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The Optimization-Based Design and Synthesis of Water Network for Water Management in an Industrial Process: Refinery Effluent Treatment Plant

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The increasing awareness of the sustainability of water resources has become an important issue. Many process industries contribute to high water consumption and wastewater generation. Problems in industrial water management include the processing of complex contaminants in wastewater, selection of wastewater treatment technologies, as well as water allocation, limited reuse, and recycling strategies. Therefore, a water and wastewater treatment network design requires the integration of both economic and environmental perspectives. The aim of this work was to modify and develop a generic model-based synthesis process for a water/wastewater treatment network design problem utilizing the framework of Quaglia et al. (2013) in order to effectively design, synthesize, and optimize an industrial water management problem using different scenarios (both existing and retrofit system design). The model-based mathematical problem was formulated as mixed integer linear (MILP) and mixed integer non-linear programming (MINLP) and strived to identify the best wastewater treatment processes among a set of predefined alternatives that produce a minimum total annualized cost, while meeting all wastewater specification criteria. In addition, the effluent options (for different retrofit scenarios) in the modified superstructure could be set as discharge only, zero liquid discharge (total recycling), or a combination of recycling and discharge with the aim of minimizing the amount of fresh process water consumption through the recycling of treated wastewater. Also, an industrial case study of a refinery wastewater treatment plant was implemented. Alternative recycling schemes (retrofit design problem) were proposed and solved. The retrofit design solution using developed generic model-based synthesis offered a preliminary guideline for a better wastewater treatment network in terms of economic benefits and environmental impact compared to the existing process and accomplished it in an effective time frame.

1. Introduction

Many industrial processes consume large amounts of water; therefore, the balance among conservation, management and distribution has to be taken into account when considering the sustainability of water resources. The upward trend of fresh water consumption along with wastewater treatment cost, and more stringent environmental regulations have also pushed many industries from a conventional end-of-pipe treatment towards a more sustainable solution (Jeżowski, 2010). Over the past 30 years, a seminal work on water allocation problem was produced by Takama et al. (1980), and a wastewater treatment network was presented by Wang and Smith (1994). They designed a distributed effluent treatment system network targeting synthesis, based on the insight method. Then, Alva-Argáez et al. (1999) used a transshipment model for the wastewater problem (multi-contaminant) without a regeneration process (MILP has an objective of minimizing freshwater usage). Next, Hernández-Suárez et al. (2004) synthesized and designed a distributed wastewater treatment network (WWTN) for multi-contaminant problem by superstructure optimization with selected technology and arrangement of a short-cut model of treatment

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units (NLP model). Then, Statyukha et al. (2008) employed a simple sequential approach applying both the insight and optimization method for industrial WWTN (applicable for synthesis and retrofit). In addition, Teles et al. (2009) presented a new method with two-stage solution strategy (MILP and NLP) for distributed WWTN design. This WWTN superstructure included a set of basic model of treatment units for multi-pollutant problem to meet only limitation of discharged water. Recently, Tudor et al. (2011) implemented an approach for multi-objective optimization problem of total water/wastewater networks to minimize both fresh water utilization and total cost. The design was applied to synthetic problem and also studied the possibility of both internal and treated wastewater reuse option. Moreover, Galán and Grossmann (2011) presented a general superstructure (MINLP) for the design of a WWTN for the metal finishing industry. This was designed for a real world process problem with five contaminants and thirteen types of best available technologies. Although many works have been continuously advanced WWTN designs, problems are based on simple and small problems of wastewater treatment design and are difficult to apply in more challenging problems based on real industrial practices. Recently**,** a systematic framework-based optimization technique for applying industrial WWTN synthesis and design was proposed by Quaglia et al. (2013) to solve more complex problems.

Thus, in this contribution, we aimed at extending the systematic design of the water management system of Quaglia et al. (2013) by developing a generic model-based synthesis for optimization of water/wastewater networks through an MILP/MINLP model. The model is expected to manage real industrial problems emphasizing the reduction of the amount of fresh process water through the recycling of treated wastewater. Also, a real industrial case was studied and the economic benefit as well as process specification for both existing and retrofit process was evaluated.

2. Problem statement

The optimization-based design and synthesis of WWTN problem in this work based on the framework of Quaglia et al. (2013) could be stated as follows: given are a set of different multiple wastewater streams (sources) from an industrial process defined by their flow rate, contaminant types and level, a set of alternative wastewater treatment units (relative to refinery effluent treatment) defined by a different functional model in each unit (i.e. removal ratio, reaction conversion, etc.), and treatment objective (sinks) defined by both maximum specification of flow rate, contaminant types and level (for discharge and recycling). The problem was to determine the optimal water treatment network configuration in order to satisfy certain defined treatment objectives with respect to both economic and environmental perspectives.

3. Methodology for wastewater treatment network (WWTN) design and synthesis

3.1 Framework of WWTN design and synthesis problem

A WWTN problem was synthesized and designed through the systematic framework proposed by Quaglia et al. (2013) in four main steps including i) defining the problem ii) generating alternatives iii) developing the model and collecting data, and iv) formulating and solving an optimization problem. The model was formulated based on the optimization method and complemented by two software tools: EXCEL for data input and GAMS (General Algebraic Modeling Software) for the problem solution.

3.2 Model formulation and database

A model for wastewater characterization and a wastewater treatment process (simple short-cut model) was considered and based on the same method proposed by Quaglia et al. (2013). In brief, this model was defined as a sequence of the functional generic model relating to the use of and mixing of utilities, reaction, waste and product separation. To solve the problem in the model, two options were considered: “non-split” and “split”. The “non-split” option was defined as a single stream problem where the flow could not be split and there was only one process interval selected per treatment task where only one effluent could be selected (i.e. wastewater discharge (WWD) only, recycle to cooling water (CW) makeup only, and recycle to boiler feed water (BFW) makeup only). The “split” option was defined as a multi-stream problem where the streams could be split and a maximum of two process intervals (for a treatment unit and/or its bypass) per treatment task was allowed. This option also allowed for the selection of more than one effluent streams (i.e. two of the following sources could be selected: WWD, CW, BFW and DS—Desalter makeup) Also, the model database (Quaglia et al., 2013), regarding generic treatment model was implemented and modified to the specific problem.

3.3 Solution strategy

3.3.1. One-stage solution strategy for MILP problem (Direct linearization)

Direct linearization was employed for the non-split option and the problem was solved directly through solver CPLEX (Rosenthal, 2012). Also, the solution for this option would be loaded as the initialization point for the MINLP model.

3.3.2. Two-stage solution strategy for MINLP problem (Sequential solution procedure)

Since the split option was allowed for the selection of a maximum of two process intervals per treatment task, the problem was formulated as the MINLP model. Thus, the loading initialization point from the MILP solution and fixed binary variables were preliminary processes (first stage). Then, the model was solved directly by solver DICOPT (Rosenthal, 2012) for retrofit designs.

4. Case study and results

A case study design dealing with a petroleum refinery wastewater treatment plant (Figure 1) in Thailand (PTT Global Chemical) was formulated and solved through the four main steps of the method described above. The case study was applied by considering both the design of the existing PTT process (base case) and the retrofit of the existing PTT process, with emphasis on the recycling opportunity for greater economic benefit.

4.1 Problem

The objective function (Eq(1)) of the optimal WWTN design was to minimize the total annualized cost (TAC) through various retrofit design scenarios focusing on the recycling aspect

$$TAC = Cost_{capital} \cdot \left[\frac{i \cdot (1+i)^n}{(1+i)^n - 1} \right] + Cost_{operation} - Savings_{recycling} \tag{1}$$

where TAC mainly consisted of capital expenditure (CAPEX) and operational expenditure (OPEX). CAPEX was amortization based on a 15 y plant lifetime at an interest rate of 5 % per annum while OPEX (utility consumption and waste disposal cost) was calculated on a yearly basis. The savings cost is a yearly reduction cost of using recycled water. Moreover, four wastewater sources obtained from the plant were investigated and four treatment objectives (water sinks) were considered including WWD, recycling to CW makeup, recycling to BFW makeup, and recycling to DS makeup. In addition, the configuration of the effluent treatment processes in the plant (existing process) was analyzed and adapted to synthesize and design the water network.

4.2 Wastewater treatment network superstructure

The model database regarding the treatment process interval of Quaglia et al. (2013) was referred to and modified in this case study to construct the WWTN superstructure for a specific problem. The modified superstructure of the WWTN was proposed and is shown in Figure 2. Depending on the superstructure, different process paths (treatment alternatives) were identified, given possible interconnections in the series of the treatment processes. Details of each treatment task in this model were referred to the general wastewater treatment principle and treatment process data based on the principle of Tchobanoglous et al. (2003) together with the modern practical treatment principle for wastewater in a refinery from IPIECA (2010).

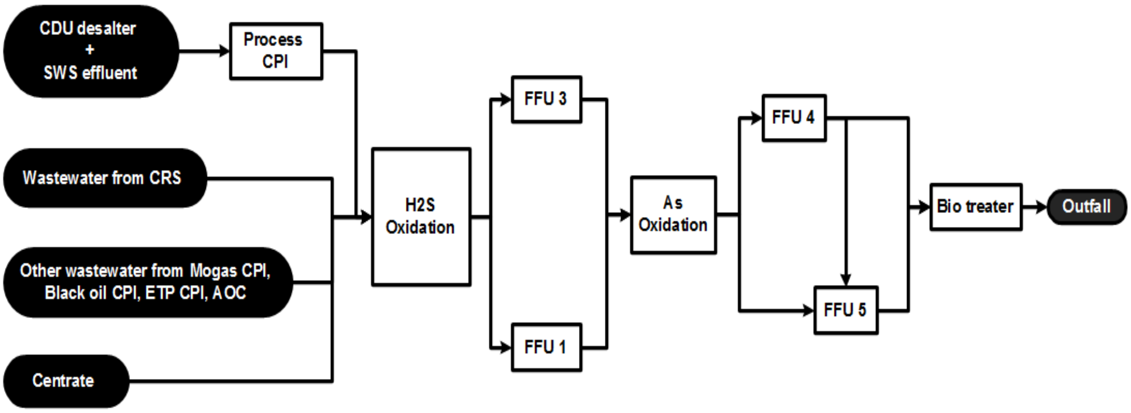

Figure 1: Simplified diagram of PTT's effluent treatment plant

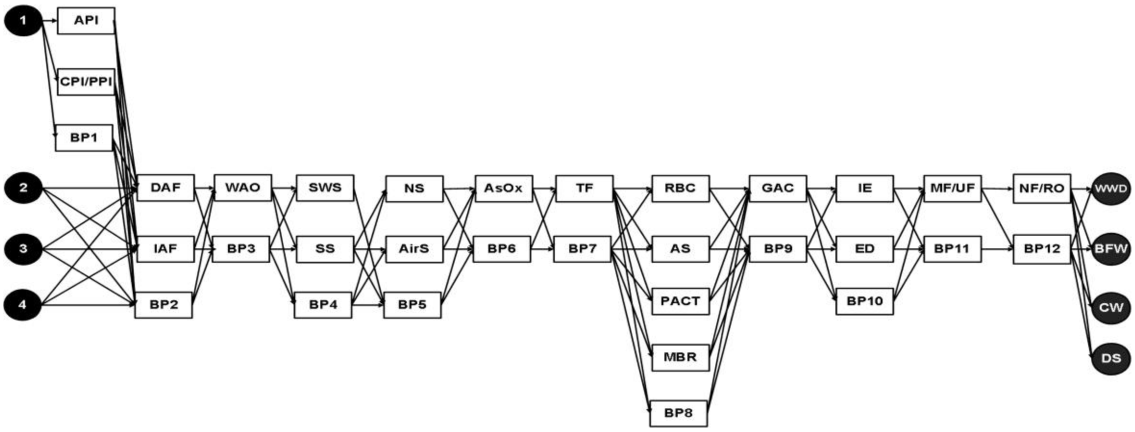

Figure 2: Modified superstructure for all possible treatment processes in existing and retrofit design

The process CPI (corrugated plate interceptor) unit was represented as a CPI/PPI (corrugated/parallel plate interceptor) unit interval. The H_2S oxidation unit, FFU1 and 3 (flocculation floatation unit) that removed mainly H_2S, NH_4^+, COD (chemical oxygen demand), O&G (oil and grease), and TSS (total suspended solid) were considered and formulated as a WAO (wet air oxidation) unit (modified as a series of treatments with flocculation floatation unit in the process interval) combined with the AirS (air stripper) unit. The role of the arsenic oxidation unit following by the flocculation floatation unit was to remove arsenic, COD, O&G, and TSS. It was represented as an AsOx (arsenic oxidation) unit. In addition, bio-treaters involving a biological treatment were represented by the TF (trickling filters) and AS (activated sludge) units. Finally, all tertiary treatment units (GAC—adsorption on granular activated carbon, IE—ion exchange, ED—electrodialysis, MF/UF—micro/ultrafiltration and NF/RO—nanofiltration/reverse osmosis) were set up as supporting alternative treatment units to further help remove various contaminants to industry standards for the future recycling options.

4.3 Optimization problem formulation and solution

A total of nine different scenarios were considered including the base case (P1) and eight retrofit designs (P2-P9) with different effluent classification and selection (Table 1).

The MILP and MINLP models consisted of more than 240,000 single variables, 10 binary variables, 400,000 equations, with 9,000 non-linear equations—only the MINLP problem. An average CPU time (s) was 9 s for the MILP problem and 2,640 s for the MINLP problem. It is of interest to note that some scenarios for some recycled effluent required more additional treatment processes (IE, ED, MF/UF and NF/RO) in order to polish the wastewater for recycling to CW or BFW makeup. The cost breakdown analysis for TAC is shown in Figure 3.

Table 1: The description of each PTT's network scenario

Network (Scenarios)	Water effluent		Zero liquid discharge (ZLD)		Stream option	
	Single	Multiple	Non-ZLD	ZLD	Non-split	Split
P1	WWD	-	✓		✓	
P2	WWD	-	✓			✓
P3	CW	-		✓	✓	
P4	CW	-		✓		✓
P5	BFW	-		✓	✓	
P6	BFW	-		✓		✓
P7	-	WWD+DS	✓			✓
P8	-	CW+DS		✓		✓
P9	-	BFW+DS		✓		✓

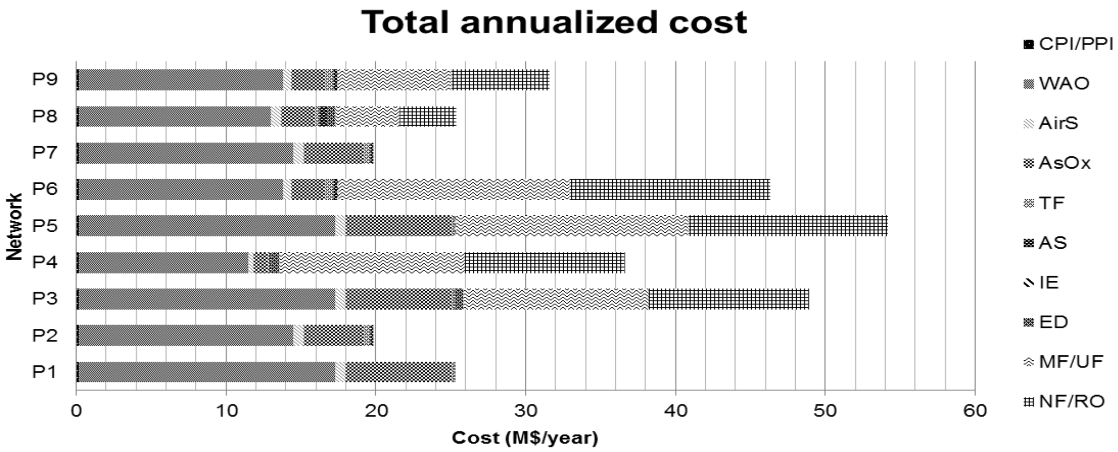

Figure 3: Cost breakdown (Total annualized cost) for network scenario P1-P9

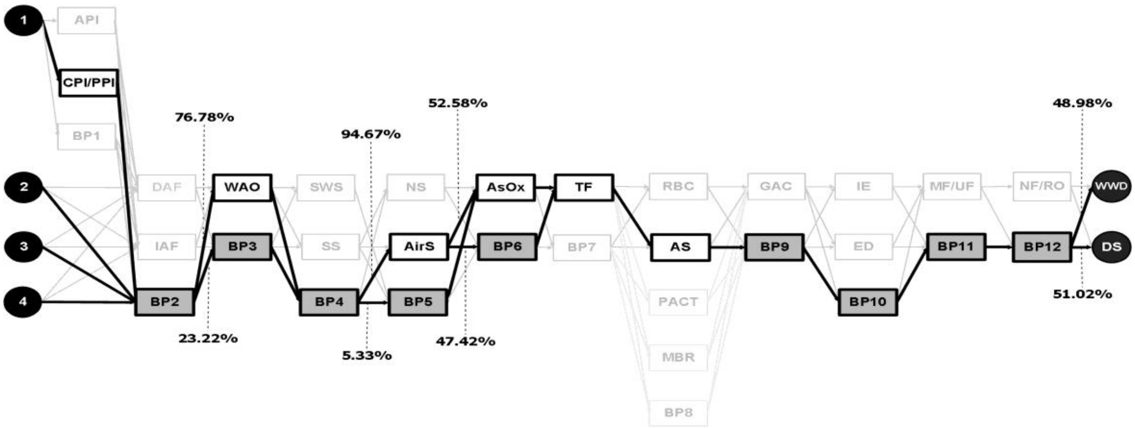

Figure 4: Network solution (P7) for wastewater discharge and desalter makeup effluent

The best scenario for retrofit design was the network P7 (Figure 4) that had the split option to bypass before the inlet stream of WAO, AirS, AsOx and to two effluents (WWD and DS makeup). Additionally, part of water (51.02 %) could be used as recycled water for DS makeup without the requirement of any additional treatment processes. The advantage of the network P7 is the reduction of not only discharge flow, but also a reduction of the TAC (21.70 %) as compared to the base case. The comparison between the existing process and the best retrofit scenario is concluded in Table 2.

Table 2: Network comparison between the existing process (P1) and the retrofit process (P7)

Index	UOM	Network P1 (Existing process)	Network P7 (Retrofit process)	% Relative variation
Economic aspect				
TAC	M$/y	25.246	19.767	-21.702
CAPEX	M$/y	5.437	5.437	0.000
OPEX	M$/y	19.809	14.338	-27.619
Utility cost	M$/y	18.553	12.884	-30.556
Waste disposal cost	M$/y	1.256	1.454	+15.764
Savings cost	M$/y	-	0.008	-
Environmental aspect				
Water discharged	t/h	78.402	38.400	-51.022
Water wasted	t/h	0.000	0.000	0.000
Water recycled	t/h	-	39.993	-
Total water	t/h	78.402	78.393	-0.011

5. Conclusion

The method based on the framework of WWTN design and synthesis could be applied to develop a new superstructure and model for any large scale industrial problem. Hence, the developing this approach could be a beneficial tool for screening the optimal network solution in a time-effective manner via different scenarios. Also, the retrofitting of the existing process was flexible. By solving different alternative recycling schemes, results could be used as a preliminary guideline for a better water network design in terms of economic and environmental perspectives compared to the existing process. In order to develop a more satisfactory design and synthesis model, further work should focus on a network for waste and sludge handling and/or other wastewater characteristics (i.e. temperature and pH) for a more exact treatment process model.

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