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Multi-Objective Optimization of Semi-Continuous Water Networks

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There is an increasing interest in complex optimization of resource utilization in industrial processes, like energy and utilities such as water or steam. Traditionally, optimization of water networks (WNs) was performed using mono-objective functions (freshwater consumption, investment and/or operating costs etc). Lately, multi-objective function optimization was used in order to get a set of solutions (Pareto front - PF) from which to choose using non-quantifiable criteria. In the present paper, we used a complex two level optimization. The outer level optimizes the schedule of the water using units (WUs) according to their windows of opportunity with respect to the freshwater consumption, while the inner level uses a dual-objective function to optimize the topology of the semi-continuous WN: *a)* the freshwater consumption and *b)* the combined investment and operating cost of the pipe network, designed for the optimum diameter. The targeted schedule should ensure a maximum wastewater reuse between the discontinuous WUs and a minimum quantity of water for storage. The WN has N discontinuous WUs with respect to the processed raw materials, but continuous with respect to water flow, each handling at most K contaminants, and one storage tank (ST) of limited capacity. A single freshwater source is available. For each time interval, the network (the overlapping WUs) is abstracted as an oriented graph having the WUs and the ST as nodes and the flow pipes as arches. The WUs operating within a time interval are ranked also according to their maximum critical outlet concentration of contaminants. Therefore, water reuse is allowed from the WUs having lower maximum outlet concentrations to the ones with higher limits. The mathematical model consists of total and partial mass balance equations for each WU and the ST. Multi-objective genetic algorithm was the method of choice for optimization, as implemented in Matlab™. The same synthetic case study optimized for minimum freshwater consumption was used to test this new approach. The results are analyzed and discussed with respect to the mono-objective optimization as well.

1. Introduction

Water's availability is questionable on the long term due to climate changes and large consumption. Therefore, many studies focused on finding better and better approaches to curb water using in industry. The methods used for the optimization of wastewater networks can be split into insight based (mainly pinch analysis and derived methods) and mathematical modelling techniques. Due to the large water flows used, the continuous processes were first subjected to optimization (Foo, 2009).

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An increasing number of studies addressed also wastewater minimization for batch processes which are very popular in food and drugs industry. Batch water networks (BWN) are optimized using variations of methods already in place for continuous WNs, according to the discreteness of BWN operations. Hence, the difference between continuous and batch processes consists in the time constraint, meaning that wastewater of one WU cannot be reused in a different WU unless this latter WU starts immediately after the former WU, regardless the concentration restrictions. This time constraint is partially bypassed by using STs, which are both sinks and supplies for WUs.

The insight based methods start from a predefined schedule and minimize the used freshwater quantity increasing the wastewater reuse. The first insight based technique extended to BWN is the one of Wang and Smith (1995) for semi-continuous WUs. Concentration intervals are built so that the water is cascaded from the lowest concentration to the highest concentration interval. The excess water is stored from an interval to the other for reuse, and on the other hand, when more water is necessary, fresh water is added. From the same category of insight-based approaches, several algebraic techniques, like water cascade analysis, time dependent concentration interval analysis were proposed. Each one uses the same concept of cascading water to a higher inlet concentration limit.

For complex problems (e.g. multiple contaminants) the insight-based techniques are no longer efficient. More appropriate proved to be the mathematical modelling techniques for water minimization. Generally, they involve a superstructure, a mathematical model describing the constraints and one or more objective functions. They can start from a predefined schedule or the optimization can include the scheduling part too. When possible, the schedule optimization gives better solutions; therefore scheduling optimization often appears in combination with diverse objective functions (Chen et al., 2010; Zhou et al., 2009; Cheng and Chang, 2007, Halim and Srinivasan, 2010).

Castro et al. (2006) present in their paper two new continuous-time formulations for the short-term scheduling of single/multistage, multiproduct batch plants, where equipment units are subject to sequence dependent changeovers, and product orders are subject to both release and due dates. Even though other approaches may perform significantly better in some situations, there are some arguments that give an edge to their formulation, the most important being its ability to always find very good solutions with modest computational efforts.

Cheng and Chang (2007) used superstructure concepts to simultaneous minimization of water and scheduling. The optimization criteria: batch schedules, water-reuse and water treatment subsystems are integrated into the same mathematical formulation. Reuse/recycle is possible only via buffer tanks, no direct connections being allowed between WUs. The constraints are represented by mass balances and BWN structure. The disadvantages are the large number of unknowns, easily attainable, and the lost of accuracy with respect to scheduling for long time intervals. In order to overcome these limitations, Zhou et al. (2009) modified the state-space superstructure to formulate a MINLP model for simultaneous optimization of batch process schedules and single- or multi-contaminant water allocation system. The main advantage of the simultaneous

water minimization and scheduling approaches is that the global optimum can almost always be identified in all case studies presented.
The present paper presents a complex two level optimization. The outer level optimizes the schedule of the WUs according to their windows of opportunity (Dogaru and Lavric, 2010) with respect to the freshwater consumption, while the inner level uses a dual-objective function (*a* – the freshwater consumption and *b* – the combined investment and operating cost of the pipe network, designed for the optimum diameter) to optimize the topology of the semi-continuous water network.

2. Mathematical Model

For each time interval, the network (the overlapping WUs) is abstracted as an oriented graph having the WUs as nodes and the flow pipes as arches (Iancu et al., 2009; Tudor and Lavric, 2010). The WUs operating within a time interval are ranked also according to their maximum critical outlet concentration of contaminants. Therefore, water reuse is allowed from the WUs having lower maximum outlet concentrations to the ones with higher limits. The mathematical model consists of total and partial mass balance equations for each WU (Dogaru and Lavric, 2010). The ST could be abstracted as both source and sink with finite volume for the BWN. Its dynamic, which influences greatly the flow structure within BWN, is given by the following system of ordinary differential equations:

$$\frac{dm}{dt} = \sum_{i=1}^{N} \left(S_i^{out} - S_i^{in} \right) \tag{1}$$

$$\frac{dC_k^S}{dt} = \frac{\sum_{i=1}^{N} S_i^{out} \cdot \left(C_{ki} - C_k^S \right)}{m} \tag{2}$$

For a full analysis of the dynamics of the BWN topology according to different mono-objective optimization scenarios, the reader is directed to (Dogaru and Lavric, 2010).

3. Case Study

The case study which is analyzed in the present paper is similar to the one investigated in (Dogaru and Lavric, 2010), except here the optimization is done with respect to scheduling too and considers the regeneration of the streams coming from ST and used as supply, when applicable; its main features are displayed in Table 1. There are six WUs, with a maximum of four overlapping during a particular working period, dealing with three contaminants. Each WU has assigned a “window of opportunity” interval, meaning it can begin anytime between t_{beg} and $t_{beg}+\Delta t_{wop}$, without disturbing the overall batch process with respect to the raw material throughput. Its total working period is equal to Δt_{length}. Instead of giving the contaminants load in mass units, the mass flow is preferred since the same WU could be part of several working periods, depending on the particular schedule the optimizer will check when searching for the best schedule; although its total mass load remains the same, the load per working period changes, according to this particular schedule.

Table 1: Operating and restriction data for the WUs and their schedule characteristics – start time, t_{beg}; duration, Δt_{length}; window of opportunity period, Δt_{wop} (maximum freshwater consumption: 2105.25 t)

Unit i	**1**	**2**	**3**	**4**	**5**	**6**
Δm_{1i}, kg/h	0.35	0.15	0.55	0.45	0.25	0.65
Δm_{2i}, kg/h	0.25	0.35	0.45	0.15	0.65	0.55
Δm_{3i}, kg/h	0.35	0.25	0.15	0.45	0.65	0.85
$C_{1i}^{in,\max}$, ppm	0	15	15	25	45	35
$C_{2i}^{in,\max}$, ppm	0	20	35	45	35	20
$C_{3i}^{in,\max}$, ppm	0	25	0	45	55	25
$C_{1i}^{out,\max}$, ppm	35	70	75	105	90	85
$C_{2i}^{out,\max}$, ppm	45	115	95	85	105	110
$C_{3i}^{out,\max}$, ppm	55	110	85	100	120	95
t_{beg}, h	5	10	0	35	20	0
Δt_{length}, h	45	70	25	65	55	70
Δt_{wop}, h	20	10	0	15	10	5

Table 2: Regeneration Unit constraints

Contaminant	Constraints, ppm	
	inlet	outlet
1	65	15
2	80	20
3	95	25

The regeneration unit (RU) is placed after the ST and works only when the supply wastewater from tank has all the contaminant concentrations greater than the inlet restrictions of RU, as presented in Table 2. This is a drawback, removable if, during the inactive period, some maintenance is foreseen.

4. Results and Discussions

The solving strategy applied when the schedule is fixed is presented in (Dogaru and Lavric, 2010), together with the way it is implemented. If the schedule is part of the optimization, we use a complex two level approach. On the outer level, the schedule of the whole batch process is optimized, according to the WUs allowed windows of opportunity, with respect to the freshwater consumption. On the inner level, a dual-objective function – *a)* the freshwater consumption and *b)* the combined investment and operating cost of the optimum diameter pipe network – optimization is carried out for each time interval delimited by two consecutive events: the beginning and the end of at least two overlapping WUs. The targeted schedule should ensure a maximum wastewater reuse between the discontinuous overlapping WUs with some contributions from ST, if applicable, together with a minimum quantity of water for storage. Knowing that the objectives used on the lower level are dichotomic, a PF is obtained, making the optimization process quite impossible for the next time interval, since it should further analyze each point of PF, in a fractal tree like manner. Instead, for each time interval, the approach is to choose the topology and pipe diameters corresponding to the middle point of the PF, making a compromise for both freshwater consumption and pipe network cost. This is not the same as optimizing with only freshwater consumption as criterion, since the PF shows that the highest investment and operating cost correspond to the minimum consumed freshwater.

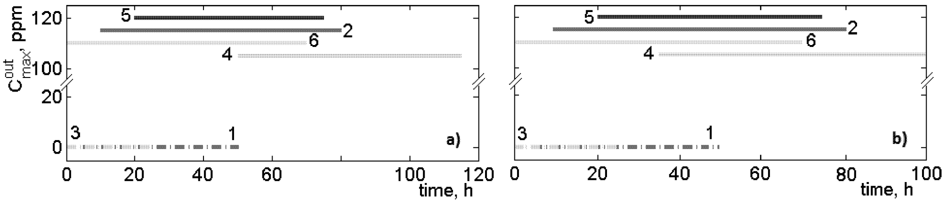

Figure 1. The optimized schedule of the batch process (a), as compared with to the original, non-optimized variant (b); dashed lines stand for inlet free of contaminant WUs

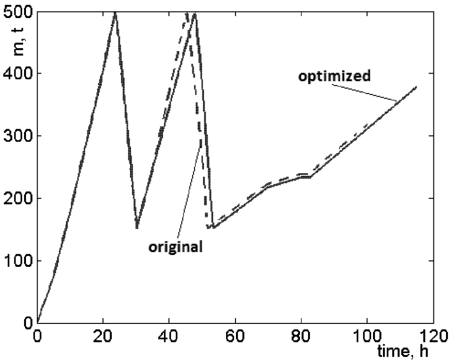

Figure 2 Mass time profile for the ST

The optimum schedule is presented in Figure 1a. In comparison to the non-optimized variant (Figure 1b), WU4 uses its opportunity window. WU4 starts later than in the original case t_{beg} = 50h. In the time interval 35÷50h all operating WUs except WU1 have high outlet concentrations and low limits for inlet concentrations, therefore the beginning of WU4 is delayed with 15h. As a result, less freshwater is used (Figure 3) in this interval, and no increase in freshwater is observed as compared to the original case, for the period when WU4 starts operating. As WU4 delays its start, there is less wastewater sent to regeneration, hence less water in ST (Figure 2) within 35÷50h. No changes in the fresh feed until the end of the process, but more regenerated water is sent to WU2 (70÷75h) and WU4 (80÷82h) (Figure 4) as compared to the original case. As the differences are not very large, the mass time profile of the water in the ST is slightly moved to lower values within 50÷120h (Figure 2).

*Table **3** Water consumption in the original and optimized cases*

	Optimized case, t	Original case, t
Consumed freshwater	1208.8	1268.8
Wastewater reused from ST	639.3	579.1
Regenerated water[*]	601.1	571.0
Wastewater left in ST[**]	378.4	318.1

[*] used by the system from ST, [**] at the end of the process

For the synthetic case analyzed in this paper the results obtained after applying the dual-objective optimization are presented in Table 3. The reduction in freshwater is not large, and corresponds to the middle point from each PF obtained for every time interval of the batch process. More wastewater is used from ST, and at the end of the whole process, more water is left in the ST, useful in case of repeated batches. (Due to lack of space, no further comparisons will be presented.)

5. Conclusions

The paper presents a complex two level optimization of a semi-continuous WN. Although not much, the freshwater consumption reduction against the original case proves that this two level approach is beneficial; the decrease is possible through the increase of both direct wastewater reuse from the ST and the regenerated water. Still, the optimum in the classical way cannot be guaranteed, as multi-objective genetic algorithm was used as optimization method. Further reductions might be possible for the freshwater consumption, with an adequate choice of the point from the PF obtained for a given time interval, from which the inner level optimization should continue for the next time interval. Unfortunately, this would correspond to higher investment and operating costs for the piping system.

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