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Synthesis and optimisation of an integrated water and membrane network framework with multiple electrodialysis regenerators

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ABSTRACT

The shrinking supplies of freshwater globally, coupled with strict environmental regulations, have driven the manufacturing industry towards sustainable water management for the minimisation of freshwater intake and wastewater generation. By using process integration and its enabling tools, this work considers the synthesis of an optimal water network with multiple regeneration capabilities. Development of the proposed framework is achieved by embedding a subnetwork of detailed electrodialysis models within a water network. Based on a superstructure and fixed flowrate, the optimisation problem is formulated as an MINLP model and solved in GAMS/DICOPT. To demonstrate the applicability of the proposed mathematical model a literature case study on a pulp and paper plant is presented and the results indicate a potential of 12% savings in freshwater intake, 16% reduction in wastewater generated and a 14% saving in the total annualised cost for the entire network.

1. Introduction

Sustainability of human activities, primarily production and consumption, has been of growing concern in the process industry. Among the sustainability mega-forces, water scarcity has risen to the top of the corporate agenda for most entities in the industrial sector. On average, the manufacturing industry consumes about 22% of the total freshwater available globally and about 90% of this is disposed of as wastewater (Sachidnanda and Rahimifard, 2012). In the face of these dire estimates, a number of industries are taking measures to become stewards of this vital resource through sustainable water management. This suggests the need to methodically and efficiently run operations such that profitability is maximised without exceeding the ecological capabilities that support these operations (El-Halwagi, 2012).

Process integration is a powerful and effective framework for sustainable design that emphasises the unity of a process because of the strong interactions that exist between the different unit operations (El-Halwagi, 2012). With regards to the minimisation of freshwater intake and wastewater generation, process integration has presented enabling tools for sustainable water network design such as water recycle, reuse as well as regeneration-recycle and regeneration-reuse. Optimisation of water networks has become a vital instrument of sustainability as it allows for the realisation of the full benefits, both economic and environmental, of using the aforementioned enabling tools.

The two optimisation approaches that remain irrefutable are the insight-based ‘pinch’ approach and mathematical programming. Most of the early work reported on water network optimisation was insight-based, which being graphically-based, focused on flowrate targeting and network design methods. Wang and Smith (1994) proposed the first graphical-based solution with a fixed load framework, to synthesise a single contaminant water network that had regeneration capabilities. Over the years, the technique has been refined and modified to extend its applicability to various systems found in the real world (Tan et al., 2007). Noteworthy is that these graphical methods offer low computation expense but are limited to mass transfer based operations and grassroots design purposes (Bandyopadhyay and Cormos, 2008; Tan et al., 2009).

Mathematical programming techniques involve the development of models based on mathematical relations that describe the system under analysis and the application of rigorous algorithms to obtain solutions. Early work on mathematical optimisation was reported by Takama et al. (1980) who used a superstructre based approach to address a water allocation planning problem for a refinery. Further work on the technique became more prominent much later, as researchers realised its capability of treating rigorous, large-scale, complex systems, which pinch analysis is incapable of handling (Tan et al., 2009). This includes the work by Quesada and Grossmann (1995) and Karuppiah and Grossmann (2006) who tackled an integrated water network problem using global optimisation approaches. Similar works that adopt mass and property

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Nomenclature

Sets

J	$\{j \mid j = \text{water sources}\}$
I	$\{i \mid i = \text{water sinks}\}$
R	$\{r \mid r = \text{regenerators}\}$

Parameters

LR_r	liquid recovery for regenerator, r
F	Faraday constant
w	cell width
z	valence
a^{LCD}	LCD constant
b^{LCD}	LCD constant
k^{tr}	conversion factor
ζ	current utilisation
α	spacer shadow factor
δ	cell thickness
ρ	total membrane resistance
β	volume factor
λ	equivalent conductance
μ	solution viscosity
η	pumping efficiency
ε	safety factor
k^{el}	cost of electricity
k^{mb}	cost of membrane
C^{FW}	freshwater cost
C^{WW}	wastewater treatment cost
n	maximum equipment life
t^d	operating time per year
p	parameter for carbon steel piping
q	parameter for carbon steel piping
m	interest rate per year
v	pipe linear velocity
$D_{j,i}^s$	Manhattan distance between source, j and sink i
$D_{r,i}^d$	Manhattan distance between regenerator, r and sink, i
$D_{r,r'}^y$	Manhattan distance between regenerators r and r’
$D_{j,r}^k$	Manhattan distance between source, j and regenerator, r

Continuous variables

TAC_r	total annualised cost for regenerator, r.
A_r	membrane area required by regenerator r.
E_r^{spec}	specific desalination energy required by regenerator r.
E_r^{pump}	specific pumping energy required by regenerator r.
I_r	electric current required by regenerator r.
L_r	stack length
v_r	linear flow velocity, at stage s
U_r	voltage applied
ΔP_r	pressure drop across the regenerator
Q_r^f	regenerator feed flowrate
R_r	recovery rate for regenerator, r
S_r	splitting rate for regenerator, r
Q_r^{dil}	final diluate stream flowrate of regenerator, r
Q_r^p	diluate stream flowrate for regenerator, r
Q_r^w	concentrate stream flowrate for regenerator, r
Q_r^{cr}	concentrate stream recycle flowrate for regenerator, r
Q_r^r	recycle stream flowrate for regenerator, r
Q_r^{con}	final concentrate flowrate for regenerator, r
$Q_{r,i}^d$	diluate flowrate to sink, i
$Q_{r,i}^c$	concentrate flowrate to sink, i
Q_j	source flowrate
$Q_{j,r}^k$	flowrate from source, j to regenerator, r
$Q_{j,i}^s$	flowrate from source, j to sink, i
$Q_{r,r'}^x$	recycle from diluate stream to regenerator feed
$Q_{r,r'}^y$	recycle from concentrate stream to regenerator feed
Q_i^b	sink, i, flowrate requirements
FW	freshwater flowrate
WW	wastewater flowrate
C_r^f	regeneration feed concentration for regenerator, r
C_r^{wf}	concentration of feed concentrate stream for regenerator, r
C_r^{cr}	concentration of recycling concentrate for regenerator, r
C_r^w	concentration of concentrate waste stream for regenerator, r
C_r^{dil}	diluate contaminant concentration
C_r^{con}	concentrate contaminant concentration
S_r^U	maximum allowable regenerator concentration
C_j	source concentration of
C_i^U	maximum allowable sink concentration
RR_r	removal ratio for regenerator, r

Integer variables

N_r	number of cell pairs per regenerator, r

Binary variable

$$y_r^{ED} = \begin{cases} 1 \leftarrow \text{if regenerator } r \text{ exists} \\ 0 \leftarrow \text{otherwise} \end{cases}$$

$$y_{r,i}^d = \begin{cases} 1 \leftarrow \text{piping exists between regenerator diluate and sink, } i \\ 0 \leftarrow \text{otherwise} \end{cases}$$

$$y_{r,i}^c = \begin{cases} 1 \leftarrow \text{piping exists between regenerator concentrate and sink, } i \\ 0 \leftarrow \text{otherwise} \end{cases}$$

$$y_{r,r'}^x = \begin{cases} 1 \leftarrow \text{recycle exists from regenerator diluate to regenerator, } r \\ 0 \leftarrow \text{otherwise} \end{cases}$$

$$y_{r,r'}^y = \begin{cases} 1 \leftarrow \text{recycle exists from regenerator concentrate to regenerator, } r \\ 0 \leftarrow \text{otherwise} \end{cases}$$

$$y_{j,r}^k = \begin{cases} 1 \leftarrow \text{piping exists between source, } j \text{ and regenerator, } r \\ 0 \leftarrow \text{otherwise} \end{cases}$$

$$y_{j,i}^s = \begin{cases} 1 \leftarrow \text{piping exists between source, } j \text{ and sink, } i \\ 0 \leftarrow \text{otherwise} \end{cases}$$

integration frameworks by Ponce-Ortega et al. (2010) and Khor et al. (2011) to mention a few, have also been done using powerful mathematical programing tools.

Within water networks, regeneration allows for the partial treatment of wastewater before being recycled or reused. To date, membrane-based technology emerges as one of the most sustainable contenders for regeneration mainly because of its competency to treat wastewater in single-step processes at competitive costs (Strathmann, 2010; Rangaiah and Wei, 2010). An interesting observation is that for most of the work done on water-regeneration network optimisation so far, the technologies of choice, number of regeneration units, arrangement of the regeneration train and regeneration design parameters are not set as decision variables; rather they are assumed to be known (Rangaiah and Wei, 2010). Additionally, the complexity of regenerator design has forced a