of B, with final due date T
- If the flowshop is balanced by product, then “optimal” solution is 100 A followed by 100 B (minimizes change-overs)
- What if the customer changes the order to 50 A's, 150 B's at time $T/2$?
 - ◆ Over production of A
 - ◆ Under production of B (not enough time to complete new demand)
- What if the original production sequence was to alternate 1A / 1B? 5A / 5B? 25A / 25B?

Computational Observation

- Many distinct optimal or near optimal solutions
- Vary significantly in other characteristics
- Definition of responsiveness:
 - ◆ Divide the planning horizon into Q intervals
 - ◆ For each interval, compare the quantity of product p produced in this interval to one Q^{th} of the demand for product p (responsiveness is capped at one)
 - ◆ Responsiveness metric sums these terms
 - ◆ Goal is to evenly distribute production over the planning horizon

Basic Model

■ Parameters:

- ◆ P : Number of distinct product types
- ◆ d_p : Demand for product type p
- ◆ N : Total number of “slots” in the production sequence
- ◆ S : Number of operational stages
- ◆ $\alpha_{p,s}$: Processing time of product p at stage s
- ◆ δ_p : Change-over time required to move to product type p

■ Decision variables:

- ◆ $t_{n,s}$: Time at which the n th product in the production sequence enters stage s
- ◆ $x_{n,p}$: 1 if the n th product slot in the production sequence is assigned to product type p , else 0
- ◆ $c_{n,p}$: 1 if there is change-over of product type between the $n-1^{\text{th}}$ and n^{th} slots in the sequence, else 0

Basic Model

- Objective:

Minimize $t_{N,(S+1)}$

- Constraints:

$$t_{1,1} = 0$$

$$t_{1,s} = t_{1,(s-1)} + \sum_{p=1..P} \alpha_{p,(s-1)} * x_{1,p} \quad \forall s$$

$$t_{n,1} = t_{(n-1),2} \quad \forall n$$

$$t_{n,s} \geq t_{n,(s-1)} + \sum_{p=1..P} \alpha_{p,(s-1)} * x_{n,p} \quad \forall n, s$$

$$t_{n,s} \geq t_{(n-1),(s+1)} + \sum_{p=1..P} \delta_p * c_{n,p} \quad \forall n, s$$

$$\sum_{p=1..P} x_{n,p} = 1 \quad \forall n$$

$$\sum_{p=1..P} x_{n,p} = d_p \quad \forall p$$

$$c_{n,p} \geq x_{n,p} - x_{(n-1),p} \quad \forall n, p$$

$$x_{n,p}, c_{n,p} \in \{0,1\} \quad \forall n, p$$

$$t_{n,s} \geq 0 \quad \forall n, s$$

Computational Observation

■ Example:

- ◆ 30 problem instances
- ◆ 4 products each
- ◆ 10 have balance within and across products
- ◆ 10 have balance within but not across products
- ◆ 10 have no balance
- ◆ 5% optimality gap

Computational Observation (No Changeover)

Instance	# "Opt" solutions	Makespan		Change-over		Responsiveness	
		Min	Max	Min	Max	Min	Max
1	90	870	907	9	34	54.25	84
2	68	870	900	17	34	60.5	88.5
3	37	870	900	17	34	57.25	91.75
4	14	870	879	19	34	62.25	93.25
5	11	919	927	15	26	51.25	84
6	13	878	886	12	28	41.5	81.75
7	26	874	884	5	32	50	83
8	19	882	928	4	34	40.5	90.5
9	17	882	914	10	34	49.75	88
10	10	898	914	10	31	53	92.25
11	3	1221	1255	4	7	40.5	56.25
12	3	1221	1238	7	7	46.5	49.75
13	5	1221	1228	6	9	43.5	62.5
14	2	1084	1084	4	4	46.75	46.75
15	2	1337	1346	8	13	46.75	56.25
16	2	1217	1217	3	8	41.5	45.5
17	2	970	1018	6	22	53	68.5
18	57	1070	1095	3	11	25	65.5
19	7	1204	1204	9	9	49.5	49.5
20	6	1148	1162	3	7	35.25	56.25
21	25	1449	1506	5	22	42	74.25
22	5	1268	1274	3	33	34.25	96.75
23	33	1479	1518	7	26	39	80.75
24	2	1506	1508	10	22	42	68.25
25	3	1533	1533	3	6	25	31
26	209	1018	1073	5	26	25	40.5
27	13	1207	1219	12	24	51.75	72.75
28	12	1001	1018	14	28	52	79
29	40	1189	1237	14	30	58.5	81.75
30	17	1229	1237	20	30	57.75	79

Computational Observation (Low Changeover)

Instance	# "Opt" solutions	Makespan		Change-over		Responsiveness	
		Min	Max	Min	Max	Min	Max
1	37	940.2	974.4	3	6	38.75	46.75
2	35	942.9	976	3	6	38.75	48.25
3	21	934	974.4	4	6	42	48.25
4	7	934	973.4	4	19	39	53
5	8	957.6	976	4	6	38.75	46.75
6	18	916.4	940	3	7	35.25	56.25
7	21	913.6	917.9	4	34	39.5	86
8	1	967.2	967.2	4	4	43.75	43.75
9	1	932.7	932.7	4	4	39.25	39.25
10	4	954.2	959.3	5	6	45.5	49.75
11	2	1283.9	1288.5	4	4	42	46.75
12	2	1264.1	1283.9	3	4	37.5	46.75
13	3	1261.2	1261.4	4	33	43.5	93.5
14	1	1096.5	1096.5	3	3	34.25	34.25
15	2	1359.3	1363.4	3	4	41.75	43.75
16	1	1222.7	1222.7	3	3	37.5	37.5
17	1	1011	1011	4	4	45.5	45.5
18	2	1110.4	1112.4	4	4	37	37.5
19	5	1183.1	1232.9	3	4	35.25	50
20	4	1183.1	1193	3	4	35.25	46.75
21	550	1476.3	1552.6	3	11	34.25	62.5
22	1	1366.7	1366.7	6	6	51.25	51.25
23	43	1591.5	1641.6	4	7	32.5	59.25
24	2	1574.5	1579	6	7	37.5	56.25
25	41	1591.5	1641.6	4	7	34	62.5
26	1	1063.1	1063.1	3	3	43.75	43.75
27	1	1272.1	1272.1	4	4	44.5	44.5
28	176	1056.4	1076.9	3	6	33	56.25
29	2	1245.5	1297	3	4	37.5	41.5
30	1	1297	1297	3	3	41.5	41.5

Computational Observation (High Changeover)

Instance	# "Opt" solutions	Makespan		Change-over		Responsiveness	
		Min	Max	Min	Max	Min	Max
1	4	3237	3324	3	3	40.5	43.75
2	2	3237	3258	3	3	40.5	43.75
3	3	3237	3324	3	3	40.5	43.75
4	1	3190	3190	3	3	37.5	37.5
5	2	3237	3324	3	3	40.5	43.75
6	4	3218	3282	3	3	35.25	43.75
7	2	3217	3218	3	7	41.5	50
8	4	3366	3410	3	3	22.5	25
9	17	3253	3302	3	3	33	41.5
10	1	3335	3335	3	3	35.25	35.25
11	8	3331	3523	3	3	34.25	43.75
12	6	3431	3523	3	3	34.25	43.75
13	1	4133	4133	3	3	43.75	43.75
14	2	3324	3361	3	3	34.25	40.5
15	8	3431	3641	3	3	34.25	43.75
16	8	3252	3397	3	3	35.25	43.75
17	6	3234	3279	3	3	35.25	43.75
18	3	3226	3368	3	3	22.5	25
19	7	3331	3641	3	3	33	41.5
20	2	3379	3409	3	3	35.25	35.25
21	1	4133	4133	3	3	43.75	43.75
22	7	3909	4025	3	3	34.25	43.75
23	23	4926	5171	3	3	34.25	43.75
24	15	4904	5132	3	3	34.25	43.75
25	1	4772	4772	3	3	25	25
26	2	3431	3440	3	3	35.25	43.75
27	2	3639	3641	3	3	37.5	41.5
28	19	3253	3331	3	3	33	41.5
29	2	3722	3735	3	3	33	39.5
30	6	3971	3991	3	3	33	41.5

Three Variations

- Variation One: Optimize makespan, then optimize responsiveness while maintaining makespan within 10% of optimal
- Variation Two: Optimize responsiveness, then optimize makespan while maintaining responsiveness within 10% of optimal
- Variation Three: Optimize weighted average of makespan and responsiveness

Variation One (Low Changeover)

Instance	Makespan	Responsiveness	Increase in Makespan	Increase in Responsiveness	
				Min	Max
1	1034	100	9.98%	53.25%	61.25%
2	1037	100	9.98%	51.75%	61.25%
3	1027	100	9.96%	51.75%	58.00%
4	1027	100	9.96%	47.00%	61.00%
5	1053	100	9.96%	53.25%	61.25%
6	1008	100	10.00%	43.75%	64.75%
7	1005	100	10.00%	14.00%	60.50%
8	1064	100	10.01%	56.25%	56.25%
9	1026	100	10.00%	60.75%	60.75%
10	1050	100	10.04%	50.25%	54.50%
11	1412	87.5	9.98%	40.75%	45.50%
12	1391	81.25	10.04%	34.50%	43.75%
13	1387	93.75	9.97%	0.25%	50.25%
14	1206	84.38	9.99%	50.13%	50.13%
15	1495	93.75	9.98%	50.00%	52.00%
16	1345	79.17	10.00%	41.67%	41.67%
17	1112	87.5	9.99%	42.00%	42.00%
18	1221	81.25	9.96%	43.75%	44.25%
19	1301	75	9.97%	25.00%	39.75%
20	1301	100	9.97%	53.25%	64.75%
21	1624	100	10.00%	37.50%	65.75%
22	1503	100	9.97%	48.75%	48.75%
23	1751	100	10.02%	40.75%	67.50%
24	1732	100	10.00%	43.75%	62.50%
25	1751	100	10.02%	37.50%	66.00%
26	1169	100	9.96%	56.25%	56.25%
27	1399	100	9.98%	55.50%	55.50%
28	1162	100	10.00%	43.75%	67.00%
29	1370	100	10.00%	58.50%	62.50%
30	1427	95.83	10.02%	54.33%	54.33%

Variation One (High Changeover)

Instance	Makespan	Responsiveness	Increase in Makespan	Increase in Responsiveness	
				Min	Max
1	3561	43.75	10.01%	0.00%	3.25%
2	3561	43.75	10.01%	0.00%	3.25%
3	3561	43.75	10.01%	0.00%	3.25%
4	3509	43.75	10.00%	6.25%	6.25%
5	3561	43.75	10.01%	0.00%	3.25%
6	3540	43.75	10.01%	0.00%	8.50%
7	3539	50	10.01%	0.00%	8.50%
8	3703	25	10.01%	0.00%	2.50%
9	3578	41.67	9.99%	0.17%	8.67%
10	3669	43.75	10.01%	8.50%	8.50%
11	3664	43.75	10.00%	0.00%	9.50%
12	3774	43.75	10.00%	0.00%	9.50%
13	4546	56.25	9.99%	12.50%	12.50%
14	3656	43.75	9.99%	3.25%	9.50%
15	3774	43.75	10.00%	0.00%	9.50%
16	3577	43.75	9.99%	0.00%	8.50%
17	3557	43.75	9.99%	0.00%	8.50%
18	3549	25	10.01%	0.00%	2.50%
19	3664	41.67	10.00%	0.17%	8.67%
20	3717	41.67	10.00%	6.42%	6.42%
21	4546	43.75	9.99%	0.00%	0.00%
22	4300	43.75	10.00%	0.00%	9.50%
23	5419	43.75	10.01%	0.00%	9.50%
24	5394	43.75	9.99%	0.00%	9.50%
25	5249	25	10.00%	0.00%	0.00%
26	3774	43.75	10.00%	0.00%	8.50%
27	4003	43.75	10.00%	2.25%	6.25%
28	3578	41.67	9.99%	0.17%	8.67%
29	4094	41.67	9.99%	2.17%	8.67%
30	4368	41.67	10.00%	0.17%	8.67%

Variation Two (Low Changeover)

Instance	Makespan	Responsiveness	Reduction in Makespan	Reduction in Responsiveness
1	988.3	90.63	54.12%	9.38%
2	987.7	90	53.40%	10.00%
3	983.9	90.63	54.07%	9.38%
4	960.7	90	54.05%	10.00%
5	983.9	90.63	55.24%	9.38%
6	968.8	91.67	54.27%	8.33%
7	964.9	90	54.32%	10.00%
8	1013.8	90	54.17%	10.00%
9	984.1	90	53.72%	10.00%
10	995.6	90	53.82%	10.00%
11	1424.2	90	51.99%	10.00%
12	1415.5	90	52.98%	10.00%
13	1388.7	90.63	53.30%	9.38%
14	1266.1	90	55.42%	10.00%
15	1491.9	90	50.59%	10.00%
16	1387	90	53.72%	10.00%
17	1155.1	90	57.92%	10.00%
18	1248.8	90	54.50%	10.00%
19	1380.9	92.71	54.02%	7.29%
20	1330.7	90	51.72%	10.00%
21	1560.6	90	46.16%	10.00%
22	1414.1	90	48.19%	10.00%
23	1690.4	90	48.74%	10.00%
24	1617.4	90.63	50.96%	9.38%
25	1660.8	90.63	50.02%	9.38%
26	1136.8	90	52.72%	10.00%
27	1332.6	90	49.15%	10.00%
28	1135.6	90	51.74%	10.00%
29	1304.7	92.71	50.49%	7.29%
30	1395.8	92.71	50.44%	7.29%

Variation Two (High Changeover)

Instance	Makespan	Responsiveness	Makespan	sponsiveness
1	9577	90	92.38%	10.00%
2	9435	90	92.33%	10.00%
3	9650	93.75	92.32%	6.25%
4	9346	90	92.37%	10.00%
5	9784	90	92.36%	10.00%
6	9450	90	92.41%	10.00%
7	9479	90	92.36%	10.00%
8	9904	90	92.36%	10.00%
9	10353	90	91.69%	10.00%
10	9746	90	92.32%	10.00%
11	9499	90.63	93.57%	9.38%
12	9812	90	93.53%	10.00%
13	9847	90	93.46%	10.00%
14	9864	90	93.60%	10.00%
15	13760	90	90.90%	10.00%
16	10391	90	93.11%	10.00%
17	9783	90	93.62%	10.00%
18	9504	90	93.54%	10.00%
19	11598	90	92.43%	10.00%
20	9635	90	93.55%	10.00%
21	11253	90	92.32%	10.00%
22	10744	90	92.56%	10.00%
23	0	0	100.00%	100.00%
24	13713	90	92.45%	10.00%
25	13328	90	92.52%	10.00%
26	9692	91.67	92.69%	8.33%
27	10121	90	92.68%	10.00%
28	10266	90	92.06%	10.00%
29	11520	90	91.87%	10.00%
30	12662	90	91.83%	10.00%

Variation Three

- Extreme cases may have strong inverse correlations between makespan and responsiveness
 - ◆ Near-optimal makespans may have very poor responsiveness
 - ◆ Near-optimal responsiveness may imply very high makespan
- Alternative:
 - ◆ Remove constraints bounding makespan, responsiveness
 - ◆ Minimize weighted sum of both objectives

Conclusions and Future Research

- Many different solutions to the blocking flowshop problem may have optimal or near-optimal makespans
- Other characteristics may vary substantially
- *Customer responsiveness* is one important criterion to consider
 - ◆ What are other measures of responsiveness?
 - ◆ What are other characteristics to take into consideration?