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TOWARDS SUSTAINABLE WATER USAGE IN A BEVERAGE PLANT

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The current drive towards environmental sustainability and the rising costs of freshwater and effluent treatment have forced the process industry to reduce freshwater consumption and wastewater generation, which can be achieved inter alia by water re-use. The mathematical models presented in the literature need to be modified in order to match industrial circumstances. This paper presents a mathematical model for water re-use in batch processes in the presence of continuous streams with acceptable purity. The model is based on a design method developed by Kim and Smith [7], modified to properly balance continuous streams. Continuous streams are treated as limited freshwater sources. Two cases were analysed: 1) re-use of continuous streams within those time intervals where the continuous streams exist, 2) re-use of continuous streams in later time intervals with intermediate storage of unused continuous streams. The opportunities of water re-use by the developed model were analysed in a brewery plant. By using the identified re-use connections, the brewery could save about 18% of its current freshwater demand.

Keywords: water minimisation; batch processes; continuous process; water re-use; industrial application.

Introduction

Waste minimisation and pollution prevention have become everyday terms in the process industry, as strict environmental regulations have induced producers to find new ways of reducing the environmental impact of their production. Water is one of the most important natural resources used in process industries. Excluding process changes, there are three approaches to reducing freshwater demand: re-use, regeneration-reuse, and regeneration-recycling.

In the literature, studies on the design of water re-use and wastewater treatment networks in industry have been mainly concerned with continuous processes [1, 2], while little attention has been directed towards the development of water conservation strategies for batch operations. The complexities of batch process industries lie in the fact that the production processes consist of elementary tasks with operating conditions and resource demand varying over time. Two main approaches are generally used to address the issue of freshwater demand minimisation, i.e. the graphical approach, and the mathematically based optimization approach.

Wang and Smith [3] initiated a graphical design method based on Water Pinch Analysis, where they combined time constraint with concentration driving force constraint. Foo et al. [4] have developed a two-stage graphical procedure for synthesizing the maximum water recovery network for a batch process system. Majozi et al. [5] presented a graphical method where, in the first instance, the time dimension was taken as a primary constraint, and concentration as a secondary one. Subsequently, the priority of constraints was reversed.

Almato et al. [6] developed an optimization framework for water use in batch processes based on the superstructure approach. Kim and Smith [7] developed a design method where water recovery was limited through time constraints. This model allows minimization of freshwater cost, storage tank costs and piping costs. Majozi [8] presented a continuous-time mathematical formulation for freshwater minimisation with and without central reusable water storage. Cheng and Chang [9] incorporated three optimisation problems, the batch scheduling, the water re-use network, and the wastewater treatment network, in a single MINLP model, to generate an integrated water network in batch processes.

This paper presents a mathematical model for water re-use in batch processes in the presence of continuous streams with acceptable purity. The continuous streams are treated as limited freshwater sources, which can be integrated with batch water-using operations. This model is based on the design method developed by Kim and Smith [7], modified to properly balance the continuous streams. The opportunities for water re-use were analysed in a brewery plant where several continuous waste streams with low contaminant concentrations are available for re-use in batch operations with lower purity requirements.

Extended mathematical model

The water mass balance for an overall water-using system is defined by equation:

$$\sum_{fw}\sum_{n} m_{fw,n}^{\mathrm{W}} + \sum_{ww}\sum_{n} m_{ww,n}^{\mathrm{W}} - \sum_{n} m_{n}^{\mathrm{OUT}} + \\ + \sum_{n} m_{n}^{\mathrm{GAIN}} - \sum_{n} m_{n}^{\mathrm{LOSS}} = 0 \quad (1)$$

Where:

- $m_{fw,n}^{\mathrm{W}}$ – water mass from freshwater source fw to operation n, t
- $m_{ww,n}^{\mathrm{W}}$ – wastewater mass from continuous operation ww to batch operation n, t
- m_{n}^{OUT} – wastewater mass from operation n to discharge, t
- m_{n}^{GAIN} – mass of water gain in operation n, t
- m_{n}^{LOSS} – water mass loss in operation n, t.

In comparison with the original model, the mass balance is extended with additional variable, $m_{ww,n}^{\mathrm{W}}$, which represents the integration of continuous streams with batch operations.

The contaminant mass load balance for each water-using operation is:

$$\sum_{fw}\left(m_{fw,n}^{\mathrm{W}} \cdot C_{c,fw}^{\mathrm{W}}\right) + \sum_{ww}\left(m_{ww,n}^{\mathrm{W}} \cdot C_{c,ww}^{\mathrm{W}}\right) + \\ + \sum_{nc}\left(m_{nc,n}^{\mathrm{PP}} \cdot C_{c,nc}^{\mathrm{OUT}}\right) - \left(m_{n}^{\mathrm{OP}} \cdot C_{c,n}^{\mathrm{OUT}}\right) + m_{c,n}^{\mathrm{ML}} + \\ + \left(m_{n}^{\mathrm{GAIN}} \cdot C_{c,n}^{\mathrm{GAIN}}\right) - \left(m_{n}^{\mathrm{LOSS}} \cdot C_{c,n}^{\mathrm{LOSS}}\right) = 0 \quad (2)$$

Where:

- $m_{nc,n}^{\mathrm{PP}}$ – re-use water mass from operation nc to operation n, t
- m_{n}^{OP} – water mass inside operation n, t
- $m_{c,n}^{\mathrm{ML}}$ – mass load of contaminant c removed by water in operation n, g
- $C_{c,fw}^{\mathrm{W}}$ – mass concentration of freshwater source, g/m³
- $C_{c,ww}^{\mathrm{W}}$ – mass concentration of continuous water source, g/m³
- $C_{c,n}^{\mathrm{OUT}}$ – outlet water mass concentration of operation n, g/m³
- $C_{c,n}^{\mathrm{GAIN}}$ – mass concentration of water gain in operation n, g/m³
- $C_{c,n}^{\mathrm{LOSS}}$ – mass concentration of water loss in operation n, g/m³.

The water mass balance for each operation is obtained by equation:

$$\sum_{fw} m_{fw,n}^{\mathrm{W}} + \sum_{ww} m_{ww,n}^{\mathrm{W}} + \sum_{nc} m_{nc,n}^{\mathrm{PP}} - \\ - \sum_{nc} m_{n,nc}^{\mathrm{PP}} - m_{n}^{\mathrm{OUT}} + m_{n}^{\mathrm{GAIN}} - m_{n}^{\mathrm{LOSS}} = 0 \quad (3)$$

Total water mass of the water-using operations is defined by:

$$m_{n}^{\mathrm{OP}} = \sum_{fw} m_{fw,n}^{\mathrm{W}} + \sum_{ww} m_{ww,n}^{\mathrm{W}} + \sum_{nc} m_{nc,n}^{\mathrm{PP}} + \\ + m_{n}^{\mathrm{GAIN}} - m_{n}^{\mathrm{LOSS}} \quad (4)$$

Feasibility constraints on the inlet and outlet concentrations are:

$$\sum_{fw}\left(m_{fw,n}^{\mathrm{W}} \cdot C_{c,fw}^{\mathrm{W}}\right) + \sum_{ww}\left(m_{ww,n}^{\mathrm{W}} \cdot C_{c,ww}^{\mathrm{W}}\right) + \sum_{nc}\left(m_{nc,n}^{\mathrm{PP}} \cdot C_{c,nc}^{\mathrm{OUT}}\right) - \\ - m_{n}^{\mathrm{OP}} \cdot C_{c,n}^{\mathrm{IN,\ MAX}} \leq 0 \quad (5)$$

$$C_{c,n}^{\mathrm{OUT}} - C_{c,n}^{\mathrm{OUT,\ MAX}} \leq 0 \quad (6)$$

Where:

- $C_{c,n}^{\mathrm{IN,\ MAX}}$ – maximum inlet mass concentration of operation n, g/m³
- $C_{c,n}^{\mathrm{OUT,\ MAX}}$ – maximum outlet mass concentration of operation n, g/m³.

Upper and lower bounds for the water flows of each stream in the superstructure are:

$$m_{fw,n}^{\mathrm{W}} - m_{fw,n}^{\mathrm{UB,\ W}} \cdot Y_{fw,n}^{\mathrm{W}} \leq 0 \quad (7)$$

$$m_{fw,n}^{\mathrm{W}} - m_{fw,n}^{\mathrm{LB,\ W}} \cdot Y_{fw,n}^{\mathrm{W}} \geq 0 \quad (8)$$

$$m_{ww,n}^{\mathrm{W}} - m_{ww,n}^{\mathrm{UB,\ W}} \cdot Y_{ww,n}^{\mathrm{W}} \leq 0 \quad (9)$$

$$m_{ww,n}^{\mathrm{W}} - m_{ww,n}^{\mathrm{LB,\ W}} \cdot Y_{ww,n}^{\mathrm{W}} \geq 0 \quad (10)$$

$$m_{n,nc}^{\mathrm{PP}} - m_{n,nc}^{\mathrm{UB,\ PP}} \cdot Y_{n,nc}^{\mathrm{PP}} \leq 0 \quad (11)$$

$$m_{n,nc}^{\mathrm{PP}} - m_{n,nc}^{\mathrm{LB,\ PP}} \cdot Y_{n,nc}^{\mathrm{PP}} \geq 0 \quad (12)$$

$$m_{n}^{\mathrm{OUT}} - m_{n}^{\mathrm{UB,\ OUT}} \cdot Y_{n}^{\mathrm{OUT}} \leq 0 \quad (13)$$

$$m_{n}^{\mathrm{OUT}} - m_{n}^{\mathrm{LB,\ OUT}} \cdot Y_{n}^{\mathrm{OUT}} \geq 0 \quad (14)$$

Where:

- $m_{fw,n}^{\mathrm{UB,\ W}}$, $m_{fw,n}^{\mathrm{LB,\ W}}$ – upper and lower bounds for water mass from freshwater source fw to operation n, t
- $m_{ww,n}^{\mathrm{UB,\ W}}$, $m_{ww,n}^{\mathrm{LB,\ W}}$ – upper and lower bounds for water mass from continuous water source ww to operation n, t
- $m_{n,nc}^{\mathrm{UB,\ PP}}$, $m_{n,nc}^{\mathrm{LB,\ PP}}$ – upper and lower bounds for re-used water mass from operation n to operation nc, t
- $m_{n}^{\mathrm{UB,\ OUT}}$, $m_{n}^{\mathrm{LB,\ OUT}}$ – upper and lower bounds for wastewater mass from operation n to discharge, t
- $Y_{fw,n}^{W}$ – binary variable for the existence or non existence of water mass from freshwater source fw to operation n
- $Y_{ww,n}^{\mathrm{W}}$ – binary variable for the existence or non-existence of water mass from continuous water source ww to operation n

$Y_{n,nc}^{\mathrm{PP}}$ – binary variable for re-used water mass from operation n to operation nc

Y_{n}^{OUT} – binary variable for wastewater mass from operation n to discharge.

A logic constraint is used to identify the existence or non-existence of a storage tank within a network:

$$Y_{n,nc}^{\mathrm{PP}} - Y_{n}^{\mathrm{ST}} \leq 0 \quad \forall n, \; t_{nc}^{\mathrm{S}} \geq t_{n}^{\mathrm{E}} \tag{15}$$

Where:

Y_{n}^{ST} – binary variable for storage tank to operation n

t_{n}^{S} – starting time of operation n, h

t_{n}^{E} – terminal time of operation n, h.

Eq. 15 implies that water re-use between operations over different time interval is only allowed through a storage tank, however, operations within the same time intervals can be connected directly.

The capacity of a storage tank is obtained by equation:

$$m_{n}^{\mathrm{ST}} = \sum_{nc} m_{n,nc}^{\mathrm{PP}} \quad \forall n, \; t_{nc}^{\mathrm{S}} \geq t_{n}^{\mathrm{E}} \tag{16}$$

Where:

m_{n}^{ST} – capacity of a storage tank, t.

Storage tank investment cost:

$$CT_{n} = r \cdot m_{n}^{\mathrm{ST}} + s \cdot Y_{n}^{\mathrm{ST}} \tag{17}$$

Where:

CT_{n} – storage tank investment cost of operation n, £

r – variable investment cost of storage tank

s – fixed investment cost of storage tank.

Additional equations for water re-use from continuous operations in batch operations are given in the continuation.

The overall water mass balance of the continuous stream is defined by equation:

$$q_{ww} \cdot \left(t_{J}^{\mathrm{E}} - t_{1}^{\mathrm{S}}\right) = \sum_{n} m_{ww,n}^{\mathrm{W}} + \sum_{j} m_{ww,j}^{\mathrm{OUT}} \tag{18}$$

Where:

q_{ww} – mass flow rate of the continuous stream, t/h

t_{J}^{E} – finishing time of the continuous stream in the last time interval J, h,

t_{1}^{S} – starting time of the continuous stream, h

$m_{ww,j}^{\mathrm{OUT}}$ – water mass from continuous process to discharge in the interval j, t.

The water mass balance for each time interval, j, is:

$$m_{ww,j}^{\mathrm{OUT}} = q_{ww} \cdot \left(t_{j}^{\mathrm{E}} - t_{j}^{\mathrm{S}}\right) - \sum_{n} m_{ww,n}^{W} \qquad \forall n, \; t_{n}^{\mathrm{S}} = t_{j}^{\mathrm{S}} \wedge t_{n}^{\mathrm{E}} = t_{j}^{\mathrm{E}} \tag{19}$$

Time intervals, j, for the continuous operations are defined according to the starting and ending times of batch processes. The objective function is the overall cost of the water network that involves the freshwater cost and annual investment cost of storage tank installation.

$$F_{\mathrm{Obj}} = \left[\sum_{fw}\sum_{n}\left(m_{fw,n}^{\mathrm{W}} \cdot P_{fw}^{\mathrm{W}}\right) + \sum_{ww}\sum_{j}\left(q_{ww} \cdot \left(t_{J}^{\mathrm{E}} - t_{j}^{\mathrm{S}}\right) \cdot P_{ww}^{\mathrm{W}}\right)\right] \frac{\lambda_{\mathrm{OHY}}}{\Delta t^{\mathrm{ALL}}} + \left(\sum_{n} CT_{n}\right) \cdot F_{\mathrm{AN}} \tag{20}$$

Where:

F_{Obj} – objective function, £/a

P_{fw}^{W} – price of freshwater source fw, £/t

P_{ww}^{W} – price of continuous water source ww, £/t

λ_{OHY} – annual operating time, h/a

Δt^{ALL} – overall time interval, h

F_{AN} – annualization factor.

Mathematical model extended with a storage tank

The model presented in the previous section allows for water re-use between batch process streams and continuous ones, only over those time intervals where wastewater streams exist. The unused wastewater is discharged. Collecting the unused wastewater in a storage tank would enable water re-use over the following time intervals.

The contaminant mass load balance for each water-using operation is:

$$\begin{aligned}&\sum_{fw}\left(m_{fw,n}^{\mathrm{W}} \cdot C_{c,fw}^{\mathrm{W}}\right) + \sum_{ww}\left(m_{ww,n}^{\mathrm{W}} \cdot C_{c,ww}^{\mathrm{W}}\right) + \sum_{ww}\left(m_{ww,n}^{\mathrm{ST}} \cdot C_{c,ww}^{\mathrm{W}}\right) + \\ &+ \sum_{nc}\left(m_{nc,n}^{\mathrm{PP}} \cdot C_{c,nc}^{\mathrm{OUT}}\right) - \left(m_{n}^{\mathrm{OP}} \cdot C_{c,n}^{\mathrm{OUT}}\right) + m_{c,n}^{\mathrm{ML}} + \\ &+ \left(m_{n}^{\mathrm{GAIN}} \cdot C_{c,n}^{\mathrm{GAIN}}\right) - \left(m_{n}^{\mathrm{LOSS}} \cdot C_{c,n}^{\mathrm{LOSS}}\right) = 0\end{aligned} \tag{21}$$

Where:

$m_{ww,n}^{\mathrm{ST}}$ – re-use water mass from storage tank of water source ww to operation n, t.

The additional expression in equation (21), $\sum_{ww}\left(m_{ww,n}^{\mathrm{ST}} \cdot C_{c,ww}^{\mathrm{W}}\right)$, makes possible the incorporation of a storage tank for unused wastewater into the water-using system.

The water mass balance for each operation is obtained by equation:

$$\begin{aligned}&\sum_{fw} m_{fw,n}^{\mathrm{W}} + \sum_{ww} m_{ww,n}^{\mathrm{W}} + \sum_{ww} m_{ww,n}^{\mathrm{ST}} + \sum_{nc} m_{nc,n}^{\mathrm{PP}} - \\ &- \sum_{nc} m_{n,nc}^{\mathrm{PP}} - m_{n}^{\mathrm{OUT}} + m_{n}^{\mathrm{GAIN}} - m_{n}^{\mathrm{LOSS}} = 0\end{aligned} \tag{22}$$

Total water flow through the water-using operation is defined by:

$$\begin{aligned}m_{n}^{\mathrm{OP}} = &\sum_{fw} m_{fw,n}^{\mathrm{W}} + \sum_{ww} m_{ww,n}^{\mathrm{W}} + \sum_{ww} m_{ww,n}^{\mathrm{ST}} + \\ &+ \sum_{nc} m_{nc,n}^{\mathrm{PP}} + m_{n}^{\mathrm{GAIN}} - m_{n}^{\mathrm{LOSS}}\end{aligned} \tag{23}$$

The feasibility constraint on the inlet concentration is:

$$\sum_{fw}\left(m^{\mathrm{W}}_{fw,n}\cdot C^{\mathrm{W}}_{c,fw}\right)+\sum_{ww}\left(m^{\mathrm{W}}_{ww,n}\cdot C^{\mathrm{W}}_{c,fw}\right)+$$
$$+\sum_{ww}\left(m^{\mathrm{ST}}_{ww,n}\cdot C^{\mathrm{W}}_{c,ww}\right)+\sum_{nc}\left(m^{\mathrm{PP}}_{nc,n}\cdot C^{\mathrm{OUT}}_{c,nc}\right)- \qquad (24)$$
$$-\ m^{\mathrm{OP}}_{n}\cdot C^{\mathrm{IN,\ MAX}}_{c,n}\ \le\ 0$$

Upper and lower bounds for water mass from a storage tank are defined by equation:

$$m^{\mathrm{ST}}_{ww,n}\ -\ m^{\mathrm{UB,ST}}_{ww,n}\cdot Y^{\mathrm{ST}}_{ww,n}\ \le\ 0 \qquad (25)$$

$$m^{\mathrm{ST}}_{ww,n}\ -\ m^{\mathrm{LB,ST}}_{ww,n}\cdot Y^{\mathrm{ST}}_{ww,n}\ \ge\ 0 \qquad (26)$$

Where:

$m^{\mathrm{UB,\ ST}}_{ww,n}$, $m^{\mathrm{LB,\ ST}}_{ww,n}$ – upper and lower bounds for water mass from storage tank of continuous water source *ww* to operation *n*, t

$Y^{\mathrm{ST}}_{ww,n}$ – binary variable for water mass from storage tank of water source *ww* to operation *n*.

The storage tank capacity for continuous source is obtained by summation of the re-used continuous wastewater stream, after the last time interval *J*:

$$m^{\mathrm{C,\ ST}}_{ww}\ =\ \sum_{n} m^{\mathrm{ST}}_{ww,n} \qquad \forall n,\ \ t^{\mathrm{S}}_{n}\ge t^{\mathrm{E}}_{j} \qquad (27)$$

Where:

$m^{\mathrm{C,\ ST}}_{ww}$ – storage tank capacity for the continuous stream *ww*, t.

The sum of the re-used continuous streams can not exceed the available water mass from those time intervals before the last time interval *J*, where the continuous stream exists:

$$\sum_{n} m^{\mathrm{ST}}_{ww,n}\ \le\ \sum_{j} m^{\mathrm{OUT}}_{ww.j} \qquad \forall n,\ \ t^{\mathrm{S}}_{n}\ge t^{\mathrm{E}}_{J} \qquad (28)$$

Storage tank investment cost:

$$CT_{ww}\ =\ r\cdot m^{\mathrm{C,\ ST}}_{ww}\ +\ s\cdot Y^{\mathrm{ST}}_{ww,n} \qquad (29)$$

Where:

CT_{ww} – storage tank cost for water source *ww*, £.

The objective function is:

$$F_{\mathrm{Obj}}=\left[\sum_{fw}\sum_{n}\left(m^{\mathrm{W}}_{fw,n}\cdot P^{\mathrm{W}}_{fw}\right)+\sum_{ww}\sum_{j}\left(q_{ww}\cdot\left(t^{\mathrm{E}}_{J}\ -\ t^{\mathrm{S}}_{j}\right)\cdot P^{\mathrm{W}}_{ww}\right)\right] \qquad (30)$$
$$\frac{\lambda_{\mathrm{OHY}}}{\Delta t^{\mathrm{ALL}}}+\left(\sum_{n} CT_{n}+\sum_{ww} CT_{ww}\right)\cdot F_{\mathrm{AN}}$$

Equations (6)–(18) remain unchanged.

Illustrative example

The model described in the previous section is illustrated by the first example from Kim and Smith [7], extended by one continuous stream, *Fig. 1.* The limiting conditions and timing for the batch processes are shown in *Table 1.*

Table 1: Limiting water data for batch processes

Process	Limiting mass concentration (g/m³)		Limiting water mass (t)	Time (h)	
	C_{in}	C_{out}		T_s	T_f
P1	0	200	40	0	0,5
P2	100	200	25	0,5	1,0
P3	100	400	50	0,5	1,0
P4	100	400	50	1,0	1,5

The average flow rate of the continuous process stream is 100 t/h, the contaminant concentration is 50 g/m³. The continuous stream is available within the time interval 0–1 h. In the case of no water re-use, the freshwater consumption per batch is 227,5 t. Water re-use opportunities for batch processes without integration of the continuous stream, are shown in Fig. 1. Water re-use between batch operations enables a reduction in freshwater consumption per batch from 227,5 t to 202,5 t. According to the network design, a storage tank needs to be installed, with a capacity of 37,5 t. The overall cost for the freshwater and storage tank installation is 1 080,6 k£/a.

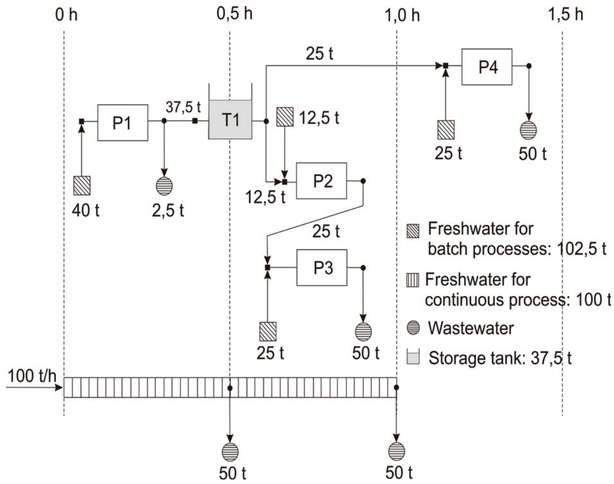

Figure 1: Water network design for batch processes

Further reduction in freshwater consumption per batch can be achieved by integrating the continuous stream in the water network. The optimal network design is shown in *Fig. 2.*

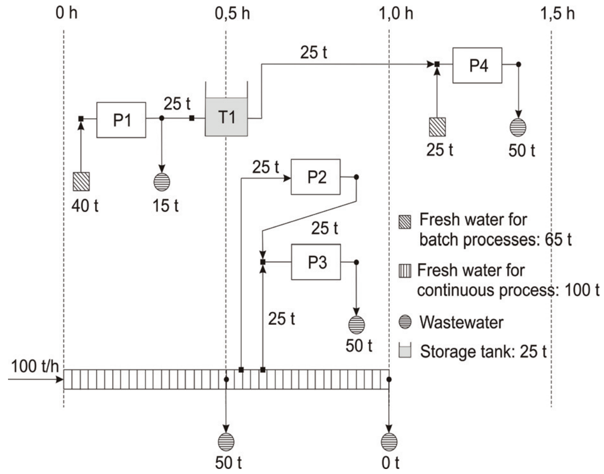

Figure 2: Water network design – extended model

Processes P2 and P3 use wastewater from the continuous process instead of freshwater, which reduces the freshwater consumption per batch to 165 t. The continuous water source can not be used in process P1 as the concentration of continuous stream is higher than the maximum inlet concentration of P1. The storage tank capacity is reduced to 25 t. The overall cost for the freshwater and storage tank installation is estimated to be 885,7 k£/a.

As the continuous stream is absent during the last time period, an extended model was applied which included a storage tank for wastewater collection from the continuous process. The final network design is shown in *Fig. 3.* The freshwater consumption per batch is reduced to 140 t. All processes, except the process P1, use wastewater from the continuous process. The capacity of the storage tank increases to 50 t, but the overall cost decreases to 753,7 k£/a because of higher water re-use.

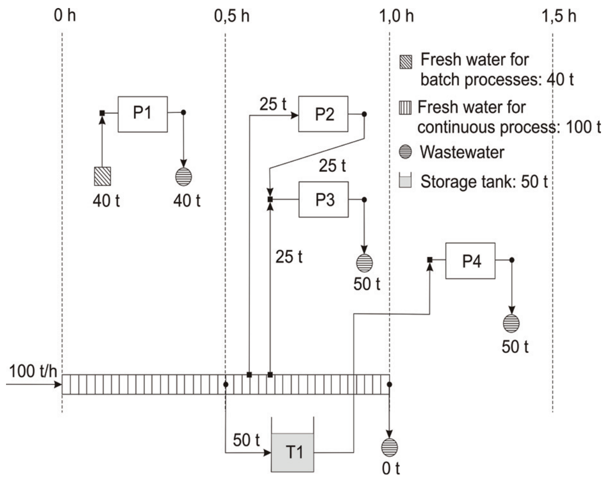

Figure 3: Final network design

Case study

In the case of the brewery studied in this paper, the volume ratio of water consumption to beer sold was 6.04 L/L or 653 300 m^3/a. Compared with the ratio specified by the Reference Document on Best Available Techniques in the Food, Drink and Milk Industries [10], the fresh water consumption exceeded the upper limit by 144 900 m^3/a.

In the first stage, the water balance was obtained and the most critical processes were identified by comparing their water consumption with those values given in BREF [10], and the European Brewery Convention [11]. When comparing the results, the cellar with filters and the packing area were marked as the critical points in the brewery. In order to estimate any possibilities of water re-use, the maximal inlet values of contaminants (COD, pH and conductivity) were determined for each water consumer, and its flow rate measured.

The water re-use opportunities were analysed in the packaging area. The freshwater consumption per batch is 5 503 t. The continues streams are: 1) the outlet stream of the rinser for non returnable glass bottles (K1), and 2) the wastewater from the rinser for cans (K2). The average water flows for the continuous processes are 48,37 t/h and 9,68 t/h, the average outlet concentrations are 34 g/m^3 and 23 g/m^3. The final water network design is shown in *Fig. 4.* The wastewater from continuous process, K2, can be re-used in the pasteurisation processes P23–P31. Based on the COD, the outlet stream of the rinser for non returnable glass bottles, K1, could be connected by the tunnel pasteurizer, however, this is forbidden because of the high quality requirements of pasteurisation. The wastewater from pasteurizers can be reused in the bottle washer for returnable bottles, processes P1–P5 and P20–P22. In case of the packing line for returnable glass bottles, filling line A and B, water consumption could be reduced by reusing the outlet stream of the bottle washer in the crate washer, processes P6–P19. The freshwater consumption per batch is reduced from 5 503 t to 4 498 t. No storage tank installation is needed.

Conclusion

A mathematical model for water re-use in batch processes in the presence of continuous streams was developed by modifying the model by Kim and Smith [7]. In the first case, the model allows for re-use of the continuous wastewater stream over time intervals, where this stream exists. In the second case, the re-use in later time intervals is possible with the collection of an unused continuous wastewater stream. The results of examples and the case study show that incorporating continuous steams in the analysis of dominant batch processes, can contribute to the reduction of freshwater consumption, as well as the total cost of the network.

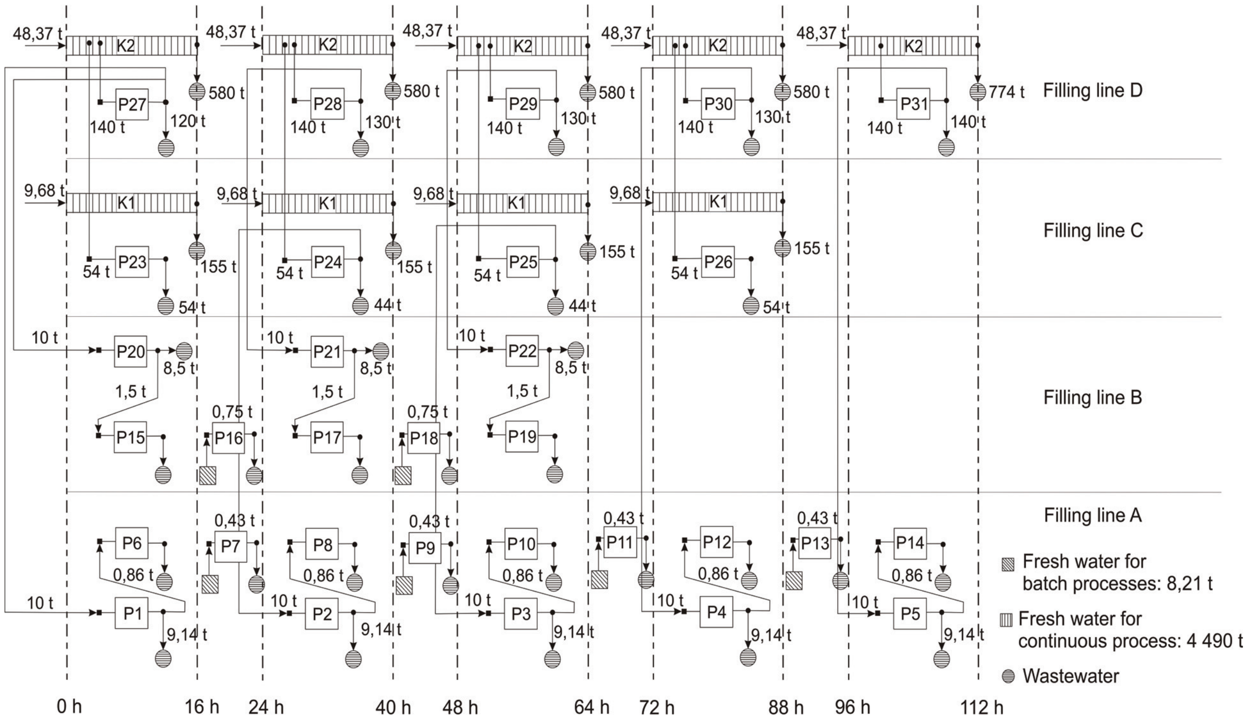

Figure 4: Water network design for the packaging area

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