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Towards an effective scheduling technique for zero-effluent multipurpose batch plants

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Abstract

Currently, wastewater minimization methodologies for batch processes are focused on reusing and recycling wastewater between units. Once this water has reached a certain concentration level or there are no feasible reuse or recycle opportunities within a time period the water is then discarded as effluent. Invariably there will always be a minimum amount of wastewater generated. In some processes the wastewater produced contains valuable product, such as wastewater produced in a pharmaceutical operation. The only way to recover the product is to use the wastewater as a product constituent in a batch of similar product. Reuse of wastewater in this manner leads to a process that can produce zero water effluent.

The methodology derived makes it possible for the operation of a zero-effluent facility and is based on the uneven discretization of the time horizon using time points. The inherent reuse and recycle opportunities of wastewater, coupled with dedicated storage vessels ensure that the required goal is met. A pharmaceuticals case study is used to demonstrate its effectiveness.

Keywords: ***Zero-effluent, batch scheduling, wastewater minimization***

1. Introduction

Wastewater minimization in all process industries is becoming more important as environmental legislation becomes more stringent and fresh water resources diminish. Ideally, one would like a process to produce zero effluent.

Wastewater minimization methodologies for batch processes are currently focused on increasing the reuse opportunities of wastewater within a process[1,2,3,4,5]. Methodologies based on this, inherently have limited reuse opportunities, due to process concentration constraints. Thus, one will never be able to operate a plant where zero effluent is produced using such a methodology. The methodologies derived thus far for wastewater minimization do not take into consideration the fact that the contaminants present in the wastewater could be used as part of a product formulation. Furthermore, the contaminants present in wastewater could be valuable products that are discarded, thereby constituting a substantial loss in revenue. Reusing the wastewater as part of the raw materials for a product can not only recapture the lost product, but also reduce the amount of effluent produced.

It is important to note what type of operations can be candidates for zero effluent operation. Firstly the operation involved must be producing a product that has water as one of the constituents. Secondly, there must be an operation where wastewater is produced, e.g. washing of vessels after product removal. Finally, any wastewater available for reuse must contain contaminants that do not jeopardize product integrity, i.e. must be compatible with the product.

2. Problem statement

The problem addressed in this paper can be stated as follows,
given,

i) the recipe for each product, including the amount of water needed for product,
ii) the processing times of each product,
iii) the quantity of water used for the cleaning and/or other wastewater producing operation,
iv) the number of storage vessels and their capacities,
v) the number of processing units and their capacities,
vi) the compatibilities of each product and
vii) the time horizon of interest,

determine the production schedule that will result in the production of zero effluent by exploring the reuse of wastewater in the product formulation.

3. Mathematical model

Sets

$P = \{p \mid p = \text{time point}\}$
$J = \{j \mid j = \text{unit}\}$
$U = \{u \mid u = \text{storage vessel}\}$
$S_{in} = \{s_{in} \mid s_{in} = \text{input state into a unit}\}$
$S_c = \{s_c \mid s_c = \text{compatible state } s \text{ stored in storage vessel } u\}$

Variables

$m_u(s_{in},j,p)$	mass of input material used
$mf(s_{in},j,p)$	mass of fresh water used in unit j, time point p
$m_s(s_c,u,p)$	compatible contaminant mass from storage vessel u
$fr(s_{in},j,j',p)$	mass of water directly reused from unit j to j'
$fs_{out}(s_c,u,p)$	mass of compatible water reused from storage vessel u
$m_{raw}(s_{in},j,p)$	mass of raw material, other than water, used for product
$m_{bulkstore}(s_{in},j,p)$	mass of raw material used from bulk storage
$y(s_{in},j,p)$	binary variable showing usage of a unit

Parameters

$M_{rmb}(s_{in})$	fixed mass of raw material used for a product
$C_{out}(s_{in})$	fixed outlet concentration of the reuse water

The zero-effluent model is based on the uneven discretization of the time horizon using a predefined number of time-points.

The methodology is derived for two cases. The first case is where the contaminant mass load in the reused wastewater is negligible and the second case is where the contaminant mass load in the wastewater is substantial and adds to the raw materials other than water. For both cases there is more than one storage vessel available for the storage of wastewater, with specific contaminants stored in specific storage vessels.

3.1. Mass balance constraints

The first step in the mathematical model is to derive the mass balances around a unit. First consider the raw material balance into a unit. Since wastewater reused to a vessel is part of the raw material, a term is included for the wastewater. The raw material used for a product is thus the sum of the fresh water, any other raw material, wastewater from storage and wastewater directly reused. In this situation the amount of water reused is not limited by concentration constraints, but rather capacity constraints. It is assumed that batch sizes are fixed. When contaminant mass is considerable, a mass balance has to be done on the raw materials, other than water, thus including the mass load from the wastewater. This is given in constraint (2).

$$m_u\left(s_{in}, j, p\right) = \sum_{j'} fr\left(s_{in}, j', j, p\right) + mf\left(s_{in}, j, p\right) + \sum_{u} fs_{out}\left(s_c, j, u, p\right)$$
$$+ M_{rmb}\left(s_{in}\right) y\left(s_{in}, j, p\right) \quad \forall\ s_{in} \in S_{in},\ j, j' \in J, p \in P, u \in U, s_c \in S_c \qquad (1)$$

$$m_{raw}\left(s_{in}, j, p\right) = m_{bulkstore}\left(s_{in}, j, p\right) + \sum_{j'} fr\left(s_{in}, j', j, p\right) C_{out}\left(s_{in}, j'\right)$$
$$+ \sum_{u} m_s\left(s_c, u, p\right) \quad \forall\ j, j' \in J, p \in P, s_{in} \in S_{in}, s_c \in S_c, u \in U \qquad (2)$$

In this formulation it is assumed that the water used for this operation is a fixed amount. Furthermore, reused wastewater can only be directly reused or sent to storage, but not both at the same time. Mass balances over the storage vessels also have to be done.

3.2. Scheduling constraints

Since the operation considered is a batch operation, the timing of each operation needs to be taken into account. The direct reuse scheduling constraints, operational scheduling constraints and storage constraints are similar to those derived by Majozi [5] for wastewater minimization in batch processes.

3.3. Objective function

The objective function for the case where the contaminant mass added from the wastewater is negligible is simply the minimization of the effluent water and fresh water for product. For the case where the mass load in the wastewater is substantial the objective function is the minimization of effluent water and raw material other than water. For both cases the model takes on the form of a mixed integer linear program (MILP).

4. Examples

The methodology was applied to two examples, with one example corresponding to each case considered. The examples stem from a pharmaceutical facility where product is mixed, removed from the mixer and the mixer is then washed out.

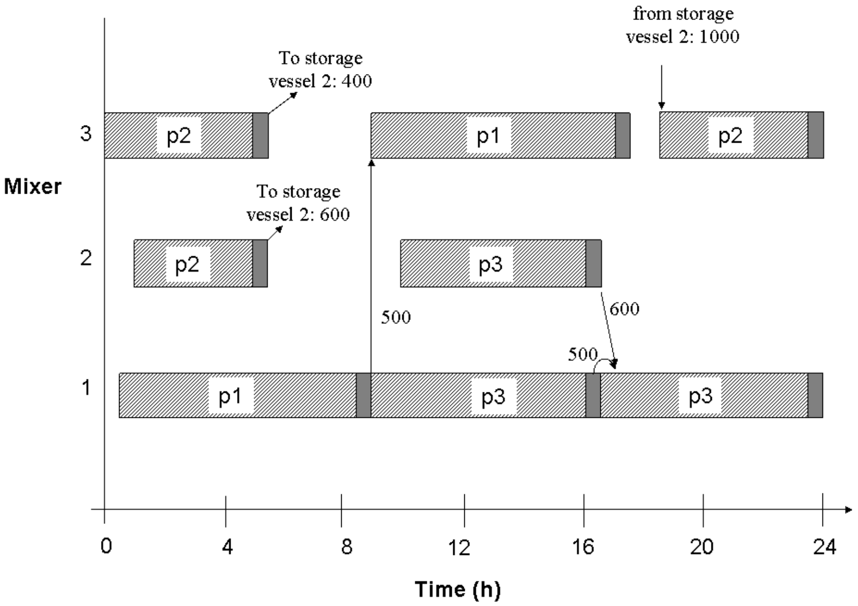

Figure 1. Schedule for first example

The first example is where the reused water has negligible amount of contaminants present and hence the contaminant mass does not add to the amount of raw material. For this case three storage vessels were considered with a maximum capacity of 2000kg. Each storage vessel could only store wastewater that was contaminated by a specific product. The time horizon considered was 24 hours. In the time horizon 2 batches of product one needed to be produced, 3 batches of product two needed to be produced and 3 batches of product three needed to be produced. The washout time was 30 minutes. The amount of water used for washing out mixer 1 was 500kg of water, mixer 2 was 600kg of water and mixer 3 was 400kg of water.

Example 1 was solved using the General Algebraic Modeling System (GAMS) using the CPLEX solver. The solution took 9.9 CPU seconds on a Pentium 4 3.2GHz processor, using 8 time points. The formulation had 432 binary variables. The resulting schedule is given in Figure 1. All mass flows shown in Figure 1 pertain water flow. The amount of water produced as effluent was 1300kg and the amount of wastewater reused for product was 1600kg. Important to note is that the reuse of this water does not compromise product integrity. Effluent is generated at the end of the time horizon as there is no opportunity for reuse at this point.

The second example deals with the case where the mass load in the wastewater is considerable and adds to the raw materials. In this case the mass gained by the washout water was assumed to be a 100kg in each mixer. Similar to the first example the number of batches that needed to be produced in the time horizon of the first product was 2, the second product was 3 batches and the third product was 2 batches. Once again there was a dedicated storage vessel for each type of wastewater.

The solution of example 2 took 1047 CPU seconds, using GAMS/CPLEX and the same processor as before. The number of binary variables was 540. The amount of raw material, other than water, used in this example is 1850kg, for all the products. Had reuse not have taken place, the amount of raw material would have been 2250kg. Furthermore, 400kg of product was recovered. Effluent was produced at the end of the time horizon and hence, 300kg of product was lost.

5. Conclusions

A methodology for zero-effluent operation in batch plants has been developed. The methodology is applicable to operations where wastewater contains contaminants that can be used as part of the raw materials for a product and where the production of a product does not generate wastewater as a by-product, i.e. the wastewater reused is generated from a separate operation.

The methodology has been applied to a pharmaceutical operation under two different zero-effluent operating assumptions, in two examples. In the first example the effluent was reduced by 55%. In the second example an 18% savings in raw materials was achieved, with a 57% recovery of product.

6. Acknowledgements

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