CHEMICAL ENGINEERING TRANSACTIONS

VOL. 94, 2022

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš, Sandro Nižetić

ISBN 978-88-95608-93-8; **ISSN** 2283-9216

DOI: 10.3303/CET2294104

Recent Progress and Future Directions in the Synthesis of Heat-Integrated Water Networks

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The synthesis of Heat-Integrated Water Networks (HIWNs) has been a very active research area over the last twenty-five years. Systematic methods based on Pinch Analysis (PA), Mathematical Programming (MP) and their combinations (PA-MP) have been developed and applied to HIWN case studies with varying levels of complexity. There have also been some attempts to apply alternative optimisation tools for the synthesis of HIWNs, such as Process Graph (P-Graph). However, most recent works have applied MP primarily to solve large-scale problems, including single and multiple freshwater sources and single and multiple contaminants in water streams. The synthesis of combined Water-Using Networks (WUNs), Wastewater Treatment Networks (WTNs) and Heat Exchanger Networks (HENs) has proven to be a challenging task for researchers to find a global solution or even good local and practical solutions. In a previous work, a comprehensive review of papers in this field was given for the period from 1997 to 2015 (Ahmetović et al., 2015). The goal of this work is to provide a review of recent progress in the synthesis of HIWNs after this period, discuss case studies solved in the literature, identify research gaps and provide suggestions that can be a driving force for future research and improvements in this field.

1. Introduction

Water and energy are resources used in large quantities in industrial processes. There is an ongoing need in industry and other sectors to raise awareness of opportunities to improve water and energy efficiency and to find solutions with reduced water and energy consumption. Over the last 25 y, the synthesis of Heat-Integrated Water Networks (HIWNs), Heat-Integrated Water Allocation Networks (HIWANs), Non-Isothermal Water Networks (NIWNs), or Combined Energy and Water Networks (CEWNs) has been an active research field. Considerable attention has been paid to the Simultaneous Energy and Water Integration (SEWI) in these networks in various manufacturing processes and design solutions for CEWNs have been proposed. In these networks, various opportunities for water saving (water reuse, regeneration reuse, and regeneration recycling) and heat exchange (indirect and direct heat transfer) are systematically explored to find optimal network design solutions with significantly reduced freshwater and utility consumption, including wastewater and waste heat discharged from the process into the environment. There are several review papers dealing with the synthesis of HIWNs. The first systematic and comprehensive review of papers and methods based on Pinch Analysis (PA), Mathematical Programming (MP) and their combinations (PA-MP), published within the period 1997 - 2015, is given by Ahmetović et al. (2015). Applications of systematic methods to solve HIWN problems are described, including industrial case studies, the main features of the problems studied and research gaps. Additionally, brief overviews of some works in this field are also given by other authors within the above mentioned period. Jeżowski (2010) provides a review of papers on Water Network (WN) synthesis with a focus on isothermal WNs. This review as well as the review of Heat, Mass, and Work Exchange Network (HMWEN) synthesis by Chen and Wang (2012) also describe the important contributions focused on NIWNs, and recognise this field as an important field for further investigation. A brief overview of several works focused on

Paper Received: 16 May 2022; Revised: 13 June 2022; Accepted: 16 June 2022
Please cite this article as: Ahmetović E., Ibrić N., Nemet A., Kravanja Z., Grossmann I.E., 2022, Recent Progress and Future Directions in the Synthesis of Heat-Integrated Water Networks, Chemical Engineering Transactions, 94, 625-630 DOI:10.3303/CET2294104

Combined Energy and Water Integration (CEWI) in NIWNs is given by Klemeš (2012), while Savulescu and Alva-Argaez (2013) describe Process Integration (PI) concepts for CEWI, highlighting the importance of considering the benefits of the engineering insights of conceptual methods and the power of MP and optimisation tools. Grossmann et al. (2014) provided a review of optimisation models for WNs and their application to biofuel processes highlighting that process flowsheets should be optimized simultaneously with Heat and Water Integration (HWI), at least at the conceptual level. Several recent papers focus on reviews related to the synthesis of HIWNs and the improvements achieved in various industrial processes by applying systematic methods. Some of these reviews are focused mainly on MP methods, solution strategies, and network features (Kermani et al., 2018), including also sectorial case studies published from 2014 to 2019 (Budak Duhbacı et al., 2021), while other papers present only a brief overview of HIWN works (Zhang et al., 2021) or applications of systematic methods for HIWNs optimisation in specific processes, e.g. Kraft pulp mills (Ahmetović et al., 2021). In the last few years, the increased development in the synthesis of HIWNs can be noticed. This year is the 25th anniversary of the synthesis of HIWNs, and significant progress has been made in recent years in the proposed models and solution strategies for various HIWN problems, especially large-scale problems. For this reason, it is necessary to review recent progress and provide possible future research directions in this field, considering applications of PA, MP and their combinations (PA-MP), as well as other alternative methods for the synthesis of HIWNs. Accordingly, the main goal of this work is to present recent progress in the synthesis of HIWNs over the period from 2015 to 2022, and to identify research gaps and challenges for possible future research directions and improvements in this field.

2. Recent progress and future directions in the synthesis of Heat-Integrated Water Networks

The literature review of HIWNs papers published within the period from 2015 to 2022, their main features regarding the methodology, solution strategy, and the trade-offs considered between operating and investment costs are shown in Table 1. As can be seen from Table 1, the majority of recent papers applied MP to synthesise HIWNs, while the number of papers using PA and a combined approach is quite similar. A typical HIWN consists of a Water-Using Network (WUN), a Wastewater Treatment Network (WTN), and a Heat Exchanger Network (HEN). The operating cost of the HIWN consists of the cost of freshwater, hot and cold utility, wastewater treatment and electricity. The investment cost consists of the cost of heat exchangers, wastewater treatment units, pipes and pumps. The complexity of HIWN network depends on the number of heat exchangers, pipes, and non-isothermal mixing points where mixing of streams is possible. Recent papers dealing with solving HIWN problems, especially large-scale problems, mainly applied the MP approach to establish appropriate trade-offs between operating and investment costs. However, it is worth pointing out that the trade-offs between operating cost, investment cost, and network complexity should be studied simultaneously to obtain an optimal solution for HIWN, which is also a practical solution in terms of network complexity and controllability. The focus in the synthesis of HIWNs should be to minimise TAC, while considering the environmental constraints, but also to obtain simple and practical networks, which have not been sufficiently considered in the literature. Further progress is needed in this direction to obtain solutions within the intersection of operating cost, investment cost and network complexity (see as presented in Figure 1).

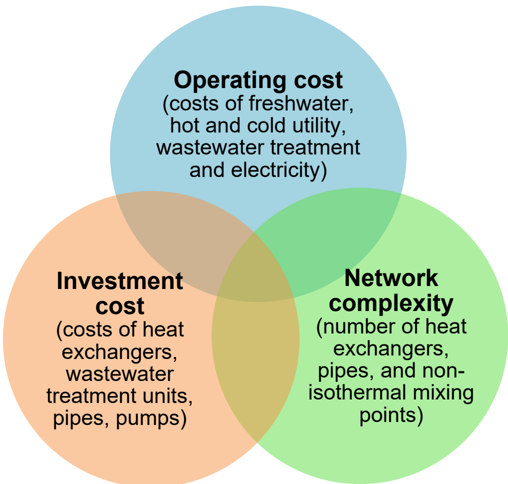

Figure 1. Trade-offs between operating cost, investment cost, and network complexity.

Table 1: Literature review of HIWNs papers published within the period from 2015 to 2022

Reference	Methodology			Solution strategy		Trade-off Operating cost				Investment cost			
	PA	MP	Combined	Sequential	Simultaneous	Freshwater	Hot and cold utility	Wastewater treatment	Pumping	Heat exchangers	Wastewater treatment	Piping	Pumps
Yan et al. (2022)		✔			✔	✔	✔	✔		✔	✔		
Ibrić et al. (2022)		✔			✔	✔	✔			✔			
Dong et al. (2022)		✔			✔	✔	✔			✔			
Kamat and Bandyopadhyay (2022)			✔	✔		✔	✔	✔		✔	✔		
Ibrić et al. (2021)		✔			✔	✔	✔	✔		✔	✔		
Kamat and Bandyopadhyay (2021a)	✔			✔		✔	✔						
Kamat and Bandyopadhyay (2021b)			✔	✔		✔	✔	✔		✔	✔		
Kamat and Bandyopadhyay (2021c)			✔	✔		✔	✔	✔		✔	✔		
Chauhan and Khanam (2021)	✔			✔		✔	✔						
Shen et al. (2019)		✔		✔		✔	✔	✔					
Kermani et al. (2019)		✔		✔		✔	✔			✔			
Kamat et al. (2019)		✔		✔	✔	✔	✔						
Kamat and Bandyopadhyay (2019)	✔			✔		✔	✔						
Chin et al. (2019)*				✔		✔	✔	✔					
Zhao et al. (2019)			✔	✔		✔	✔			✔			
Yeo et al. (2018)		✔		✔		✔	✔						
Liu et al. (2018)		✔		✔	✔	✔	✔	✔		✔	✔	✔	
Hong et al. (2018a)		✔			✔	✔	✔	✔		✔	✔		
Hong et al. (2018b)	✔			✔		✔	✔			✔			
Hong et al. (2018c)	✔			✔		✔	✔			✔			
Cheng and Adi (2018)		✔			✔	✔	✔	✔		✔			
Wang et al. (2017)			✔	✔		✔	✔						
Kermani et al. (2017)		✔		✔		✔	✔			✔			
Ibrić et al. (2017a)		✔			✔	✔	✔	✔		✔	✔		
Ibrić et al. (2017b)		✔			✔	✔	✔	✔	✔	✔	✔	✔	
Hong et al. (2017)		✔			✔	✔	✔			✔			
Ghazouani et al. (2017)		✔			✔	✔	✔			✔			
Hou et al. (2017)	✔			✔		✔	✔						
Chaturvedi (2017)	✔			✔			✔						
Xie et al. (2016)	✔			✔		✔	✔						
Liao et al. (2016)	✔			✔		✔	✔						
Yan et al. (2016)		✔			✔	✔	✔			✔			
De-León Almaraz et al. (2016)			✔	✔		✔	✔	✔		✔	✔		
Torkfar and Avami (2016)**		✔			✔	✔	✔		✔	✔			
Jagannath and Almansoori (2016)		✔			✔	✔	✔	✔		✔	✔		
Ibrić et al. (2016)		✔			✔	✔	✔	✔		✔	✔		
Hong et al. (2016)		✔			✔	✔	✔			✔			
Zhou and Li (2015)		✔			✔	✔	✔			✔			

*P-Graph (minimum freshwater flow rate, regeneration flow rate), **Power only to overcome pressure drop within heat exchangers

The capital cost of heat exchangers depends on the area size and the type of heat exchangers. The area size for the different heat exchangers (e.g. shell and tube, plate and frame, double pipe) is usually limited by their practical minimum and maximum areas. The various locations of heat exchangers, water-using and wastewater treatment units within processes and corresponding piping can have a significant influence on the capital and operation costs. Accordingly, the layout of the equipment and piping in a chemical plant are important to be considered during process design (economic, safety, operational, and maintenance reasons) (Guirardello and

Swaney, 2005). In many HIWN papers, the capital cost is associated with heat exchangers (usually shell and tube), and wastewater treatment units, without enough attention devoted to piping and pumping costs. Accordingly, HIWNs are expanded to increase the number of opportunities for splitting and mixing water streams within the networks by introducing additional degrees of freedom. However, piping cost has not been considered in the objective functions of many models, while pumping cost has even been ignored. The solutions enforced by the proposed models and approaches exhibit increased network complexity in terms of mixing points and piping, and decreased network complexity in terms of the number of heat exchangers. The trade-off between operating cost, investment cost, and network complexity is not explored simultaneously. This is rarely considered in the synthesis of HIWNs and should be the focus of further research. The goal of many proposed HIWN models is to minimize the TAC consisting of freshwater, hot and cold utility costs, and investment costs for heat exchangers and wastewater treatment units. The options introduced for mixing water streams resulted in increased network complexity that is ignored during optimisation as for instance piping and pumping. Various network design solutions in the literature for the same case study in most cases exhibit the minimum freshwater and utility consumption. Additional improvements to the network have been achieved by decreasing the investment cost of heat exchangers (indirect heat transfer) due to the increase in degrees of freedom provided by non-isothermal mixing points (direct heat transfer). This usually reduces the number of heat exchangers in a final design, but increases the complexity of the network in terms of piping connections. In addition to the investment cost of heat exchangers, the cost of piping is also important that it be considered in the synthesis of optimal HIWN (Polley et al., 2010). The flow rates of water in some piping connections in the reported HIWN design solutions have very small values and could be impractical. This can be avoided by setting a practical value for the minimum flow rate through the piping connections based on an average pipe diameter, and a practical value for the water velocity through the pipes. Further research is required to consider these issues in future models to obtain more practical network design solutions.

3. Conclusions

There are several challenges in the synthesis of HIWNs that need to be addressed in future research. One is related to the development of models and solution strategies to efficiently solve large-scale HIWN problems with multiple contaminants to obtain good local solutions or the global optima. More detailed models for units considered within HIWN should be developed to obtain more practical solutions. In HIWNs, mainly shell and tube heat exchangers are considered. There is a room to explore various types of heat exchangers depending on their practical values of the minimum and maximum heat exchange areas. The vast majority of papers consider only networks consisting of water-using and heat exchange units, while significantly fewer papers consider a combined network of water-using, wastewater treatment, and heat exchange units. The trade-offs between investment and operating costs are considered in previous works without much attention paid to the network complexity. Many works have been focused on increasing the possibilities for mixing of streams (non-isothermal points) and splitting of streams within superstructures, without considering cost in the objective function for introducing new connections (piping cost) as well as pumping water through pipes (pumping costs). Accordingly, further progress in HIWNs is expected to simultaneously explore the trade-offs between operating cost, investment cost and network complexity. Additional opportunities for Water Integration (WI) and Heat Integration (HI) can be explored by enabling HI with streams outside of WN. Batch processes are also rarely addressed in the literature. It is expected that the HIWN research field will continue to be active in the future to address the issues important in different sectors related to sustainable utilisation of natural resources, improving water and energy efficiency and profitability, minimising waste streams, and protecting the environment.

Acknowledgments

The authors gratefully acknowledge the programme for Scientific and Technological Cooperation between the Republic of Slovenia and Bosnia and Herzegovina (Project acronym: “SISUMP”, No: 01-1282-1/20) and Erasmus+ programme (Project acronym: “INTERBA”, Reference number: 610429-EPP-1-2019-1-AL-EPPKA2-CBHE-JP). Also, the support from the Slovenian Research Agency (P2-0414 and J7-1816) and the Federation of Bosnia and Herzegovina (Decision No.: 05-35-3210-1/21) is acknowledged.

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