DESIGN OF A CHEMICAL BATCH PLANT: a study of dedicated parallel lines with intermediate storage and the plant performance

Highlights

- MI(N)LP model for design of **multiproduct batch plants with parallel production lines**
- Examination of **SCOR performance attributes**: cost effectiveness and asset efficiency
- Influence of installing **intermediate storage tanks per production line**

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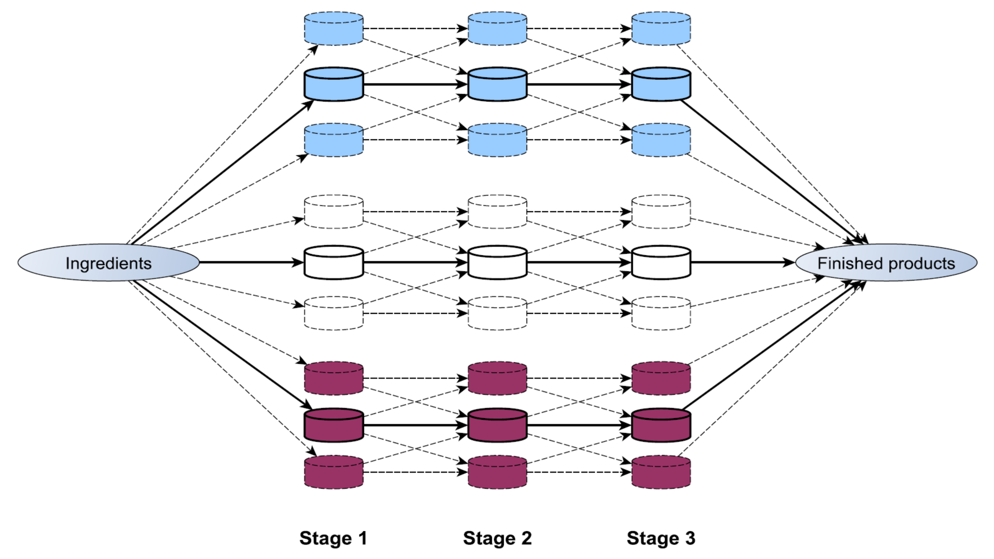
1. Objective

Production plant with parallel lines



Determine:

- Optimal **number and size of batch equipment** per stage per line
- Optimal **assignment** of products to different lines

while satisfying constraints so as to minimise **costs**

Costs

- **Capital costs:** costs associated with the acquisition of batch equipment
- **Setup costs:** costs for preparation of equipment for every product
  ➡ SCOR performance attribute[6]: cost effectiveness
- **Opportunity costs:** penalty for leaving installed equipment unused
  ➡ SCOR performance attribute: asset efficiency

Characteristics

- Each line: same stages, operates independently but simultaneously
- One bottleneck stage: long processing time, expensive equipment
- Specific product families vs neutral products[3]
- Discrete set of equipment sizes and numbers to choose from (y_{ljsn})[7]
- Operation in single product campaigns, identical parallel equipment out-of-phase[1,2]

Intermediate storage tank per production line

- Short-term storage: decoupled subprocesses[4]
- Location is pre-defined: before bottleneck stage
- Discrete set of equipment sizes to choose from ($\hat{y}_{g(sp)}$)
- Constraint on tank size: sum of an incoming and outgoing batch of every product

2. Mathematical Model

Objectives

- Minimisation of capital costs

$$\sum_{l=1}^{L}\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{n=1}^{N} n\,\alpha_j\, v_s^{\beta_j}\, y_{ljsn}$$

- Minimisation of setup costs

$$\sum_{i=1}^{P}\sum_{l=1}^{L}\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{n=1}^{N} n\, C_{seti}\, y_{ljsn}\, t_{li}$$

- Minimisation of opportunity costs

$$\sum_{l=1}^{L}\sum_{i=1}^{P} C_{opp} n_{li}$$

Constraints

- Design constraints:

$$n_{li} \geq \sum_{s=1}^{S}\sum_{n=1}^{N} \frac{q_{li} S_{ij}}{v_s} y_{ljsn} \qquad \forall l,i,j$$

$$\sum_{s=1}^{S}\sum_{n=1}^{N} y_{ljsn} = 1 \qquad \forall l,j$$

- Horizon constraints:

$$\theta_{li} \geq \sum_{s=1}^{S}\sum_{n=1}^{N} \frac{\tau_{ij}}{n} n_{li} y_{ljsn} \qquad \forall l,i,j$$

$$\sum_{i=1}^{P} \theta_{li} \leq H \qquad \forall l$$

- Demand constraint:

$$\sum_{l=1}^{L} q_{li} = Q_i \qquad \forall i$$

- Boundaries:

$$y_{ljsn}, z_{li}, t_{li} \in \{0,1\}$$
$$n_{li}, \theta_{li}, q_{li} \geq 0 \qquad \forall l,i$$
$$n_{li} \leq M q_{li} \qquad \forall l,i$$
$$\theta_{li} \leq M n_{li} \qquad \forall l,i$$
$$q_{li} \leq M z_{li} \qquad \forall l,i$$

Produce P products i, that need J stages j[5], on L lines l.

- q_{li}: amount produced per line; Q_i: total demand
- n_{li}: number of batches
- θ_{li}: time spent on every product ; H: total horizon
- y_{ljsn}: if stage j of line l has n parallel units of size s
- z_{li}: if product i is allowed on line l
- t_{li}: if product i is produced on line l
- v_s: equipment unit with size s
- S_{ij}: size factor; τ_{ij}: processing time
- α_j,β_j: cost coefficients

3. Math. model with intermed. storage

Objective function:

$$\min \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{n=1}^{N} n\,\alpha_j v_s^{\beta_j} y_{jsn} + \sum_{sp=1}^{SP-1}\sum_{g=1}^{G} \gamma_{sp} v_g^{\delta_{sp}}\, \hat{y}_{g(sp)}$$
$$+ \sum_{i=1}^{P}\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{n=1}^{N} n\, C_{seti} y_{jsn} + \sum_{i=1}^{P}\sum_{sp=1}^{SP-1}\sum_{g=1}^{G} C_{seti}\, \hat{y}_{g(sp)}$$

Opp. cost: ex post calculation

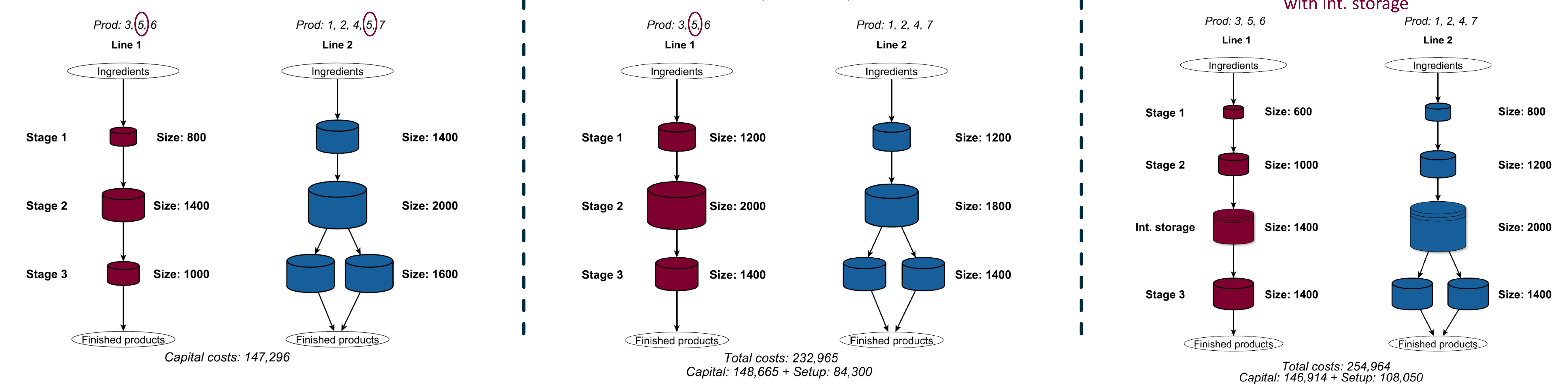
- $\hat{y}_{g(sp)}$: if intermediate storage tank succeeding subprocess sp has size g
- $\gamma_{(sp)}$, $\delta_{(sp)}$: cost coefficients

4. Case study

Problem:

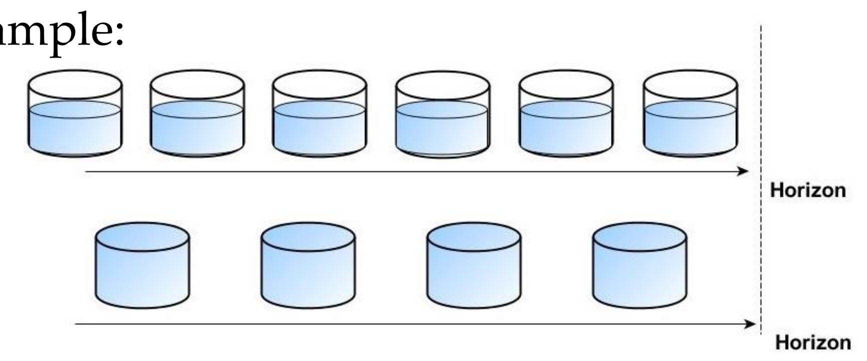
- 7 products to produce over 2 parallel production lines.
- 3 stages per line, stage 3 is the bottleneck
- Line dedication to product families is given (z_{li}), neutral products (prod 1, 5) can be produced on both production lines.
- Amounts to produce, production horizon, size factors, processing times, cost coefficients and equipment options known upfront

5. Results



Equipment utilisation (in %): opportunity costs

Example:



No intermed. storage:

	Line 1			Line 2		
	Prod 3	Total vol.	Total time	Prod 1	Total vol.	Total time
Stage 1	72.7-100	86.6	37.2	93.1-97.2	86.4	50.6
Stage 2	52.3-72.0	75.5	25.8	86.9-90.7	76.4	54.6
Stage 3	68.5-94.3	97.3	96.5	95.7-100	100	98.9

Intermed. storage:

	Line 1			Line 2		
	Prod 5	Total vol.	Total time	Prod 1	Total vol.	Total time
Stage 1	52.5-53.5	63.1	94.7	96.2-100	79.8	81.8
Stage 2	31.5-32.1	55.0	69.2	89.8-93.3	70.6	90.7
Stage 3	98.3-100	94.0	99.3	95.7-99.5	99.9	99.0
Int.Stor	98.1-100	100		94.3-98.1	85.4	

6. Conclusion

Contributions:

- Objective function: including setup costs and opportunity costs
- Design option - **parallel production lines**:
  - Capital costs, setup costs ++
  - Volume-wise asset utilisation
- Intermediate storage tank per line:
  - Capital costs ++
  - Setup costs, asset utilisation --

Future research: relation cost structures and SCOR performance attributes

References

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