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Designing Optimal Water Networks for the Appropriate Economic Criteria

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The syntheses of water network systems are usually performed by minimizing the total annual cost. In this contribution, Mixed Integer Nonlinear Programming (MINLP) syntheses of water networks are performed by using various economic objectives, in order to investigate their effects on the structural, environmental, and economic characteristics of optimal water networks. Batch-semicontinuous and isothermal continuous water networks were analyzed during this study. Significant differences between optimal networks were obtained when using different economic objectives. Minimization of freshwater costs produced highly integrated designs with high levels of water reuse, regeneration reuse or recycling, but low profitability. In contrast, maximization of the internal rate of return resulted in highly profitable designs with low investment and a low level of water integration. Either minimization of the total annual cost, maximization of the net present value, or maximization of the annual profit produced designs with intermediate or high levels of integration between water using operations, and modest profitability. These criteria produced compromise solutions with proper trade-offs between the profitabilities and sustainabilities of water network designs.

1. Introduction

Over the last three decades the synthesis of water networks within process industries has been recognized as an active research area. Batch-semicontinuous and continuous operations have been considered within water networks. Different solution methods, namely insight-based (pinch technology) and optimization-based (mathematical programming) have been used in order to address water network synthesis problems. The reader is referred to the review paper (Jeżowski, 2010), and recent developments in this research area (Klemeš, 2012). Syntheses of water network systems are usually performed by minimizing the total annual cost by assuming grass-root network installations. Some authors have performed water network synthesis by also considering other economic and non-economic criteria, e.g. Nápoles-Rivera et al. (2014) designed a macroscopic water distribution system while maximizing a total revenue calculated as the sales income minus the costs of water treatment, storage and distribution. Deng and Feng (2012) optimized water networks for different objectives, such as the minimum flow rates, mass loads and number of connections. Faria and Bagajewicz (2009) maximized the net present value and the return on investment, while Lim et al. (2008) minimized the total freshwater flow rate and the total freshwater cost.

The main goal of this paper was to address the synthesis of batch and continuous isothermal water networks by considering different optimization criteria, e.g. minimum freshwater cost, the total annual cost, maximum profit, internal rate of return, or the net present value. The effects of particular objectives on establishing proper trade-offs during network synthesis was investigated as well as their influence on the differences between the obtained optimal networks. The profitabilities of water network designs obtained by different objective functions were evaluated together with their structural and environmental characteristics.

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2. Economics for the retrofitted integrated water networks

Mathematical models for water network synthesis mainly consist of mass balances, sizing equations, and cost calculations, while in the case of batch operation also of time constraints. In order to evaluate the economic efficiencies of water designs properly, two additional economic figures should be defined within the model: the cash flow and the investment. The cash flow needs to be defined incrementally, i.e. as a difference between the final/integrated network and the initial/base case. The latter could be assumed to be a non-integrated network where all water demands would be satisfied by the freshwater, heating and cooling demands by the utilities, and discharged wastewater would be treated in an off-site treatment facility. In this case the cash flow of an optimal integrated water design can be defined as:

$$F_{\mathrm{C}} = (1 - r_{\mathrm{t}}) \cdot S + r_{\mathrm{t}} \cdot D \tag{1}$$

where: F_{C} is the cash flow (€/y), r_{t} tax rate, S annual savings (€/y), D annual depreciation (€/y). Savings may arise from the changes in freshwater cost, treatment cost, utility cost, pumping cost etc.:

$$\begin{aligned} S &= S_{\mathrm{FW}} + S_{\mathrm{TR}} + S_{\mathrm{UT}} + S_{\mathrm{PU}} = (c_{\mathrm{FW}}^{\mathrm{b}} - c_{\mathrm{FW}}^{\mathrm{a}}) + (c_{\mathrm{TR}}^{\mathrm{b}} - c_{\mathrm{TR}}^{\mathrm{a}}) + (c_{\mathrm{UT}}^{\mathrm{b}} - c_{\mathrm{UT}}^{\mathrm{a}}) + (c_{\mathrm{PU}}^{\mathrm{b}} - c_{\mathrm{PU}}^{\mathrm{a}}) \\ &= (c_{\mathrm{FW}}^{\mathrm{b}} + c_{\mathrm{TR}}^{\mathrm{b}} + c_{\mathrm{UT}}^{\mathrm{b}} + c_{\mathrm{PU}}^{\mathrm{b}}) - (c_{\mathrm{FW}}^{\mathrm{a}} + c_{\mathrm{TR}}^{\mathrm{a}} + c_{\mathrm{UT}}^{\mathrm{a}} + c_{\mathrm{PU}}^{\mathrm{a}}) = c_{\mathrm{op}}^{\mathrm{b}} - c_{\mathrm{op}}^{\mathrm{a}} \end{aligned} \tag{2}$$

where: S_{FW}, S_{TR}, S_{UT}, S_{PU} are the changes in freshwater, treatment, utility, and pumping costs (€/y), $c_{\mathrm{FW}}^{\mathrm{b}}, c_{\mathrm{FW}}^{\mathrm{a}}$ the freshwater costs (€/y), $c_{\mathrm{TR}}^{\mathrm{b}}, c_{\mathrm{TR}}^{\mathrm{a}}$ the treatment costs (€/y), $c_{\mathrm{UT}}^{\mathrm{b}}, c_{\mathrm{UT}}^{\mathrm{a}}$ the utility costs (€/y), $c_{\mathrm{PU}}^{\mathrm{b}}, c_{\mathrm{PU}}^{\mathrm{a}}$ the pumping costs, and $c_{\mathrm{op}}^{\mathrm{b}}, c_{\mathrm{op}}^{\mathrm{a}}$ the total operating cost before and after integration (€/y), respectively.

Annual depreciation, D, can be calculated using straight-line depreciation Eq(3), or using the annualization factor with the interest rate as given by Eq(4):

$$D = \frac{I}{t_{\mathrm{D}}} \tag{3}$$

$$D = f_{\mathrm{AN}} \cdot I \ ; \quad f_{\mathrm{AN}} = \frac{p \cdot (1+p)^n}{(1+p)^n - 1} \tag{4}$$

where: I is the total investment (€), t_{D} depreciation period (y), f_{AN} annualization factor (1/y), p interest rate, and n annualization period (y). The investment includes various capital costs, such as piping, storage, treatment units, heat exchanger units cost etc.:

$$I = I_{\mathrm{PIP}} + I_{\mathrm{STOR}} + I_{\mathrm{TR}} + I_{\mathrm{HEN}} \tag{5}$$

where: I_{PIP} represents the piping capital cost (€), I_{STOR} the storage tanks capital cost (€), I_{TR} the treatment units capital cost (€), I_{HEN} the heat exchanger network capital cost (€). Two options could be adopted regarding the investment of water networks:

1) All those pipelines, storage tanks, heat exchanger units etc. that already existed before integration, are excluded from the investment equation; for example, the pipelines between the freshwater sources and water using operations, and between the operations and wastewater discharge. In this case only the investment of newly-installed equipment would be taken into account, such as pipelines between the integrated water using operations, pipelines between the operations and treatment units, new on-site treatment units, additional storage capacities etc.
2) Alternatively, it could be assumed that the existing equipment, e.g. piping, could not be reinstalled within the retrofitted network, and therefore, all the equipment should be assumed as newly installed.

Based on the cash flow and investment, the following economic criteria could be defined:
The net present value (NPV):

$$\max V_{\mathrm{NP}} = -I + f_{\mathrm{PA}} \cdot F_{\mathrm{C}} \tag{6}$$

where: V_{NP} is the net present value (€) and f_{PA} the present value annuity factor for constant cash flows (y) as given by Eq(7). Note that the present value annuity factor is the inverse of the annualization factor f_{AN}.

$$f_{\mathrm{PA}} = \frac{(1+p)^n - 1}{p \cdot (1+p)^n} \tag{7}$$

The profit:

$$\max P_{\mathrm{B}} = \frac{1}{1-r_{\mathrm{t}}}(F_{\mathrm{C}} - D) \tag{8}$$

where: P_{B} is the profit before tax (€/y). If the depreciation is calculated by using the annualization factor f_{AN}, instead of straight-line depreciation, the profit and the net present value would generate equal optimal solutions.
The internal rate of return (IRR):
The maximization of the internal rate of return could be transformed into the minimization of the investment vs. cash flow ratio, which is equivalent to the payback time minimization:

$$\max r_{\mathrm{IRR}} = \min \frac{I}{F_{\mathrm{C}}} \tag{9}$$

where: r_{IRR} is the internal rate of return (€/y). The internal rate of return, r_{IRR}, is calculated iteratively from the ratio I/F_{C} after optimization, as given by Eq(10):

$$\frac{I}{F_{\mathrm{C}}} = \frac{(1+r_{\mathrm{IRR}})^{n} - 1}{r_{\mathrm{IRR}}(1+r_{\mathrm{IRR}})^{n}} \tag{10}$$

The total annual cost (TAC) can be presented by Eq(11):

$$\min c_{\mathrm{TAC}} = c_{\mathrm{op}}^{\mathrm{a}} + D \tag{11}$$

It was shown by (Kasaš et al., 2012) that the above criteria produce different optimal process flow sheets because of different stationary conditions. However, significant differences would be obtained only if the applied mathematical models are accurate and precise enough. This was tested on two water network examples.

3. Examples

3.1 Example 1

In the first example, the MINLP mathematical model was applied for batch-semicontinuous water networks, as developed by (Tokoš and Novak Pintarič, 2012). This network consists of 6 batch water using operations, a source of freshwater, and a semicontinuous source of low-contaminated water which is available within the first two time intervals. The option of installing an on-site batch regeneration unit was considered. All the equipment was assumed as newly-installed, except the pipelines between the freshwater and operations, and between the operations and the discharge. An interest rate of 15 %, and an annualization period of 3 years were applied yielding the annualization factor f_{AN} = 0.437977. The freshwater consumption before integration was 848,000 t/y. The synthesis of an optimal water network was performed by minimizing the freshwater consumption (FW) and TAC, as well as maximizing the NPV, Profit and IRR. The results obtained are summarized in Table 1.
The optimal water network with minimum freshwater consumption consumed 512,000 t/y of freshwater. In this design, the processes were highly integrated and the investment cost was high because two storage tanks and several new pipelines were installed. The ratio of cash flow vs. investment (F_{C}/I), which could

Table 1: Results of the Example 1

Objective	min FW	min TAC, max NPV, max Profit	max IRR
Freshwater consumption, (t/y)	512,000	520,000	544,533
Operating cost, (€/y)	735,488	747,840	794,133
Investment, (€)	131,954	96,045	26,480
Cash Flow, (€/y)	301,248	288,221	245,092
TAC, (€/y)	793,280	789,905	805,730
NPV, (€)	555,863	562,028	533,122
Profit, (€/y)	304,319	307,694	291,869
Ratio F_{C}/I, (y^{-1})	2.283	3.000	9.256
IRR, (%)	221	295	925

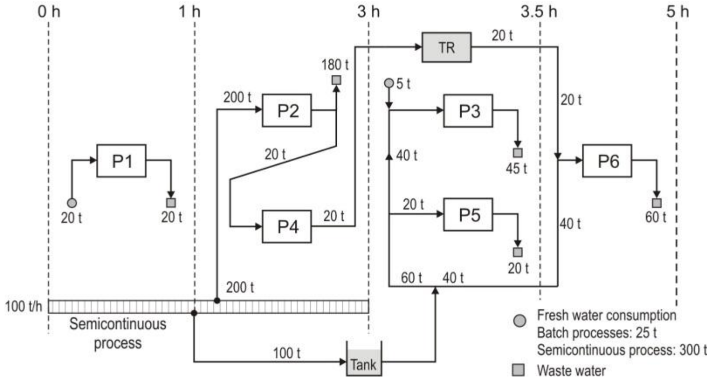

Figure 1: Optimum water network for minimum TAC, maximum NPV and maximum Profit

measure the profitability, was low, and the same applied to the NPV, which indicated that the minimum freshwater design was economically less efficient.

Maximization of the NPV or the Profit or minimization of the TAC generated the water network design (Figure 1) with somewhat higher freshwater consumption (325 t within 5-hrs time period or 520,000 t/y). Processes P1 and P3 utilized the freshwater, while process P2 consumed 200 t of the semicontinuous water source. 20 t of wastewater from the process P2 was reused directly within process P4, while wastewater from this process was regenerated within the new on-site batch treatment unit (TR), and reused later in the process P6. 100 t of the semicontinuous water source was stored in the tank, and reused in the subsequent time intervals for processes P3, P5 and P6.There were fewer connections between water using operations than in the previous design. The cash flow and investment were lower; however, their ratio was higher, thus indicating more profitable design.

Maximization of IRR generated the least environmentally friendly solution (Figure 2). The freshwater consumption was high (340.33 t in 5 h time interval or 544,533 t/y), water reuse between the processes was discouraged, and a regeneration unit was not installed. Typical for maximum IRR design were the low investment and low cash flow, but the ratio of cash flow vs. investment was high. The criteria TAC, NPV and Profit favoured a higher level of water reuse between processes, the installation of a treatment unit in order to enable regeneration reuse, installation of storage tanks for the semicontinuous water source and regenerated water in order to enable their reuse within the subsequent time intervals. The ratio of the cash flow vs. investment, i.e. the profitability, was moderate, indicating compromise designs between environmental impact (freshwater consumption) and long-term cash flow generation.

3.2 Example 2

In this example we considered the continuous isothermal water networks synthesis problem involving three process units, three treatment units and three contaminants (A, B, C). Data for the process units (Dong et al., 2008), as well as for treatment units (Kuo and Smith, 1997), were taken from the literature. Freshwater cost and maximum concentration of contaminants A, B and C in the wastewater stream discharged into the environment were assumed to be 0.375 €/t and 30 ppm. Tax rate and interest rate were assumed to be 20 % and 10 % the depreciation period was 10 y, and the annual operating time 8,000 h/y.

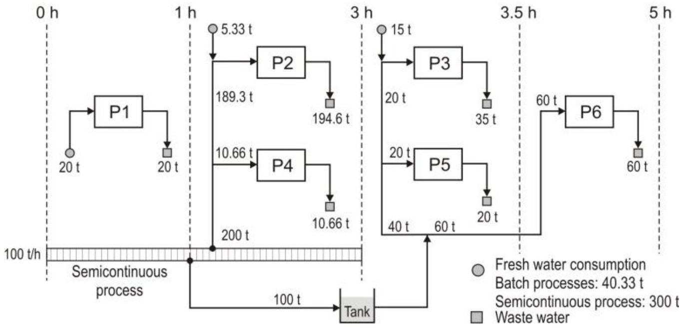

Figure 2: Optimum water network for maximum IRR

Table 2: Results of the Example 2

Objective	min FW	min (FW+FTR)	min TAC, max NPV, max Profit	max IRR
Freshwater consumption, (t/y)	864,000	1,119,032	864,000	2,016,000
Operating cost, (€/y)	387,777	471,494	377,701	807,024
Investment, (€)	938,744	679,257	774,564	576,325
Cash Flow, (€/y)	3,161,457	3,089,293	3,166,234	2,818,811
TAC, (€/y)	481,651	539,420	455,157	864,656
NPV, (€)	18,487,040	18,303,112	18,680,573	16,744,049
Profit, (€/y)	3,834,478	3,776,709	3,860,972	3,451,473
Ratio F_C/I, (y^{-1})	3.368	4.548	4.088	4.891
IRR, (%)	336	454	408	489

In this example, savings were calculated on the basis of the non-integrated process network (base case) in which all the process units (PUs) consumed the freshwater, and wastewater was treated in an off-site centralized treatment facility (CTR) with the operating cost (€/h) assessed by the linear equation 1.5 (€/t) × Flow rate (t/h). As an alternative to the CTR, three on-site treatment units were considered for installation. The MINLP model proposed by Ahmetović and Grossmann (2011) was extended using the Eqs(1)-(11) given in this paper in order to evaluate water network designs for different optimization criteria. The freshwater consumption before integration was 2,294,512 t/y (or 286.814 t/h). The syntheses of water networks were performed by minimizing the freshwater consumption (FW), the total flow rate of freshwater and wastewater treated within the treatment units (FW+FTR), and minimizing the TAC, as well as maximizing the Profit, NPV, and IRR. The results obtained are presented in Table 2.

The minimum freshwater consumption (108 t/h or 864,000 t/y) was obtained for different objective functions (min FW, min TAC, max Profit, and max NPV), while in the case of max IRR and min (FW+FTR) the freshwater consumption was higher. The objective function (min FW) excluded any trade-offs between the operating cost of freshwater and wastewater treatment, and the capital investment cost of treatment units. The optimal solution obtained was at least profitable and had the lowest F_C/I ratio. Note that this solution demonstrated the increased investment cost of treatment units, as the flow rate through the treatment units or treatment unit costs were not minimized.

Minimization of the total flow rates of FW+FTR increased the freshwater consumption (139.8 t/h vs.108 t/h) due to the reduced amount of wastewater recycled to process units. Minimization of TAC, maximization of Profit and maximization of NPV generated the same solutions as well as network designs presented in Figure 3.

Two treatment units were chosen during the optimization, and minimum freshwater consumption (108 t/h) was achieved by wastewater regeneration-recycle. The optimum TAC, Profit and NPV solutions were much more sustainable when compared to the freshwater consumption of the maximum IRR design in Figure 4 (252 t/h or 2,016,000 t/y).

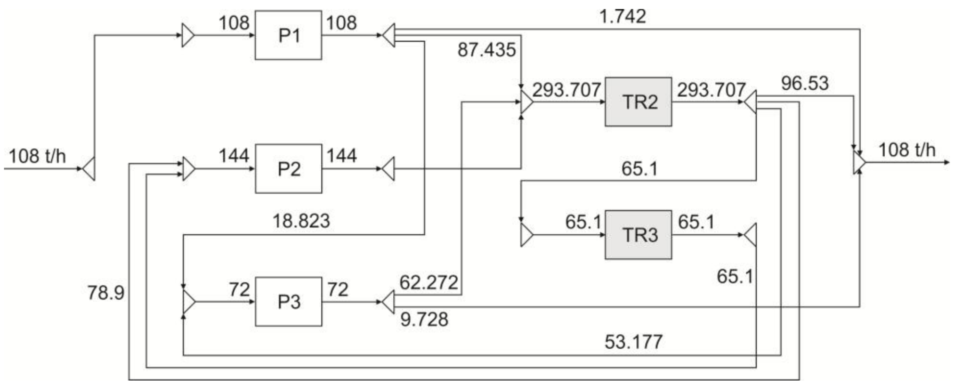

Figure 3: Optimal network design for minimum TAC, maximum NPV and maximum Profit

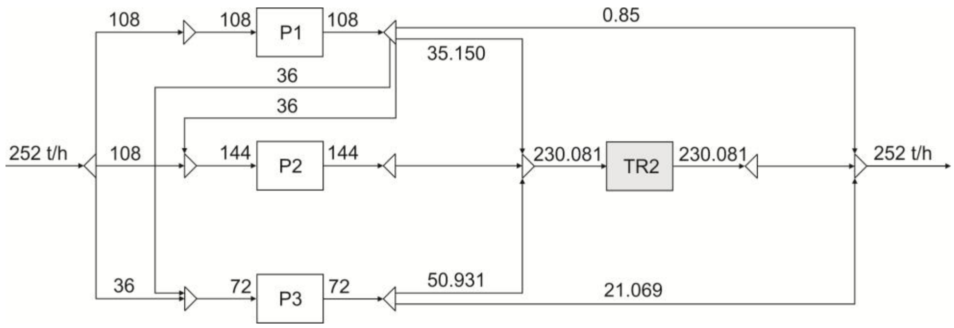

Figure 4: Optimal network design for maximum IRR

Water regeneration reuse and recycle were not selected during IRR maximization. This network consisted of one treatment unit only, and consequently, investment cost was lower. This led to an increased freshwater consumption causing less sustainable water network.

4. Conclusions

In this paper different economic criteria were used in order to design and evaluate isothermal batch-semicontinuous and continuous water networks by MINLP. It was shown for both types of problems that maximization of IRR generated less sustainable solutions with higher freshwater consumption, higher wastewater generation and less water reuse. Minimization of TAC, maximization of Profit, and maximization of NPV generated same results in both cases with higher level of water integration. The solutions obtained by minimizing the freshwater cost were economically less efficient. The criteria NPV, TAC and Profit could be adopted as good compromise objectives for designing water networks using mathematical programming. In the future work, the analysis presented in this paper would be applied to non-isothermal water networks.

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