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Integrated water resource management through water reuse network design for clean production technology: State of the art

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Abstract−This article considers new and existing technologies for water reuse networks for water and wastewater minimization. For the systematic design of water reuse networks, the theory of the water pinch methodology and the mathematical optimization are described, which are proved to be effective in identifying water reuse opportunities. As alternative solutions, evolutionary solutions and stochastic design approaches to water system design are also illustrated. And the project work flow and an example in a real plant are examined. Finally, as development is in the forefront in process industries, this paper will also explore some research challenges encountered in this field such as simultaneous water and energy minimization, energy-pinch design, and eco-industrial parks (EIP).

Key words: Eco-Industrial Park (EIP), Mathematical Optimization, Process Integration, Water System Design, Water and Wastewater Minimization, Water Reuse Network, Water Pinch Technology

INTRODUCTION

Water is one of the most important natural resources being used in the process industry. Process water, for instance, can be used as solvent in a direct or indirect way, for transportation, cleaning and cooling medium. On the other hand, wastewater is generated in the different processes and utility systems, creating a stream which eventually needs to be treated. However, in recent years, the increased price of fresh water and the increased cost for processing wastewater treatment to meet environmental requirements has orced process industries to search for ways that efficiently minimize the amount of water usage and wastewater generation. A number of efforts for the clean production technology have been increasingly made within not at the end-of-pipe technologies but toward achieving the goal of fundamental structural changes that allow extensive water reuse or decreasing wastewater generation [1-11].

Two strategies can be implemented for reducing water demand in a plant: (1) one strategy consists of modifying individual process and utility units to reduce their inherent need for water (i.e., including replacing water-cooling with air cooling, improving control of boiler and cooling tower blow down, and increasing the number of stages in an extraction unit that employs water as its extractant); (2) the engineer seeks opportunities to use the outlet water from one operation to satisfy the water requirement of another or the same operation. In some cases, the water may require some regeneration prior to re-use as examples these include pH adjustment, filtration, membrane separation, sour-water stripping, and ion exchange. Specifically, systematic strategies for such reuse maximization can lower freshwater usage and wastewater discharges by 50% or more, while also significantly reducing capital investment in treatment facilities [12].

In turn, there are four methods to water minimization: process changes, water reuse, regeneration reuse and regeneration recycling. Identifying the optimum water reuse in accordance with process constraints is a combinatorial optimization problem where all possible maximum reuse structures of the systems are analyzed in a tree-type fashion using a branch and bound strategy with maximum viable options for reuse structures of the system are analyzed. In identifying water reuse opportunities, systematic methodologies for analyzing water networks and reducing water cost have been suggested [2,5,13-15]. There have been two approaches to obtaining fundamental designs of the water-using systems:

1. Conceptual graphical design (water pinch)
2. Mathematical optimization

A simple but elegant solution is offered by water pinch analysis, which recommends simple methods and beneficial results when applied to water-using industries [3]. However, water pinch analyses suffer from a major drawback: as the number of contaminants increases it becomes increasingly difficult to be applied. Another approach is to use mathematical optimization to treat the multiple contaminants or constraints, economic cost evaluation, and plant layout. Despite the progress made in optimization algorithms, they often require considerable computing time and do not guarantee a global solution if the complexity of the design problem rises due to the number of process units, contaminants and possible network

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topologies [16].

In the first section, this paper reviews the concepts underlying water pinch analysis, the mathematical optimization and its approach to water and wastewater minimization. In the second section, research works of alternative solutions, stochastic design and batch-reusing approaches to water system design are illustrated. Following this discussion, the project workflow and case studies in several different industries will be detailed following conclusions exploring the recent research challenges.

WATER PINCH TECHNOLOGY

Generally, it is estimated that the water pinch achieves large reduction in effluent flow and contaminant loading by identifying water re-use, recycling and regeneration opportunities within the process as the method can be achieved through a typical water flow reduction of 30% and a significant COD reduction before final treatment. Water pinch is a systematic technique for analyzing water networks and reducing water costs for processes. It uses a graphical design method to identify and optimize the best water re-use, re-generation and effluent treatment opportunities [17]. The pinch methodology was initially developed for the optimization of heat exchanger networks (heat pinch) by Linhoff [18];this is best illustrated by El-Halwagi and co-workers [19-21] and by Smith and co-workers [2-4,22] who have pioneered the fundamental theoretical formulations for the application of pinch analysis principles to water problems.

Simply, the motto of water pinch technology is rephrased into a simple logic: "*the best way to minimize pollution is not to produce it". Therefore, find in-process solutions, before focusing on the 'end of pipe'*!" [17]. Pinch analysis principles to waste and wastewater problems have been successfully applied to a broad range of industries with freshwater savings of 15-40% and wastewater savings of 20-50%; a listing of the application results is given in Table 1 [17].

Table 1. Wastewater savings by water-reusing projects [17]

Company	Process/Industry	Location	WW flow reduction,%
Confidential	Chemical & Fibers	Germany	25
Cerestar	Corn processing	UK	25
Gulf oil	Oil refining	UK	30
Monsanto	Chemicals	UK	40
Parenco	Paper mill	Netherlands	20
Sasol	Coal chemicals	South Africa	50
Unilever	Polymers (batch)	UK	60
US air force	Military Base	USA	40
Confidential	Oil refining	Netherlands	40
Confidential	Chemicals	USA	40
Confidential	Chemicals & Fibres	USA	25

Wang and Smith [2] introduced a water pinch method for targeting maximum water reuse for single contaminant problems based on the construction of a composite curve of the limiting water profiles for each operation. The basic idea is that wastewater can be re-used directly in other operations when water-using operations can accept the contamination level of previous operations. The first task consists of developing a limiting water profile for each water-using process operation, based on maximum inlet and outlet concentration for the water stream for each operation [12].

The limiting water stream concentrations of all the process units are recombined together to construct the limiting composite curve for the overall plant (Fig. 1a). A freshwater line is then constructed and matched against the limiting composite curve to set the mini-

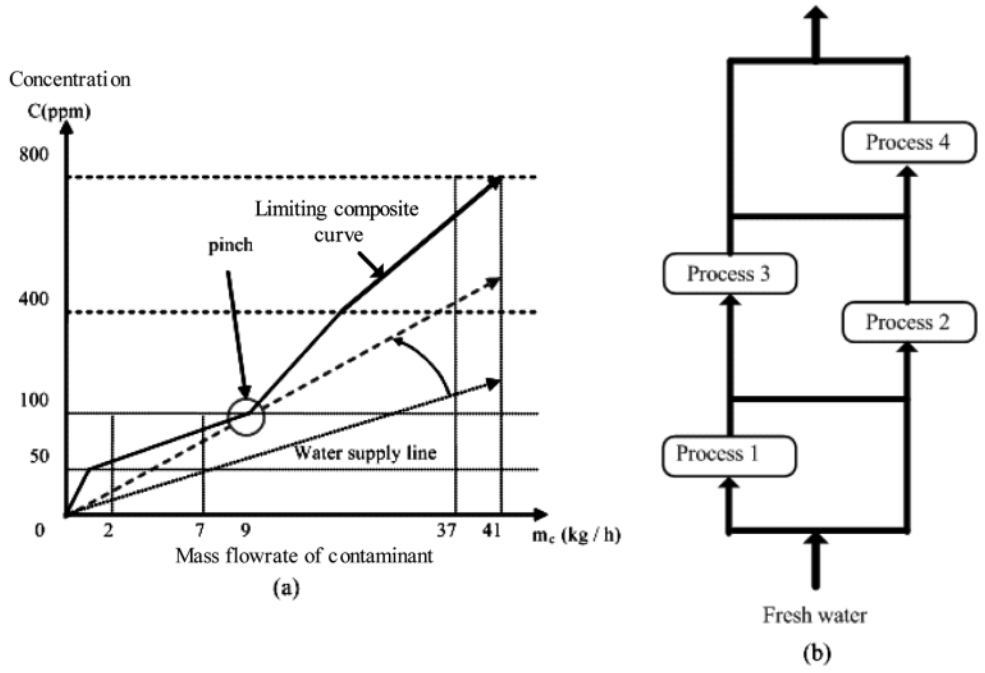

Fig. 1. Targeting minimum fresh water and reuse network design, (a) limiting composite curve [2] and (b) water reuse flow scheme after network design [12].

mum fresh water demand for the overall plant. The minimum freshwater line touches the limiting composite curve at two points: at zero concentration and at an intermediate position called the pinch point (100 ppm concentration). This line, which corresponds to the minimum water flow rate required for the plant, establishes the "target" for maximizing water reuse. By maximizing the outlet concentration of the water supply line, the minimum consumption of freshwater is obtained and the slope of the water supply line gives the target for minimum fresh water flow rate (90 t/h). At the pinch, the driving force goes to a minimum since the limiting profile data contains the process constraints of minimum driving force. The limiting composite curve construction also shows the critical section of the plant (regions close to pinch concentration) that require especially close attention in order to achieve the minimum water requirement [7,12].

To develop the water-reuse network that minimizes the freshwater demand, Wang and Smith [2,3] use network-design methodology analogous to the pinch design method from the heat integration. The initial network tends to have a complex structure, but an evolutionary and heuristic procedure then simplifies this to yield a practical network (Fig. 1b, [12]). However, the graphical design of water pinch is difficult to apply to large problems when dealing with multiple contaminant or constraints, economic cost evaluation, and plant layout. Mathematical programming approaches have been used to optimize system cost and account for all contaminants and trade-offs. Several research works have developed a water-reuse design based on mathematical optimization techniques to overcome the difficulties of the water pinch approach [5,23].

MATHEMATICAL OPTIMIZATION

Mathematical optimization can be used as an effective method for the analysis, synthesis, and retrofit of water-use networks for industrial water reuse and wastewater minimization and of distributed effluent treatment systems for minimizing the wastewater treatment flow rate. Man and Liu [24] introduced the method of superstructure to formulate the water network as linear programming (LP) and nonlinear programming (NLP) for single and multiple contaminants systems. The solution of those models is the optimal allocation of species and streams throughout the process with minimum freshwater flow rate target.

As a combinatorial optimization approach, the superstructure model generates every possible configuration of a water-using network (see Fig. 2) and eliminates unfavorable and infeasible matches between a water source and a water-using operation. Capital cost, including mass exchanger and piping costs, as well as the design complexity can be considered for the simultaneous design of water-using

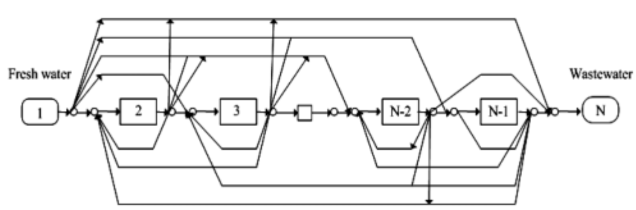

Fig. 2. General superstructure model for water reuse system design.

and water treatment subsystems. Fig. 2 illustrates the general superstructure of the system under consideration. Among *N* subsystems, the subsystems 1 and *N* are a source of fresh water supplied to any subsystem and a final holding basin which collects wastewater from all other subsystems and discharges it to the environment [1].

The automated method relies on the optimization of a superstructure. All possibilities for water reuse, regeneration, recycling and treatment are included in the mathematical formulation. The model includes mass balances for every contaminant around each mixing and splitting point as well as mass balances around every operation. In order to control the structural feature of the design, the binary variables associated with each possible connection are introduced. Therefore, the problem is formulated as a mixed integer nonlinear programming (MINLP) model that is then decomposed for this solution in sequence of an MILP problem, as the capital cost and investment of the piping, the operating cost of the network and the constraints from the inhibited connections and small flow rates can be added to the mathematical formulation of the optimization problem. The solution to this problem will result in the minimum freshwater consumption and the topology of the reuse network, where all flow rates and concentrations for each contaminant in each stream are also identified [25].

Doyle and Smith [26] developed an automated procedure based on mathematical optimization techniques to overcome the difficulties of the conceptual design approach. Alva-Argaez et al. [25] modeled the entire water management problem by means of a superstructure with an MINLP formulation. Yang et al. [23] proposed a mathematical optimization approach to design a wastewater reuse network for a cleaning and rinsing operations in an electroplating process, a papermaking process and a semiconductor manufacturing process. Bagajewicz [5] present a comprehensive paper of water network design in refineries and process plants. Gunaratnam et al. [27] suggested an automated design of total water systems, which considers simultaneously the optimal distribution of water to satisfy process demands and optimal treatments of effluent streams. These automatic design approaches result in an individual network design with water-reuse systems, regeneration and effluent treatment systems.

1. Summary of Water Pinch and Mathematical Optimization

Water pinch technology is a stepwise approach in identifying the minimum freshwater flow rate and synthesizing a water use network to meet this level. It is also an effective approach to discovering the operational bottlenecks and revamping existing water use networks. This technology is used in the following sequence: first, identify the minimum freshwater flow rate; second, construct a preliminary water reuse network guaranteed to meet the minimum freshwater flow rate; third, simplify the preliminary water reuse network through a heuristic approach by reducing the number of water reuse operation; fourth, identify regions where water reuse is limited and suggest process changes to further reduce the minimum freshwater flowrate [24].

Mathematical optimization yields a minimum value for the freshwater flowrate subject to constraints defined by the designer and engineer. In comparison to water pinch technology, mathematical optimization is a black box approach where the engineer is provided with little insight to understand how the water reuse network is constructed. However, in certain situations (i.e., large multiple contaminant problems), mathematical optimization outperforms water pinch technology. In addition, mathematical optimization has an advantage when the choice of a model for each water use operation must be flexible; these expenses may include connection, operating, and piping and pumping costs. Since the mathematical optimization approach of NLP and MINLP is sensitive to the choice of initial values, it may identify a local optimum and less than global optimal treatment-network configuration; thus, the two approaches are complementary. The visualization ability improves engineering understanding and the mathematical model allows the handling of complex problems [5,12,24].

ALTERNATIVE SOLUTIONS OF WATER-REUSING NETWORK

1. Evolutionary Solutions to Water Reuse Network

Despite the efforts made to overcome this drawback, in finding the optimal reuse network based on deterministic algorithms, however, it is often difficult to remedy the mathematical optimization problems, such as non-convexity, linearization, and locality. Since the mathematical representation for the multiple contaminants becomes the class of nonlinear programming (NLP), this class of problem has more than one local optimum [28]. The accuracy and efficiency of conventional techniques for finding the global optimum depends on the initial guess. The inappropriate one leads to the solution getting struck at the local optimum. A well-known technique for avoiding local optima in improving search is stochastic optimizations such as evolutionary algorithm [16].

Stochastic optimizations using evolutionary algorithm of genetic algorithm (GA), simulated annealing (SA) and ant colony optimization (ACO), have been developed to find the optimal solutions to non-convex problems [16,28,29]. For this approach, Garrard and Fraga [29] suggested a new methodology for the synthesis of mass exchange network (MEN) with regeneration using GA. They defined an encoding for MEN synthesis problems that determines both the structure and the actual mass exchanges simultaneously, which does not require the solution of a nonlinear program as part of the fitness evaluation. It represents that all encoded solutions are feasible and require a simple evaluation to yield a cost for a small-sized problem, which results in an efficient GA to eliminate the need for a penalty function under a large class of the water reuse synthesis. For other large-sized problems, the number of infeasible solutions is small and the convergence of the GA operator is quite fast.

In discussing advancing Garrad and Fraga [29], Prakotpol and Srinophakun [28] developed a GA-based program called the GAPinch to solve the wastewater minimization problem. It covers both single and multiple contaminant systems. Moreover, the GA was tested on three separate water-using case studies--single contaminant of water reuse, regeneration recycle, and multiple contaminants of water reuse--and compared to a mathematical program. For single contaminant, the results from GAPinch and mathematical approach reach the same value of minimum freshwater consumption but present different configurations. For multiple contaminants, GAPinch gives better than or equal minimum freshwater consumption when compared to the mathematical approach because this software package could get in a local optimum while GAs has the ability to escape from there. A further development should include cost-related functions such as cost constraints of piping and pumping for more conceptual design.

Lavric et al. [16] suggested a hybrid optimization based on an improved version of GA for water consumption and wastewater network topology. It uses each network's internal flow as a gene, assembling the topology into a chromosome. The restrictions are applied with naturally rejecting genes outside their feasible domain. When several water supply sources are available (fresh or contaminated), it enables their allocation according to closeness between their contamination level and the inlet restrictions for each unit.

2. Stochastic Design Approaches in Water Reuse Network

Most of the mathematical models in water reuse systems have attempted the water reuse problem under two assumptions; first, water always removes fixed loads of contaminants, and another assumption is that solubility and corrosion limits can be used to set maximum inlet and outlet concentration units imposed on contaminants. These assumptions are necessary to simplify the problem and make it easier to solve [5]. In water reuse processes, concentrations of contaminants in the water reuse process may reach their solubility limits, but such limits are functions of process parameters (temperature and pressure). Hence the loads of contaminants are variable with respect to the flow rate [30]. This suggests that the design of wastewater networks should be resilient and able to accommodate different pollutant levels which may easily result from deviations in operating conditions. From this point of view, a stochastic design for the uncertainty of water reuse network can be carried out.

To incorporate the uncertainty associated with operation conditions, a stochastic design in water reuse network usually has the following procedure. (1) The process identification and the problem formulation are the first step. (2) A deterministic optimization model is developed and tested. This model searches for the network configuration with minimum freshwater use and optimal wastewater reuse and regeneration/reuse. (3) The third step involves a sensitivity analysis in which uncertainty is introduced as maximum and minimum ranges in operating conditions. (4) A stochastic formulation is developed based on fuzzy programming [31] or the two-stage recourse problem method with finite number of realization; in particular, a two-stage stochastic optimization approach [32] is widely used.

In a two-stage stochastic optimization approach, the uncertain model parameters are considered random variables with an associated probability distribution and the decision variables are classified into two stages. The first-stage variables correspond to those decisions that need to be made prior to the realization of the uncertainty. The second-stage or recourse variables correspond to those decisions made after the uncertainty is unveiled and are usually referred to as wait-and-see decisions. After the first-stage decisions are taken and the random events realized the second stage decisions are made subject to the restrictions imposed by the second-stage problem. Due to the stochastic nature of the performance associated with the second-stage decisions, the objective function consists of the sum of the first-stage performance measure and the expected second-stage performance [30].

3. Water-reusing Network Design in Batch Industries

The water streams for continuous processes are specified by flow rate, concentrations of contaminant, temperature, heat capacity, etc.

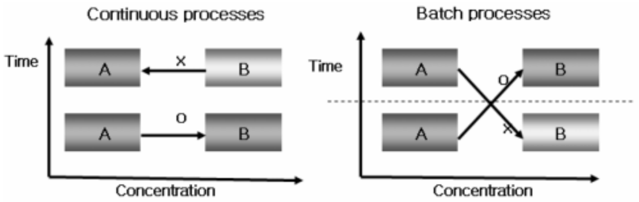

Fig. 3. Comparison of water reuse network design in continuous and batch processes.

In continuous processes, water streams are uninterrupted during operating time, and the starting/ending times are identical for all streams. Hence, the time dimension for continuous processes is not a relevant consideration or need at this stage. However, the water streams for batch processes also have the starting/ending times because of procedural tasks. Fig. 3 compares the characteristics of water reuse network design of continuous and batch process. For instance, most of characteristic factors of the water streams in the batch process have a time dimension to take account of the above facts. Although the concentration of the water from task A is lower than that of water required in task B, the water from task A cannot be reused in task B unless task A precedes task B. Thus, in consideration of the concentrations and time dimensions of water streams for water reuse in batch process, this feature makes the water reuse for batch processes more difficult than that of continuous processes [33,34]. Therefore, researches of water reusing network for batch process systems have failed to draw wide consensus from the related industries and researchers when compared to the continuous process.

Wang and Smith [35] applied the water pinch to the batch processes by treating time as the primary constraint, the "time pinch". They used the amount of contaminant mass to be removed within each time interval instead of the concentration to describe a batch water-using process. Due to the added dimension (time), they plotted this diagram in each concentration interval, and the water reuse opportunities are detected among the time interval in the same diagram and among the diagrams that match each concentration interval. However, it is inappropriate that this graphical method is used in the complicated systems, and this method cannot show the variations with time (the concentration profiles and level profile of storage tanks)- the objective of the design is limited to the wastewater minimization.

To design complicated water reuse systems for a batch process, several mathematical optimization models are used [33-37]. Almato et al. [33] suggested incorporating the mathematical methodology into a modeling framework for batch/semi-continuous processes. Specifically, the streams classified into either inlet or outlet streams are characterized by the starting/ending time as well as the maximum possible contamination concentration. A new stream chart is generated from the Gantt chart. This stream chart provides the water stream distribution and the contamination concentration. The direct water reuse opportunities can be identified in this chart. To raise the indirect water reuse opportunities, a certain number of tanks of a given capacity are necessary. Consequently, this model determines the best tank and stream assignments. Moreover, this mathematical model makes it possible to optimize the water system from various points of view: for example, freshwater use minimization, water and utility cost minimization, and water, utility and network cost minimization [34]. The optimization results display the tank levels and their contamination concentrations. In order to solve the mathematical optimization model, the time horizon is discretized by each starting/ending time of water streams. Thus, the variables containing time dimension are computed at each discrete time. As the model is an NLP-problem of large dimensions, the global optimality is not guaranteed and a feasible initial solution is required to solve the NLP-problem.

The above graphical and mathematical methods cover only the mass transfer-based processes where water functions as a mass separating agent (MSA). However it does not deal with non-mass transfer-based operations where water is utilized as a raw material, a product, or a byproduct in a chemical reaction. This is presented a two-stage procedure for a maximum water recovery (MWR) networks for a batch process, covering both mass transfer-based and non-mass transfer-based water using processes. In the first stage, the various network targets and storage capacity target are established using the time-dependent water cascade analysis (WCA) developed by Manan et al. [24].

In the second stage, a time-water network diagram is introduced to represent the overall batch water recovery network. Recently, Kim and Smith [36] constructed an MINLP model to automate the design procedure of discontinuous water-reuse system, and Li and Chang [37] suggested a mathematical model for discontinuous water-reuse system design by an MINLP formulation and imposing suitable logical constraints for determining the number and sizes of buffer tanks. In various industrial plants (i.e. food, pharmaceutical and biochemical manufacturing), processes are commonly operated in batch mode. But relatively few results have been published and reported about the water reuse of a batch process. The development of a systematic procedure for water minimization for batch process systems would have great challenges and changes.

APPLICATION EXAMPLES OF WATER-REUSING NETWORK IN INDUSTRIES

1. Project Work Flow of Water Pinch Technology [40]

From the time that water pinch technology was introduced, several user-friendly dedicated softwares such as AspenWater™ and WaterPinch™ [39,40,43] have been developed. Many application results of water pinch software have been reported in the process industries which include but are not limited to the following: specialty chemicals [4], cleaning processes [38], pulp and paper industries [42], polymer plants [39-40], and petrochemical plants [24,41]. Further, the results have been successfully applied to a broad range of industries with fresh water savings of 15-40% and wastewater savings of 20-50%.

For an industrial application, the project work flow of water pinch methodology is illustrated in Fig. 4 in a step-by-step manner. The practical application can be broken down into the following six steps in Fig. 4 [39,40,43].

1-1. Step 1 (Plant Data Gathering)

Find flow data. Develop a simple flow sheet model of the water system, showing where water is used (including utility services), and where (waste) water is generated. Develop a water balance accurate in the 10% range of the metered amounts of the larger streams. Define the appropriate data for the Water Pinch analysis, i.e., de-

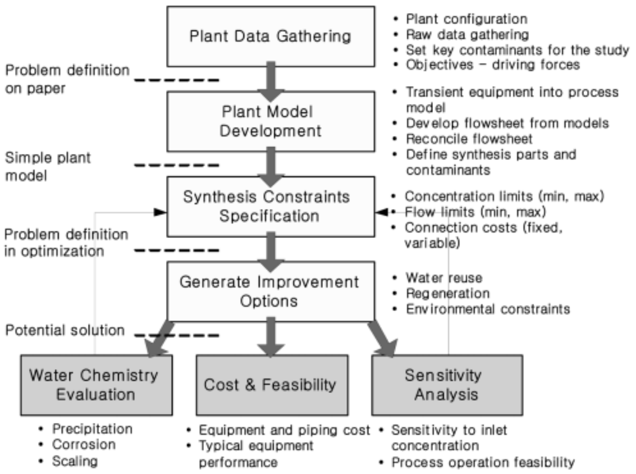

Fig. 4. Project work flow of water pinch in process industries [39].

termine water 'sources' and 'sinks'.

1-2. Step 2 (Plant Model Development)

Find contaminant data. Select key contaminants - e.g., COD, salts, suspended solids. A key contaminant is any property that prevents the direct re-use of a wastewater stream; this might include temperature and/or acidity. Choose design concentrations - maximum allowable for sinks and minimum practical for sources. Eventually, this may require input from experts in the relevant process technologies.

1-3. Step 3 (Synthesis constraints Specification)

Run water pinch analysis. Carry out the water pinch analysis to determine optimum matches between sources and sinks (using software). The first round of results will probably not be a practical design as it represents an unconstrained solution.

1-4. Step 4 (Generate Improvement Options)

- Identify pinches, examine the sensitivity plots, and relax constraints. Consider process modifications and regeneration options that may result in lower targets.

- Review design and examine the resulting network design. In most instances, it is necessary at this point to evaluate the design and determine which additional contaminants should be considered, which matches should be forbidden which to be forced, if any.

Table 2. Contaminant level of shadow mask process [44]

Process	Contaminant	Mass load (g/hr)	C_{in} (ppm)	C_{out} (ppm)
WO-1	COD	29.707	1.400	6.000
	SS	6.458	8.000	9.000
	Fe	4.004	0.000	0.620
	Cr	0.129	0.000	0.020
	Zn	0.032	0.010	0.015
WO-2	COD	18.082	1.600	4.400
	SS	77.496	11.000	23.000
	Fe	48.112	0.150	7.600
	Cr	0.000	0.000	0.000
	Zn	0.000	0.015	0.015
WO-3	COD	0.708	1.500	1.600
	SS	2.833	0.700	1.100
	Fe	1.062	0.000	0.150
	Cr	0.000	0.000	0.000
	Zn	0.007	0.006	0.007
WO-4	COD	11.084	0.000	1.400
	SS	3.167	0.000	0.400
	Fe	0.000	0.000	0.000
	Cr	0.000	0.000	0.000
	Zn	0.048	0.000	0.006
Pure water rinsing	COD	0.000	0.000	0.000
	SS	0.000	0.000	0.000
	Fe	0.000	0.000	0.000
	Cr	0.000	0.000	0.000
	Zn	0.001	0.000	0.001

1-5. Step 5 (Repeating)

- Repeat steps 3-5 until a practical design is formulated.

1-6. Step 6 (Synthesis constraints Specification)

Water chemistry evaluation, cost & feasibility issues and sensitivity analysis should be further studied in the final application [40].

2. Example of Water Minimization in Shadow Mask Manufacturing Process

Shadow mask is a core part in the CRT monitor system. When shadow mask is manufactured, the following are necessary: coating PR process, UV exposure process, developing PR process, and

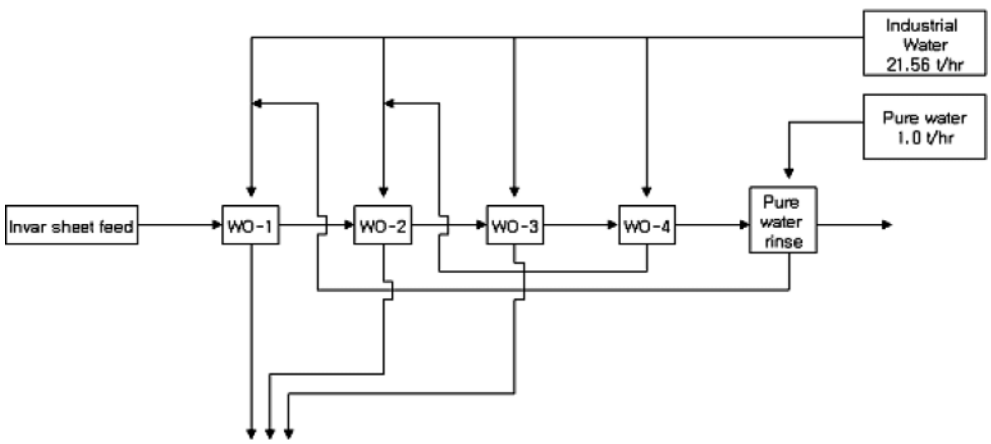

Fig. 5. Existing water network of wash process diagram [44].

etching process. In detail, Fig. 5 maps the initial water network of the shadow mask manufacturing process that requires water rinsing and wash out operations. For coating PR process, this is labeled as WO-1 for wash out operation, wash out operation in UV exposure process as WO-2, wash out operation in developing PR process as WO-3, wash out operation in etching process as WO-4, and finally, the rest of the products needing rinsing process of pure water. In this regard, five multiple contaminants of chemical oxygen demand (COD), suspended solid (SS), three metal ions (Fe, Cr, Zn) are considered. Table 2 shows the contaminant level in the shadow mask process [44].

In close examination, pure water and industrial water to the process have no contaminant with COD, SS, Fe, Cr, Zn. The finding shows that the total amount of fresh water needed in whole process is 541.5 ton/day, which is the accumulated total required for each process: 80.8 ton/day for WO-1 process, 80.8 ton/day for WO-2 process, 170.0 ton/day for WO-3 process, 185.9 ton/day for WO-4 process, and 24.0 ton/day for the pure water rinsing process. A mathematical optimization approach by using commercial software of water™ [44] was applied.

Fig. 6 shows the first optimized reuse network by considering only reuse. In the reuse network, it achieved 324.9 t/day of water amount for full coverage of water usage in this example plant. This first reuse network can save about 40% of fresh water and reduce about 25% of the generated wastewater. Moreover, we can save more water intuitively by simply changing several stream flows. This is illustrated in Fig. 7 where the final process is designed by heuristically changing several stream flows for minimization of water in a shadow masks manufacturing plant. It achieves a total water amount of 309.6 t/day and therefore more than 45% of fresh water can be saved.

RECENT RESEARCHES IN WATER REUSE NETWORK

1. Simultaneous Water and Energy Minimization

Analyzing the sources of the effluent streams in detail can possibly reduce wastewater and waste heat discharge to the effluent collection point. Reducing wastewater and waste heat at the source can reduce thermal pollution to the environment and cut down on the overall cost of cooling. Also, the minimization of wastewater and waste heat is favourable from the viewpoint of usage and production of process utilities [7,45,46]. For instance, Savulescu et al. [45, 46] addressed the simultaneous management of energy and water reduction and developed a separate systems approach for energy recovery in combined water and heat integration problems. From

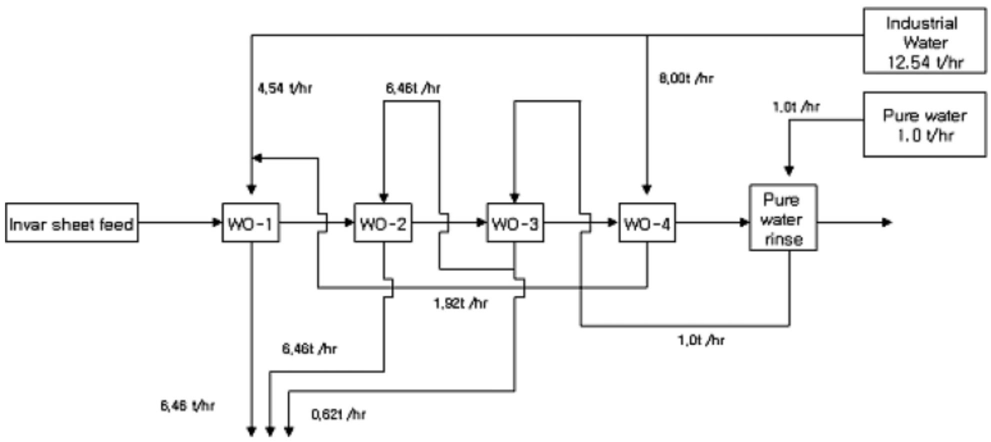

Fig. 6. Initial solution design by a water reuse design logic [44].

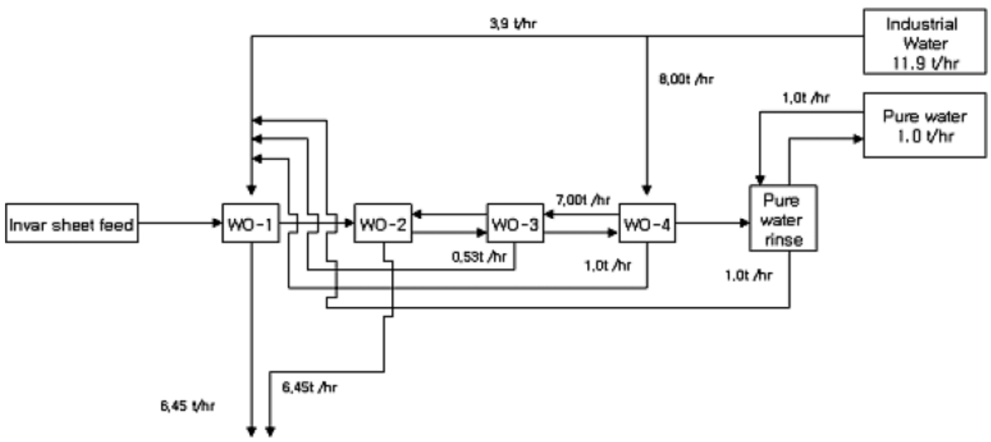

Fig. 7. Final design of water reuse network for water minimization [44].

tematically investigated, including system interactions of water and energy integration [7].

2. Energy-Pinch Analysis

Water integration studies have focused on reducing the amount of water used by a process on the assumption that environmental impact is reduced through efficient water reuse. However, the environmental impact of retrofitting a water network through the installation of pumps and pipes and energy for their utilization, which may even lead to a network with a higher environmental cost as measured by using a more comprehensive metric, is rarely, if at all, considered.

Some papers [38,47,48] show the power of energy analysis and its ability for simultaneous consideration of different industrial resources, goods and services for the purposes of decision-making. Accompanied by the pinch concept, which by now tries to deal separately with each of the resources (energy, water, hydrogen, oxygen, etc.), the combined energy-pinch analysis provides a wide range of benefits boosted with extra inside and design guidelines improving the integration of processes and the ability to consider the 'past' and the 'future' of the resources (the effort of making them available and the effort of minimizing their environmental impact). A theoretical background is presented of the energy and pinch combination into the general resources management technique, which proves this concept on classical energy and pinch examples accompanied with a combined resources management industrial problem considering the environmental impact of industrial activities [38,47, 48].

Zhelev and Ridolfi [49,50] presented an approach which combines the energy efficiency and the environmental impact of the selected process. The only way of reducing the environmental impact of a process is through a reduction of its energy usage, which is feasible by reducing the quantity of raw material (less energy) or using product with lower transformity such as renewable resources that have lower level of transformity.

Additionally, Ku-Pineda and Tan [51] address the question on water integration and environmental impact using the sustainable process index (SPI) as a means of measuring environmental impact. This study proposes that optimizing SPI instead of water consumption may eventually provide means of integrating existing water pinch and process integration principles into a broader clean production framework with life-cycle considerations. Moreover, it is shown that a balance must be achieved between water savings and water network modifications. Wang et al. [47,48] dealt with the application of an energy analysis of an eco-industrial park with a power plant. Moreover, they suggest several new energy indices and evaluate them in consideration of both the material circulation and energy and water utilization.

3. Water Pinch Role in Developing Eco-industrial Park (EIP)

Sustainable industrial development, which can minimize an ecological effect by human exertion, has been introduced recently due to an environmental contamination and a resource exhaustion problem. An eco-industrial park (EIP) is a community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in managing environmental and resource issues including energy, water, and materials [52]. EIP developments which improve a production plant within an eco-friendly green field and design a new industrial ecosystem

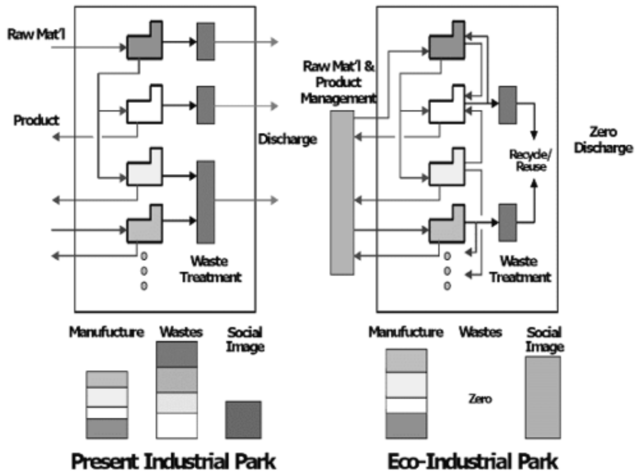

Fig. 8. Basic concept of Eco-industrial park (EIP) [52].

are accomplished, which can efficiently re-use the waste and resources from each company within EIP. As a sub-discipline of industrial ecology, industrial symbiosis is concerned with resource optimization among collocated companies. The industrial symbiosis complex in Kalundborg, Denmark is a valuable example of industrial symbiosis in industrial ecology. Fig. 8 compares an eco-industrial park with a conventional industrial park. EIP is to exchange and reuse energy, water, and waste among industries of the industrial park for cleaner production and pollution prevention [52-57].

Water is used in all industrial plants and major opportunities exist for reuse since only a small amount of water is consumed, as most water in industrial applications is used for cooling, heating or processing of materials and not as a reactant. Furthermore, different industrial processes and industrial sectors have widely varying demands for water quality. For example, wastewater from a semiconductor manufacturing facility that requires ultra pure water may be suitable for a variety of other industrial applications. Thus, water exchanges and reuse through different industrial processes provide a significant opportunity [54].

Water pinch technology can be useful to design water reuse networks and water cascading systems for water management in an industrial park, which would be a cornerstone technology to develop the EIP. It can be used to evaluate water reuse opportunities for a variety of scenarios, including redesigning the industrial water reuse network, adding a facility to the network, limiting the total water available to the network, and varying the price of the water. Yoo et al. [57] reported a pioneering research project of water-reuse network between different industrial facilities in the EIP. They proposed three scenario-based optimal water-reusing networks between the industries in an industrial steel complex. Three economically feasible water-reuse networks were identified that could reduce the total freshwater used at least 30%, while simultaneously reducing the water costs by 20%. They showed that water pinch could systematically optimize the water-reuse network between different industrial facilities in the EIP. This is the first research that applied the water pinch technology to design water reuse network in EIP.

On the other and, Allen and Butner [55] suggested using the geographical information system (GIS) to help identify water reuse networks and to allow transportation costs to be explicitly included in the optimization of these industrial waste exchange networks. Using information from the GIS, the model of water pinch matches wastewater characteristics of facilities with the feed water requirements of other facilities in the area. By matching streams with compatible water quality criteria, the water pinch model identified feasible water reuse opportunities. A GIS-based tool was used to identify and optimize water reuse and find reuse opportunities within a complex of approximately 20 different industrial facilities at the Baytown industrial complex. Economically feasible water-reuse networks were identified that had the potential to reduce the total freshwater used by more that 90% while simultaneously reducing the water costs by 20%. This approach using GIS and a mathematical optimization of water pinch would be valuable for designing an industrial material exchange network in the near future.

CONCLUSIONS

Water pinch, which has been shown to be a powerful methodology to identify the bottlenecks in water streams, allows for a precise analysis of a water network. It recognizes the importance of the process integration technology in a water reuse system for clean production. Collectively, this paper reviews the theory of water and wastewater minimization (water pinch technology), project works and application examples in industries, and alternatives in water reuse networks of stochastic design approaches and water-reusing network design in batch industries. Furthermore, it introduces several recent research topics such as simultaneous water and energy minimization and energy-pinch analysis. Practical challenges in industrial applications, such as EIP development are still needed for integrated water resource management.

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