WATER, ENERGY AND CIRCULAR ECONOMY IN THE PROCESS INDUSTRIES

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Abstract: The introduction describes the usage of natural resources in the process industries and the various concepts to reduce the usage of resources, the need for integrating these concepts in research, and highlights the circular economy as an opportunity and a challenge for process systems engineering. The materials and methods briefly describe an optimization problem of water networks to be solved using a systematic methodology based on mathematical programming and superstructure optimization. A recently proposed mixed-integer nonlinear optimization model and a solution strategy are used to solve this problem by simultaneously and systematically exploring all water and energy/heat integration opportunities and different wastewater treatment technologies. The objective function of an optimization model is to minimize the total annualized cost and determine an optimal water network design. The model for this problem is developed and solved using the General Algebraic Modeling System. The optimal network design results show that a minimum freshwater consumption, wastewater generation, and hot utility consumption can be obtained for the considered example in this work by the proposed model, which incorporates the opportunities for wastewater reuse, and wastewater recycling, and waste heat recovery from hot wastewater streams. The application of the mathematical programming approach is very promising in solving problems related to water, energy and circular economy in the process industries. The developed optimization models are usually independent of input data and can be applied to solve various industrial problems.

Keywords: water, energy, process industries, circular economy, mathematical programming.

1. INTRODUCTION

The process industries use large amounts of natural resources (e.g., raw materials, water, energy) to produce various products to satisfy market and customer needs. However, these industries also discharge waste streams (e.g., wastewater, waste heat, greenhouse gas emissions) from their manufacturing processes into the environment. Recent research is focused on pollution prevention, increased process efficiency, utilization of raw materials, water, and energy, and the minimization of waste streams discharged into the environment.

Accordingly, concepts of reuse, regeneration, recycling, closed loops and circular economy of resources are considered and implemented in the process industries to improve process efficiency and utilization of resources and reduce greenhouse gas emissions. These concepts can be applied to retrofit existing industrial processes to improve efficiency and to plan and design new and optimal processes. Process systems engineering tools, process integration, systematic methods, a holistic approach, green engineering and industrial ecology principles, and circular economy are considered in implementing these concepts and systematically exploring resources and process interactions to achieve economic, environmental, and social benefits.

Process integration is a holistic approach to design and operation that emphasizes the unity of the process (El-Halwagi, 2017). This approach enables a systematic overview of flows of raw materials, water, and energy in the process, optimal utilization of these resources and obtaining economic and sustainable environmental solutions. Industrial ecology is a new approach to the industrial design of products and processes and the implementation of sustainable manufacturing strategies. In this concept, an industrial system is viewed not in isolation from its surrounding systems but in concert with them (Jelinski et al., 1992). There are many definitions of circular economy and this concept can be interpreted and implemented in a variety of ways. Recent work analyses 221 definitions of circular economy (Kirchherr et al., 2023), and concludes that much of the literature lacks applicability. It also notes that circular economy studies are industry- and country-specific, with 70-80 % of articles recognizing „reuse“ and „recycle“ as two fundamental principles of the circular economy. Approximately 40 % of definitions mentioned value maintenance of resource efficiency as a key aim of the circular economy. Additionally, the alliance for circular economy includes not only consumers and producers but also policymakers and scholars. The study highlights the importance of a consensus definition of the circular economy.

The consideration and integration of various concepts and trans-disciplinary collaborative research is recognized as an important research challenge. Accordingly, the proposed concept of circular integration combines elements of process integration, industrial ecology and circular economy into a unified approach, which can be considered in further research related to the sustainable development of processes, industries, and economies

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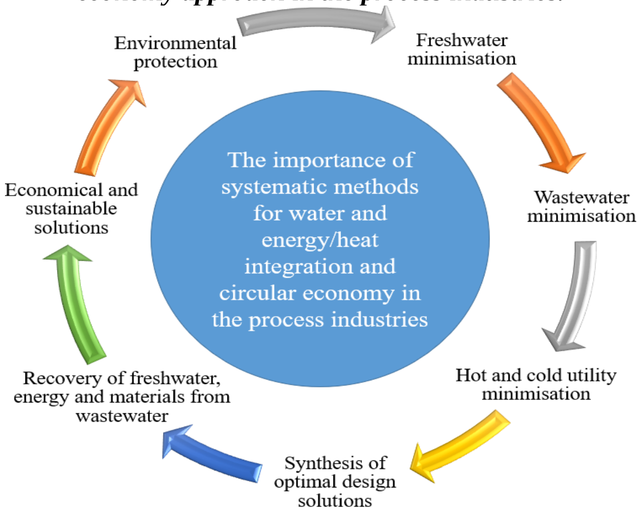
A recent study also discusses the cross-disciplinary approaches towards a smart, resilient and sustainable circular economy, which are devoted to clean technologies, process modelling, monitoring and management framework to mitigate greenhouse gas emissions, and air and water pollution (Fan et al., 2019).

The circular economy is recognized as a challenge and an opportunity for process systems engineering (Avraamidou et al., 2020). A circular economy system engineering framework and decision-making tools are proposed to optimize food supply chains (Baratsas et al., 2021). The interrelation between water, energy, and food and the various process systems engineering tools for the water-energy-food nexus are explored in recent work (Ramírez-Márquez & Ponce-Ortega, 2023).

Water is used in manufacturing processes for various purposes, such as washing raw materials, cooling hot process streams, steam generation, and sanitation. Wastewater streams generated within processes can be sent to centralized or distributed wastewater treatment systems to be treated and purified and reused/recycled in the processes or discharged into the environment. In some cases, water must be heated in heat exchangers using hot utility before being used in process units operating at different temperatures, or it must be cooled in heat exchangers to satisfy temperature constraints before being discharged into the environment. To reduce freshwater consumption, wastewater generation, and hot and cold utility consumption, water and energy/heat integration opportunities should be simultaneously explored within processes by systematic conceptual and mathematical programming methods. The importance of the applications of systematic methods in the circular economy approach (Figure 1) in the process industries is highlighted as a challenge for process engineers (Ahmetović et al., 2022a).

Recent work proposes conceptual and mathematical programming methods, along with the methodology and main steps required to address the issue of water and energy integration in Kraft mills (Ahmetović et al., 2021). Over the last several decades, the synthesis of water and energy networks or heat-integrated water networks has been a very active research field. The reader is referred to review papers for more information on this field (Ahmetović et al., 2015; Ahmetović et al., 2022b; Budak Duhbacı et al., 2021; Kamat et al., 2022; Kermani et al., 2018). The various water-saving opportunities (water reuse, wastewater regeneration reuse, wastewater regeneration recycling) and heat transfer opportunities (direct and indirect heat transfer) are explored within water networks and heat exchanger networks by using conceptual and mathematical programming tools to minimize freshwater consumption, wastewater generation and utility consumption (e.g., heating steam and cooling water) and to find an optimal network design.

Figure 1. The importance of applications systematic methods for water and energy/heat integration and circular economy approach in the process industries.



Source: After Ahmetović et al. (2022a).

In the synthesis of water networks and the circular economy approach, wastewater is not treated as waste. It is a valuable resource from which water, heat, and various materials can be recovered and reused. Accordingly, wastewater treatment plants and the progress and developments in wastewater treatment technologies play an important role in the utilization and recovery of wastewater streams from various manufacturing processes. The ideal scenario of this recycling approach in which all wastewater streams can be recovered within the system is known as zero-liquid discharge (Sarrafzadeh, 2022).

The objectives of this paper are to show the importance of water, energy and circular economy in the process industries, the simultaneous optimization of water and energy/heat integration, the selection of wastewater treatment technologies, and an application of a mathematical programming approach to design an optimal water network with the minimal total annualized cost.

2. MATERIALS AND METHODS

The optimization problem to be solved can be formulated as follows: the process consists of a set of process water-using units (PUs) requiring water at different temperatures and contaminant concentrations and wastewater treatment units (TUs) employing different treatment technologies to enable wastewater regeneration, reuse and recycling. Water is supplied from freshwater sources, and wastewater is discharged into the environment under specified environmental constraints. The aim is to determine the optimal water network design to minimize the total annualized cost (TAC), which includes operating costs (freshwater, utilities, and wastewater treatment) and investment costs for equipment (heat exchangers and wastewater treatment technologies).

To solve the optimization problem the mathematical programming approach based on superstructure optimization is employed. A recently proposed superstructure (Ibrić et al., 2022) has been extended to include wastewater regeneration, reuse, and recycling. The mixed-integer nonlinear programming (MINLP) model was developed using the General Algebraic Modelling System (GAMS), and solved with SBB as the MINLP solver and Conopt4 as the nonlinear sub-solver, and using the solution strategy proposed by Ibrić et al. (2022).

3. RESULTS AND DISCUSSION

The example considered in this work was previously studied in the literature (Karuppiah & Grossmann, 2006) as an isothermal water network (WN) synthesis problem. This example was modified to consider a non-isothermal water network by introducing temperature constraints for process and treatment units (see Table 1, and Table 2). The maximum allowable concentrations of the contaminants A and B in wastewater discharged into the environment were set at 10 ppm, with the wastewater temperature fixed at 30 °C. A lower bound of 1 °C was imposed on the exchanger minimum approach temperature (EMAT) to identify suitable trade-offs between operating and investment costs. Other cost data for freshwater, utilities and equipment were taken from the literature (Ibrić et al., 2014).

This example was also studied by Ibrić et al. (2014) as a non-isothermal water network problem involving only two wastewater treatment units, to minimize the total annualized cost (TAC) of the network. The example was extended to allow for the selection of different wastewater treatment technologies for removing contaminants from wastewater streams. For instance, for wastewater treatment unit TU_1, which removes only contaminant A, two different wastewater treatment technologies were available (TU_{11} and TU_{12}). These technologies differ in their contaminant removal efficiency and in their operating and investment costs. Similarly, for wastewater treatment unit TU_2, which removes only contaminant B, two wastewater technologies were also available (TU_{21} and TU_{22}). The objective was to identify the optimal network design by selecting cost-effective wastewater treatment technologies that enable more efficient water reuse and recycling. This was achieved by introducing binary variables to represent the selection of wastewater treatment technologies and specifying that the sum of binary variables for a given treatment unit equals 1, ensuring that only one technology is selected.

Table 1. Process units' data for Example.

Process unit	Contaminants mass load (kg/h)		Contaminants maximum inlet concentration (ppm)		Contaminants maximum outlet concentration (ppm)		Temperature (°C)
	A	B	A	B	A	B	
PU_1	1	1.5	0	0	25	37.5	40
PU_2	1	1	50	50	70	70	50
PU_3	1	1	50	50	66.667	66.667	75
PU_4	2	2	50	50	78.571	78.571	100

Source: After Karuppiah and Grossmann (2006), Ibrić et al. (2014).

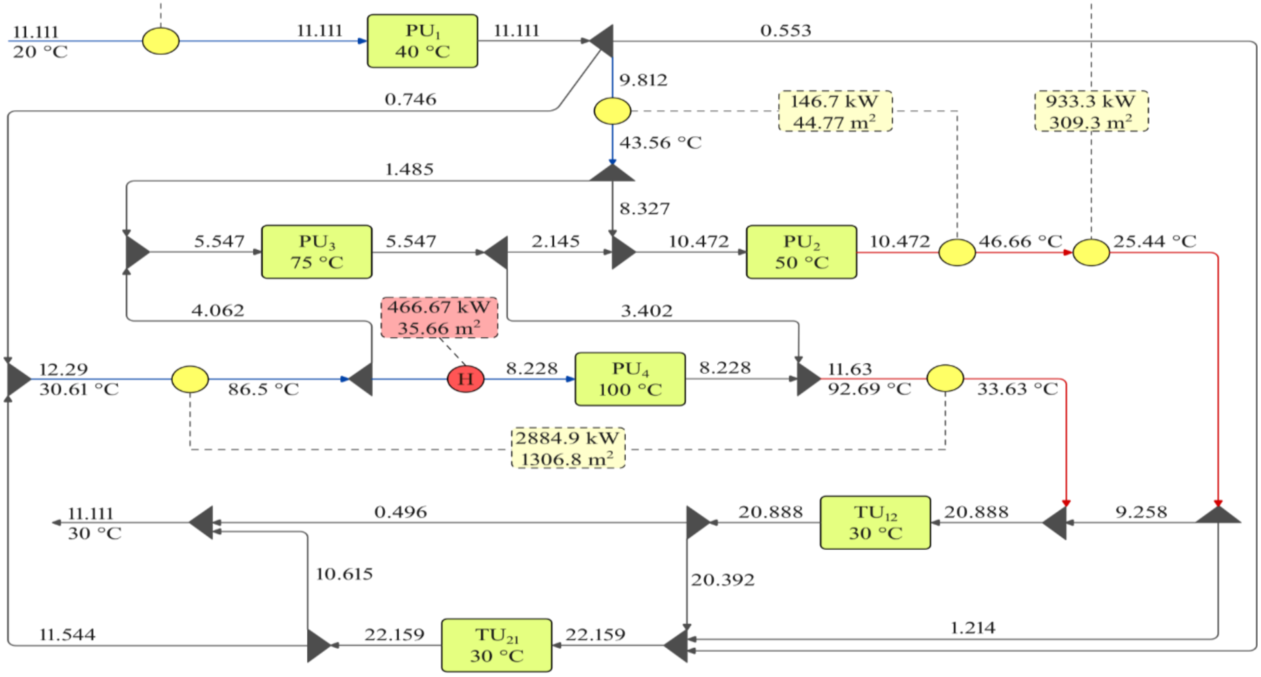
Table 2. Treatment units' data for Example.

Treatment technologies	Removal percent of contaminants (%)		Investment cost coefficient (IC)	Operating cost coefficient (OC)	Cost exponent (α)	Temperature (°C)
	A	B				
TU_{11}	95	0	16,800	1	0.7	30
TU_{12}	90	0	4800	0.5	0.7	30
TU_{21}	0	90	12,600	0.0067	0.7	30
TU_{22}	0	95	36,000	0.067	0.7	30

Source: After Ibrić et al. (2014).

The optimal heat-integrated water network design (Figure 2) achieved a minimum freshwater consumption of 11.111 kg/s, consistent with the result reported by Karuppiah and Grossmann (2006) for the isothermal network and by Ibrić et al. (2014) for the non-isothermal water network. The network design required a hot utility consumption of 466.67 kW within a single heater with a heat transfer area of 35.66 m^2. The network included three heat exchangers (total area: 1660.87 m^2) recovering 3964.9 kW of heat. The total investment cost for the heat exchanger network (HEN) was 180,338 $/y. Since the objective was to minimize the TAC of the network, wastewater treatment technologies with lower removal ratios and investment costs were selected (TU_{12} and TU_{21}). Further removals of contaminants with more expensive technologies were not justified, as it would not reduce freshwater consumption, which had already reached the theoretical minimum. Freshwater was used only by PU_1, which requires pure freshwater with 0 ppm of contaminants. The operating and investment costs for the selected wastewater treatment technologies were 305,063.7 and 36,895.3 $/y. The TAC of the network was 818,230.285 $/y.
In comparison, the optimal designs reported by Ibrić et al. (2014) and Yan et al. (2022) exhibited TAC values of 1,087,259.5 and 1,094,050.6 $/y, respectively. However, this problem was solved in these works with a fixed choice of treatment technologies (TU_{11} and TU_{21}), resulting in networks with higher TAC values. By extending the pool of available treatment technologies, improved solutions can be obtained, further reducing the TAC of the network design. Compared to the optimal design obtained by Ibrić et al. (2014) not only operating and investment costs of the wastewater treatment technologies were reduced, but also the HEN investment cost was reduced by 17.5 % (180,338 vs. 218,672.4 $/y) while having the same number of heat exchangers.

Figure 2. The optimal heat-integrated water network design with the selected wastewater treatment technologies.



Source: Author research.

4. CONCLUSIONS

The extended superstructure and mixed-integer nonlinear programming (MINLP) model applied in this work provides effective frameworks for designing optimal heat-integrated water networks. By incorporating wastewater reuse, wastewater regeneration reuse, wastewater regeneration recycling, and both direct and indirect heat transfer within the superstructure, the proposed approach yields more economical and sustainable solutions. Water reuse within the network was improved compared to designs that excluded wastewater treatment or considered fixed wastewater treatment technologies for contaminant removal. The solutions obtained are consistent with the results reported in the literature. However, the results demonstrate that including the selection of wastewater treatment technologies enables the development of economically more efficient and sustainable networks.

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