

## **A simultaneous approach for designing optimal wastewater treatment network**

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Wastewater reclamation charges and expenses on treatment processes contribute largely to total site operating and capital costs. Hence, problem of optimizing wastewater treatment plant is vital for economy and environment. The paper addresses single-stage optimization based approach for designing optimal wastewater treatment network (WWTN). The proposed method consists in solving optimization model of WWTN superstructure. To cope with complex nonlinear problem a direct stochastic random search technique has been employed. The contribution addresses designing method and example of application.

### **1. Introduction**

Expenses on wastewater treatment plant depend on flow rates of effluents via treatment operations. Appropriate scheme of mixing and splitting effluent streams to be treated allows reducing the total cost of treatment. Hence, redistributed network of wastewater treatment operations is most often cheaper than the centralized plant in which overall stream of effluents flows via all operations in sequence.

Several approaches have been suggested to date to design optimal redistributed WWTN. They can be classified into two broad classes: insight-based and optimization ones. Water pinch concept featuring close resemblance to heat pinch methodology is the leading technique in the first category. Wang and Smith (1994) developed the basis, which, then, has been modified and extended by Kuo and Smith (1997). The calculation procedure is iterative and complex. Despite the obvious advantages of the approach it does not guarantee cost optimal solutions. Additionally, it is limited to simple model of treatment operation reduced to definition of removal ratio with given value of the ratio. The alternative is to apply optimization approach based on superstructure concept. This requires solution of NLP model or MINLP one if cost piping and/or selection of treatment technology is to be accounted for. The approaches developed to date, require solution of numerous relaxed LP problems and/or sophisticated solvers. The reader is referred to, for instance: Galan and Grossmann (1998), Lee and Grossmann (2003), Hernández-Suárez et al. (2004), Meyer and Floudas (2006).

In this paper we address the application of simple adaptive random search (ARS) optimization technique to cope with WWTN superstructure model. We have applied the modified Luus and Jaakola algorithm suggested first in Luus and Jaakola (1973). The modification has been described in Jeżowski and Bochenek (2002), Jeżowski et al. (2005).

The paper is structured as follows. First we will present problem formulation and optimization model of WWTN superstructure. Then, description of crucial points of solution algorithm follows. Finally, an example of method application will be given.

## 2. Problem formulation

The problem consists in designing optimal WWTN for given effluents (wastewater sources). Hence, wastewater streams from water using processes (sources) are known as for the number, composition (contaminants concentration) and flow rate. The treatment processes have to reduce concentration of contaminants to given environmental limits. In this paper we impose the following assumptions on the general WWTN problem:

- 1) The goal function is the operation cost of treatment processes. This implies that expenses on piping and stream transportation are not accounted for.
- 2) Wastewater treatment technologies are fixed. In consequence the number of treatment operation is known.
- 3) The design equation of treatment operation is given by removal ratio definition with fixed values of the ratio for the contaminants at each process.

The assumptions cause that the use of binary variables for selecting treatment technologies and connections amongst processes, sinks of effluents and water disposal sites are not necessary.

## 3. Superstructure and optimization model

We have developed simultaneous approach by single-stage solution of WWTN superstructure optimization model. The superstructure consists of given wastewater sources, treatment operations and disposal sites. Here we limit to a single disposal site in order to simplify the model. All possible connections amongst the basic items of WWTN are embedded into the superstructure by applying splitters and mixers. Each effluent source has one splitter to redistribute the stream to processes and disposal site. Likewise, one splitter is attached at the outlet of each treatment operation. Such splitter can redistribute outlet stream to other processes and to disposal site. One mixer is attached to each treatment process at its inlet to gather streams from the sources and the processes. Also, there is a mixer for the disposal site. This is illustrated by Fig.1. Notice that all possible connections are embedded into the superstructure.

The model consists of the goal function as well as balances and design equations of all processes within the superstructure. The goal function in the approach is total cost of treatment operation, which depends only on flow rate via treatment processes. The constraints are as follows:

- 1) Overall mass balances for splitters of sources (isothermal process).
- 2) Overall mass balances of treatment operations.
- 3) Design equations for treatment operations. This is the definition of removal ratio together with mass balances of contaminants. Notice that the removal ratio for each contaminant is fixed for each treatment process.
- 4) Mass balances of contaminants for mixers of treatment processes.
- 5) Mass balances of contaminants for mixer of the disposal site.

- 6) Inequality constraints on contaminant concentrations to the disposal site. They ensure that the concentrations are not higher than the given environmental limits.
- 7) Other technological case specific constraints as for instance lower limits on flow rate via piping sections.

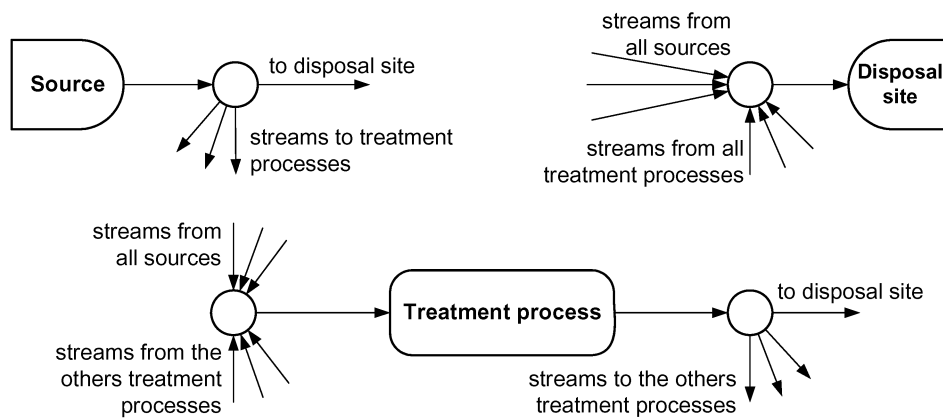


Fig.1. Superstructure of WWTN

The model is of NLP type because of bilinear terms in some mass balances. The variables are flow rates via piping sections and contaminant concentrations at inlets and outlets of treatment processes as well as at the mixer of disposal site.

#### 4. Overview of solution approach

The complex nonlinear optimization model with both equality and inequality constraints and numerous variables has been solved by ARS optimization method. Since the technique is efficient rather for unconstrained optimization tasks with small or medium number of variables we have to solve some problems to achieve robustness and efficiency of solving WWTN model. The problems are as follows:

- 1) How to deal with constraints
- 2) How to find feasible starting point

As for inequality constraints we have applied so called “death penalty”. It means that the solutions generated by the ARS algorithm infeasible in regards to the inequalities are simply rejected. This mechanism works well in ARS optimization – see e.g. Jeżowski and Bochenek (2002), Jeżowski et al. (2005). Equality constraints are hard problem for all types of stochastic optimization approaches. We applied the direct solution of equalities within optimization procedure. Such scheme performs well if the constraints are linear what is not the case in WWTN model. Hence, we additionally applied the division of variables into two groups: decision variables generated by ARS procedure and dependent variables that are calculated from the equations. Such decision variables have been chosen, based on problem analysis, which cause that the equations become linear in respect to dependent variables for given values of decision variables. Notice, that this mechanism is very efficient in the ARS method due to the possibility of

sequential solution scheme. In case of WWTN problem the decision variables are: flowrates of all streams except of those sent to disposal site. All other variables are calculated from equality constraints. Notice that number of decision variables is reduced to the number of degrees of freedom of the WWTN model

Though for many nonlinear optimization problems ARS technique does not need feasible starting point this is not the case for the WWTN model due to small space of feasible solutions and large number of variables. We have tested some initialization methods and found that the following simple solution performs well in all cases we have solved to date. The initial starting points for the solver are all possible centralized treatment networks for the given treatment processes. The networks differ as for the sequence of treatment operations. Hence, for  $N$  processes there exists  $N!$  possible sequences. For illustration purposes we present in Fig. 2 two initial solutions for the case of two processes. Notice, that in industry the number of treatment processes is limited and, thus, the number of initial points is acceptable. It should be noticed that there are cases where these starting solution aren't feasible. We have developed alternative initialization schemes which aren't give here due to space limitation.

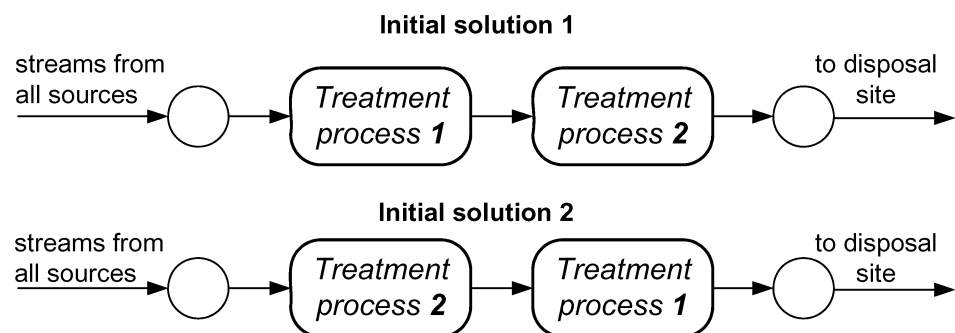


Fig. 2. Initial structures for the solution algorithm in case of two treatment processes.

## 5. Example of application

This problem is taken from the paper by Hernández-Suárez et al. (2004). The problem has seven wastewater sinks with five contaminants. The data for sources are given in Table 1. The last row of the Table gives values of environmental limits on contaminants. The values of the removal ratios for two treatment operations are given in Table 2.

The objective is to minimize total flow rate via treatment operations. The solution obtained by the developed approach is identical to that calculated by Hernández-Suárez et al. (2004). It has the goal function of 238.13 t/h and the structure shown in Fig. 3. Average CPU time for a single run of the solver amounts to approximately 270 seconds for processor Intel Centrino 1.5 GHz. It is necessary noticing that some runs are necessary for the stochastic solver. It is important to notice that the optimization model applied in our method does not eliminate certain connections what is necessary in the approach by Hernández-Suárez et al. (2004).

Table 1 Data for wastewater sources and disposal site for the example

Source	Flowrate [t/h]	Concentration of contaminants (ppm)				
		A	B	C	D	E
1	18	1390	10	250	200	400
2	25	14000	110	400	600	2800
3	50	25	100	1350	2500	3115
4	60	8550	800	45	220	230
5	36	500	300	600	500	500
6	12	50	1500	400	200	100
7	8	2300	12500	200	1000	200
Environmental limits		150	200	140	175	200

Table 2 The removal ratios for treatment operations for the example

Treatment processes	$\Psi$ (%)				
	A	B	C	D	E
1	99	70	80	60	55
2	90	88	55	85	90

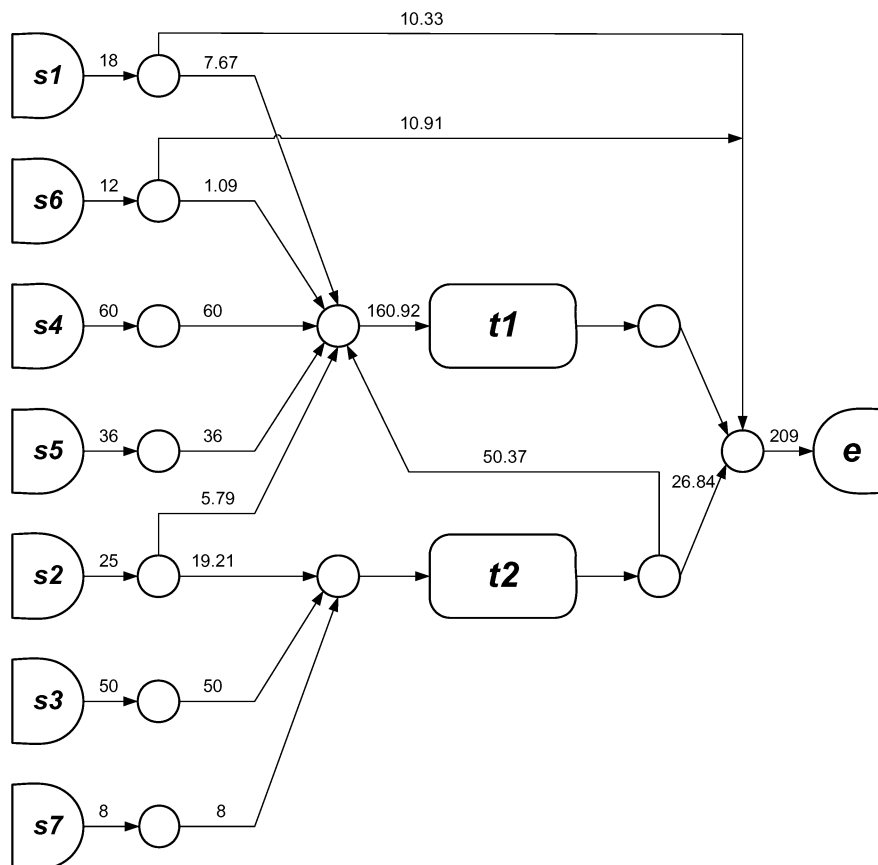


Fig. 3. Optimal solution for the example.

## 6. Summary

A simple single-stage approach has been developed for designing wastewater treatment processes. The method does not require sophisticated optimization solver. No limitations on WWTN structure are necessary. The calculation load is moderate even for large scale processes. The problems solved to date proved that the approach is able to calculate optimal or good suboptimal networks even for large scale problems. The investigations are continued on adapting the method for general cost function and applying more detailed models of treatment operations.

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