Design of a chemical batch plant : a study of dedicated parallel lines with intermediate storage and the plant performance

Reference:
Verbiest Floor, Cornelissens Trijntje, Springael Johan.- Design of a chemical batch plant : a study of dedicated parallel lines w ith intermediate storage and the plant performance
Proceedings of the 26th European Symposium on Computer Aided Process Engineering, June 12th-15th, 2016, Portoroz, Slovenia / Kravanja, Zdravko [edit.] - ISSN 1570-7946 - Amsterdam, Elsevier science bv, 38A(2016), p. 739-744
Full text (Publisher's DOI): https://doi.org/10.1016/B978-0-444-63428-3.50128-4
To cite this reference: http://hdl.handle.net/10067/1449080151162165141

Zdravko Kravanja (Editor)
Proceedings of the 26th European Symposium on Computer Aided Process Engineering
June 12th - 15th, 2016, Portorož, Slovenia.

Design of a chemical batch plant: a study of dedicated parallel lines with intermediate storage and the plant performance

Floor Verbiest[a,*], Trijntje Cornelissens[a] and Johan Springael[a]

[a]*Dept of Engineering Mgmt, University of Antwerp, Prinsstraat 13, Antwerp 2000, Belgium*
**floor.verbiest@uantwerpen.be*

Abstract

Production plants worldwide face huge challenges in satisfying high service levels and outperforming competition. These challenges require appropriate strategic decisions on plant design and production strategies. In this paper, we focus on multiproduct chemical batch plants, which are typically equipped with multiple production lines and intermediate storage tanks. First we extend the existing MI(N)LP design models with the concept of parallel production lines, and optimise the assignment of products to these lines, together with the number and size of the equipment, by minimising capital costs. Next, we examine the cost effectiveness and asset efficiency, both Supply Chain Operations Reference (SCOR) performance attributes, of the plant by introducing setup costs and asset-related opportunity costs. Finally, we analyse the influence of installing intermediate storage per production line on the different cost components. An example of a lubricant production plant demonstrates the applicability of our model.

Keywords: batch plant design, parallel production lines, intermediate storage, plant performance

1. Introduction

Increasing pressure on plant performance forces production companies nowadays to take major decisions on strategic and tactical level, as improvements based solely on the operational level appear to be no longer sufficient. In our research we focus on strategic decisions on plant design and production strategies and their mutual influence. The design of batch plants addresses plant configuration (i.e. number, size and connectivity of equipment) and the related batch sizes of the different manufactured products. The aim of these design problems, generally formulated as MINLP models, is mostly to minimise only capital costs (Barbosa-Póvoa, 2007). Production strategies, on the other hand, define how plants should be operated (e.g. by dedicating products to equipment) and are normally translated into objectives for plant performance indicators such as the SCOR performance attributes: asset efficiency, cost effectiveness, reliability, responsiveness and flexibility. For now, we will only consider the first two internally focused attributes, whereas the other three attributes are more customer-focused (Stephens, 2001).

In this paper, we focus on the design of multiproduct chemical batch plants, also denoted as flow shop plants (Biegler et al., 1997). In section 2, we include the concept of parallel production lines, i.e. specific lines that can be dedicated to particular products or product families, into existing plant design models. The design problem then aims at optimising both the allocation of products to these lines and the number and size of the plant equipment per line so as to minimise, at first, only capital costs. Next, we add step by step setup costs, consisting of a fixed startup cost and a sequence dependent changeover cost, and asset-related opportunity costs to the objective function and study their impact on the plant configuration. These costs can be considered as implementations of the attributes cost effectiveness and asset efficiency respectively. Finally, in section 3, we include intermediate storage per line and investigate the effect on the aforementioned cost components.

2. Chemical batch plants and parallel production lines

2.1. Description

A chemical batch process consists typically of one or more bottleneck stages. In general, these stages involve longer processing times and/or capital intensive equipment. Suboptimal use of bottleneck equipment may slow down the entire process. As discussed in literature (Biegler et al., 1997), introducing parallel equipment per stage and intermediate storage between stages aim at reducing the dominance of these bottlenecks.

In practice, we observe another design option that is frequently used in chemical plants: the installation of parallel production lines (Hill et al., 2016). Each production line consists of all stages and operates independently but simultaneously with the other line(s). As the total production volume can now be split over these lines, products no longer need to share all equipment, which may reduce the required size of the expensive bottleneck stages. For the same reason, a decrease of the total setup cost can be expected as well. On top of this, when products with similar characteristics (product families) are dedicated to specific lines, high sequence dependent changeover costs can be avoided and the setup costs will be limited to the startup costs.

2.2. Mathematical model

In this model, we consider P products i that are to be produced over J stages j. The demand for every product (Q_i) and the total horizon (H) are known upfront, as well as the characteristic size factors (S_{ij}) and the fixed batch processing times (τ_{ij}), which are assumed independent of the product batch size. We based our model on that described by Sparrow et al. (1975) and used a linearisation introduced by Voudouris and Grossmann (1992). The assumptions are: (1) Process/recipes are determined upfront; (2) Only batch equipment is considered; (3) Operation in single product campaign mode (SPC) (see Fig.1); (4) Cycle time of product i is the longest processing time over all stages - $\max\limits_{j=1,\ldots,J} \frac{\tau_{ij}}{n_j}$ (see Fig.1); (5) Zero-wait policy between batch stages; (6) Identical parallel batch equipment per stage, operating out of phase (see Fig.1, stage 1); (7) Discrete set of S equipment sizes v_s for all stages j to choose from and (8) Stage dependent cost factors α_j and β_j, resulting in capital cost $\alpha_j v_s^{\beta_j}$.

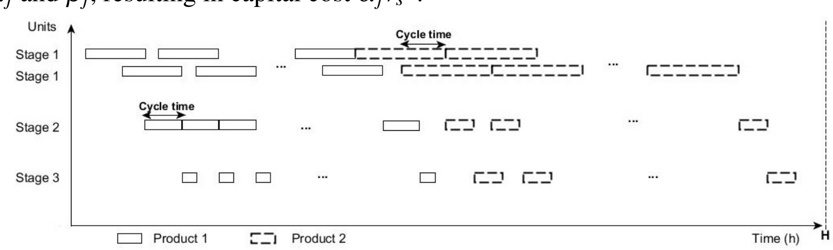

Figure 1: Single product campaign, cycle time and parallel equipment

Furthermore, we assume that line dedication to similar products (product families) is determined upfront. This relation between a line l and a product i is expressed by the binary variable z_{li} being 1 if product i is allowed on line l and 0 otherwise. For neutral products, where multiple production lines are allowed, it follows that: $\sum_{l=1}^{L} z_{li} \geqslant 1$. Since production of these can be split over lines, the amounts produced (q_{li}), number of batches (n_{li}) and time spent on product i (θ_{li}) become line dependent. This leads to the following MINLP design problem when minimising only capital costs:

$$\min \left[\sum_{l=1}^{L} \sum_{j=1}^{J} \sum_{s=1}^{S} \sum_{n=1}^{N} c_{jsn} y_{ljsn} \right]$$

s.t.

Design constraints:

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

$$\sum_{s=1}^{S} \sum_{n=1}^{N} y_{ljsn} = 1 \quad \forall l,j \tag{2}$$

Horizon constraints:

$$\theta_{li} \geqslant \sum_{s=1}^{S} \sum_{n=1}^{N} \frac{\tau_{ij}}{n} n_{li} y_{ljsn} \qquad \forall l,i,j \tag{3}$$

$$\sum_{i=1}^{P} \theta_{li} \leqslant H \qquad \forall l \tag{4}$$

Demand constraint:

$$\sum_{l=1}^{L} q_{li} = Q_i \qquad \forall i \tag{5}$$

Boundaries:

$$y_{jlsn} \in \{0,1\} \qquad n_{li}, \theta_{li}, q_{li} \geqslant 0 \text{ and } n_{li} \leqslant M q_{li} \quad \theta_{li} \leqslant M n_{li} \quad q_{li} \leqslant Q_i z_{li} \quad \forall l,i \tag{6}$$

where $c_{jsn} = n\alpha_j v_s^{\beta_j}$, M is a very large positive number and y_{ljsn} indicates whether or not stage j of line l has n equipment units in parallel of size s. The multiple choice character of discrete sizes and parallel units enables linearising the aforementioned model. Eq.(1) states that for every stage j of every line l the capacity v_s should be large enough to hold a batch of every product i, multiplied by its size factor. Eq.(2) indicates that for every stage on every line a number of units with one particular size is chosen. The time spent per line on one product (θ_{li}) corresponds to the time necessary to complete one batch (i.e. cycle time) multiplied by the number of batches (Eq.(3)). Lastly, total production time per line should not exceed the allowed horizon (Eq.(4)) and production of product i split over multiple lines should sum up to the demand (Eq.(5)). When including line and stage independent setup costs $Cset_i$, the objective function becomes:

$$\min \left[\sum_{l=1}^{L} \sum_{j=1}^{J} \sum_{s=1}^{S} \sum_{n=1}^{N} c_{jsn} y_{ljsn} + \sum_{i=1}^{P} \sum_{l=1}^{L} \sum_{j=1}^{J} \sum_{s=1}^{S} \sum_{n=1}^{N} nCset_i y_{ljsn} t_{li} \right]$$

where t_{li} is a binary variable indicating whether or not product i effectively uses line l.
Lastly, to optimise the volume-wise asset utilisation, we add the opportunity cost:

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

This opportunity cost is a penalisation for using more, smaller batches that leave installed capacity unused. Minimising these opportunity costs corresponds to maximising the batch sizes. Time-wise asset utilisation, on the other hand, will be lower. Of course, these setup and opportunity costs can also be used pro-actively by translating e.g. a maximum setup cost or a certain targeted asset utilisation into additional (SCOR performance) constraints for this extended design model.

2.3. Example of a lubricant plant

We illustrate our model with the following example. Assume a lubricant plant where 7 lubricants with a specific demand need to be produced within a certain planning horizon. Production is done on 2 lines with identical stages (stage 3 is the bottleneck stage), size factors and processing times as given in Table 1. As indicated, line dedication is decided and the rather neutral products (product 1 and 5) can be produced on both production lines.

Table 1: Data of the lubricant example

production horizon $H = 6,200$ h
discrete set of tank sizes (in L) = $\{200 \rightarrow 2,000\}$ with interval 200
stage dependent tank cost factors $\alpha_j = \{200, 225, 400\}$ $\beta_j = \{0.39, 0.40, 0.65\}$

	prod 1	prod 2	prod 3	prod 4	prod 5	prod 6	prod 7
Product demand Q_i (in kg x 1,000)							
	400	300	100	350	330	270	250
Product to line matrix z_{li}							
line 1	1	0	1	0	1	1	0
line 2	1	1	0	1	1	0	1
Setup cost $Cset_i$							
	4,000	2,500	3,000	2,750	4,200	3,500	3,800
Size factor (Processing time) S_{ij} in L/kg (τ_{ij} in h)							
stage 1	1.0 (3.1)	1.0 (2.4)	1.0 (1.8)	1.0 (2.1)	1.0 (2.5)	1.0 (4.9)	1.0 (2.4)
stage 2	1.4 (2.3)	0.7 (3.2)	1.2 (3.0)	1.8 (1.9)	1.0 (2.0)	2.1 (2.6)	1.3 (4.0)
stage 3	1.2 (9.0)	1.5 (12.2)	1.1 (6.9)	1.5 (6.3)	1.3 (8.4)	1.4 (10.0)	1.2 (13.5)

The outcome of this problem is presented in Table 2 and shows for each line the optimal size and number of equipment per stage, as well as the (possible) volume split over the two lines, both without (case 1) and with setup costs (case 2). In case 2, in order to avoid setup costs, product 5 is transferred completely to line 1. For this dataset, it seems optimal to reduce the setup costs to one line for each product. Capital costs however become slightly higher.

Table 2: Product assignment and equipment design

Case 1 : without setup costs				*Case 2: with setup costs*			
Total costs = 147,296 (only Capital)				Total costs = 232,965 (Capital: 148,665 + Setup: 84,300)			
Line 1 (size(numb))		*Line 2* (size(numb))		*Line 1* (size(numb))		*Line 2* (size(numb))	
stage 1	800(1)	stage 1	1,400(1)	stage 1	1,200(1)	stage 1	1,200(1)
stage 2	1,400(1)	stage 2	2,000(1)	stage 2	2,000(1)	stage 2	1,800(1)
stage 3	1,000(1)	stage 3	1,600(2)	stage 3	1,400(1)	stage 3	1,400(2)

Case 1: without setup costs - production volumes q_{li} (x 1,000)	prod 1	prod 2	prod 3	prod 4	prod 5	prod 6	prod 7
line 1	0	0	100	0	85	270	0
line 2	400	300	0	350	244	0	250
Case 2: with setup costs - production volumes q_{li} (x 1,000)							
line 1	0	0	100	0	330	270	0
line 2	400	300	0	350	0	0	250

Problem size: 2758 var.(194 bin.var.); 7815 const., solved in 4.0 s (case 1) and 1.8 s (case 2) - All numerical results were obtained using the Gurobi Optimizer 6.0 on an Intel(R) Core i5 - 2430M CPU, 2.4 GHz computer.

For case 2 (with setup costs), the resulting volume and time-wise equipment utilisation is shown in Table 3. It turned out that there is at least one product on each line for which there is still a range of batch sizes, and thus a number of batches, allowed within the chosen equipment (see volume-wise utilisation range for product 3 and 1). By introducing the opportunity cost mentioned earlier, the number of batches are forced to the minimum. This results in considering the largest batch sizes of the range (and a 100 % volume-wise utilisation per product for at least one of the stages). Moreover, this implies a shorter total finishing time, i.e. before the end of the horizon. Although the time-wise utilisation is lower, and idle time will occur, this phenomenon can provide a welcome buffer for small unforeseen events.

Table 3: Equipment utilisation: volume and time in %

	Line 1			**Total**		*Line 2*				**Total**	
	prod 3	prod 5	prod 6	**Vol.**	**Time**	prod 1	prod 2	prod 4	prod 7	**Vol.**	**Time**
stage 1	72.7-100	89.7	79.4	86.6	37.2	93.1-97.2	77.8	77.8	97.2	86.4	50.6
stage 2	52.3-72.0	53.8	100	75.5	25.8	86.9-90.7	36.3	93.3	84.3	76.4	54.6
stage 3	68.5-94.3	100	95.2	97.3	96.5	95.7-100	100	100	100	100	98.9
Total horizon: 5,984 - 6,200						Total horizon: 6,131 - 6,200					

Problem sizes: line 1: 370 var. (90 bin.var.); 845 const., solved in 0.15 s – line 2: 459 var. (90 bin.var.); 1121 const., solved in 0.10 s

3. Introducing intermediate storage

3.1. Description

In this section, we introduce intermediate storage tanks per production line. We use the MINLP model of Modi and Karimi (1989) where intermediate storage is considered as short term storage and purely used for decoupling the entire production process into subprocesses. As stated, this design option reduces also the influence of the bottleneck stages which results mostly in reduced equipment sizes and less idle time for the remaining stages.

3.2. Mathematical model

The assumptions used for this type of intermediate storage are: (1) The process is divided into subprocesses sp; (2) Location of intermediate storage is pre-defined (before the bottleneck subprocess/stage); (3) No parallel intermediate storage is allowed (only one tank) and (4) Intermediate storage must be able to contain the sum of an incoming and outgoing batch of every product. Furthermore, we introduced an extra assumption: (5) Discrete set of G tank sizes $\hat{v}_g$ for intermediate storage to choose from. Through the use of this discrete set, the model of Modi and Karimi can be linearised and hence solved up to optimality. Due to space limitations, we only present the objective function for each line with capital and setup costs.

$$\min \left[\sum_{j=1}^{J} \sum_{s=1}^{S} \sum_{n=1}^{N} c_{jsn} y_{jsn} + \sum_{sp=1}^{SP-1} \sum_{g=1}^{G} c_{g(sp)} \hat{y}_{g(sp)} + \sum_{i=1}^{P} \sum_{j=1}^{J} \sum_{s=1}^{S} \sum_{n=1}^{N} nCset_i y_{jsn} + \sum_{i=1}^{P} \sum_{sp=1}^{SP-1} \sum_{g=1}^{G} Cset_i \hat{y}_{g(sp)} \right]$$

where $\hat{y}_{g(sp)}$ is a binary variable indicating whether or not the intermediate storage tank succeeding subprocess sp has size g and $c_{g(sp)}$ the capital cost expression. The setup costs are formulated as earlier, but now account for the setup of intermediate storage as well. The opportunity cost is not included in the objective function, but is calculated ex post since it generates non-convex constraints which make the optimisation more arduous.

3.3. Example

We continue the previous example of the lubricant plant with 7 products. As we are particularly interested in the influence of the intermediate storage on the different cost components, we fix the previous assignment of products to lines and re-optimise the number and size of the stages, including the intermediate storage tanks, per line.

Table 4: Influence of int. storage on equipment design

Case 2 - continued: capital and setup costs with intermediate storage			
Total costs = 254,964 (Capital: 146,914 + Setup: 108,050)			
Line 1 (size(numb))		*Line 2* (size(numb))	
stage 1	600(1)	stage 1	800(1)
stage 2	1,000(1)	stage 2	1,200(1)
int. stor.	*1,400*	int. stor.	*2,000*
stage 3	1,400(1)	stage 3	1,400(2)

Problem size line 1: 752 var. (106 bin.var.); 1977 const., solved in 0.23 s
Problem size line 2: 967 var. (106 bin.var.); 2634 const., solved in 0.33 s

Table 4 contains the optimal solution for the plant configuration with intermediate storage per line. As can be seen, intermediate storage does indeed result in a decrease of the capital costs for the non bottleneck subprocess (sizes of stage 1 and 2 become smaller in comparison to Table 2). In fact, this is only true when certain conditions are met: the cost for installing an intermediate storage tank must be small in comparison to the costs of batch equipment and the difference in processing times between the bottleneck and the remaining stages must be large enough. However, total setup cost is higher since the intermediate storage tanks have to be prepared too. We assumed in this example identical setup costs for batch and intermediate storage tanks, however, in practice, these costs might be lower for inventory tanks.

Table 5: Equipment utilisation - int. storage: volume and time in %

	Line 1			**Total**		*Line 2*				**Total**	
	prod 3	prod 5	prod 6	**Vol.**	**Time**	prod 1	prod 2	prod 4	prod 7	**Vol.**	**Time**
stage 1	70.7	52.5-53.5	76.7	63.1	94.7	96.2-100	61.2	77.8	86.4	79.8	81.8
stage 2	50.9	31.5-32.1	96.7	55.0	69.2	89.8-93.3	28.6	93.3	74.9	70.6	90.7
stage 3	76.7	98.3-100	94.0	94.0	99.3	95.7-99.5	100	100	100	99.9	99.0
Int. storage	100	98.1-100	100	100		94.3-98.1	71.1	77.8	92.9	85.4	
Total horizon: 6,155 - 6,200						Total horizon: 6,140 - 6,200					

Problem sizes: see table 4

Lastly, the equipment utilisation is examined for our model with intermediate storage (Table 5). When compared with the previous case (Table 3), we notice that idle times are indeed reduced, which results in higher time-wise utilisation of the equipment (e.g. 94.7 % vs 37.2 % without intermediate storage for stage 1 of line 1). Regarding the volume-wise equipment utilisation, we optimise again the allowed batch size ranges (product 5 and 1) by minimising the number of batches. We notice however that the total volume-wise equipment utilisation of the three batch stages decreased. Indeed, the imposed minimum size of the intermediate storage tank, i.e. sum of an incoming and outgoing batch of every product, adds an extra constraint on the batch sizes which might hinder 100 % utilisation of the more expensive batch stages.

4. Conclusion

In this paper, the design of a chemical batch plant equipped with parallel production lines is studied. The presence of parallel lines allows for a reduction in capital and setup costs as not all products have to share all equipment any more. Also, the dedication of these lines to product families lower setup costs by avoiding high sequence-dependent changeovers. Furthermore, optimising volume-wise asset utilisation, within the bounds of the optimal equipment sizes, generates spare time that can be used as a time buffer improving reliability. In a second phase, intermediate storage is introduced per line and proved to be beneficial regarding capital costs, but not necessarily on setup costs and asset utilisation. In future research, we will study long term intermediate storage so as to gain additional advantages, e.g. providing a buffer for larger unexpected events as batch- and equipment failure etc. Furthermore, we will elaborate on the relation between cost structures and the SCOR performance attributes, not only for cost effectiveness and asset efficiency but also for reliability, responsiveness and flexibility.

5. Acknowledgements

Floor Verbiest acknowledges financial support from the Research Foundation - Flanders (FWO).

References

A. P. Barbosa-Póvoa, 2007. A critical review on the design and retrofit of batch plants. Comp. & Chem. Eng. 31 (7), 833 – 855.

L. T. Biegler, A. W. Westerberg, I. E. Grossmann, 1997. Systematic methods of chemical process design. Upper Sadle River, N.J., Pearson.

A. Hill, T. Cornelissens, K. Sörensen, 2016. Efficient multi-product multi-bom batch scheduling for a petrochemical blending plant with a shared pipeline network. Comp. & Chem. Eng. 84, 493–506.

A. Modi, I. Karimi, 1989. Design of multiproduct batch processes with finite intermediate storage. Comp. & Chem. Eng. 13 (12), 127 – 139.

R. E. Sparrow, G. J. Forder, D. W. T. Rippin, 1975. The choice of equipment sizes for multiproduct batch plants. heuristics vs. branch and bound. Ind. Eng. Chem. Process Des. Dev. 14 (3), 197–203.

S. Stephens, 2001. Supply chain operations reference model version 5.0: A new tool to improve supply chain efficiency and achieve best practice. Information Systems Frontiers 3 (4), 471–476.

V. T. Voudouris, I. E. Grossmann, 1992. Mixed-integer linear programming reformulations for batch process design with discrete equipment sizes. Ind. Eng. Chem. Res. 31 (5), 1315–1325.