An MILP Approach for Short-term Scheduling of Batch Operations

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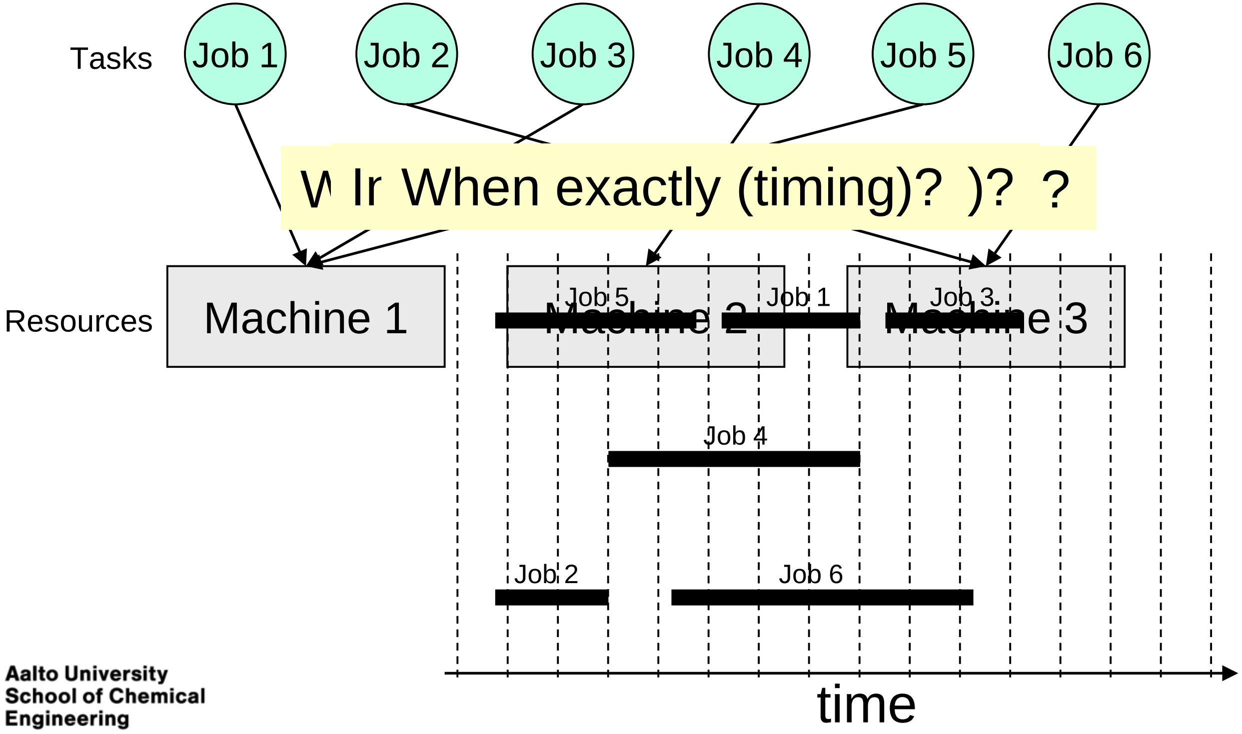
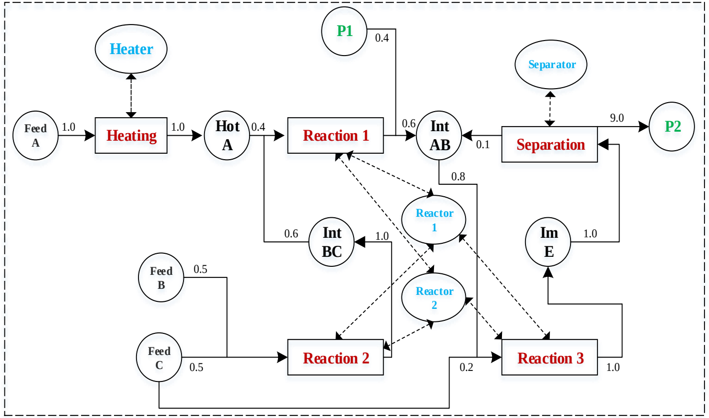
Scheduling → 3 Key-decisions



Introduction

Batch Plant Scheduling

- Optimal allocation of a set of limited resources to some tasks over time
- Generic representations of batch process: Resource-Task Network (Pantelides, 1994) and State-task Network (Kondili et al., 1993)



Resource-Task Network

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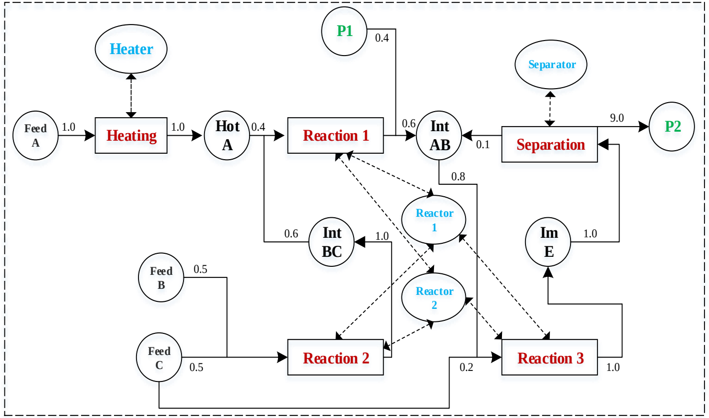
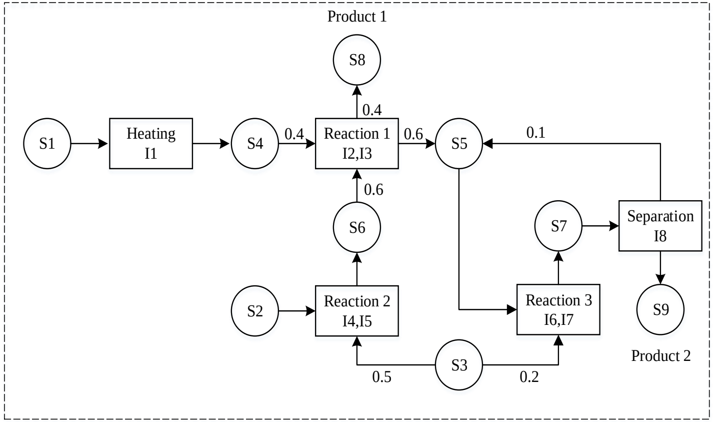


Resource-Task Network



State-Task Network

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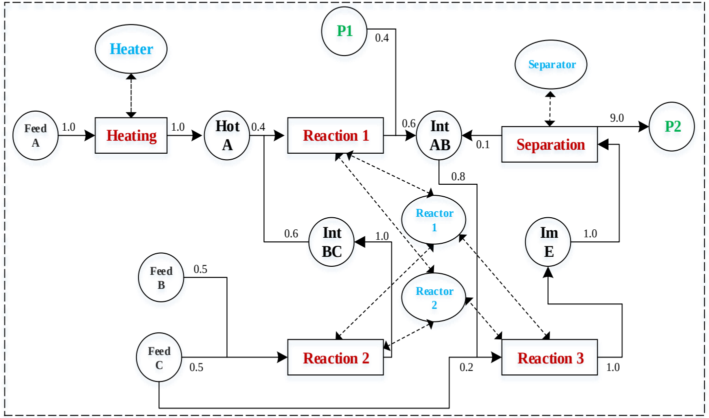
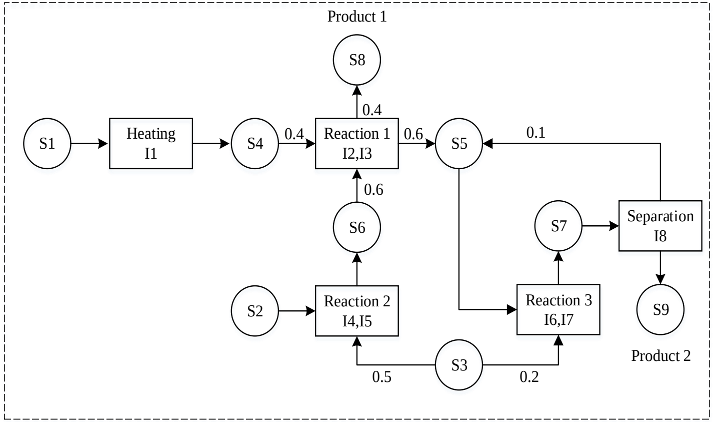
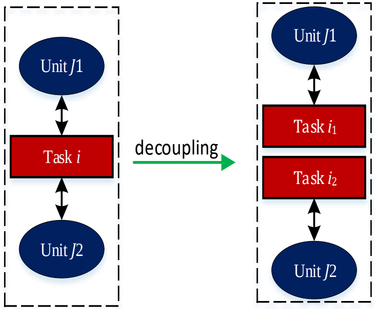


Resource-Task Network

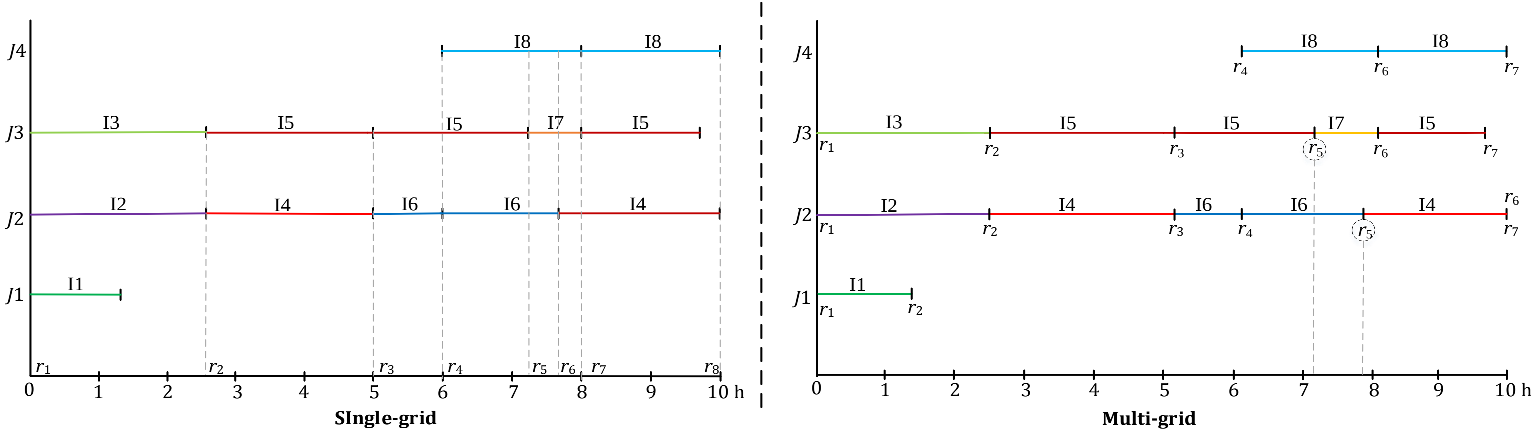


State-Task Network



Time representation

- **Common reference grid (Single-grid, SG)**
  - The time slots are common for all units
- **Non-common reference grid (Multiple-grid, MG)**
  - The occurrences of each event can vary across the units



Common constraints for SG and MG

Batch size and processing time

- $X_{i,r,r'}$ = 1 task i is processed during time interval $[r, r']|_{r<r'\leq\Delta r+r}$
- $V_{i,r,r'}$ = batch size of task i during time interval $[r, r']|_{r<r'\leq\Delta r+r}$
- $LR_{i,r,r'}$ = processing time of task i during time interval $[r, r']|_{r<r'\leq\Delta r+r}$

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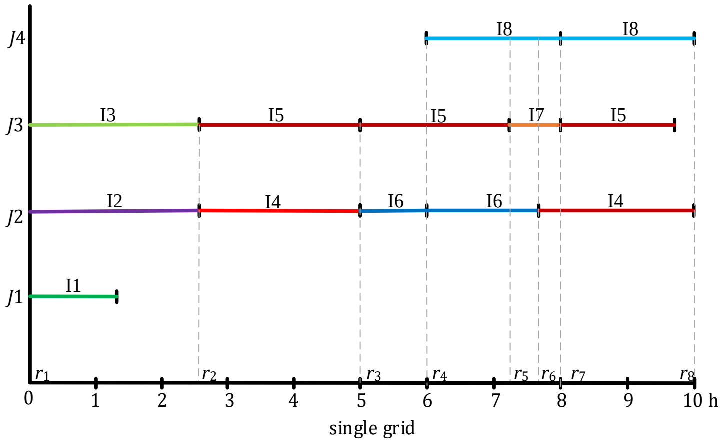
$$\bigvee_{i\in I_j}\begin{bmatrix} X_{i,r,r'} \\ v_i^{\min} \leq V_{i,r,r'} \leq v_i^{\max} \\ LR_{i,r,r'} = cp_i + vp_i V_{i,r,r'} \end{bmatrix} \underline{\bigvee} \begin{bmatrix} X_{r,r'}^{\text{no task}} \\ V_{i,r,r'} = 0, \quad \forall i \in I_j \\ LR_{i,r,r'} = 0, \quad \forall i \in I_j \end{bmatrix} \quad \forall j \in J, r, r'|_{r<r'\leq r+\Delta r}$$



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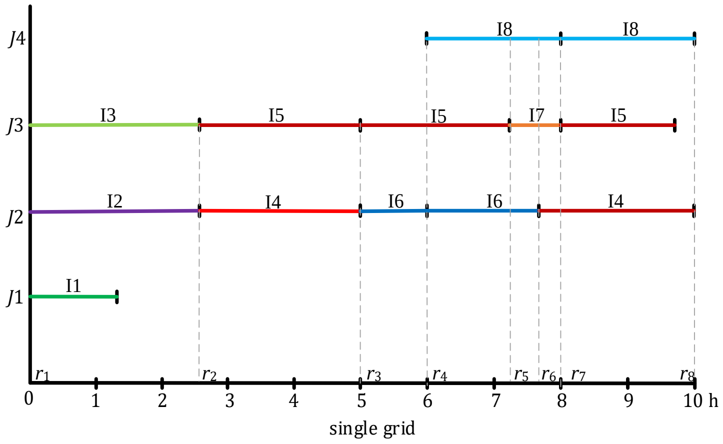


Convex hull reformulation

$$\sum_{i\in I_j} X_{i,r,r'} \leq 1, \quad \forall j \in J, r, r'|_{r<r'\leq r+\Delta r}$$

$$v_i^{\min} X_{i,r,r'} \leq V_{i,r,r'} \leq v_i^{\max} X_{i,r,r'} \quad \forall i \in I_j, j \in J, r, r'|_{r<r'\leq r+\Delta r}$$

$$LR_{i,r,r'} = cp_i X_{i,r,r'} + vp_i V_{i,r,r'} \quad \forall i \in I_j, j \in J, r, r'|_{r<r'\leq r+\Delta r}$$

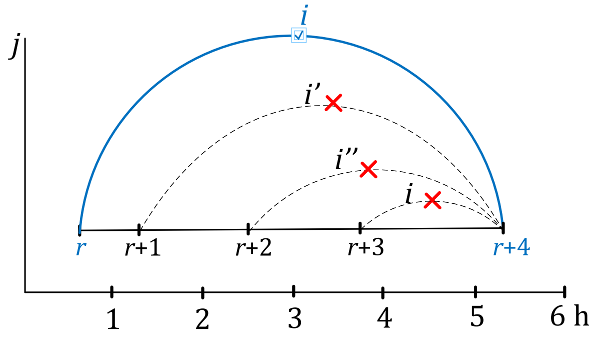
Common constraints for SG and MG

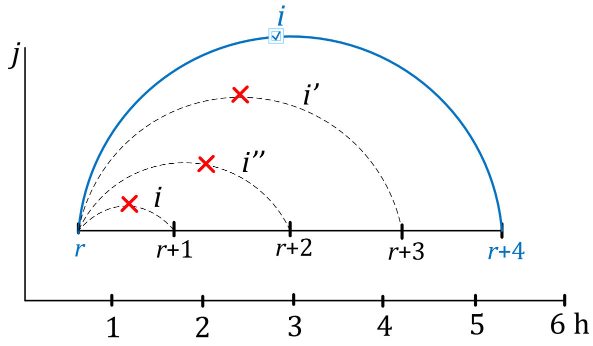
Allocation constraints

- For each unit only one task can start and finish at each time point

$$\bigvee_{i\in I_j} \; \bigvee_{\substack{r'\in R \\ r<r'\le r+\Delta r}} X_{i,r,r'} \;\underline{\bigvee}\; X^{no\,i}_{r,r'} \qquad \forall j \in J, r \in R$$

$$\bigvee_{i\in I_j} \; \bigvee_{\substack{r\in R \\ r<r'\le r+\Delta r}} X_{i,r,r'} \;\underline{\bigvee}\; X^{no\,i}_{r,r'} \qquad \forall j \in J, r' \in R$$





Common constraints for SG and MG

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- For each unit only one task can start and finish at each time point

$$\bigvee_{i \in I_j} \bigvee_{\substack{r' \in R \\ r < r' \leq r + \Delta r}} X_{i,r,r'} \veebar X_{r,r'}^{no\,i} \quad \forall j \in J, r \in R$$

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$$\sum_{\substack{r \in R \\ r < r' \leq r + \Delta r}} \sum_{i \in I_j} X_{i,r,r'} \leq 1 \quad \forall j \in J, r' \in R$$

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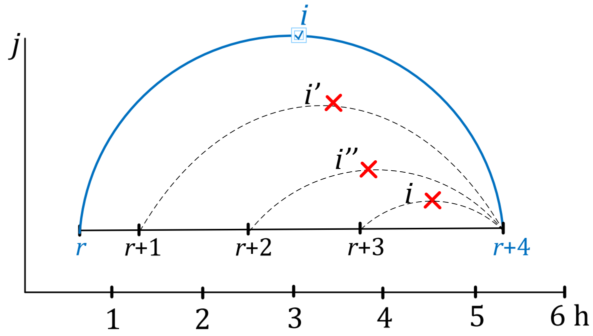

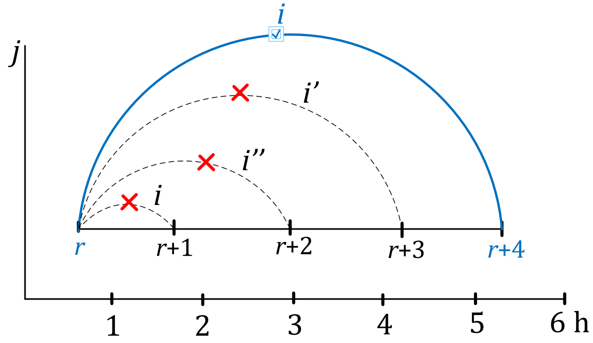

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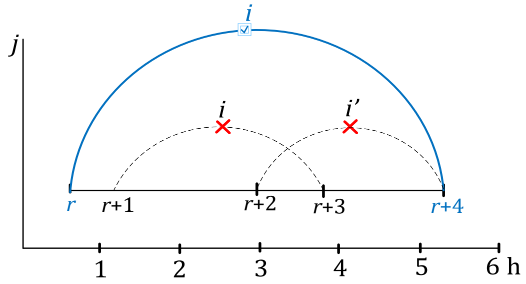
Common constraints for SG and MG

Allocation constraints

- Task i is processed in unit j during time interval$[r,r']|_{r+1<r'\leq r+\Delta r}$, the same or other tasks suitable in unit j cannot be processed in any time interval $[k,r''] \subseteq [r,r']$



$$X_{i,r,r'} \Rightarrow \neg\left(\bigvee_{\substack{r''\in R \\ k<r''\leq k+\Delta r}} X_{i',k,r''}\right) \quad \forall i,i' \in I_j, r, r', k \in R|_{r+1<r'\leq r+\Delta r, r+1\leq k, r'\geq k+1}$$

$$X_{i,r,r'} + \sum_{k<r''\leq k+\Delta r} X_{i',k,r''} \leq 1 \qquad \forall i,i' \in I_j, r, r', k \in R|_{r+1<r'\leq r+\Delta r, r+1\leq k, r'\geq k+1}$$

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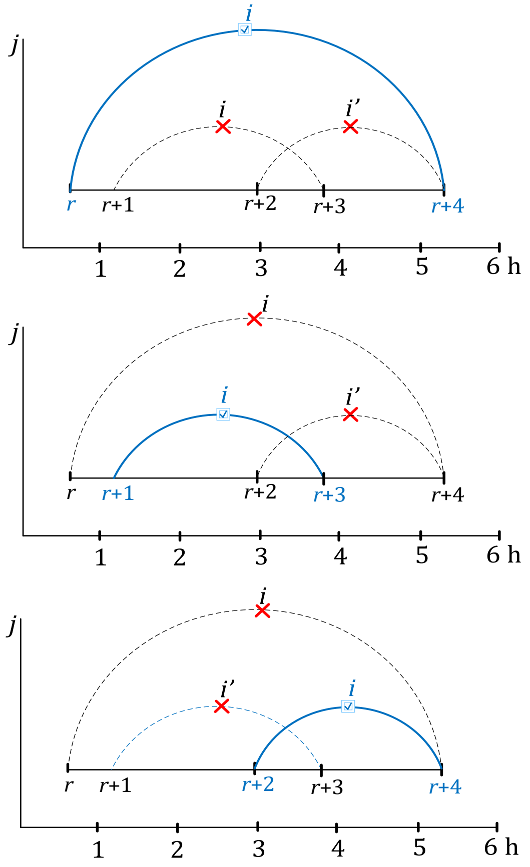

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Common constraints for SG and MG

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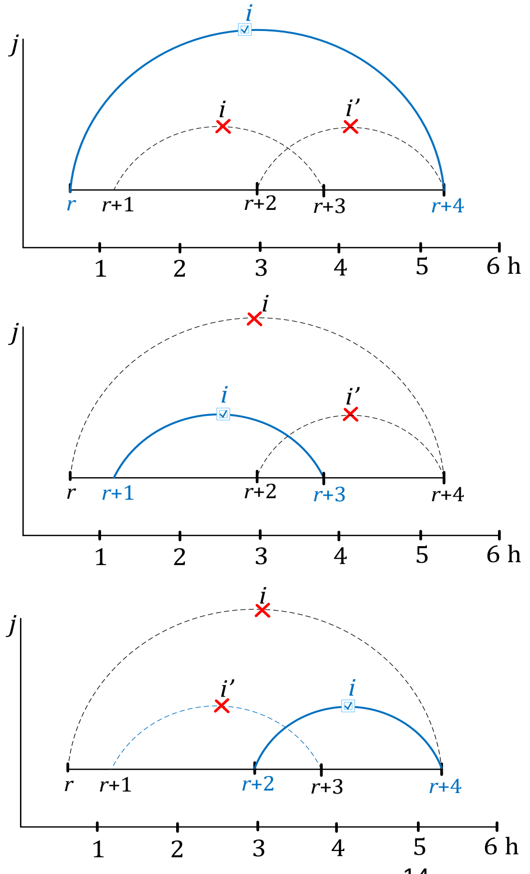
$$(P \Rightarrow Q) \equiv (\neg Q \Rightarrow \neg P)$$



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Common constraints for SG and MG

- **Mass balance**

$F_{s,r}$ excess amount of state s at time point r

$$F_{s,r} = f_s^0|_{r=1} + F_{s,r-1}|_{r>1} + \sum_{i \in I_s^p} \rho_{i,s}^p \sum_{\substack{r' \in R \\ r' < r \leq r' + \Delta r}} V_{i,r',r} + \sum_{i \in I_s^p} \rho_{i,s}^c \sum_{\substack{r' \in R \\ r < r' \leq r + \Delta r}} V_{i,r,r'} \quad \forall s \in S, r \in R$$

- **Meeting demand**

Demands (d_s) at states $s \in SM$ storing final products are enforced as a hard at

$$F_{s,r} \geq d_s, \quad \forall s \in SM, r = |R|$$

Timing constraints

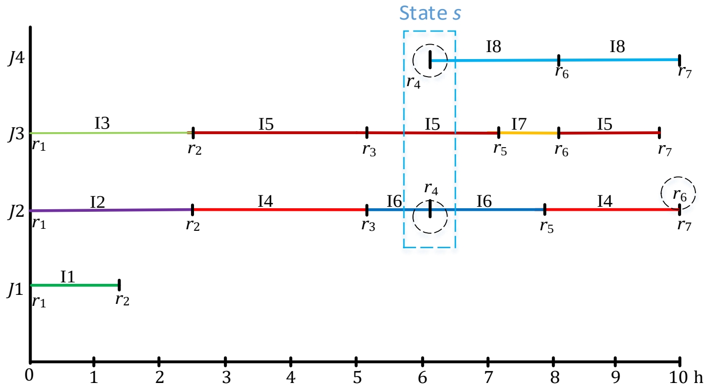
- **Timing constraints for MG**

➢ $SR_{j,r}$ the time that unit j starts at event point r

$$SR_{j,r'} \geq SR_{j,r} + \sum_{i \in I_j} LR_{i,r,r'} \quad \forall j \in J, r, r'|_{r<r' \leq r+\Delta r}$$

$$SR_{j,r'} \geq SR_{j',r} + \sum_{i \in I_{j'}} LR_{i,r,r'} \quad \forall j \in J_s^c, j' \in J_s^p (j \neq j'), s \in S, r, r'|_{r<r' \leq r+\Delta r}$$

$$SR_{j,r} + \sum_{i \in I_j} LR_{i,r,r'} \leq h_{\max} \quad \forall j \in J, r, r' \in R|_{r<r' \leq r+\Delta r}$$



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Timing constraints

- **Timing constraints for MG**

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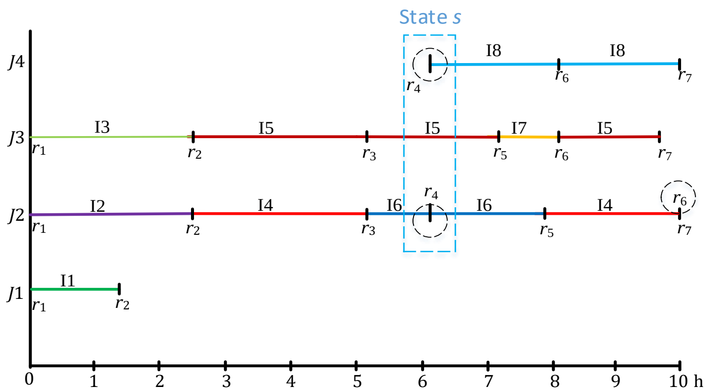
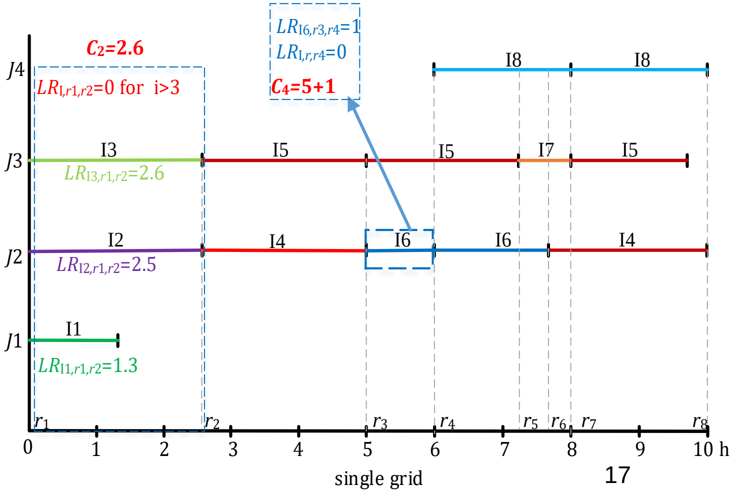
- **Timing constraints for SG**

➢ CR_r the absolute time of event point r

$$CR_{r'} - CR_r \geq LR_{i,r,r'} \quad \forall i \in I_j, j \in J, r, r' \in R|_{r<r' \leq r+\Delta r}$$

$$C_r \leq h_{\max} \quad \forall r \in R$$





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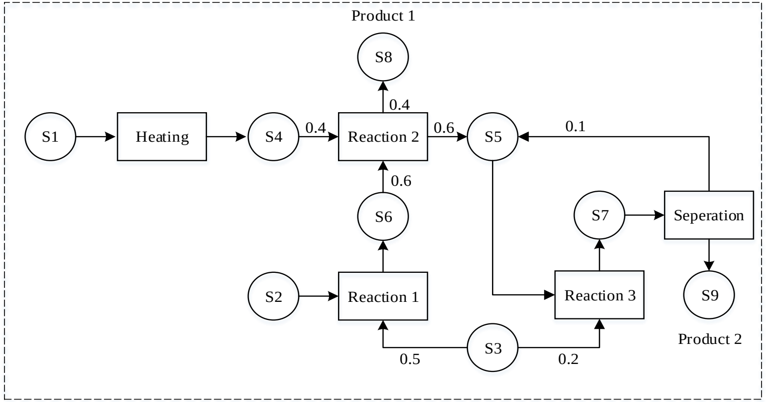
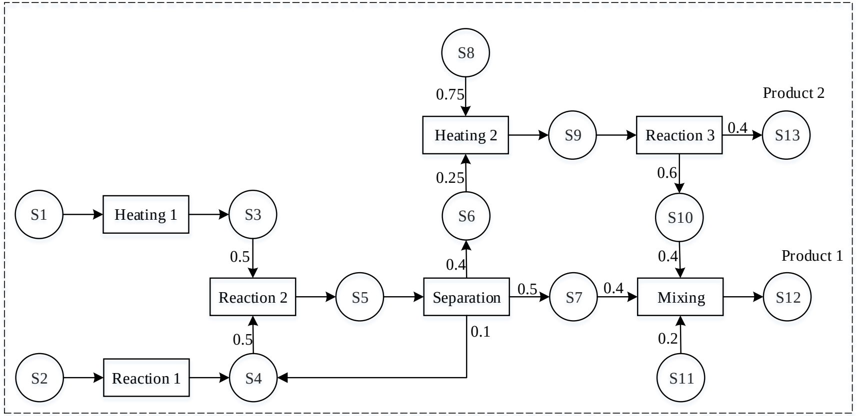
Results and discussion

- **Two benchmark problems Ex1-Ex2**
  - Maravelias and Grossmann 2003 (M&G) vs. SG
  - Shaik and Floudas 2009 (S&F) vs. MG
- **GAMS 24.9.1 / CPLEX 12.7.1**
  - Option optcr =10^{-3}
  - Option threads = 0
  - Option reslim = 7200 s.



State-task network representation for Ex 1



State-task network representation for Ex 2

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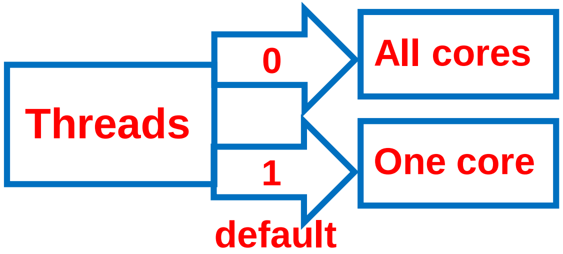
Results and discussion

- **Effect of threads on the CPU time and solution quality**
  - Cost maximization
  - Time horizon 10 h
  - Global optimum = 2358.2



Changing threads option from 0 to 1 increases the CPU time considerably!

Number of cores =4

Profit maximization

Optcr	S&F (8 event points , $\Delta n = 1$) CPU (s)	MILP ($)	RMILP ($)	MG (9 event points , $\Delta r = 2$) CPU (s)	MILP ($)	RMILP ($)
			Option threads = 0			
10^{-1}	10.96	2338.7	3618.6	9.35	2331.3	3618.6
10^{-2}	549.5	2345.3	3618.6	102.7	2345.3	3618.6
10^{-3}	353.7	2358.2	3618.6	119.6	2358.2	3618.6
10^{-4}	462.4	2358.2	3618.6	146.6	2358.2	3618.6
10^{-5}	462.7	2358.2	3618.6	145.7	2358.2	3618.6
10^{-6}	459.1	2358.2	3618.6	147.3	2358.2	3618.6
			Option threads = 1			
10^{-1}	31.9	2292.5	3618.6	51.65	2330.9	3618.6
10^{-2}	572.6	2345.3	3618.6	655.1	2358.2	3618.6
10^{-3}	875.4	2358.2	3618.6	947.6	2358.2	3618.6
10^{-4}	714.8	2358.2	3618.6	979.4	2358.2	3618.6
10^{-5}	710.7	2358.2	3618.6	950.5	2358.2	3618.6
10^{-6}	708.4	2358.2	3618.6	950.0	2358.2	3618.6

Results and discussion

- **Effect of threads on the CPU time and solution quality**
  - Cost maximization
  - Time horizon 10 h
  - **Global optimum = 2358.2**

Changing threads option also affect the Solution quality!

Profit maximization

	S&F (8 event points , $\Delta n = 1$)			MG (9 event points , $\Delta r = 2$)		
Optcr	CPU (s)	MILP ($)	RMILP ($)	CPU (s)	MILP ($)	RMILP ($)
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Results and discussion (SG vs. M&G)

Maximum revenue

- **Same number of event points**
- **Both perform equally in 3 cases**
- **SG performs better in 2b (10 times faster)**
- **Fewer constraints, but slighty more binary variables**
- **SG leads to weaker RMILP**

	Event points	CPU (s)	Binary variables	Total variables	Eqs.	MILP ($)	RMILP ($)
			Ex 1a ($H = 8\ h$)				
M&G	5	0.23	80	496	1095	1498.56	1730.8
SG	5 ($\Delta r = 1$)	0.04	32	147	212	1498.56	1730.8
	5 ($\Delta r = 2$)	0.06	56	219	368	1498.56	1730.8
			Ex 1b ($H = 10\ h$)				
M&G	8	25.01	128	793	1719	1962.69	2690.5
SG	8 ($\Delta r = 1$)	0.17	56	249	359	1860.72	2775.4
	8 ($\Delta r = 2$)	6.50	104	393	671	1958.99	2775.6
	8 ($\Delta r = 3$)	9.45	144	513	1031	1962.69	2775.6
	8 ($\Delta r = 4$)	10.87	176	609	1399	1962.69	2775.6
			Ex 2a ($H = 8\ h$)				
M&G	7	7.50	154	946	2076	1583.44	2560.6
SG	7 ($\Delta r = 1$)	0.50	66	297	436	1274.48	2750.9
	7 ($\Delta r = 2$)	0.70	121	462	781	1583.44	2750.9
	7 ($\Delta r = 3$)	0.76	165	594	1157	1583.44	2750.9
			Ex 2b ($H = 10\ h$)				RMILP
M&G	10	7200[a]	220	1351	2934	2307.66	3473.9
SG	10 ($\Delta r = 1$)	5.87	99	438	643	1963.88	3618.6
	10 ($\Delta r = 2$)	326.92	187	702	1195	2156.36	3618.6
	10 ($\Delta r = 3$)	148.4	264	933	1853	2307.66	3618.6
	10 ($\Delta r = 4$)	188.29	330	1131	2567	2307.66	3618.6

[a]Relative gap (RG)=8.67%

700 s

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Results and discussion (SG vs. M&G)

Maximum revenue

- **Same number of event points**
- **Both perform equally in 3 cases (out of 6)**
- **SG performs better in other 3 cases**
- **Fewer constraints, but slighty more binary variables**
- **Roughly same RMILP**

equally

better

	Event points	CPU (s)	Binary variables	Total variables	Eqs.	MILP (h)	RMILP (h)
		Ex 1c (d_{S8} = 200 mu, d_{S9} = 200 mu)					
M&G	10	7.06	160	992	2137	19.34	18.68
SG	10 ($\Delta n = 1$)	8.65	72	318	459	19.78	18.68
	10 ($\Delta n = 2$)	1.39	136	510	875	19.34	18.68
	10 ($\Delta n = 3$)	1.79	192	678	1379	19.34	18.68
		Ex 1e (d_{S8} = 600 mu, d_{S9} = 600 mu)					
M&G	20	7200[a]	320	1982	4217	46.52	45.57
SG	20 ($\Delta n = 1$)	7200[b]	152	658	949	46.52	45.57
		Ex 1d (d_{S8} = 500 mu, d_{S9} = 400 mu)					
M&G	25	7200[c]	400	2477	5257	56.81	56.05
SG	25 ($\Delta n = 1$)	7200[c]	192	828	1194	56.81	56.05
		Ex 2c (d_{S12} = 100 mu, d_{S13} = 200 mu)					
M&G	11	71.1	242	1487	2980	13.36	11.33
SG	11 ($\Delta n = 1$)	0.62	110	486	714	14.61	11.25
	11 ($\Delta n = 2$)	6.09	209	783	1335	13.53	11.25
	11 ($\Delta n = 3$)	11.07	297	1048	2087	13.36	11.25
	11 ($\Delta n = 4$)	13.03	374	1278	2920	13.36	11.25
		Ex 2d (d_{S12} = 250 mu, d_{S13} = 250 mu)					
M&G	12	23.60	264	1622	3508	17.02	14.40
SG	12 ($\Delta n = 1$)	0.79	121	533	783	18.97	14.27
	12 ($\Delta n = 1$)	1.36	231	863	1473	17.02	14.27
	12 ($\Delta n = 3$)	1.78	330	1160	2319	17.02	14.27
		Ex 2e (d_{S12} = 930 mu, d_{S13} = 840 mu)					
M&G	29	691.4	638	3917	8370	51.82	50.92
SG	29 ($\Delta n = 1$)	12.43	308	1332	1956	59.74	49.92
	29 ($\Delta n = 2$)	49.28	605	2223	3819	51.82	49.92
	29 ($\Delta n = 3$)	110.21	891	3081	6263	51.82	49.92

[a]RG=2.01%, [b]RG=0.79%, [c]RG=1.15%

Results and discussion (MG vs. S&F)

Maximum revenue

- Both perform equally well (2 cases out 4)
- MG performs better than SF 1b and 2b
- MG leads to tighter formulations
- MG needs on more event point
- But, same binary and fewer Eqs

	Events	CPU (s)	Binary variables	Total variables	Eqs.	MILP ($)	RMILP ($)
				Ex 1a ($H = 8$ h)			
S&F	4 ($\Delta n = 0$)	0.14	32	165	307	1498.56	1730.8
MG	5 ($\Delta r = 1$)	0.10	32	162	250	1498.56	1730.8
		CPU		Ex 1b ($H = 10$ h)			RMILP
S&F	8 ($\Delta n = 1$)	1829.87	120	441	1255	1962.69	2805.4
MG	9 ($\Delta r = 2$)	302.12	120	478	920	1962.69	2804.2
				Ex 2a ($H = 8$ h)			
S&F	6 ($\Delta n = 1$)	8.82	121	453	1280	1583.44	2750.9
MG	7 ($\Delta r = 2$)	3.73	121	497	977	1583.44	2682.0
				Ex 2b ($H = 10$ h)			
S&F	8 ($\Delta n = 2$)	1570.12	231	743	2008	2358.20	3618.6
MG	9 ($\Delta n = 3$)	321.20	231	865	1997	2358.20	3618.64

Results and discussion (MG vs. S&F)

Minimum makespan

- **Both perform equally well (5 cases out 6)**
- **MG performs better than S&F in Ex 2e (22.89 s vs. 7200)**
- **MG leads to tighter formulations**
- **MG needs on more event points**
- **But, same binary and fewer Eqs**

CPU RMILP

	Events	CPU (s)	Binary variables	Total variables	Eqs.	MILP (h)	RMILP (h)
	Ex 1c ($d_{S8} = 200$ mu, $d_{S9} = 200$ mu)						
S&F	9 ($\Delta n = 0$)	1.10	72	371	652	19.34	18.68
MG	10 ($\Delta n = 1$)	1.09	72	348	547	19.34	18.68
	Ex 1d ($d_{S8} = 500$ mu, $d_{S9} = 400$ mu)						
S&F	20 ($\Delta n = 0$)	0.59	160	822	1477	46.11	45.57
MG	21 ($\Delta n = 1$)	1.48	160	755	1196	46.11	45.57
	Ex 1e ($d_{S8} = 600$ mu, $d_{S9} = 600$ mu)						
S&F	25 ($\Delta n = 0$)	3.17	200	1027	1852	56.68	56.05
MG	26 ($\Delta n = 1$)	2.25	200	940	1491	56.68	56.05
	Ex 2c ($d_{S12} = 100$ mu, $d_{S13} = 200$ mu)						
S&F	7 ($\Delta n = 0$)	0.21	77	401	702	13.36	11.25
MG	8 ($\Delta n = 1$)	0.34	77	385	631	13.36	12.31
	Ex 2d ($d_{S12} = 250$ mu, $d_{S13} = 250$ mu)						
S&F	10 ($\Delta n = 0$)	0.46	110	572	1017	17.02	14.27
MG	11 ($\Delta n = 1$)	0.45	110	541	892	17.02	14.53
	Ex 2e ($d_{S12} = 930$ mu, $d_{S13} = 840$ mu)						
S&F	29 ($\Delta n = 0$)	1013	319	1655	3012	51.82	49.92
	29 ($\Delta n = 1$)	7200[a]	627	2271	6299	51.82	49.92
MG	30 ($\Delta n = 1$)	5.35	319	1529	2545	51.82	50.26
	30 ($\Delta n = 2$)	22.89	627	2453	4981	51.82	49.92

[a]Relative GAP=3.68%

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Conclusions

Novel continuous-time MILP scheduling formulation for multipurpose batch plants

- **Pros**
  - Little effort is required to move from a single-grid model to a multi-grid one
  - No big-M constraints
  - The formulation can be extended to address continuous processes (Grade change, crude oil pooling problem, pipeline scheduling)
  - Tighter LP-relaxation with MG
- **Cons**
  - Two tuning parameters ($\boldsymbol{r}$ and $\Delta\boldsymbol{r}$)
  - Weaker LP-relaxation with SG
  - The single grid model is not capable of handling changeover times constraints

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Thank you for your attention!

Any Questions?