Computation of optimal production intervals for an ultra filtration plant processing surface water
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Computation of optimal production intervals for an ultrafiltration plant processing surface water

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Abstract

A chemical cleaning sequence model is developed that can be used to predict the fouling status of a membrane over multiple chemical cleaning cycles. The model is used to optimize the operating costs - based on chemicals usage, energy requirement and investment costs - over a fixed time horizon The production of a specified volume of permeate should be guaranteed, while the number of cycles, the net production, the production time and the subsequent cleaning time are computed. The fouling status of the membrane is bounded. Optimization of the cleaning variables does not strongly influence operational costs; however, optimization of the chemical cleaning cycle is useful as a means to control fouling.

Keywords: Ultra filtration, modeling, cyclic behavior, multi-level-optimization.

1. Introduction

Ultra filtration (UF) is increasingly used as a surface water purification technique. UF membranes have a high selectivity, are easy to scale up and have become economically attractive during the last fifteen years. However, during filtration, the membranes are subject to fouling and frequent cleaning is required. In the short term, membrane fouling is removed from the membrane by means of backwashes, in the long-term the membrane is treated with cleaning chemicals.

Currently operating settings for UF membranes are based on rules of thumb and pilot plant studies. The settings are generally conservative and it is expected that operating costs can be reduced by means of process optimization. Process optimization of membranes is not done extensively. Dynamic optimization of membranes to minimize filtration costs and to control membrane fouling was first reported in the 1990's by van Boxtel et al. [1,2]. Also some efforts were reported on the automation and advanced control of membrane units [3-5].

A membrane filtration process shows cyclic behaviour (switching between filtration, backwashing and chemical cleaning). The process takes place over different time horizons and optimization should subsequently be performed at different levels. These issues have not been addressed extensively in the literature on membrane operation. On optimization of a membrane unit over multiple production cycles a few publications appeared [6, 7], however, for other applications in the field of chemical engineering, the mentioned issues have been studied more extensively. Optimization of cyclic processes has been reported for tubular reactors [8, 9] and for example, steam generators [10]. Mixed integer maintenance scheduling problems are often used to deal with cyclic behaviour of processes [11-15]. Hierarchical optimization or multi-level optimization is frequently performed in management systems, computer networks or electronic circuits [16-18].

If a process can be divided into several decision layers, multi-level optimization may be very useful. In figure 1 the cyclic nature of an ultra filtration process as studied in this paper, is visualized.

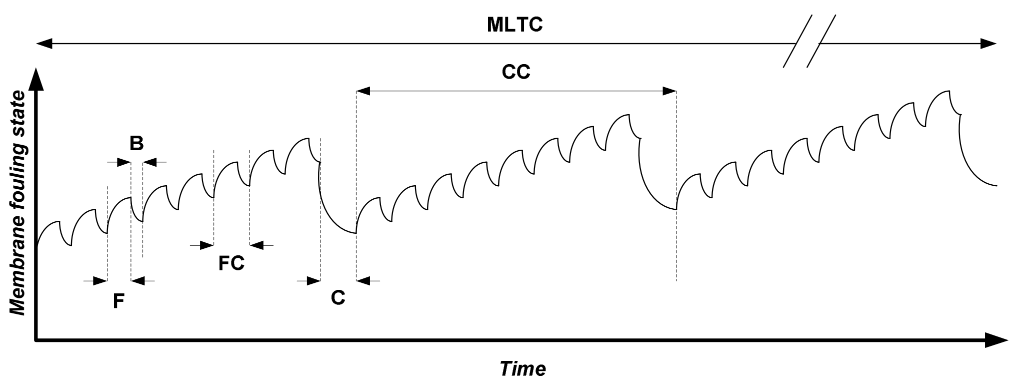

Figure 1: Schematic representation of the cyclic behaviour of the ultra filtration process.

Figure 2 shows the multi-level optimization structure for the ultra filtration process schematically. Optimal values are calculated in each layer and passed downwards, while costs are passed upwards. In the lowest layers, or short-term levels (Filtration (F), Backwash (B) and Chemical cleaning phase (C)) decisions are made concerning actual process control (settings for valves, pumps, sensors, etc). In the upper layers, or intermediate-term-levels, (Filtration cycle and Chemical cleaning cycle) decisions are made concerning settings at the production level (assignment of volumes and times over the cycles). In principle a third layer or long-term level can be added where strategic decisions are made (operational settings with respect to membrane life time).

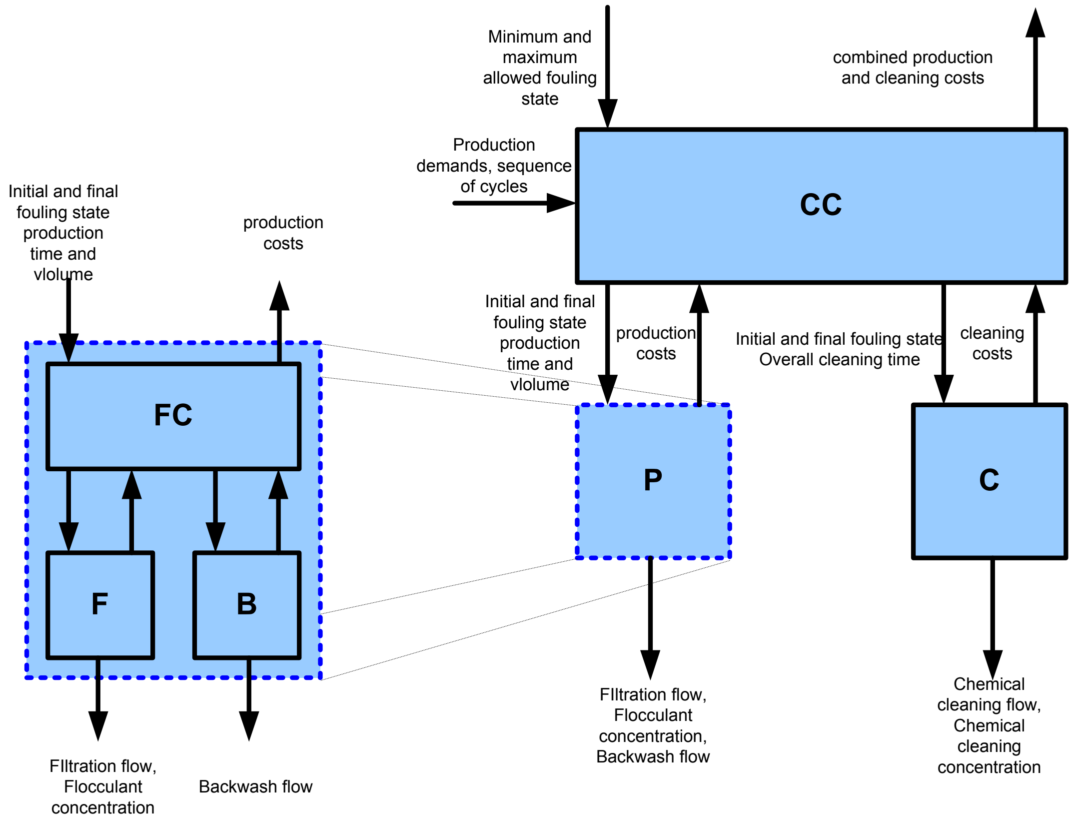

Figure 2: Hierarchical optimization structure for the ultra filtration process

During the filtration phase (F) surface water is filtrated in dead-end mode, as a result fouling builds up and a backwash phase (B) is performed to restore the membrane fouling status. A filtration phase followed by a backwash phase is called a filtration cycle (FC). During a production phase (P), or filtration sequence (FS) a number of filtration cycles are performed. During the filtration sequence, backwashing does not always result in complete membrane fouling status recovery, for this reason, a filtration sequence is normally followed by a chemical cleaning phase (C), in which the membrane is cleaned with chemicals to restore the membrane fouling status. A filtration sequence followed by a chemical cleaning phase is called a chemical cleaning cycle (CC) and a number of chemical cleaning cycles is referred to as a chemical cleaning sequence (CS). It is further noted that in a higher hierarchical layer the membrane lifetime cycle (MLTC) membrane lifetime is optimized.

Blankert et al. already reported on the modelling and optimization of the filtration phase [19, 20] and backwash phase [21] in membrane operation. In addition, the modelling aspects of the chemical cleaning phase were reported by Zondervan et al. [22]. Results on the modelling and optimization of a sequence of filtration cycles were published in [21]. In this paper the modelling and optimization aspects of a sequence of chemical cleaning cycles will be discussed.

2. Theory

For the optimization, the required models, cost function and constraints are defined:

2.1. The process models

Darcy's equation is given as:

$$R_M + R_f = \frac{\Delta P}{\mu J} \tag{1}$$

Where ΔP is the trans membrane pressure, μ is the viscosity, J is the flux, R_M is the membrane resistance and R_f is the resistance as a result of fouling. For ideal cake filtration, the membrane fouling resistance can be described as:

$$R_f = \alpha\left(x_{W,i} + x_{W,s} + x_{W,f}\right) \tag{2}$$

Where α is the specific cake resistance and where $x_{w,i}$, $x_{w,s}$, $x_{w,f}$ are fouling state variables for irreversible, slow and fast fouling removal. The fouling states can be modelled for filtration, backwashing and chemical cleaning. The dynamic models for these different phases are shown in figure 3. The models for the filtration- and backwash phase are connected by a filtration sequence model that acts as a scheduler between the two phases. Similarly, the chemical cleaning sequence model connects the filtration sequence model to the chemical cleaning phase model and acts as a scheduler between these phases.

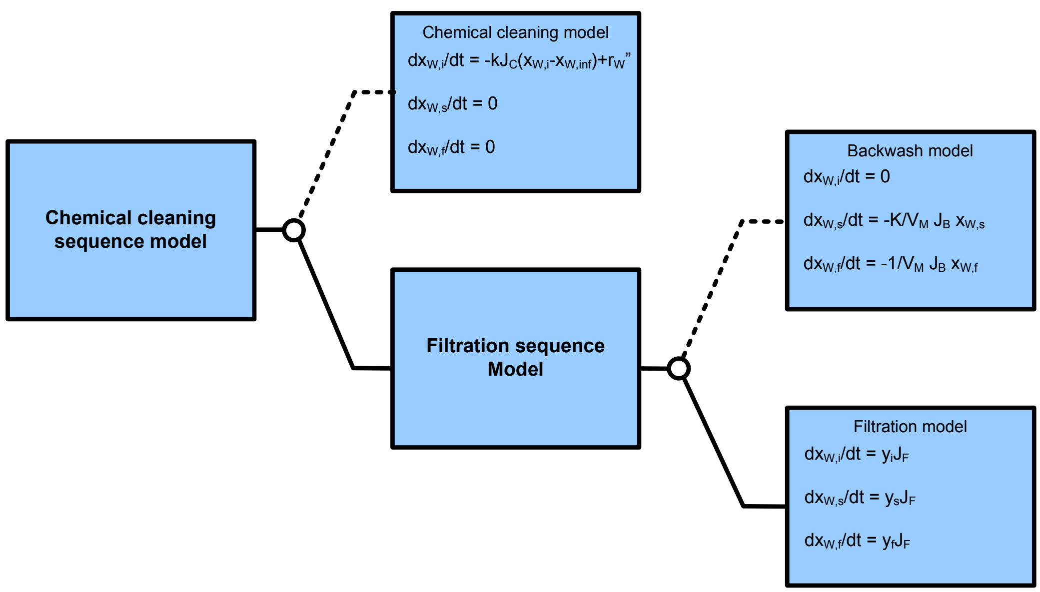

Figure 3: Schematic model structure

2.2. Cost function

The operating costs are a measure for the economic performance of the process and can be divided into:

- Energy costs (typically short-term)
- Material costs (typically intermediate-term)
- Depreciation- and maintenance costs (typically long-term)

The energy consumption $C_{E,CS}$ during a chemical cleaning sequence is the sum of the energy consumption of all filtration phases, backwash phases and chemical cleaning phases:

$$C_{E,CS} = \frac{W_E}{V_{CS}} \sum_{n_C=1}^{N_C} \left(\int_0^{t_C} \frac{\mu J_C^2 R}{\eta_P} dt + \sum_{n_F=1}^{N_F} \left(\int_0^{t_F} \frac{\mu J_F^2 R}{\eta_P} dt + \int_0^{t_B} \frac{\mu J_B^2 R}{\eta_P} dt \right) \right) \tag{3}$$

where W_E is a cost factor, η_P the pump efficiency, V_{CS} is the volume produced in a chemical cleaning cycle, N_C is the number of chemical cleaning cycles and N_F is the number of filtrations in a chemical cleaning cycle.

The total costs for material streams $C_{M,CS}$ are based on waste disposal costs, chemicals consumption and feed:

$$C_{M,CS} = \frac{1}{V_{CS}} \sum_{n_C=1}^{N_C} \left(V_C x_{C,in} W_C + \sum_{n_F=1}^{N_F} \left(V_F \left(W_F + C_F W_{Fl} \right) + W_W V_B \right) \right) \tag{4}$$

in which W_F is a cost factor for the feed water costs, W_W are the waste disposal costs, W_{Fl} are the coagulant costs, C_F is the coagulant concentration, W_C are the costs for cleaning chemicals and $x_{C,in}$ is the cleaning agent concentration.

The depreciation costs $C_{I,CS}$ of the membranes are proportional to the duration of the chemical cleaning sequence:

$$C_{I,CS} = \frac{1}{V_{CS} W_I t_{CS}} \tag{5}$$

in which the cost factor W_I representing the depreciation costs is normalized for the membrane life time. These costs do not influence the results of an optimization with a fixed final volume and fixed final time. When the final volume is a degree of freedom, the depreciation costs are balanced against the other costs.

The total costs are the sum of the energy costs, materials costs and depreciation costs.

$$C_{tot} = C_{E,CS} + C_{M,CS} + C_{I,CS} \tag{6}$$

2.3. Constraints and optimization

The problem consists of 13 optimization variables: two integer control variables: N_C the number of chemical cleaning cycles and N_F, the number of filtration cycles. There are eleven continuous control variables: (V_F, the volume of permeate produced during filtration, t_F, the filtration time, C_F, the coagulant concentration, V_B, the volume consumed during backwashing, t_B, the backwash time, V_{FS}, the volume of permeate produced in the filtration sequence, t_{FS}, the time of the filtration sequence, V_C, the volume of cleaning chemicals used for chemical cleaning, t_C, the chemical cleaning time, V_{CS} the volume of permeate produced in the chemical cleaning sequence and t_{CS}, the time of the chemical cleaning sequence.. The continuous variables can assume different values for each individual filtration, backwash or chemical cleaning; however, in this study the optimal stationary values are determined.

The optimization objective is to minimize the operating costs, while producing a specified volume V_H within a specified time t_H.

For this reason, the optimization problem deals with a fixed time:

$$t_{CS} = t_H \tag{7}$$

And a fixed final volume:

$$V_{CS} = V_H \tag{8}$$

For this reason, not all variables can be chosen independently. If it is assumed that conditions are the same for each cycle, the following time constraints can be defined:

$$t_{FS} = \frac{t_H}{N_C} - t_C \tag{9}$$

$$t_F = \frac{t_{FS}}{NF} - t_B \tag{10}$$

And for the volumes:

$$V_{FS} = \frac{V_H}{N_C} + V_C \tag{11}$$

$$V_F = \frac{V_{FS}}{N_F} + V_B \tag{12}$$

It is further noted that the backwash strategy is based on flushing with maximal flux, for this reason duration and volume of the backwash can not be chosen independently:

$$V_B = J_B t_B \tag{13}$$

Given the constraints of equations 7 to 13, the number of optimization variables reduces to 6, namely the backwash time t_B, the coagulant concentration C_F, the cleaning agent volume V_C, the chemical cleaning time t_C, the number of filtration cycles N_F and the number of chemical cleaning cycles N_C.

The total number of filtration cycles and chemical cleaning cycles are integer variables, which pose problems for normal optimization algorithms. For this reason, the following optimization procedure is used: For a certain number of filtration- and chemical cleaning cycles, the minimal costs are calculated as a function of the backwash duration, the coagulant concentration, the cleaning time and the cleaning agent volume. By repeating this for different values of the number of chemical cleaning cycles, the values of N_F and N_C are found for which these costs are minimal. The optimal value of the number of cycles can be found by a direct search method. The objective function is in this case given as a bi-level-programming problem:

$$J = \min_{N_C, N_F} \left(\min_{t_B, C_F, t_C, V_C} \left(C_{tot} \right) \right) \tag{14}$$

3. Results and discussion

Simulations were performed with the parameter settings of table 1.

R_M (1/m)	$8.80.10^{11}$	W_E (EUR/kWh)	0.10
α (1/m^2)	$1.5.10^{13}$	W_F (EUR/m^3)	0.03
M (Pa.s)	$1.01.10^{-3}$	W_W (EUR/m^3)	0.25
J_B (l/h/m^2)	250	W_I (EUR/m^2/yr)	14
J_C(l/h/m^2)	125	W_{fl} (EUR/m^3.ppm)	5000
η_P (-)	0.35	W_C (EUR/m^3)	500

Table 1: Parameters used for optimization

In figure 4, optimal calculated fouling profiles are shown for a production horizon of t_{CS} = 72*h*, with a net production flux of 66 *l/h/m*^{2}, for three different values of N_C, respectively 1, 9 and 24 times. The maximum resistance level decreases when the number of chemical cleaning cycles over a given time horizon is increased.

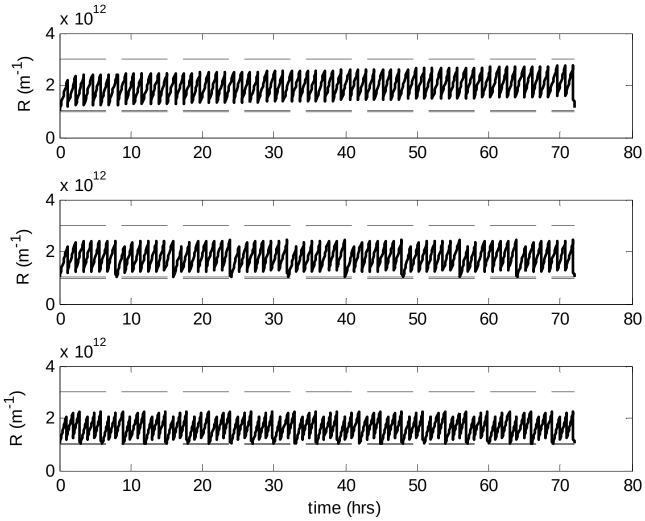

Figure 4: Resistance trajectories for an operating horizon of 72 hours, for different values of N_C: 1, 9 and 24

Figure 5 shows optimal settings for the control variables for different values of the chemical cleaning cost (W_C): 50 $EURO/m^3$ (low), 500 $EURO/m^3$ (reference) and 5000 $EURO/m^3$ (high). The optimal values for t_F , C_F , t_C and N_F are not sensitive to changes in W_C.

V_C decreases for higher values of W_C, from which can be concluded that if chemical cleaning becomes more expensive, optimization results in lower cleaning volumes.

In general it can be observed that for increasing values of N_C, the filtration time decreases, the filtration flux increases, the backwash time and coagulant concentration remain constant.

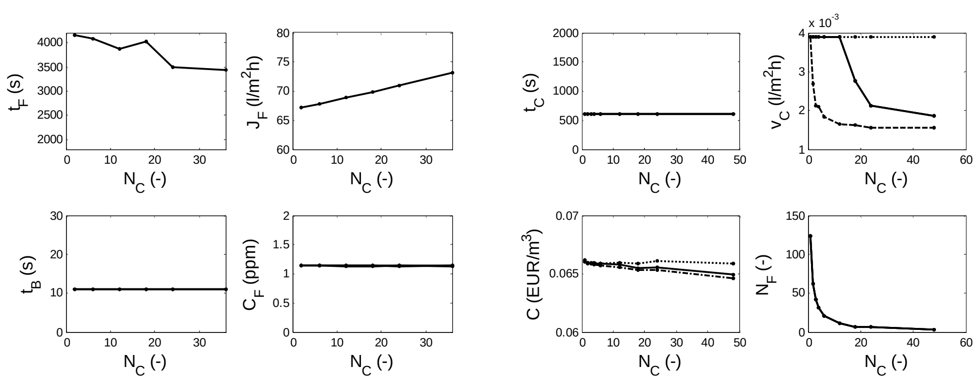

Figure 5: Optimal settings for different values for the chemical cleaning costs, low (dotted), high (dashed), reference (line). It should be noted that in some of the figures, the lines coincide.

As N_C is increasing, the available production time decreases. Consequently the filtration flux is higher and the filtration time and the number of filtration cycles is decreasing. As the filtration flux is increasing, the fouling rate also increases.

From figure 5 (the lower row, 3rd figure from left) it can be seen that the operating costs slightly decrease with the number of chemical cleaning cycles N_C), however, the operational costs do not have a minimum for a specific value of N_C within the admissible range. From an environmental point of view, N_C should not be chosen too high, in order to reduce chemicals consumption and it should also not be chosen too low, in order to meet legal hygienic regulations.

To deal with the increased fouling rate, the backwash duration or flocculant concentration can be increased. This is not necessary, due to the fact that the fouling rate is controlled by increasing the number of chemical cleaning phases.

As observed earlier, as N_C is increasing, the cleaning agent volume is decreasing. This is an interesting observation. In principle two strategies exist to obtain the desired cleaning effectiveness. In the first strategy the volume of cleaning agent flushed through the membrane can be increased, while keeping the cleaning time short, in the second strategy the volume may be kept minimal and the cleaning time is increased. It may be expected that in order to minimize costs, while reaching the desired cleaning effectiveness, the volume of cleaning agent should be reduced, while increasing the cleaning time.

Figure 6 shows the relationship between the overall operating costs, t_C and V_C for a given situation (t_H = 144, N_C = 6, N_F = 21, C_F = 1.15 and t_B = 11). A large plane can be seen where the costs are minimal for different values of t_C and V_C, i.e. different conditions of t_C and V_C result in the same operating costs.

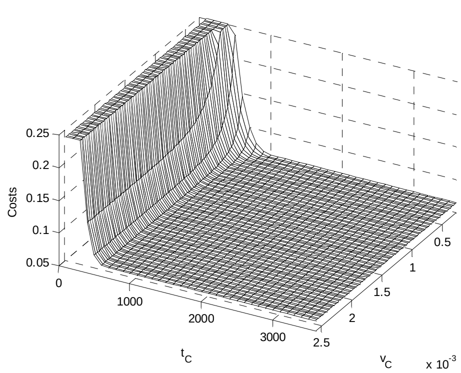

Figure 6: Surface plot of the costs as function of the cleaning time and cleaning agent volume. The costs were capped at 0.25 EURO/m3.

In table 2 the most important optimization results are summarized. A reference case is compared to four other cases, 1) A high chemical cleaning interval, 2) A low chemical cleaning interval, 3) High costs for chemical cleaning and 4) Low costs for chemical cleaning. It can be seen that N_C and W_C do not strongly influence the operationg costs. For the reference case, the chemical cleaning costs are less than 0.2% of the overall operating costs. Even if the number of chemical cleanings over the specified time interval is doubled, or the cleaning agent costs are ten times more expensive, the cleaning costs hardly influence the overall operating costs, where minor compensations are made with respect to energy costs or flocculant costs. In figure 7 the division of the operational costs for the reference case are shown.

		reference	Low cleaning interval	High cleaning interval	Low cleaning costs	High cleaning costs
N_C	(-)	6	3	12	6	6
W_C	(EUR/m^3)	500	500	500	50	5000
J_F	(l/h/m^2)	67.1	67.3	67.8	67.3	67.3
t_F	(sec)	4074	4089	3862	4074	4074
t_B	(sec)	11.0	11.0	11.0	11.0	11.0
C_F	(ppm)	1.14	1.14	1.14	1.14	1.12
V_C	(m^3)	0.0039	0.0039	0.0039	0.0039	0.0027
t_C	(sec)	600	600	600	600	600
N_F	(-)	21	42	11	21	21
C_{tot}	(EUR/m^3)	0.0660	0.0662	0.0659	0.0658	0.0660
R	x10^{12} (1/m)	2.50	2.60	2.35	2.50	2.50

Table 2: Summary of optimization results

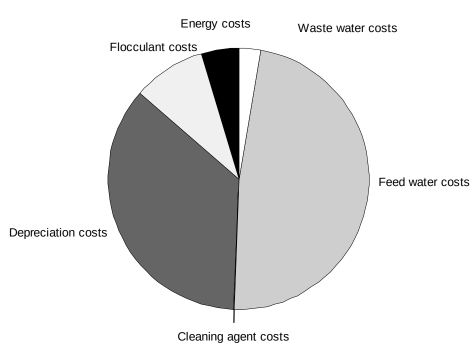

Figure 7: Pie chart of the operational costs for the reference case.

It can be seen that the costs for chemical cleaning are small compared to the overall operating costs. Optimization of the cleaning variables (N_C, t_C and V_C) will therefore not result in a significant reduction in the operating costs, however, chemical cleaning settings do influence the membrane resistance fouling profiles.

4. Conclusions

Computation of optimal operating settings (t_F , C_F , t_B, t_C, V_C, N_F) as function of the number of chemical cleaning cycles N_C for a fixed time horizon (t_{CS}) while producing a specified volume (V_{CS}), over that time horizon, was performed. The simulation results show that operational costs and optimal operating variables are not sensitive to the number of chemical cleaning cycles and the cleaning intensity (t_C and V_C). Optimizing the number of chemical cleaning cycles will not reduce operating costs and for this reason optimization should be used to accomplish other objectives such as, controlling membrane fouling. At a higher hierarchical level fouling control is an important issue with respect to membrane life time.

5. Acknowledgements

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