A Priority-Rule Based Method for Scheduling in Chemical Batch Production

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Outline

1. Scheduling problem
2. Priority-rule based method
    - Preprocessing
    - Iteration
3. Performance analysis
4. Conclusions

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Scheduling problem I

Operations and states

- Set $\mathcal{O}$ of operations i (process executions) with processing times p_i
- Each operation transforms given amounts of input states into given amounts of output states
- Intermediate states may be chemically instable (perishable products)

Equipment

- Multi-purpose processing units
- Dedicated storage facilities of limited capacity for stocking states

Scheduling problem II

Constraints

- Non-overlapping execution of operations on processing units
- Sequence-dependent changeover times
- Availability of input materials and storage space for output products
- Immediate consumption of perishable products

Scheduling problem

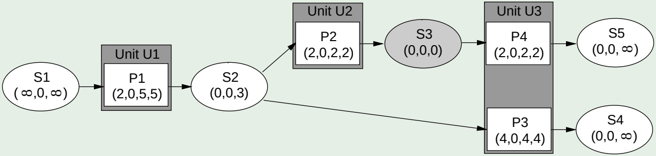
Determine feasible production schedule

- allocation of processing units to operations
- assignment of start times to operations

complying with constraints such that makespan is minimized

Scheduling problem III

Example (State-task network)



- 3 processing units
- 4 processes, no changeover times
- 4 storage facilities (1 finite intermediate storage)
- 5 states (1 perishable product)
- Primary requirements $\rho_{S4} = 8$, $\rho_{S5} = 2$
- Batching provides 6 operations ($2 \times P1$, $1 \times P2$, $2 \times P3$, $1 \times P4$)

Outline

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Preprocessing I

Preprocessing principle

- Generate time lags δ_{ij} between starts of operations $i, j \in \mathcal{O}$ that are satisfied by some optimal schedule
- Translate time lags into operation-on-node network

(1) Operations of same process

- Arrange operations in arbitrary order
  - Operations have to be executed on same processing unit:
    $\triangleright$ $\delta_{ij} = p_i$ for any two consecutive operations i, j
  - There are alternative processing units:
    $\triangleright$ $\delta_{ij} = 0$ for any two consecutive operations i, j

Preprocessing II

(2) Intermediates produced by only one process

- Identify minimum time lags $\delta_{ij} = p_i$ between producing operations i and consuming operations j necessary to avoid shortages of input materials

(3) Intermediates consumed by only one process

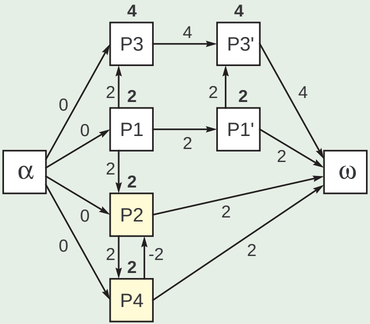
- Identify maximum time lags $-\delta_{ji} = p_i$ between producing operations i and consuming operations j necessary to avoid capacity overflows

(4) Perishable intermediates

- Associate fictitious storage facility of capacity zero
- Apply (3) in case of unique consuming operation

Preprocessing III

Example (Operation-on-node network)



- α, ω: production start, production end
- Longest path length d_{ij}: transitive time lag between starts of i and j
- Strong components $\mathcal{O}' \subseteq \mathcal{O}$ of network: any two nodes $i, j \in \mathcal{O}'$ mutually linked by transitive time lags

Iteration I

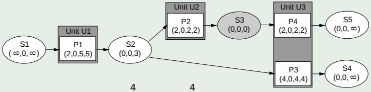
Priority-rule based method

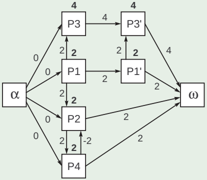
initialize $\mathcal{C} := \emptyset$ and put latest start times $LS_i := \infty$ for all $i \in \mathcal{O}$;
while $\mathcal{C} \neq \mathcal{O}$ **do**
  determine set $\mathcal{E}$ of eligible operations $i \in \mathcal{O} \setminus \mathcal{C}$;
  compute priority value $v(i)$ for all $i \in \mathcal{E}$;
  remove operation j with highest priority value $v(j)$ from set $\mathcal{E}$;
  compute earliest start time ES_j of j; (∗ disregard storage capacities ∗)
  if $ES_j \leq LS_j$ **then**
    schedule j at time ES_j and put $\mathcal{C} := \mathcal{C} \cup \{j\}$;
    update latest start times LS_i of operations $i \in \mathcal{O} \setminus \mathcal{C}$;
  else
    perform an unscheduling step;
  end if
end while

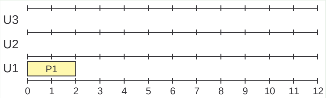
Iteration II

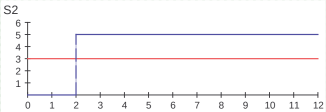
Example (Priority-rule based method)

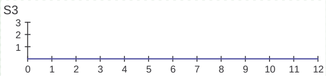
- $\mathcal{E} = \{P1\}$, $j = P1$
- $ES_{P1} = 0$, $LS_{P1} = \infty$
- Schedule $j = P1$ at time 0









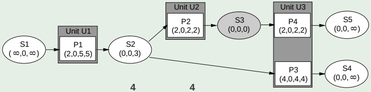


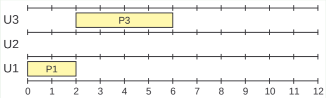
- $LS_{P2} = LS_{P3} = LS_{P3'} = 2$

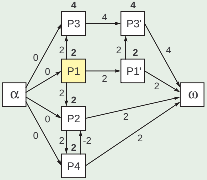
Iteration II

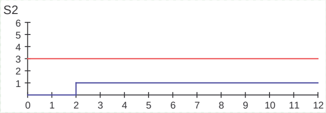
Example (Priority-rule based method)

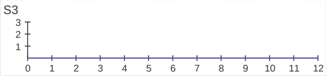
- $\mathcal{E} = \{P1', P2, P3\}$, $j = P3$
- $LS_{P3} = 2$, $ES_{P3} = 2$
- Schedule $j = P3$ at time 2









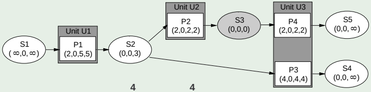


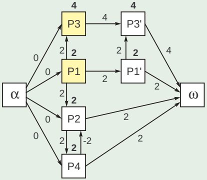
- $LS_{P2} = LS_{P3'} = \infty$

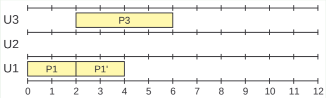
Iteration II

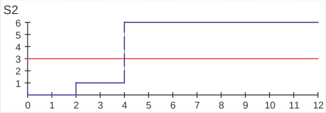
Example (Priority-rule based method)

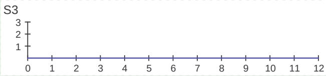
- $\mathcal{E} = \{P1'\}$, $j = P1'$
- $LS_{P1'} = \infty$, $ES_{P1'} = 2$
- Schedule $j = P1'$ at time 2









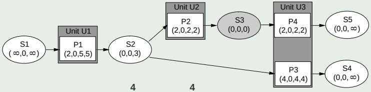


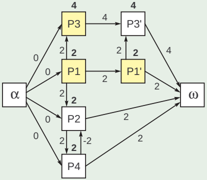
- $LS_{P2} = LS_{P3'} = 4$

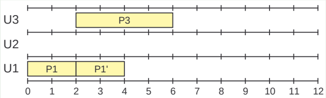
Iteration II

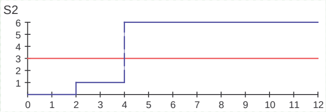
Example (Priority-rule based method)

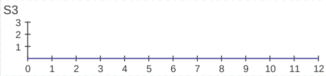
- $\mathcal{E} = \{P2, P3'\}$, $j = P3'$
- $LS_{P3'} = 4$, $ES_{P3'} = 6$
- $P3'$ cannot be scheduled







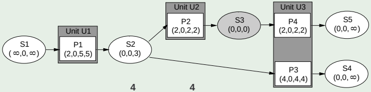


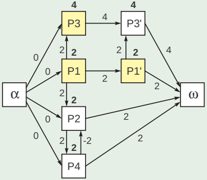


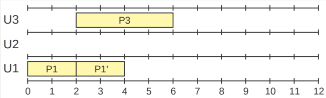
Iteration II

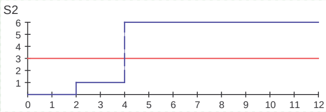
Example (Priority-rule based method)

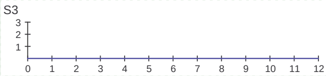
- Call unscheduling
- Origin of conflict: $i = P1'$
- Add release date $r_{P1'} = 4$









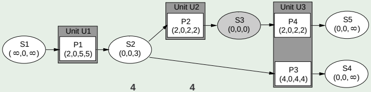


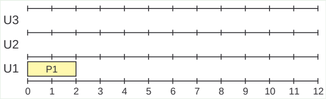
- put $\mathcal{C} := \emptyset$

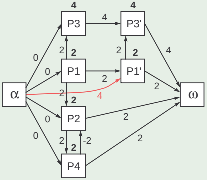
Iteration II

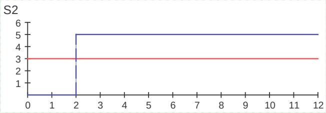
Example (Priority-rule based method)

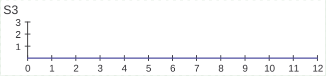
- $\mathcal{E} = \{P1\}$, $j = P1$
- $ES_{P1} = 0$, $LS_{P1} = \infty$
- Schedule $j = P1$ at time 0









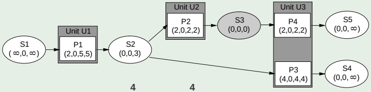


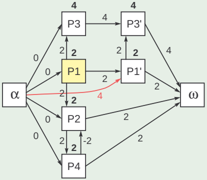
- $LS_{P2} = LS_{P3} = LS_{P3'} = 2$

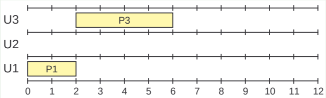
Iteration II

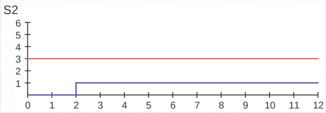
Example (Priority-rule based method)

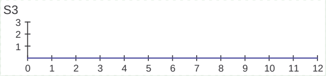
- $\mathcal{E} = \{P1', P2, P3\}$, $j = P3$
- $LS_{P3} = 2$, $ES_{P3} = 2$
- Schedule $j = P3$ at time 2









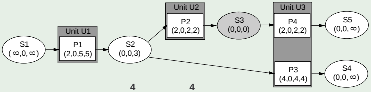


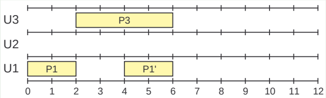
- $LS_{P2} = LS_{P3'} = \infty$

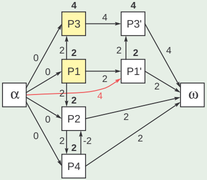
Iteration II

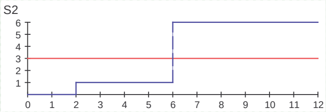
Example (Priority-rule based method)

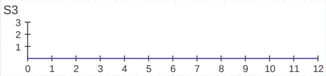
- $\mathcal{E} = \{P1'\}$, $j = P1'$
- $LS_{P1'} = \infty$, $ES_{P1'} = 4$
- Schedule $j = P1'$ at time 4









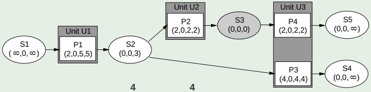


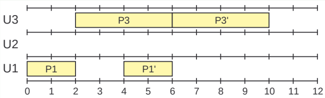
- $LS_{P2} = LS_{P3'} = 6$

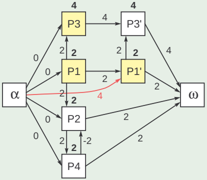
Iteration II

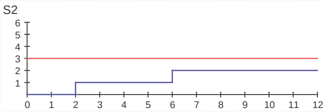
Example (Priority-rule based method)

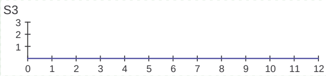
- $\mathcal{E} = \{P2, P3'\}$, $j = P3'$
- $LS_{P3'} = 6$, $ES_{P3'} = 6$
- Schedule $j = P3'$ at time 6









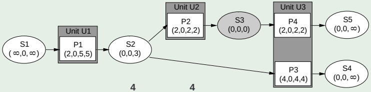


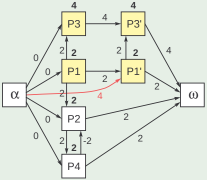
- $LS_{P2} = \infty$

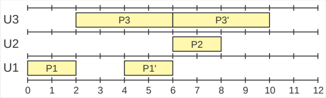
Iteration II

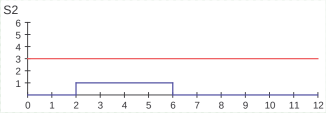
Example (Priority-rule based method)

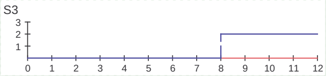
- $\mathcal{E} = \{P2\}$, $j = P2$
- $LS_{P2} = \infty$, $ES_{P2} = 6$
- Schedule $j = P2$ at time 6









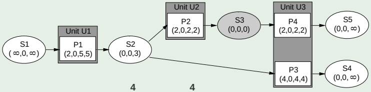


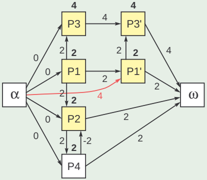
- $LS_{P4} = 8$

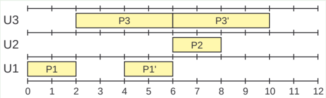
Iteration II

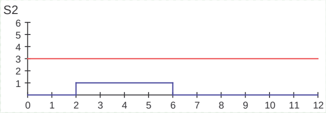
Example (Priority-rule based method)

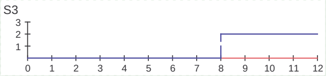
- $\mathcal{E} = \{P4\}$, $j = P4$
- $LS_{P4} = 8$, $ES_{P4} = 10$
- $P4$ cannot be scheduled







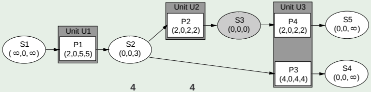


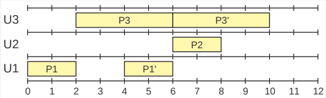


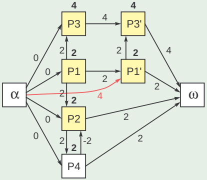
Iteration II

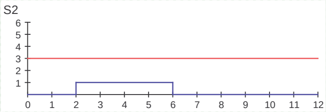
Example (Priority-rule based method)

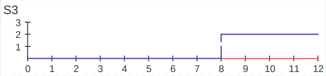
- Call unscheduling
- Origin of conflict: $i = P2$
- Add release date $r_{P2} = 8$









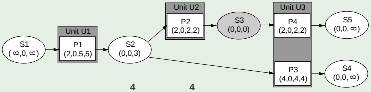


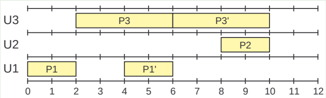
- put $\mathcal{C} := \{P1, P1', P3, P3'\}$

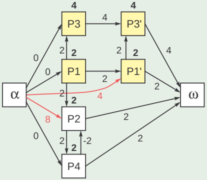
Iteration II

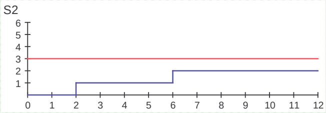
Example (Priority-rule based method)

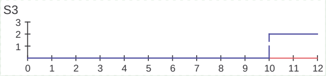
- $\mathcal{E} = \{P2\}$, $j = P2$
- $LS_{P2} = \infty$, $ES_{P2} = 8$
- Schedule $j = P2$ at time 8









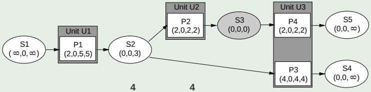


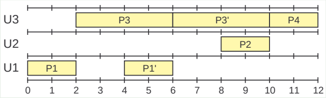
- $LS_{P4} = 10$

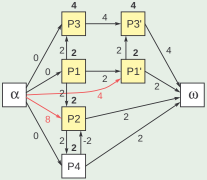
Iteration II

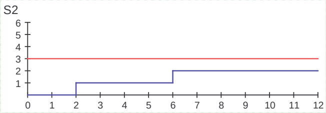
Example (Priority-rule based method)

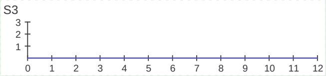
- $\mathcal{E} = \{P4\}$, $j = P4$
- $LS_{P4} = 10$, $ES_{P4} = 10$
- Schedule $j = P2$ at time 10











- $\mathcal{C} = \mathcal{O}$: stop

Outline

1. Scheduling problem
2. Priority-rule based method
   - Preprocessing
   - Iteration
3. Performance analysis
4. Conclusions

Test bed

Test set

- 22 instances generated by Blömer and Günther (2000)
- Operations obtained by solving MILP batching models

Implementation and test conditions

- Scheduling method implemented as randomized multistart procedure
- Tests performed on 2.08 GHz PC with 1 GB RAM
- Run time limit of 23 sec

Benchmark algorithms

- Time grid heuristic based on monolithic MILP model [BloGue00]
- Truncated branch-and-bound algorithm [NeuSchTra02]
- Two-phase priority-rule based method [SchTra04]

Computational results

Table: Results for instances of Blömer and Günther

Instance	1	2	3	4	5	6	7	8	9	10	11
[BloGue00]	36	42	42	48	44	48	52	48	54	60	68
[NeuSchTra02]	36	38	38	39	41	43	38	39	53	50	66
[SchTra04]	39	47	48	42	41	49	44	43	49	54	64
This paper	36	42	42	39	39	47	40	40	46	49	56

Instance	12	13	14	15	16	17	18	19	20	21	22
[BloGue00]	60	64	66	148	124	112	124	208	184	184	214
[NeuSchTra02]	52	50	57	114	80	91	91	135	100	112	134
[SchTra04]	48	57	61	100	80	92	90	159	97	124	114
This paper	45	50	53	80	66	72	70	98	78	82	83

Outline

1 Scheduling problem

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4 Conclusions

Conclusions

Summary

- New priority-rule based method for batch production scheduling in the process industries
  - Operations-on-node network
  - Capacity-driven latest start times
  - Unscheduling technique
- Very good schedules obtained within short amount of CPU time

Current research

- Expansion of method to case of uncertain processing times, uncertain yields, and unit breakdowns
- Process scheduling of multi-product continuous production plants

References

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International Journal of Production Research **38**:1029–1051

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Advanced production scheduling for batch plants in process industries
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