FME HighEFF

Centre for an Energy Efficient and Competitive Industry for the Future

Deliverable D1.1_2020.02

Work Exchange Networks (WENs) and Work and Heat Exchange Networks (WHENs) – A Review of the current State-of-the Art

Delivery date: 2020-02-15

Organisation name of lead beneficiary for this deliverable:

NTNU

HighEFF- Centre for an Energy Efficient and Competitive Industry for the Future is one of Norway's Centre for Environment-friendly Energy Research (FME).
Project co-funded by the Research Council of Norway and Industry partners.
Host institution is SINTEF Energi AS.

Dissemination Level		
PU	Public	PU
RE	Restricted to a group specified by the consortium	

Deliverable number:	D1.1_2020.02
ISBN number:	
Deliverable title:	WENs and WHENs – A Review of the current State-of-the Art
Work package:	WP 1.1
Deliverable type:	JP
Lead participant:	NTNU

Quality Assurance, status of deliverable		
Action	Performed by	Date
Verified (WP leader)	Olaf T. Berglihn	
Reviewed (RA leader)	Egil Skybakmoen	
Approved (dependent on nature of deliverable)*)		

*) *The quality assurance and approval of HighEFF deliverables and publications have to follow the established procedure. The procedure can be found in the HighEFF eRoom in the folder "Administrative > Procedures".*

Authors		
Author(s) Name	Organisation	E-mail address
Haoshui Yu	NTNU	
Chao Fu	SINTEF Energy Research	
Truls	Gundersen	Truls.gundersen@ntnu.no

Abstract:

This paper provides a current state-of-the-art review of literature on work exchange networks (WENs) and work and heat exchange networks (WHENs). Heat exchange networks (HENs) and mass exchange networks (MENs) have been widely adopted and extensively studied for heat and material recovery to save energy and other resources. However, work recovery can also result in significant energy savings in the process industries, such as oil refineries, petrochemical plants, and cryogenic processes (e.g., the production of liquefied natural gas (LNG) and air separation units (ASUs)). The concept of WENs was first proposed and identified as a new research topic in process synthesis in 1996. This research area has broadened considerably during the last 5−10 years, and it covers both flow work (material streams) and shaft work (energy streams or nonflow processes). Flow work recovery is referred to as direct work exchange and shaft work recovery is referred to as indirect work exchange. More recently, there has also been considerable development in the combined problem of WENs and HENs. This problem is referred to as work and heat exchange networks (WHENs). The WHENs problem is generally studied by pinch based methods and mathematical programming. The corresponding literature is reviewed, analyzed, and compared in this paper. The present review covers WENs (both flow work and shaft work) and WHENs (with a focus on both mechanical energy and thermal energy). The development progress, current state, challenges, and future research in WENs and WHENs are discussed and analyzed thoroughly.

I&EC research
Industrial & Engineering Chemistry Research
Review
Cite This: Ind. Eng. Chem. Res. 2020, 59, 507−525
pubs.acs.org/IECR

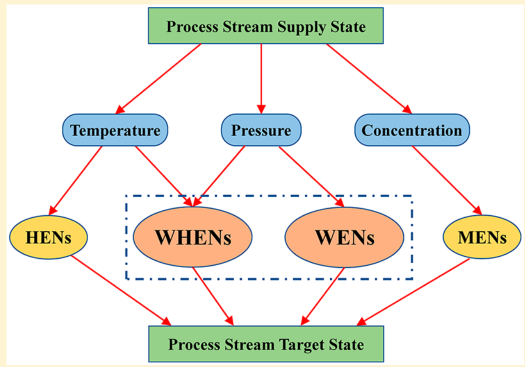
Work Exchange Networks (WENs) and Work and Heat Exchange Networks (WHENs): A Review of the Current State of the Art

Haoshui Yu,[†] Chao Fu,[‡] and Truls Gundersen*,[†]

[†]Department of Energy and Process Engineering, Norwegian University of Science and Technology, Kolbjoern Hejes vei 1A, NO-7491 Trondheim, Norway

[‡]SINTEF Energy Research, Kolbjoern Hejes vei 1A, NO-7491 Trondheim, Norway

ABSTRACT: This paper provides a current state-of-the-art review of literature on work exchange networks (WENs) and work and heat exchange networks (WHENs). Heat exchange networks (HENs) and mass exchange networks (MENs) have been widely adopted and extensively studied for heat and material recovery to save energy and other resources. However, work recovery can also result in significant energy savings in the process industries, such as oil refineries, petrochemical plants, and cryogenic processes (e.g., the production of liquefied natural gas (LNG) and air separation units (ASUs)). The concept of WENs was first proposed and identified as a new research topic in process synthesis in 1996. This research area has broadened considerably during the last 5−10 years, and it covers both flow work (material streams) and shaft work (energy streams or nonflow processes). Flow work recovery is referred to as direct work exchange and shaft work recovery is referred to as indirect work exchange. More recently, there has also been considerable development in the combined problem of WENs and HENs. This problem is referred to as work and heat exchange networks (WHENs). The WHENs problem is generally studied by pinch based methods and mathematical programming. The corresponding literature is reviewed, analyzed, and compared in this paper. The present review covers WENs (both flow work and shaft work) and WHENs (with a focus on both mechanical energy and thermal energy). The development progress, current state, challenges, and future research in WENs and WHENs are discussed and analyzed thoroughly.



1. INTRODUCTION

Plants in the process industries require specific utilities in their processing of raw materials to produce valuable products. Examples of such utilities are thermal energy forms for heating and cooling, mechanical energy forms such as power and work, and materials such as water, air, nitrogen, hydrogen, and oxygen. These utilities have quality indicators such as temperature (heating and cooling), pressure (work related to expansion/compression), and concentration (materials). Prior to using external utilities, internal recovery of resources should be attempted. Whenever demands of the opposite type exist, such as heating/cooling and compression/expansion, integration opportunities exist that can reduce the need for external utilities. To fully utilize the heat in processes with multiple streams, methods for heat exchange networks (HENs) emerged.[1−3] HENs have been widely investigated since the 1970s and reviewed many times. Among them, the review by Gundersen and Naess[4] and the one by Furman and Sahinidis[5] provide insightful reviews on HENs.

Using the analogy between heat transfer and mass transfer, the concept of mass exchange networks (MENs) was introduced by El-Halwagi and Manousiouthakis[6] and applied to minimize fresh water consumption and thus wastewater production by Wang and Smith.[7] HENs and MENs aim at recovering thermal energy and materials, respectively. In industrial plants, such as refineries, petrochemical plants, and natural gas liquefaction plants, pressure is equally important as temperature. Similar to HENs and MENs, the concept of work exchange networks (WENs) was first proposed by Huang and Fan[8] to recover pressure-based mechanical energy (work). A review paper[9] lists 108 references covering heat exchange networks (HENs), mass exchange networks (MENs), water allocation heat exchange networks (WAHENs), and work exchange networks (WENs). However, this review paper does not include work and heat exchange networks (WHENs) and WENs is only briefly discussed. Nevertheless, it contains a good overview of devices for pressure-based energy recovery.

A pressurized process stream represents valuable energy. Once expanded, both work and cooling duty can be produced if a turbine (expander) is used. The relative importance of the work and the cooling duty depends on whether the expansion takes place above or below ambient temperature. In industrial plants, streams can be pressurized or depressurized in order to

Received: September 4, 2019
Revised: December 1, 2019
Accepted: December 16, 2019
Published: December 16, 2019

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525

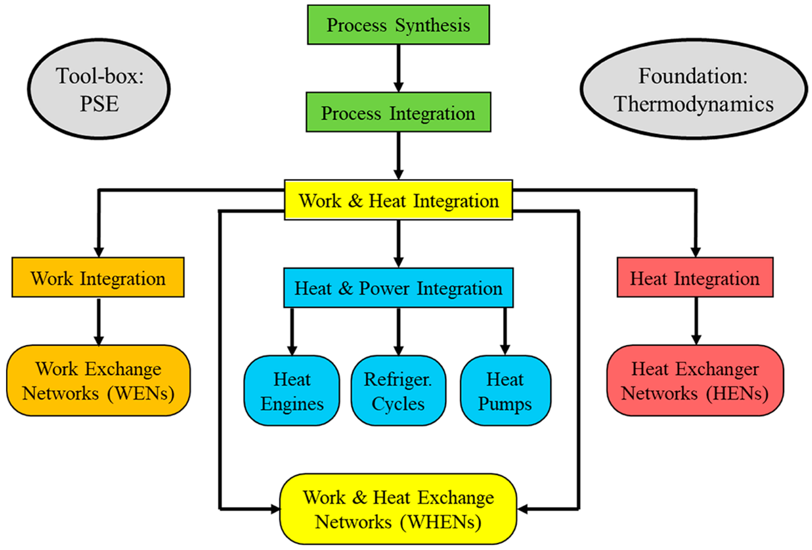


Figure 1. Work and heat integration as a new field in process synthesis and PSE.[26] (Reproduced with permission from ref 26. Copyright 2019 John Wiley and Sons.)

meet specifications in the process. Since work and heat are interchangeable, simultaneous integration between work and heat can result in considerable energy savings or total annualized cost reductions. The problem referred to as WHENs arises when considering both temperature and pressure specifications of streams in a system. In the last few decades, the WHENs problem has received increasing attention from both industrial and academic communities. It is noticeable that this research area has grown considerably since 2014. These studies will be thoroughly analyzed in this review. A list of chronological milestones in the field of WENs and WHENs are presented in the following:

- 1967, the flow work exchanger was introduced.[10]
- 1983, the appropriate placement concept in pinch analysis was extended to heat engines and heat pumps.[11,12]
- 1987, a superstructure based optimization model for integration of heat engines and heat pumps was introduced.[13]
- 1996, the concept of WENs was first proposed.[8]
- 2007, the ExPAnD procedure combining heuristics, pinch, and exergy analyses for subambient design was developed.[14]
- 2011, a superstructure and MINLP model based on ExPAnD was developed for offshore LNG production.[15]
- 2014, a superstructure based MINLP optimization model for WHENs was suggested.[16]
- 2014, a graphical approach to WEN design was proposed.[17]
- 2015, new insight was developed for appropriate placement of compressors and expanders with a corresponding manual design procedure.[18−21]
- 2018, an extensive superstructure for WHENs was proposed.[22]
- 2019, a decomposed approach to WHENs based on first identifying optimal Thermodynamic Paths for streams with pressure change was suggested.[23]
- 2019, an extended Superstructure for WENs was proposed.[24]
- 2019, a Building Block based synthesis method for WHENs was proposed.[25]

This review presents the state-of-the-art in the literature, as well as challenges and future directions for WENs and WHENs. These research fields are still at an early stage of development and the corresponding literature is rather limited compared with HENs. This paper provides a review of the literature on WENs and WHENs aiming at (i) defining WENs and WHENs in a systematic way, (ii) providing a critical review of the current state-of-the-art in WENs and WHENs, (iii) making a comparison of studies concerning WENs and WHENs, and (iv) discussing the challenges and future research in these fields.

As illustrated in Figure 1, work and heat integration belongs to the class of process integration methodologies, an important process synthesis activity. It is a relatively new research field based firmly on thermodynamics, while the tool-box is process systems engineering. The fundamental difference between work and heat integration (WHI) on one hand and heat and power integration (HPI) on the other is related to the consideration of pressure change. In WHI, process streams are allowed to change pressure, while in HPI only the working fluids change pressure. WHI has recently been referred to as a new field in process synthesis and process systems engineering.[26]

This paper is organized as follows: In section 2, problem definitions of WENs and WHENs are presented in a systematic way to facilitate the scientific communication in the process systems engineering (PSE) field. In section 3, the applications of WENs and WHENs in industry are presented. In section 4, the equipment used in WENs and WHENs are briefly discussed. In sections 5 and 6, critical reviews on WENs and WHENs are provided, respectively. The challenges and future research trends are presented in section 7. Finally, section 8 makes some concluding remarks.

2. PROBLEM DEFINITIONS FOR WENS AND WHENS

In the literature, there is no consistent nomenclature and problem definition for WENs and WHENs. To avoid the corresponding ambiguity, consistent problem definitions and nomenclature will be presented in this review paper.

Due to the similarity of HENs, WENs, and WHENs, the HENs problem definition is briefly introduced first. The classical definition of HENs is as follows:[27]

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525

A set of hot streams to be cooled and a set of cold streams to be heated are given with fixed mass flow rates, supply, and target temperatures. Heating and cooling are available from a set of hot and cold utilities. The target is to derive a heat exchanger network that minimizes specific objectives such as utility cost, number of heat exchangers, total heat exchanger area, total annualized cost, etc.

In a similar way, the WENs and WHENs problems can be defined as follows:

WENs Problem Definition. In the general work exchange network (WEN) problem, a set of process streams with given flow rate, specified supply and target pressures should be attempted integrated (expansion and compression) in order to obtain maximum energy efficiency, minimum exergy destruction or minimum total annualized cost.

In the basic WENs problem, heat integration is not considered. This problem arises in the cases where temperature is not important, thermal energy is cheap, or the pressure change will not cause significant temperature variations. For example, in seawater reverse osmosis (SWRO) desalination systems, the pressure change of liquids causes very small temperature changes.[28] Therefore, pressure and temperature are weakly related, and work integration and heat integration can be performed separately. The recovery of pressure energy not only depends on the performance of the standalone work exchanger but is also related to the WEN configuration. Although high-efficiency work exchangers are vital to pressure energy recovery, the synthesis of WENs from a holistic view may result in significantly higher energy savings. If pressure and temperature are strongly related, such as for gaseous streams, work and heat integration should be considered simultaneously. The WHENs problem emerges on this background.

WHENs Problem Definition. HENs are designed to utilize hot streams to heat cold streams in order to save hot and cold utilities. In HENs, the only key parameter is temperature. WENs are designed to utilize high-pressure streams to pressurize low-pressure streams in order to save mechanical energy. In WENs, the only key parameter is pressure. In the WHENs problem, however, both temperature and pressure are critical parameters to be considered. Therefore, the definition of streams in WHENs should incorporate both temperature and pressure. In the literature, there is no consistent definition and nomenclature for WHENs. The pressure−temperature diagram is used to define streams in the WHENs problem, as shown in Figure 2. The yellow square in Figure 2 is the supply state. The stream target state can be located in any position. However, eight representative possible states are selected to define the streams. For target state 1, the pressure and temperature are greater than that of the supply state. This kind of stream is defined as low-pressure cold stream. For state 2, the target pressure is greater than the supply pressure, but the target temperature is equal to the supply temperature. This kind of stream is defined as a low-pressure stream. As the temperature of this kind of stream is constant, the temperature attribute is ignored in the stream definition. Similar situations apply to states 4 and 8. For these cases, the pressure is constant. Streams 0−4 and 0−8 are defined as hot and cold streams, respectively, as in the definition of streams in HENs. Streams 0−5, 0−6, and 0−7 are defined as high-pressure hot stream, high-pressure stream, and high-pressure cold stream, respectively. This systematic definition aims at establishing a consistent problem definition and nomenclature to facilitate the communication among the researchers in the field of WHENs.

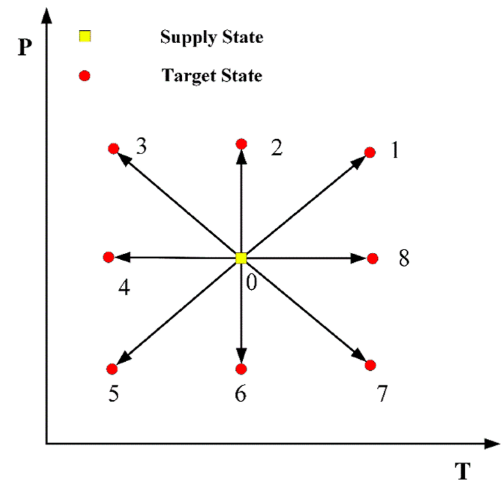


Figure 2. Stream classifications in WHENs.[23] (Reproduced with permission from ref 23. Copyright 2019 John Wiley and Sons.)

However, it should be noted that for streams with different supply and target pressures, the terms "hot" and "cold" do not consistently indicate the stream identity (hot/cold) as in the HENs problem. The first reason is that pressure change can cause temperature change, especially for gaseous streams. The second reason is that the thermodynamic path of pressure changing streams is unknown a priori. Figure 3 shows the possible thermodynamic paths of a low-pressure cold stream from supply to target state. The stream can be compressed directly at the supply state and the outlet temperature can be less than, greater than or coincidently equal to the target temperature as the three direct compression paths indicate in Figure 3. Similarly, the stream can be heated or cooled before compression. Thus, there are nine possible thermodynamic paths for this stream. As a result, the stream can act as a hot stream, a cold stream, or both a hot and cold stream or have no contribution to heat integration. The unknown thermodynamic path is the main reason why WHENs are more complex than HENs.

Another special category of streams contains those that experience phase change. Such streams add complexity and challenges to WHENs. Because phase change behavior is closely related to the equilibrium of phases, a rigorous thermodynamic model is required to guarantee reliable results. Phase changing streams complicate the WHENs problem considerably and need special attention.

A detailed problem definition for the WHENs problem is provided by Yu et al.[23] All streams are defined with given supply and target states (pressure, temperature, and phase). Stream sets are defined on the basis of pressure change (increase, decrease, or constant), temperature change (increase or decrease), and combinations of these. Further, sets are defined for streams that represent potential work sources or sinks. Finally, there is a set for streams that change phase. The objective of the WHEN synthesis problem is then to design a network of pressure changing equipment, heat transfer units, as well as splitters and mixers, in such a way that total exergy consumption or total annualized cost is minimized.

Before continuing, the contrast between HENs, WENs, and WHENs is illustrated in Figure 4. In HENs only temperature manipulating equipment such as heat exchangers, heaters, and coolers are considered. The driving force in HENs is temperature difference. Temperature is the only critical

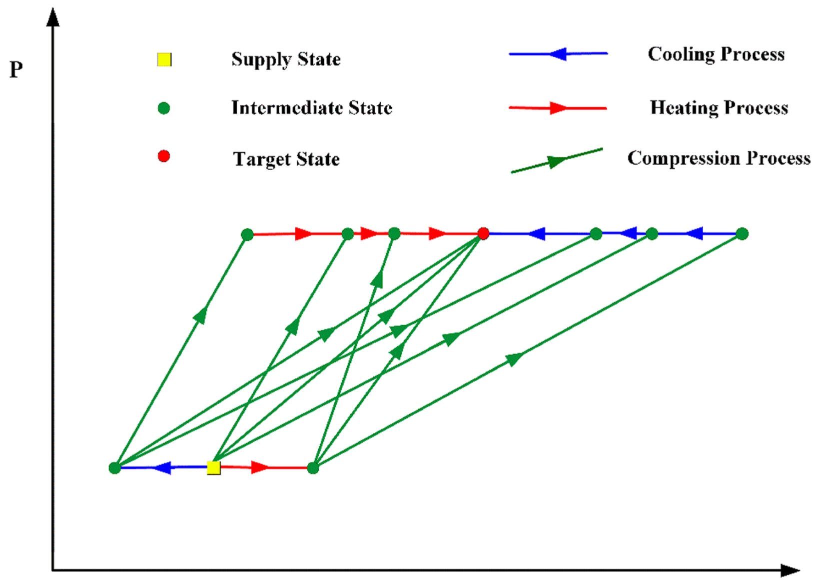


Figure 3. Possible thermodynamic paths for a stream in the WHENs problem.[23] (Reproduced with permission from ref 23. Copyright 2019 John Wiley and Sons.)

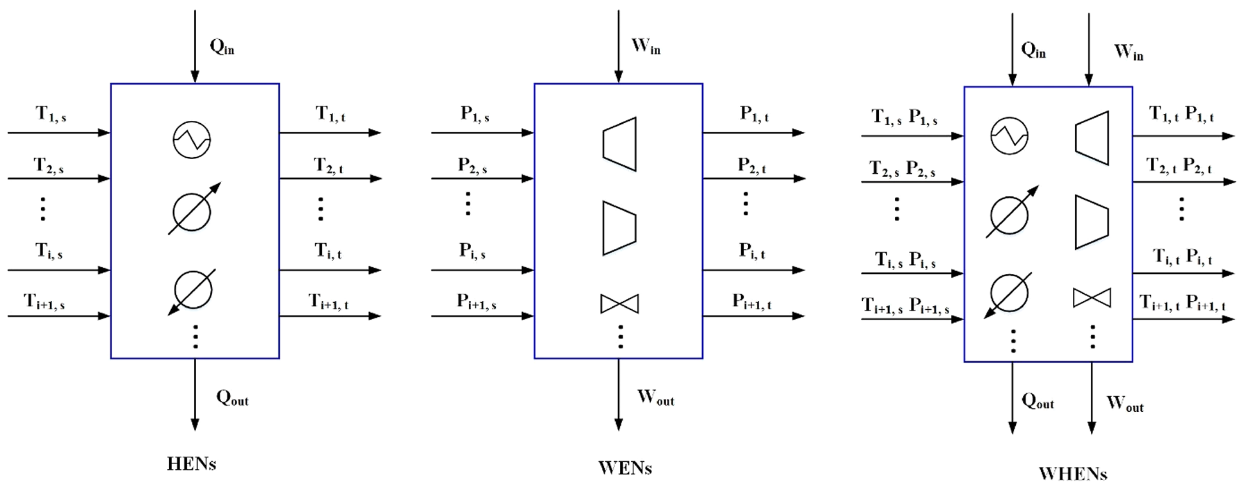


Figure 4. Comparison of HENs, WENs, and WHENs.

parameter and thermal energy savings is the focus. In WENs, only the pressure manipulating equipment are involved in synthesizing the network. Temperature manipulation is out of scope for WENs. Due to the different operating principles of work exchangers (will be discussed in section 4), a pressure-based driving force is not required in WENs consisting of indirect work exchangers. Thus, there is no work/pressure pinch. WENs aim at saving work (shaft work or electricity).

In WHENs, both temperature and pressure manipulating equipment are considered to synthesize the network, and both work and heat are considered. The trade-off between thermal energy savings and consumption of mechanical energy (or vice versa) has to be optimized. In addition, the heat duty of a stream in HENs is a piecewise linear function of temperature change with the assumption of constant heat capacity flow rate in stream segments, while work duty is a highly nonlinear function of pressure change in WENs and WHENs. Even though HENs, WENs, and WHENs share some similarities, the above differences result in significant barriers to apply HEN synthesis methods to WEN and WHEN problems.

3. APPLICATIONS OF WORK EXCHANGE NETWORKS (WENS) AND WORK AND HEAT EXCHANGE NETWORKS (WHENS)

There are extensive applications of WENs and WHENs in the process industries. For WENs, seawater reverse osmosis (SWRO) is a well-known application.[28] The power consumption to drive the high-pressure pump typically takes up the largest portion of the operating cost of the SWRO system. The pressure energy from the brine rejecting stream can be recovered by a work exchanger. The recovery of pressure energy contributes to as much as 60% energy savings in the SWRO system. Since all the streams are liquid in this system, pressure changes cause very small and negligible temperature changes. In addition, the temperature is not a critical parameter in this system. Since heat and work are weakly related, only pressure energy (work) needs to be considered. There are also other potential applications of WENs, such as manufacture of phenol by hydrolysis of chlorobenzene, hydrogenation of oil and coal, and synthetic ammonia production. In these processes, some streams need to be pressurized to very high pressure through one

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525

or more stages of compression, while some other streams need to be depressurized to low pressure. In the ammonia synthesis process, the natural gas is pressurized before it enters the primary reformer, and the air is pressurized before it enters the secondary reformer. Thus, both the natural gas and the air streams need pressurization. The ammonia product needs depressurization. The integration between these streams can save significant amounts of energy.

Since both heat and work are involved in WHENs, there are even more extensive applications in the process industries. In many industrial processes, such as LNG processes, oil refining, and air enrichment, some streams need to be compressed, while others are subject to expansion. In subambient processes, the pressure is an equally or even more important design parameter than temperature. For example, refrigeration is generated by a sequence of compression and expansion, and pressure exerts great influence on the temperature level and the capacity of the refrigeration cycle. For an offshore LNG process as shown in Figure 5, high-pressure natural gas is liquefied by liquid CO_2 and liquid N_2. In fact, the pressures of all streams involved in this process are subject to pressure change. If heat integration is also considered while performing work integration, considerable energy savings may be achieved. The WHEN synthesis problem arises from this background.

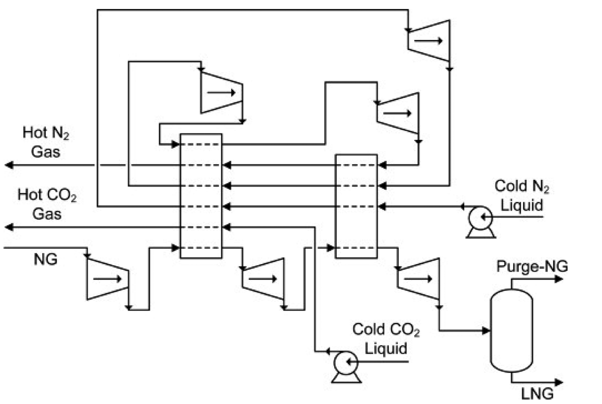


Figure 5. Flow diagram of an LNG process.[29] (Reprinted with permission from ref 29. Copyright 2012 Elsevier.)

A multistage CO_2/N_2 separation process using two membranes has been proposed[30] as a way to capture carbon in a postcombustion scheme. This process represents a potential application of the WHENs methodology. On the basis of thermodynamic insight about simultaneous work and heat integration, Fu and Gundersen[31] modified the process and saved 12.9% in specific work consumption. A key to these savings is the fact that both membranes operate at 8 bar, and the retentate streams can be preheated by the flue gas and then expanded to 1 bar to produce work.

Pump network synthesis aiming at saving pump work in a cooling water system is another application of the WENs problem.[32] Simultaneous optimization of the pump network and the cooler network in a circulating cooling water system is also similar to the WHENs problem.[33] The hydrogen distribution network[34] is also a promising field where the WHENs methodology can be applied, since there are requirements on both temperature and pressure.

As indicated above, there are many potential applications of WENs and WHENs in the process industries, both onshore and offshore as well as above and below ambient temperature. Especially low-temperature processes can be energy intensive due to the demand for mechanical power or electricity to drive the refrigeration cycles. For offshore processes, more practical aspects should be considered, such as utility availability, space, and weight. Therefore, appropriate work and heat integration is of paramount importance in these cases.

From this brief introduction, it is clear that there are many industrial applications for WENs and WHENs. WHENs is more complicated since both work and heat are considered simultaneously for the system. In addition, more equipment types are involved in WHENs. Each type of equipment has its own operating principle, which complicates the synthesis problem. This makes WENs and WHENs challenging design problems in process systems engineering.

4. EQUIPMENT IN WENS AND WHENS

Similar to heat exchangers, work exchangers are proposed for work exchange between process streams. Flow work exchangers, Single-Shaft-Turbine-Compressors (SSTCs), compressors, turbines, valves, and pumps are commonly used pressure manipulating equipment. They can be classified into direct and indirect devices based on the operating mechanism. Similar to HENs, heat exchange equipment such as heaters, coolers, two-stream and multistream heat exchangers are also used in WHENs. In what follows, all these devices are analyzed with special focus on pressure manipulating equipment.

Flow Work Exchanger. The flow work exchanger was introduced by Cheng et al.[10] as a unit to pressurize one process stream by depressurizing another stream. Together with compressors, turbines, pumps, valves and so-called single-shaft-turbine-compressor (SSTC) units, the flow work exchanger belongs to the category of pressure changing equipment that potentially can be used in WHENs. While the SSTC indirectly transfers shaft work, the flow work exchanger directly transfers flow work. The flow work exchanger operates essentially in a batch mode incorporating four consecutive steps. A sketch of a flow work exchanger in provided in Figure 6.[17] The detailed working principle can be found in the following papers.[8,10,17] The flow work exchanger has been applied successfully in seawater desalination.[35] However, the flow work exchanger is originally limited to condensed state fluids.

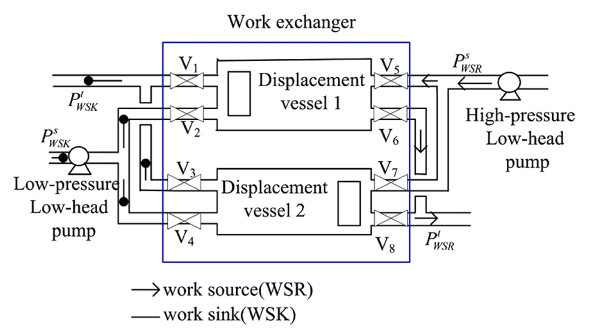


Figure 6. Sketch of flow work exchanger.[17] (Reprinted with permissino from ref 17. Copyright 2014 Elsevier.)

A situation with multiple gas streams at different pressure levels is quite common in the process industries. For the potential application field of hydrogen management in the oil refining industry, Deng et al.[36] proposed a gas−gas work exchanger based on the flow work exchanger. They analyzed a gas−gas work exchanger from a thermodynamic perspective.

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525

Due to the higher compressibility of gases compared to liquids, mechanical and thermal energies are transferred simultaneously, and this unit has more work losses compared to the liquid−liquid flow work exchanger. The work recovery efficiency of gas−gas work exchangers depends on the compression ratio, relative clearance volume, and the gas category, e.g., monatomic, diatomic, and polyatomic gases. A simplified equation for a quick estimate of work recovery efficiency of gas−gas work exchangers was derived. This kind of work exchanger is a reciprocating machine. Later, Deng et al.[37] analyzed the efficiency of the reciprocating machine and a centrifugal machine as work exchangers. They found that under specific pressure ratios, the liquid−liquid reciprocating work exchanger has the highest efficiency (nearly 100%), a liquid−gas reciprocating work exchanger has the second highest, and the gas−gas reciprocating work exchanger has the lowest efficiency. The work recovery efficiency of centrifugal work exchangers was also more influenced by the initial volume flow rate than the reciprocating work exchangers.

In order to maintain continuous operation of the reciprocating flow work exchanger, the target pressure of the high-pressure stream must be lower than the supply pressure of the low-pressure stream. The relationship between stream pressure and work is complex. For incompressible liquids, the relationship between pressure and work is linear. Figure 7 shows the $P-W$ diagram of a direct reciprocating work exchanger for an incompressible fluid.[17] For an ideal gas, the relationship between logarithmic pressure and work is linear. In general, any stream can be represented by a curve between incompressible liquid and ideal gas.[38] In contrast, a heat exchanger or mass exchanger is operated in a continuous mode, where the source stream temperature or concentration is always greater than that of the sink stream. This is totally different from the flow work exchanger. Due to this fundamental difference, WENs and WHENs cannot be integrated through directly constructing and shifting the sink and source composite curves; i.e., the widely used pinch analysis methods for HENs cannot be directly applied to WENs and WHENs. This results in a considerable challenge for the synthesis of WENs and WHENs considering direct work exchangers. The efficiency of the direct work exchanger can theoretically reach 100%. However, the stream matching for direct work exchange networks is difficult. Not only the pressure constraints but also the volume flow rate and phase change should be considered while matching two streams in a flow work exchanger. For the WENs problem, most of the studies focus on synthesizing a network consisting of flow work exchangers.

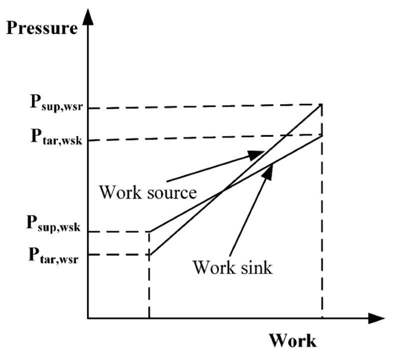


Figure 7. $P-W$ diagram of a direct work exchanger[17] (Reprinted with permission from ref 17. Copyright 2014 Elsevier.)

Single-Shaft-Turbine-Compressor (SSTC). Work can also be exchanged through indirect work exchangers, which include separate turbines (expanders), compressors (pumps) and single-shaft-turbine-compressor (SSTC) units. Pressure energy is traditionally exchanged in three steps: pressure energy of the high-pressure stream is converted to mechanical energy through a turbine, then mechanical energy is converted to power by using a generator, and finally electricity is converted to pressure energy for the low-pressure stream through a compressor (or pump). This technology is mature and easier to implement in practice, but the disadvantage is the relatively lower energy recovery efficiency and high capital cost compared with direct work exchangers. To improve the recovery efficiency, the turbine and compressor can be connected via a common shaft running at a constant speed. This device is called a single-shaft-turbine-compressor (SSTC). The SSTC can be generalized to include multiple turbines and compressors with several high- and low-pressure streams using a single shaft. It may use one helper motor to compensate for any power shortage or one generator to produce electricity from excess pressure energy. Of course, the generator and helper motor cannot exist simultaneously in an SSTC. The sketch of an SSTC unit is shown in Figure 8. It is notable that a minimum pressure driving force is not required for an SSTC unit. The shaft can transfer the work from depressurized streams to pressurized streams without any pressure limitations. To distinguish the turbine on an SSTC from a conventional turbine, the latter is referred to as a utility turbine. SSTC compressors and utility compressors are defined in the same way. If the SSTC unit operates on a single process stream, it is often referred to as a compander.

The outlet pressure of compressors and turbines is a function of the flow rate of the stream with a constant shaft speed of the SSTC unit. For stable operation, the flow rate through the SSTC turbine and compressor must stay within a certain range to avoid choking and surging. Therefore, coupled SSTC units need to consider more practical issues in reality. However, in most studies, the operability and shaft speed are not considered while synthesizing WENs and WHENs.

Compressors, Turbines, and Valves. Since the SSTC unit has limitations regarding the operability, the coupled system is more difficult to control. On the contrary, the stand-alone (utility) turbines and compressors are more flexible in operation. Separate turbines and compressors have no constraints on the rotation speed of the shaft as the case is for the SSTC unit. If the flow rate of one stream is very low, it is not economic to place a turbine on that stream. In this case, a valve could be a better alternative, even though valves result in large

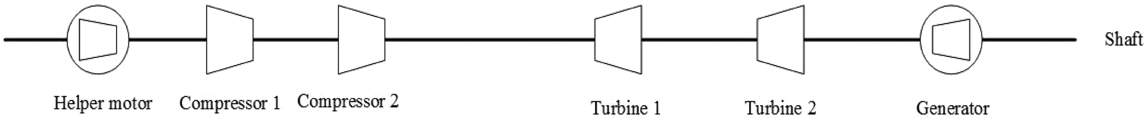


Figure 8. Sketch of an SSTC unit.

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525

exergy destructions. The valve is not an efficient device from the perspective of energy utilization. However, the capital cost of the valve is negligible compared to a turbine. Therefore, there is a trade-off between valves and turbines for a process stream that needs to be depressurized. If the objective function is total annualized cost (TAC), valves could be adopted in WENs and WHENs. If the objective function is energy-related, valves will be excluded. It can be shown that standalone compressors and turbines as well as valves are necessary components to synthesize WENs and WHENs. Each pressure manipulating equipment has its own advantages and disadvantages. A comparison of different pressure manipulating equipment is provided in Table 1.

Table 1. Comparison of Different Pressure Manipulating Equipment

items	efficiency	flexibility	equipment cost
flow work exchanger	high	low	low
SSTC unit	medium	medium	high
utility turbines and compressors	low	high	high
valves	very low	very high	negligible

It should be noted that there are many other types of direct work exchangers, such as Pelton wheels, turbochargers, and PX pressure exchangers. However, these devices are specially designed for the seawater desalination process and seldom used in the process industries. Thus, these devices are not analyzed in detail in this study. For more information, please refer to refs 9 and 39.

Other Components in WENs and WHENs. In addition to the pressure manipulating equipment discussed above, heaters, coolers, and heat exchangers are also used in WENs and WHENs. Multistream heat exchangers are widely used in LNG liquefaction processes and air separation units. Other equipment types such as splitters and mixers are necessary components as well. These components are simple and well-known; thus, no detailed analysis is presented in this review paper. As heat integration is not considered in WENs, only heaters and coolers are included in such systems. An analogy can be made between pressure manipulating equipment and heat exchange equipment. Flow work exchangers and SSTCs are similar to two-stream and multistream heat exchangers, respectively. Compressors, turbines, and valves are similar to heaters, coolers, and furnaces in HENs.

5. CRITICAL REVIEW OF PAPERS ON WORK EXCHANGE NETWORKS (WENS)

Since the operating principles of different pressure manipulating equipment are quite different, the synthesis methods for WENs are closely related to the type of pressure manipulating equipment that is used. Most of the studies concerning WENs are based on flow work exchangers. For SSTC units as well as separate compressors and turbines, temperature also changes with the manipulation of pressure; thus, these devices are more often considered in WHENs. A critical review of studies on WENs will be presented and grouped according to the actual pressure manipulating equipment used.

Review of Studies on WENs based on Flow Work Exchangers. In 1996, Huang and Fan[8] introduced WENs as a new design task based on an analogy to HENs and MENs. Necessary and sufficient conditions for matching process streams in flow work exchangers were proposed. In contrast to HENs, the target pressure of a stream that represents a work source must be lower than the supply pressure of a stream that represents a work sink. The focus of this work was, however, on analysis rather than synthesis.

Zhou et al.[40] extended Pinch Analysis to WENs based on flow work exchangers. The problem table algorithm is applied to WENs to determine the minimum work utility. This method is applied to isothermal and adiabatic processes, respectively. To simplify the problem, they assumed that the work source pressure is always higher than the pressure of the work sink. This assumption violates the operating principle of flow work exchangers. As a result, this method only calculates an approximation to the energy target, while network configuration and the match between streams are beyond the scope of their study.

Liu et al.[17] developed a graphical integration method for WENs based on flow work exchangers. They proposed work source and sink composite curves in an ln P−W diagram. On the basis of the assumption of an isothermal process in the flow work exchanger, ln P and W are in a linear relationship. Five matching rules are proposed for optimally matching the work source sink streams. This method is simple and easily understood, but difficult to apply in practice due to the assumptions made. The reason is that the final work exchanger network requires a large number of work exchangers, turbines, and compressors to achieve the energy target. This graphical integration method relies on the ln P−W diagram, which assumes isothermal compression and expansion. Pressure changing processes are, however, far from isothermal for gas systems. This assumption may therefore result in large errors, and the method cannot reliably handle adiabatic pressurization and depressurization processes.

Zhuang et al.[41] proposed to use the transshipment model to obtain minimum utility consumption, which makes it easier to identify the optimal WENs configuration. The proposed approach for WEN synthesis is a linear programming model assuming isothermal compression and expansion. In addition, adjacent pressure intervals are merged according to proposed rules aiming at decreasing utility consumption and optimizing network structure. The work utility is reduced by 57.1%, and the work recovery is increased by 22.8% compared with the results by Liu et al.[17] However, the shaft work is evaluated as linear equations based on the isothermal process assumption, which is not able to realistically reflect the relationship between pressure and temperature. In addition, this method could result in a complex WEN configuration, where the operability and capital cost become new challenges. Further, Zhuang et al.[42] proposed two heuristic strategies and six matching rules to assist in identifying a feasible match between high- and low-pressure streams. To consider operating cost and capital cost simultaneously, Zhuang et al.[43] proposed a mathematical model to synthesize direct work exchange networks minimizing total annualized cost. Two upgraded stagewise superstructures with and without stream splits are proposed to determine the optimal network configuration. The isothermal process assumption is still adopted in these studies, which limits the application of the method for real cases. To overcome this limitation, Zhuang et al.[44] extended the linear programming model to a nonlinear programming model for the synthesis of direct work exchange networks including adiabatic processes. This model is also based on the transshipment model with minimum utility consumption as the objective function and the WEN configuration is optimized using matching rules. To

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525

Table 2. Comparison of Studies on WENs[a]

references	method	equipment	OBJ	network
Huang and Fan[8]	PA/GM	FWE		no
Zhou et al.[40]	PA/GM	FWE	EC	no
Liu et al.[17]	PA/GM	FWE	EC	yes
Zhuang et al.[41]	MP	FWE	EC	yes
Zhuang et al.[42]	MP	FWE	EC	yes
Zhuang et al.[43]	MP	FWE	TAC	yes
Zhuang et al.[44]	MP	FWE	TAC	yes
Amini-Rankouhi and Huang[46]	MP	FWE	EC	no
Chen and Feng[38]	PA/GM	UC/UT	EC	no
Razib et al.[29]	MP	SSTC/UC/UT/VAL	TAC	yes
Razib et al.[47]	MP	UC/UT	TAC	yes
Du et al.[48]	MP	SSTC/UC/UT/VAL	EC/MNU	yes

[a]PA: pinch analysis. GM: graphical method. MP: mathematical programming. FWE: flow work exchanger. UC: utility compressor. UT: utility turbine. VAL: valve. OBJ: objective function. TAC: total annualized cost. EC: energy consumption. MNU: minimum number of units.

consider the heat integration, heat exchange equipment is introduced after the work exchange network has been synthesized. Thus, this study extended the WEN problem to a WHEN problem and will be analyzed in detail in the WHENs review section.

Zhuang et al.[45] proposed an upgraded graphical method for the synthesis of direct work exchange networks under isothermal, isentropic, and polytropic conditions. In this method, the improved composite curves of work sources and work sinks are plotted in a pressure index versus work diagram. The pressure index, which is a function of pressure and heat capacity ratios, has different formulations under isothermal and isentropic/polytropic conditions. The improved composite curves result in wider applicability of the method compared with the method proposed by Liu et al.[17] However, the methodology cannot deal with the trade-off between operating cost and capital expenditure. To overcome this limitation, Zhuang et al.[24] proposed an extended superstructure-based model for WEN synthesis with direct work exchangers. Amini-Rankouhi and Huang[46] proposed a thermodynamic modeling and analysis method to identify the maximum amount of recoverable work of a system for direct work exchange network synthesis. A matrix of pressure intervals is constructed to target the maximum recoverable mechanical energy. However, this method did not consider network synthesis. There may be many network configurations with the same energy target, however with different total annualized cost.

Review of Studies on WENs Based on Indirect Work Exchange Devices. For indirect work exchange devices (SSTCs, utility compressors, and turbines), it is important to notice that there are no driving force requirements ($\Delta p \geq \Delta p_{\min}$) as for flow work exchangers and thus there is no work recovery pinch. Chen and Feng[38] proposed a novel graphical approach for targeting work exchange networks. This graphical method constructs composite work curves in a pressure−work diagram to determine the theoretical work target. Since this method is proposed for indirect WENs, the composite curves of low- and high-pressure streams can be crossed. The composite curves are shifted until the left end points or right end points have the same abscissa value to get the maximum energy recovery target. However, this study only focuses on the work target and not the network synthesis. Razib et al.[47] proposed a multistage superstructure to integrate high- and low-pressure streams optimally in an SSTC unit. They referred to this problem as a turbo-compressor network instead of a WEN. Only pressure changing streams are considered in this study. Since heat integration is not considered in WENs, coolers are implemented after each compression. The objective is minimizing the total annualized cost. However, all the equipment cost correlations are assumed to be linear functions, which may not be able to realistically represent the investment. This study did not consider operational constraints such as surging, choking and shaft speed. In addition, valves are not considered because of the inefficiency from an energy perspective. However, for techno-economic optimization, valves should be considered. On the basis of this work, Razib et al.[29] proposed a superstructure for WENs and developed a mixed-integer nonlinear programming (MINLP) model to minimize total annualized cost. This model can synthesize optimal WENs for multiple streams. In this study, the highlight is that operational concerns (surging, choking, shaft speed) are considered, which is not the case in other studies. However, heat integration is not part of their study, and heaters and coolers are located at the end of the WEN stage in order to reach target temperatures for the streams.

Du et al.[48] studied the synthesis of indirect WENs based on a transshipment model. The compression and expansion ratios are regarded as variables as well. Compared with the superstructure-based method, this approach can more easily find the optimal WEN configuration since the model is linear. However, the assumptions of ideal gas and isothermal reversible compression/expansion may result in large errors. Feng and Chen[49] proposed matching rules between pressurization and depressurization streams based on both energy and economic considerations. These matching rules consider practical issues and economic factors while designing a WEN based on SSTC units. However, this method cannot deal with large-scale problems since it in essence is a heuristic method.

All studies mentioned above have made great contributions to the WENs field. A comparison of these studies is shown in Table 2, where equipment and objective functions in the WENs are indicated.

6. CRITICAL REVIEW OF PAPERS ON WORK AND HEAT EXCHANGE NETWORKS (WHENS)

Process synthesis can be defined as the task of selecting process equipment and their interconnection in order to convert raw materials into desired products. In order to increase process efficiency with respect to raw material utilization, energy consumption, and equipment utilization (e.g., process intensi-

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525

fication), process integration has emerged as a discipline with powerful tools that can be used to design HENs, MENs, WENs, and WHENs. Two schools of methods, both with a systems approach, are available. Pinch analysis is based on the first and second law of thermodynamics, while mathematical programming formulates the design task as a mathematical model with equality and inequality constraints, and an objective function that is based on economy or energy. These schools have their advantages and disadvantages that have inspired researchers to develop hybrid approaches. Pinch analysis offers fundamental insight that is intuitive for the designer, with graphical diagrams that provide an overview of the design problem and step-by-step procedures for the design process; however, this manual methodology cannot properly handle the multiple trade-offs involved. Optimization in the form of mathematical programming or stochastic search can handle the complicated trade-offs in design and represents a possible framework for automatic design. The main disadvantage is that the designer is removed from the decision making, since these tools act like black boxes.

Two research methods have been developed for WHENs; graphical methods (GM) based on pinch analysis (PA) and optimization approaches based on mathematical programming (MP) as discussed in the Introduction. In what follows, the studies on WHENs will be analyzed and classified according to the approach used.

Review of Studies on WHENs based on Pinch Analysis. The first relevant study concerning work and heat integration dates back to 1983. Townsend and Linnhoff[11,12] presented a two-part study on the appropriate placement of heat engines and heat pumps in a heat exchanger network during the early stages of pinch analysis. Criteria for heat engine and heat pump placement in heat exchanger networks were derived to improve the efficiency of processes. They concluded in part I that appropriate placement of heat engines in a heat exchanger network can produce work from heat at 100% efficiency.[11] Following these criteria, the design procedure for equipment selection and process matching were proposed in part II.[12] These studies represent pioneering work related to heat and power integration in process synthesis. In 1987, Colmenares and Seider[13] proposed a nonlinear programming strategy for the integration of heat engines and heat pumps in chemical processes. This study will be mentioned later in the mathematical programming section; however, to make a comparison with the studies of Townsend and Linnhoff,[11,12] the work of Colmenares and Seider[13] is analyzed in this part. They concluded that optimal integration of heat engines above pinch involves extracting heat from temperature intervals with a heat surplus, while the optimal integration of heat pumps involves releasing the condensation heat to temperature intervals with heat deficit. These conclusions violate the initial guidelines of Townsend and Linnhoff.[11] The heat and power integration problem is in essence a special case of the work and heat exchange network synthesis problem. Regular process streams can be regarded as candidate working fluids for heat engines and heat pumps by allowing for pressure changes.

In 1990, Yoon proposed a new strategy for simultaneous synthesizing utility plants and heat recovery networks.[50] Heat engines, heat pumps, and refrigeration cycles were considered in the utility plant. This method combines heuristic rules and mathematical programming. Linnhoff and Dhole[51] extended pinch analysis for the design of low-temperature processes to establish shaft work targets from basic process data. Their method treats the HEN and the refrigeration system as one coherent design task. Anantharaman et al.[52] modified and extended the concept of energy level proposed by Feng and Zhu,[53] and thus proposed a new graphical methodology for energy integration taking into account composition and pressure effects. Energy level is defined as the ratio between exergy and enthalpy. This graphical diagram attempts to represent thermal, mechanical and chemical energies in a way that is similar to the composite curves. The method provides insight and understanding of energy levels in various processes, but it cannot give any explicit recommendation for the integration of the process units.

In 2007, Aspelund et al.[14] presented the extended pinch analysis and design (ExPAnD) procedure, where traditional pinch analysis is extended with pressure considerations and exergy analysis. They proposed 10 heuristic rules for manipulating pressure in order to utilize pressure-based exergy in the process streams. It was suggested that even the pressure of a stream with the same supply and target pressure could be subject to compression and expansion in order to reduce total irreversibilities. ExPAnD considers pressure, temperature, phase change, two-stream and multistream heat exchangers, compressors, and expanders simultaneously, and the methodology was illustrated by developing a novel process for offshore liquefaction of natural gas. Rigorous thermodynamic properties of the streams are retrieved from Aspen HYSYS.[54] The main disadvantage of ExPAnD is that it relies heavily on heuristic rules, and the sequence of applying these rules can result in different designs. In addition, compressors and expanders are configured separately, and SSTCs are not considered.

An important spin-off from the research behind ExPAnD is new insight about the appropriate placement of compressors and expanders. Compressors provide heating and should operate above pinch, while expanders provide cooling and should operate below pinch. These guidelines are in conflict with current industrial practice. Homsak and Glavic[55] had earlier noticed, while discussing appropriate placement of chemical reactors, that compressors are donors of energy and should be placed above pinch. The new insight was further developed by Gundersen et al.[56] who found that compression and expansion should start at the Pinch temperature. They also observed, however, that the pinch point may change as a result of pressure manipulations. Based on the findings in refs 14 and 56, ExPAnD was applied to design an efficient energy chain for liquefaction, transportation, and utilization of natural gas for power production with CO_2 capture and storage.[57−60]

Marmolejo-Correa and Gundersen[61] proposed a methodology combining exergy and pinch analyses to design a reverse Brayton cycle for the liquefaction of natural gas. On the basis of this study, Marmolejo-Correa and Gundersen[62] developed a novel diagram for exergy and energy targeting for a heat recovery system subject to changes in both temperature and pressure. This diagram is based on a new energy quality parameter called exergetic temperature. The method is particularly suitable for low-temperature systems such as LNG processes.

Fu and Gundersen[18] presented a systematic graphical design procedure for the integration of compressors in HENs above ambient temperature based on new thermodynamic insight related to the appropriate placement concept. They concluded that compression should be performed at pinch or ambient temperature in order to achieve minimum exergy consumption. No other inlet temperature will result in lower exergy consumption. Similarly, Fu and Gundersen[19] studied the integration of compressors with heat exchanger networks

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525

below ambient temperature. Four theorems were proposed and used as the basis for the design methodology. For subambient processes, it is concluded that compression should start at pinch temperatures, ambient temperature or cold utility temperature in order to minimize exergy consumption. Fu and Gundersen also studied the integration of expanders into heat exchanger networks above[20] and below[21] ambient temperature. All possible compression and expansion schemes proposed in these studies are illustrated in Figure 9. Similar conclusions can be drawn for these cases, and the methodology was illustrated with the integration of one pressure changing unit into a heat recovery system.

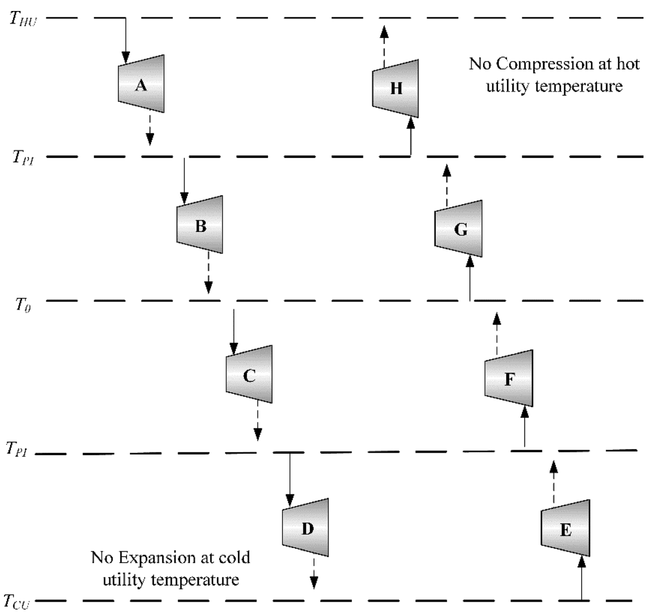


Figure 9. All possible pressure manipulations proposed by Fu and Gundersen.

The thermodynamic insight as well as a manual and iterative design procedure based on extensive use of the grand composite curve (GCC) can be summarized as follows: There are 4 design situations (compressor or expander to be integrated above or below ambient temperature) and 4 theorems for each of these design situations; a total of 16 cases. Candidates for optimal inlet temperature to compressors and expanders are limited to pinch temperatures, hot and cold utility temperatures and ambient temperature. No other inlet temperature will result in lower exergy consumption (or higher exergy production). It should be mentioned that as a result of compression or expansion from pinch temperature, new pinch points may arise; however, the design procedure accounts for this by splitting streams and compressing or expanding also from these new pinch points. Two fundamental properties define which of the 4 theorems that are applicable for the various design cases: (1) the cooling (heating) effect of expansion (compression) at the pinch and (2) the outlet temperature from expanding (compressing) at hot (cold) utility temperature. The first of these properties is measured against the minimum external cooling (heating) requirement of the process, while the second is measured against ambient temperature.

However, the studies by Fu and Gundersen summarized above only deal with one stream being subject to pressure change, and only one hot and cold utility with constant temperature were assumed. These rather limiting assumptions were only made to develop new fundamental insight under simple conditions. When having multiple process streams with pressure change, the manual design procedure will be extremely time-consuming. Multiple hot/cold utilities and multistage compression/expansion represent additional challenges.

Fu and Gundersen[63] further investigated work and heat integration when both compression and expansion are needed in the system. In such cases, the sequence of integrating compressor(s) and expander(s) becomes an important issue. Compression heat can be used to preheat a stream to be expanded, which results in more work being produced. Opposite, the cooling effect of expansion can be used to precool a stream to be compressed, which results in less work being required. Obviously, the sequence of integrating compressors and expanders can have a significant effect on the exergy efficiency of the process. Unfortunately, the relative prices of work and heat do not always follow the second law of thermodynamics, which means that exergy may not be an appropriate parameter to balance the trade-off between work and heat in real processes.

On the basis of an additional theorem, Fu and Gundersen were able to develop a design procedure for integrating both compressors and expanders above[64] and below[65] ambient temperature. Another minor adjustment was made to the insight related to appropriate placement of compressors and expanders. Since process streams to be compressed or expanded temporarily may change identity (hot/cold) and there are two Pinch temperatures (one for hot streams and one for cold streams), Fu et al.[66] concluded that the actual pinch temperature to be used as inlet temperature to compression/expansion should reflect the identity (hot/cold) of the stream segment to be compressed/expanded and not the identity of the parent (original) stream. Fu and Gundersen[31] summarized the fundamental insight about work and heat integration and applied the new design methodology to three carbon capture processes.

Significant energy savings can be achieved by proper work and heat integration. The applicability of the ExPAnD method has been successfully demonstrated for LNG and carbon capture processes. More recently, a new method combining heuristic rules from the ExPAnD methodology and insight about appropriate placement of compressors and expanders is proposed.[67] This process design methodology is particularly useful for processes below and across ambient temperature. The main novelty of this methodology is that exergy analysis is performed at the conceptual stage of design, which is in contrast to established practice where exergy analysis is used as a postdesign tool. An exergy cascade and a new exergy diagram are proposed to target the requirement, rejection, destruction, and recovery of exergy. However, this method just considered one stage compression and expansion. It is difficult to apply this method to multistage pressure manipulations. The method also relies on heuristic rules, which makes it difficult to apply to large-scale problems and still guarantee an optimal solution.

Deng et al.[68] proposed a systematic method for synthesizing work and heat exchange networks based on pinch analysis. A pressure pinch is proposed in a similar way as the temperature pinch. For indirect work recovery, however, there are no driving force constraints related to pressure. Thus, there is no pressure (or work) pinch for such systems. A systematic procedure for designing WHENs is presented in their study. The method is applied to a rectisol process in the coal−water slurry gasification

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525

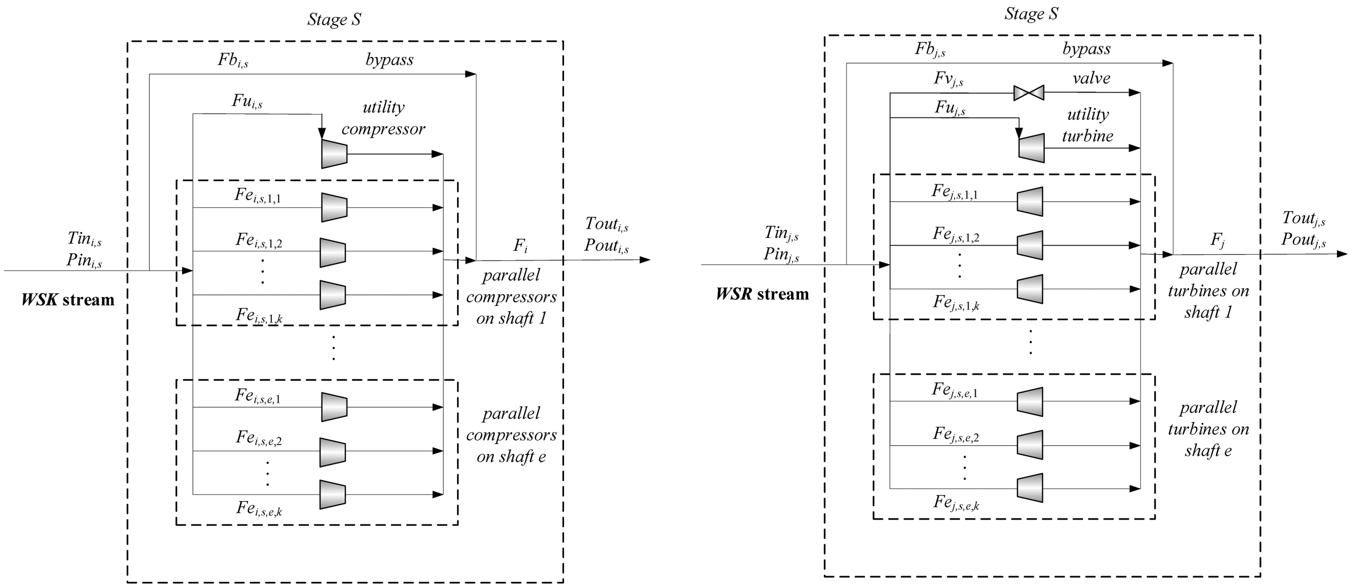


Figure 10. Multistage superstructure for WSK and WSR streams (modified from ref 16). (From ref 16 with permission. Copyright 2014 Elsevier.)

section of an ammonia plant. However, this method can only deal with liquid streams. Since the temperature is approximately the same after pressure change, the WEN has little effect on the HEN synthesis. Thus, the WEN and HEN can be designed separately, and this problem is much easier than general WHENs.

Pinch analysis has been successfully applied in the process industries to address heat recovery problems. As indicated by the studies mentioned in this section, the methodology also has a lot to offer for simultaneous work and heat integration. The downside is the inability to properly handle energy-capital tradeoffs. In the studies using energy (or exergy) as the key performance indicator, highly efficient designs can be developed; however, they may be far from an economically attractive solution. One important issue here is that compressors and expanders are much more expensive than heat exchangers. As mentioned in the beginning of section 6, mathematical programming has advantages related to handling the economic trade-offs in design as well as being a tool for automatic design. The main disadvantage is numerical complexity related to handling discrete variables (combinatorial explosion) and nonconvex nonlinear relations (local optima). In a combined or hybrid system, Pinch analysis can be used to reduce the size of the optimization problem by screening alternatives and reducing the feasible search space for the optimizer. In what follows, studies of WHENs using mathematical programming will be presented.

Review of Studies on WHENs based on Mathematical Programming. In 1987, Colmenares and Seider[13] proposed a nonlinear programming strategy for heat and power integration in chemical processes as discussed in the previous section. In 2002, Holiastos and Manousiouthakis[69] proposed a mathematical model for the minimum hot/cold/work utility cost for heat exchange networks. They first proposed the term “work utility”, which refers to the generation or consumption of work (electricity and shaft work). In their study, the pressures of all process streams are constant. Heat pumps and heat engines are introduced into the system to reduce total utility cost of the system. Streams related to heat pumps and heat engines can be regarded as pressure changing streams, which makes this problem a particular case of WHENs. They suggested that heat pumps should be placed entirely above the pinch to obtain cost optimal network configurations. This is an indication that the appropriate placement principle not always holds when focus is shifted from energy to economy. Their primary objective is to change the temperature level of process streams using heat pumps and heat engines to achieve a better match between the composite curves and to reduce the overall irreversibility and total utility cost. Their model aims at solving heat integration problems with very poor match between hot and cold composite curves. However, the pressure change of process streams is not considered. This fact limits the methodology when applied to the general WHENs problem. Later, Posada and Manousiouthakis[70] applied the above methodology to a methane reforming based hydrogen production process. The optimal integration of heat exchange equipment, heat engines, and heat pumps can lead to electricity generation in excess of process demand. Utility cost and carbon dioxide emissions are reduced by 36% and 6.5%, respectively. However, the limitations that apply to their previous work[69] still apply here.

Fu and Gundersen[71] also investigated the optimal integration of a heat pump into a background process. They found that a sensible heat pump appropriately integrated with the background process can save significant amounts of energy. The optimal inlet temperatures of the compressor and the expander of the heat pump are determined to be at the pinch according to established thermodynamic insights for WHENs. The optimal compression ratio is determined by mathematical analysis with respect to minimizing exergy consumption. Wechsung et al.[15] combined pinch analysis, exergy analysis, and mathematical programming to synthesize HENs below ambient temperature with compression and expansion of process streams. A state space model incorporating a pinch operator (heat integration) and a pressure operator (work integration) was proposed. The pinch operator is based on the simultaneous heat integration and process optimization model proposed by Duran and Grossmann.[72] The objective is to minimize total irreversibility. An industrial application related to LNG with streams undergoing pressure change, temperature change, and phase change demonstrated that the optimization formulation was capable

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525

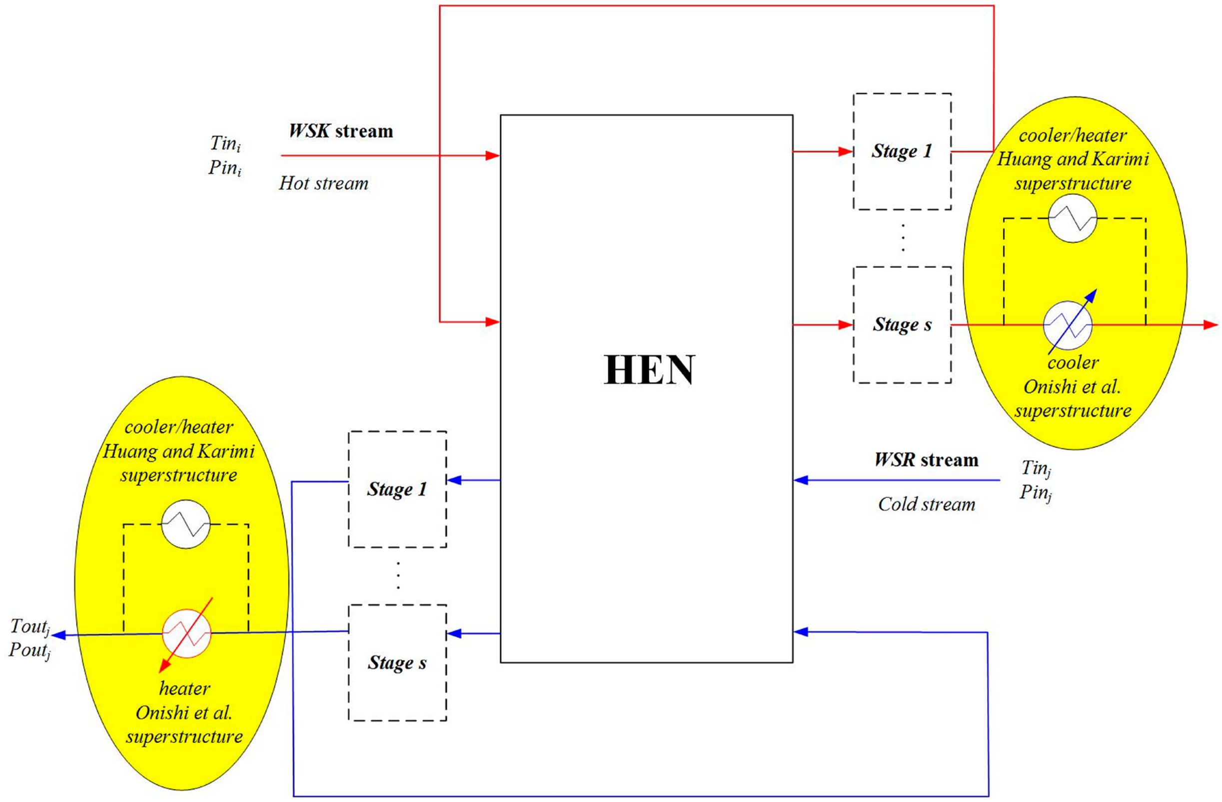


Figure 11. Multistage superstructure comparison (modified from refs 16 and 77). (From refs 16 and 77 with permission. Copyright 2014 and 2016 Elsevier.)

of generating reasonable designs. A particular thermodynamic route of compression and expansion of streams can significantly reduce the exergy destruction in the system. However, ideal gas is assumed for the thermodynamic behavior of the fluids, which may lead to unreliable results. Rigorous thermodynamic models should be implemented, especially for subambient processes. In addition, they assumed a fixed thermodynamic path based on pinch analysis, and indirect work integration using SSTCs was not considered.

Process synthesis approaches in process systems engineering using mathematical programming are often based on the superstructure concept. Onishi et al.[73] proposed a new HEN synthesis model, which considers pressure handling of process streams to enhance heat integration. Later, Onishi et al.[74] proposed a mathematical model for the simultaneous synthesis of work and heat exchange networks as an extension of their previous work. A superstructure based on Yee and Grossmann[75] was adapted to synthesize heat exchanger networks considering work recovery. This model is formulated by using generalized disjunctive programming (GDP) and reformulated as a mixed integer nonlinear programming (MINLP) problem. The superstructure is also based on a fixed specific pressure manipulation route of expansion and compression similar to Wechsung et al.[15] However, compressors and turbines were either operated on a single common shaft or separately. To overcome this shortcoming, a new model considering the use of several SSTC units, as well as helper motors and generators, was proposed to avoid a large number of devices running on the same SSTC unit.[76] Of course, the space requirements in the plant should be considered when introducing several SSTC units, especially for off-shore processes.

Similarly, Onishi et al.[16] proposed another superstructure for work exchange networks (WENs) considering heat integration. The proposed WEN superstructure is composed of several stages of compression or expansion for each pressure changing stream. Figure 10 illustrates the WEN superstructure for low-pressure (WSK) and high-pressure (WSR) streams. It is evident that a high-pressure stream only passes through pressure reduction equipment, while a low-pressure stream only passes through pressure increasing equipment. However, the manipulation of stream pressure involving both compression and expansion may lead to a significant reduction of irreversibilities in the system. Thus, the monotonic behavior of the superstructure with respect to pressure is a limitation. Heat integration is performed between the compression and expansion stages of the work exchange network. Figure 11 shows the overall superstructure involving both WENs and HENs. Onishi et al.[16] assumed that heaters and coolers are used to reach the target temperatures for high-pressure and low-pressure streams, respectively. Furthermore, they assumed that all streams are gaseous without phase change. The high-pressure streams are considered to be cold streams, while the low-pressure streams are considered to be hot streams. The monotonic WEN superstructure may miss the optimal configuration of the system.

Later, Onishi et al.[78] proposed a mathematical model for the retrofit of heat exchanger networks considering pressure recovery for process streams. The proposed multistage superstructure allows increments of the existing heat transfer area, as well as the use of new heat exchangers and pressure manipulators. A new multiobjective mathematical model for optimal WHEN synthesis considering both environmental impacts and economic performance[79] was also proposed based

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525

Table 3. Comparison of Different Superstructure-Based Methodologies

superstructure	objective	variable stream identity (heat integration)	variable stream identity (work integration)	stream split (work integration)	isothermal mixing assumption	manipulation of constant pressure streams	heat integration model
Onishi et al.[16]	TAC	no	no	yes	yes	no	Yee−Grossmann
Huang and Karimi[77]	TAC	no	no	yes	yes	no	Yee−Grossmann
Onishi et al.[80]	TAC	yes	yes	no		no	Duran−Grossmann
Pavão et al.[81]	TAC	yes	yes	no	no	no	Yee−Grossmann
Nair et al.[22]	TAC	yes	yes	no	yes	yes	Yee−Grossmann
Yu et al.[23]	Exergy	yes	no	yes	no	no	Duran−Grossmann

on the superstructure by Onishi et al.[16] The LCA-based Eco-indicator 99 methodology is chosen to evaluate the environmental effects. This mathematical model can determine a set of alternative Pareto-optimal solutions to support decision-makers towards more environment-friendly and cost-effective WHENs. Their paper is the first study considering the conflicting environmental and economic objective functions in WHENs.

Huang and Karimi[77] proposed a superstructure for WHENs based on the study by Onishi et al.[16] Two distinct networks were part of the model: one for heat integration and one for work integration. These networks are interconnected as shown in Figure 11. Constant pressure streams are explicitly considered in the superstructure, thus enabling optimal selection of end-heaters and end-coolers. Compared to the best solution obtained by Onishi et al.,[16] the approach by Huang and Karimi[77] resulted in 10.6% more work exchange and 81.0% more heat exchange. As a result, total annualized cost was reduced by 3.1%. This superstructure has S stages, indicating that each pressure changing stream passes through the HEN and WEN S times. In contrast, the constant pressure streams pass only once through the HEN. The superstructure allows for the flexibility of selecting heaters or coolers at the end of the HEN superstructure as shown in Figure 11. This flexibility is a key difference between this study and that of Onishi et al.[16] The superstructure of Onishi et al.[16] simply places a heater for high-pressure streams and a cooler for low-pressure streams at the last stage of the WEN.

According to Huang and Karimi,[77] their model has fewer variables, fewer and/or tighter constraints, tighter relaxations, fewer nonlinear terms, better numerical stability, faster solutions, and better objective values. However, they also assumed the low- (WSK) and high-pressure (WSR) streams to be cold and hot streams, respectively, before entering the WEN. The purpose of this assumption is to boost the power recovery from a WSR by increasing its temperature and to reduce the power consumption for a WSK by decreasing its temperature. However, this superstructure may eliminate more efficient heat integration opportunities in HENs. Heat integration may be more important in cases where heat (cold thermal energy) is more expensive than work, such as in LNG offshore processes. It should be noted that LNG processes use multistream heat exchangers instead of conventional countercurrent two-stream heat exchangers. This model therefore needs to be revised before being applied to LNG processes. In addition, Huang and Karimi[77] assumed that liquid nitrogen and natural gas pressure is above 10 MPa to attain supercritical fluids. Then the streams can be treated as single segment streams with average heat capacities. This assumption may result in large deviations between conceptual design and actual operation.

The superstructures proposed by Onishi et al.[16] and Huang and Karimi[77] assume that high-pressure streams and low-pressure streams are cold and hot streams, respectively, to boost the power generation from the high-pressure streams and to reduce the power consumption for the low-pressure streams. While this assumption is based on the general understanding that work is more valuable than heat, it eliminates solutions where modest investment in mechanical energy (work) can give considerable savings in thermal energy (heating/cooling).

To overcome these shortcomings, Onishi et al.[80] proposed a new optimization model for cost-effective synthesis of WHENs. In this model, the specific scheme of pressure manipulations and classification of streams (hot/cold, low pressure/high pressure) are no longer fixed in order to explore a larger feasible search space for the design problem.

Based on the superstructures proposed by Onishi et al.[74] and Wechsung et al.,[15] Pavão et al.[81] proposed an extended superstructure, where a stream can pass several times through a HEN-specific stagewise superstructure, and between each of these passes, there is an option for pressure manipulation. A metaheuristic solution method (simulated annealing and rocket fireworks optimization), which was originally developed for HEN synthesis, was modified to handle the new variables associated with the WHEN design problem.

Zhuang et al.[44] proposed a stepwise work and heat exchange network synthesis methodology that combines mathematical programming and heuristic rules. The method first synthesizes a direct work exchange network based on a transshipment model. Compressors and expanders with small loads are removed to save equipment cost. This can be done by adjusting the load of some pressure changing units and by introducing heat exchangers to compensate for temperature effects. Five rules and three strategies are proposed to integrate heat exchange equipment into direct work exchange networks. This work is the only study of WHENs considering direct work exchangers as equipment type. However, this is a stepwise methodology based on heuristic rules, and the manual procedure to synthesize WHENs cannot guarantee optimal network configurations. In addition, this method is very complicated to apply.

Nair et al.[22] proposed a generalized framework for WHENs based on mixed-integer nonlinear programming. In this study, streams are not preclassified as hot/cold or high/low-pressure streams. Pressure change is allowed for streams with the same supply and target pressure. Liquid−vapor phase change is also considered. This framework is successfully applied to a propane-propylene separation process and an offshore natural gas liquefaction process. At present, the superstructure proposed by Nair et al.[22] appears to be the most comprehensive in the WHENs field. Due to a considerable number of binary variables, however, computing times could be a limiting factor for large scale problems.

Yu et al.[23] proposed a new superstructure to determine the optimal thermodynamic paths of pressure changing streams in

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525

Table 4. Analysis and Comparison of Literature on WHENs[a]

reference	method	pressure manipulating equipment	nonideal property model	phase change	OBJ	network configuration	solver/algorithm
Townsend and Linnhoff[11,12]	PA/GM	UC/UT	no	yes	EC	no	
Anantharaman et al.[52]	PA/GM	UC/UT	yes	yes	EC	no	
Aspelund et al.[14]	PA/GM	UC/UT	yes	yes	EC	no	
Gundersen et al.[56]	PA/GM	UC/UT	no	no	EC	no	
Aspelund et al.[57−60]	PA/GM	UC/UT	yes	yes	ExE	yes	
Marmolejo-Correa and Gundersen[61,62]	PA/GM	UC/UT	no	no	ExE	yes	
Fu and Gundersen[31]	PA/GM	UC/UT	no	no	ExE	yes	
Fu and Gundersen[64]	PA/GM	UC/UT	no	no	ExE	yes	
Fu and Gundersen[65]	PA/GM	UC/UT	no	no	ExE	yes	
Fu and Gundersen[71]	PA/GM	UC/UT	no	no	ExE	yes	
Marmolejo-Correa and Gundersen[67]	PA/GM	UC/UT	no	no	ExE	no	
Deng et al.[68]	PA/GM	UC/UT/PDWE/VAL	no	no	ExE	yes	
Colmenares and Seider[13]	MP	UC/UT	no	yes	MUC/TAC	no	MINOS
Holiastos and Manousiouthakis[69]	MP	UC/UT	no	no	EC	no	
Posada and Manousiouthakis[70]	MP	UC/UT	yes	yes	MUC	yes	MINOS
Wechsung et al.[15]	MP	UC/UT	yes	yes	ExC	yes	BARON
Onishi et al.[73,74]	MP	UC/UT	no	no	TAC	yes	SBB
Onishi et al.[16,76]	MP	UC/UT/SSTC/VAL	no	no	TAC	yes	DICOPT
Huang and Karimi[77]	MP	UC/UT/SSTC/VAL	no	no	TAC	yes	DICOPT
Onishi et al.[78]	MP	UC/UT/SSTC	no	no	RTAC	yes	SBB
Onishi et al.[79]	MP	UC/UT/SSTC/VAL	no	no	TAC/EI	yes	DICOPT
Onishi et al.[80]	MP	UC/UT/SSTC/VAL	no	no	TAC	no	BARON
Zhuang et al.[44]	MP	UC/UT/DWE	no	no	MUC/TAC	yes	
Dong et al.[84]	MP	UC/UT/VAL	no	no	MECPUE	yes	GA
Dong et al.[85]	MP	UC/UT	no	no	MECPUE	yes	
Liao et al.[86]	MP	UC/UT/VAL	yes	yes	TAR	yes	CONOPT3/DICOPT
Nair et al.[22]	MP	UC/UT/SSTC/VAL	yes	yes	TAC	yes	BARON

[a]MUC: minimum utility cost. ExE: exergy efficiency. PDWE: positive displacement work exchanger. ExC: exergy consumption. RTAC: retrofit total annualized cost. EI: environmental impacts. DWE: direct work exchanger. GA: genetic algorithm. MECPUE: minimum economic cost per unit exergy. TAR: total annualized revenue.

WHENs. In this superstructure, even the stream identities (hot/cold) are unknown. The methodology aims at determining the pressure manipulations of the process system first, and then the WHENs problem becomes a standard HENs problem. On the basis of this study, three reformulations, namely, smooth approximation, explicit disjunction, and direct disjunction are proposed and compared by Yu et al.[82] Later, another reformulation called intermediate temperature strategy was studied.[83]

The proposed superstructure-based methodologies mentioned above are reviewed and compared in Table 3.

There are several studies focusing on the simultaneous integration of HENs, WENs, and MENs. Obviously, introducing MENs will cause new challenges in WHENs. Currently, even the integration of HENs and WENs is not mature, let alone the simultaneous integration of HENs, WENs, and MENs. Dong et al.[84] developed a state space model for the simultaneous integration of heat, mass, and work exchange networks. To optimize HENs, WENs, and MENs simultaneously, a unified criterion for the three different networks should be proposed. Therefore, exergoeconomic analysis is carried out in their study that mainly focuses on a water distribution network considering temperature, pressure, and concentration simultaneously. The proposed state space model performs well in synthesizing the integrated network. This study offers a good solution for water distribution network synthesis of integrated MENs, HENs, and WENs. However, since pressure change of water hardly causes any temperature change, the HENs and WENs are weakly related. Therefore, the interaction between HENs and WENs is neglected.

Ding et al.[34] studied hydrogen distribution networks with pressure constraints. A methodology to construct average pressure profiles of hydrogen sources and sinks is proposed in their study. This can be used as an assistant tool for the traditional graphical method. Dong et al.[85] investigated a hydrogen distribution network considering work and heat recovery. A mathematical model based on a state space superstructure is established. The simultaneous integration of work and heat reduces energy consumption and economic cost significantly. Liao et al.[86] presented a systematic network design procedure for effluent gas recovery at subambient temperature. A state space superstructure containing HEN operator, pressure operator, and separation operator is proposed. To recover the effluent gas, the flashing temperature and pressure should be within a certain range. Compressors and turbines are considered in a compression condensing block and a cryogenic separation block, respectively. To avoid rigorous thermodynamic calculations and still guarantee sufficient accuracy, empirical correlations are adapted to calculate the thermodynamic properties of the effluent gas streams.

The mathematical formulation of WHENs results in complex MINLP problems, whose effective solution is a challenge.

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525

Further work to develop more efficient formulations and tools is required. To avoid high nonlinearity and nonconvexity of the models, most studies mentioned above assumed the streams to behave like ideal gas, and the costs are estimated by linear or simplified functions. Phase change and rigorous thermodynamic correlations are not considered, which are crucial for subambient processes such as natural gas liquefaction. Linear or simplified equipment cost correlations are not able to realistically represent the true cost of the process. Thus, mathematical programming methods also have their inherent limitations. As an example, to consider the effect of pressure on phase change, thermodynamic models for the process fluids should be incorporated. However, most of the proposed methods do not incorporate such rigorous thermodynamic models.

The quality of the solution to mathematical optimization models relies heavily on the performance of the numerical solver. Most of the commercial optimization software vendors offer a variety of NLP and MINLP solvers. These solvers can be classified as local and global solvers. However, the modeling and solution of MINLP optimization problems have not yet reached the stage of maturity and reliability compared with linear, mixed integer and nonlinear programming formulations.[87] The solution of the model depends heavily on the structure of the model, the presence of nonlinearity and nonconvexity, and the size of the model. Therefore, it is hard to say which solver performs better than others.

BARON,[88] DICOPT,[89] and SBB[90] are widely used MINLP solvers in the PSE community. BARON can solve MINLP problems to global optimality, but the computation time can be excessive. DICOPT and SBB are local MINLP solvers. Only limited size MINLP problems can be solved efficiently with BARON. Wechsung et al.[15] used BARON to solve their models with CPLEX[91] and SNOPT[92] as the subsolvers; however, a number of simplifications had to be made to be able to obtain solutions in reasonable times. These simplifications may lead to an infeasible design in practice even though it is a globally optimal solution from BARON. Hence, BARON is not widely used to solve WHEN problems, although BARON has the advantage that it does not require feasible starting points.

Huang and Karimi[77] used local MINLP algorithms to solve their models. They compared the performance of DICOPT and SBB, and the results indicate that DICOPT performs much better than SBB. The reason is that DICOPT performs better on models with a significant combinatorial part, while SBB may perform better on models that have fewer discrete variables but more challenging nonlinearities and nonconvexities. Due to the nonconvexity of the models, a large number of local solutions exist, and the final result may get trapped in suboptimal solutions. The branch-and-bound based solvers are typically less sensitive to nonconvexity of the model. SBB is adopted as the MINLP solver in some studies as shown in Table 4.

DICOPT is based on extensions of the outer approximation algorithm with the equality relaxation strategy. This algorithm solves a series of MILP master problems and NLP subproblems iteratively. DICOPT can experience difficulties if many or all the NLP subproblems are infeasible. The linearization into the MILP model should not be ill-conditioned. The linearization of the constraints in DICOPT may exclude certain parts of the feasible region from consideration. The performance of DICOPT is also related to the selected subsolvers for NLP and MILP problems. In contrast, SBB is based on a combination of the standard branch-and-bound algorithm for MILP problems and NLP solvers. SBB spends most of the effort in solving NLP problems. The NLP models can be solved quickly using a good start procedure in SBB. The solution process is fairly reliable even if good initial values are not available. Onishi et al.[78] used SBB as the algorithm to solve their MINLP model. A detailed comparison of these studies on WHENs is listed in Table 4.

7. CHALLENGES AND FUTURE RESEARCH OF WENS AND WHENS

On the basis of the present review of the studies in the field of WENs and WHENs, it is clear that these methodologies are still in an early stage of development, and there are still many challenges to be overcome before solving real life industrial problems.

Challenges in WENs and WHENs. *Challenges in WENs.* For WENs, the direct work exchanger has the advantage of high efficiency and low equipment cost, but a disadvantage is the low flexibility of the WEN configurations. For indirect work exchangers, the efficiency is average, and the flexibility is acceptable. As discussed in section 4, most studies make an isothermal assumption to simplify their model. This simplification is not acceptable in most processes. In addition, the operability and shaft speed of an SSTC unit are not considered while synthesizing WENs in most studies. The operation of pressure manipulating equipment involves highly nonlinear functions of temperature, pressure, specific heat capacity, and process efficiency. The mechanical energy (work) is a highly nonlinear function of pressure, while it is a linear function of temperature difference.[16] WEN synthesis considering typical process constraints is a challenge.

Challenges in WHENs. For WHENs, both work and heat are involved, resulting in a more complex synthesis problem. Since pinch based methods cannot properly consider the multiple capital-energy trade-offs in process plants, the resulting design may not be economically attractive in practice. Fu et al.[93] suggested that WHENs is an emerging research area and considerably more complex than HENs. Yu et al.[94] analyzed the opportunities and challenges in the WHENs area. Methods related to pinch analysis could generate a scheme that is highly energy efficient but may be economically infeasible. The economic aspects of the system should be examined while designing a process. The discussion about advantages and disadvantages of pinch analysis for HENs also applies to WHENs. For mathematical programming, the models are commonly nonconvex nonlinear programming (NLP) problems or mixed integer nonlinear programming (MINLP) problems. These models can be hard, or even practically impossible, to solve due to the nonconvex nature and the combinatorial explosion caused by integer (binary) variables. For large nonconvex NLP problems, no known algorithm can solve such problems in polynomial time. The global optimum is difficult or even impossible to obtain. Due to the equation-based approach of mathematical programming, it is not trivial to solve detailed models considering process equipment and rigorous thermodynamic behavior of the components.[95]

To overcome the disadvantages mentioned above, simplified models are established to identify the global optimum. However, the optimum for the model does not necessarily mean the optimum for the real process. In subambient processes, such as LNG, the temperature driving forces can be as low as 1−3 °C, which requires a rigorous thermodynamic model to guarantee a realistic solution. Any simplification may shift the optimum considerably. However, almost all the studies so far have

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525

assumed ideal gas behavior or neglected the phase change of fluids. These methods cannot be applied to industrial processes. A simulation-based optimization framework using metaheuristics offers an alternative for WHEN synthesis problems. A stochastic optimization engine, such as simulated annealing, genetic algorithm, tabu search, harmony search, or particle swarm optimization, is connected to a simulation. Although optimization algorithms based on stochastic search cannot guarantee global optimum, this methodology has the advantage of being able to handle accurate models for thermodynamics, unit operations and equipment cost. Evolutionary methods are unaffected by nonlinearity, nonconvexity, and nonsmoothness in the models. However, many adjustable parameters and long computational times are drawbacks of this class of methods.[96] It is interesting that no studies are found related to WHENs using evolutionary optimization methods.

Due to these challenges in WENs and WHENs, increasing attention has been paid to research in this field. Examples of such research are three recent master theses focusing on WENs and WHENs. Zhuang from Dalian University of Technology authored a thesis on the synthesis of work exchange networks based on the transshipment model.[97] This master dissertation is related to a series of papers,[41−44,48] which have been discussed in this review. The other two master theses are from the Norwegian University of Science and Technology (NTNU). Maurstad Uv[98] proposed a new model with and without using thermodynamic insights for WHEN synthesis. With insights, it is possible to fix the inlet and outlet temperatures for pressure changing units at specific temperatures, which results in a simple LP model. However, the models are only suitable for targeting and cannot design actual WHENs. Borge[99] developed a two-level optimization model using a generic algorithm that is able to find the optimal or a near optimal solution.

Another indication of the increased research activity in this field is the fact that the 20th Conference on Process Integration, Modelling and Optimization for Energy Saving and Pollution Reduction (PRES 2017) held in Tianjin (China) had a special session for work and heat exchange networks. This review paper is an extension of a keynote paper[100] from that special session. The following papers contributed to this special session: Zhuang et al.[43] proposed two upgraded stagewise superstructures with/without stream splits to synthesize direct work exchange networks for isothermal processes. Gao and Feng[101] proposed a new concept referred to as fluid machinery network, which aims at integrating pumps and water turbines in a circulating water system. This concept is within the scope of WENs since pressure change is the main concern in the process. Therefore, the circulating water system is a special application of WENs. On the basis of this study, Gao and Feng[102] proposed the concept of effective heights of a branch in a cooling water system and cooling tower to derive the necessary conditions for water turbine placement. A mathematical model to determine the minimum theoretical power requirement of the pump network and the maximum theoretical recoverable power of a water turbine network was established. Le et al.[103] proposed a method to recover both the pressure energy and thermal energy released during LNG regasification processes. Pressure energy is recovered by direct expansion and cold energy is recovered by an Organic Rankine Cycle. A net power of 246.5 kW can be recovered from 1 kg/s of LNG. Kansha et al.[104] proposed exergy recuperative pressure and heat circulation modules to a methanol synthesis process to reduce the energy consumption of the process. Nair et al.[105] extended their previous model to a framework for WHEN problems. Pressure changing streams are neither preclassified as high or low pressure nor as hot or cold streams. This provides more flexibility and broader applicability for work and heat integration. They reported lower total annualized cost without external utility for an offshore LNG process. Vikse et al.[106] investigated the three alternative optimization models for WHENs by Wechsung et al.,[15] Huang and Karimi,[77] and Maurstad Uv.[98] Some equations in these models are not differentiable everywhere; thus, they proposed to use nonsmooth algorithms to deal with the nondifferentiability. Fu et al.[107] presented the development and challenges of work and heat integration. Some of these studies have been discussed in the main body of this review. Recently, Demirel et al.[108] proposed a novel method for process design and intensification based on a block superstructure. This novel method has later been applied to WENs and WHENs by Li et al.[25]

Future Research in WENs and WHENs. Even though achievements in WENs and WHENs have been reported, it is difficult to implement these achievements in industrial processes. The main reasons are (i) practical issues are not considered and (ii) assumptions made are far from reality. The following assumptions are commonly found in literature:

- Only gas streams are considered, and these behave as ideal gases.
- Compression and expansion take place with constant efficiencies.
- Expansion through valves is isenthalpic, and the Joule−Thompson coefficient is constant.
- Gas streams undergoing expansion in valves are always below their inversion temperature.
- Process operating conditions do not require special equipment design considerations that make the applied cost correlations inappropriate.
- Pressure drop and heat losses are neglected.
- Multiple utilities and multistage pressure manipulations are not considered.

The above assumptions facilitate the modeling and solution of WEN and WHEN problems; however, they cause gaps between research and practical applications. Equipment design and operational issues are rarely considered in the literature. In practice, some turbines and compressors are available only in standard models and cannot be customized. Even when equipment can be customized, the cost will increase considerably. Hence, the selection of turbines and compressors will have a great influence on the synthesis of WENs and WHENs. The trade-offs between standard models and customized designs should be considered during the conceptual design stage. It is more difficult to achieve an exact match for an SSTC unit if only discrete sizes of equipment are considered. Such equipment constraints should be considered in the future research. In addition, the efficiency of turbines and compressors is a function of operating conditions, stream composition, equipment size, etc. Equipment operating at very high or very low temperature may be quite difficult to manufacture. However, these issues are difficult to handle in theoretical studies. Therefore, when moving from research to industrial applications, there are many practical problems that need to be addressed in the future research.

Due to the respective disadvantages of pinch based methods and mathematical programming, it is better to combine these two methods taking advantage of the merits of each method. The pinch based methods can provide fundamental thermody-

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525

namic insights, which can be used to develop more efficient superstructures. As a result, the size of the mathematical model can be reduced, which makes it easier to find optimal solutions.

Future work should focus on developing a WHEN superstructure that is rich enough while being computationally efficient. Equipment models and thermodynamic models must properly encapsulate reality. In addition, the superstructure should be able to handle issues such as (i) multiple thermal utilities with both constant and nonconstant temperatures and (ii) multistage compression and expansion. There is currently no superstructure available satisfying these criteria for WHENs. It is not trivial to propose a superstructure considering all factors concerning operating cost, equipment cost, operability, flexibility, and robustness. The trade-off between the richness and ease of computation for the superstructure should be considered.

In summary, new process synthesis methods need to be developed for WEN and WHEN problems in the future. Richer problem definitions and more practical considerations will be essential to achieve significant applications of WEN and WHEN methodologies in the process industries.

8. CONCLUSIONS

The synthesis of work exchange networks (WENs) and work and heat exchange networks (WHENs) represent challenging new research fields in process integration and process systems engineering. This review paper includes more than 100 references, where the majority of contributions are from the last 5−10 years, indicating that this is a fast-growing research area with considerable impact on energy efficiency in the process industries.

While design of heat exchanger networks (HENs) is a mature field of engineering that is used on a daily basis in the process industry around the world, with significant impact on the specific energy consumption of plants and sites, WENs and WHENs have still not reached a level of application that reflects the potential of these new methodologies. Similar to HENs, two schools of methods have emerged: one interactive based on thermodynamics and use of graphical diagrams and one automated based on the use of optimization.

For pressure changing process streams, considerable energy savings can be achieved by utilizing heating from compression and cooling from expansion in the heat recovery system. Sacrificing modest amounts of mechanical energy (work) can yield significant savings in thermal energy (heating and/or cooling). WHENs also represent a generalization of the concepts of heat engines, heat pumps, and refrigeration cycles, where the process streams act as working fluids. A promising application of WHENs is to allow pressure changes (compression and expansion) even for constant pressure streams.

This review shows the historic development in the field of Work and Heat Integration, with a chronological list of major milestones both for WENs and WHENs. A comprehensive review is made of the literature in the field highlighting some of the main concepts, insights, and representations. Finally, major research challenges are mentioned, and future directions of research are outlined in order to gain acceptance in the process industries.

■ AUTHOR INFORMATION

Corresponding Author

*truls.gundersen@ntnu.no.

ORCID

Haoshui Yu: 0000-0002-9256-852X

Chao Fu: 0000-0003-4411-9188

Truls Gundersen: 0000-0003-2553-5725

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This publication has been funded by HighEFF - Centre for an Energy Efficient and Competitive Industry for the Future. The authors gratefully acknowledge the financial support from the Research Council of Norway and user partners of HighEFF, an 8-year Research Centre under the FME-scheme (Centre for Environment-friendly Energy Research, 257632).

■ REFERENCES

(1) Linnhoff, B.; Townsend, D. W.; Bolan, D.; Hewitt, G. F.; Thomas, B. E. A.; Guy, A. R.; Marshall, R. H. *A user guide on process integration for the efficient use of energy*; Institution of Chemical Engineers: Rugby, U.K., 1982.

(2) Klemeš, J. J., Ed. *Handbook of process integration (PI): minimisation of energy and water use, waste and emissions*; Woodhead Publishing Limited: Cambridge, U.K., 2013.

(3) Smith, R. *Chemical Process Design and Integration*; John Wiley & Sons: Chichester, U..K., 2005.

(4) Gundersen, T.; Naess, L. The synthesis of cost optimal heat exchanger networks: an industrial review of the state of the art. *Comput. Chem. Eng.* **1988**, *12* (6), 503−530.

(5) Furman, K. C.; Sahinidis, N. V. A critical review and annotated bibliography for heat exchanger network synthesis in the 20th century. *Ind. Eng. Chem. Res.* **2002**, *41* (10), 2335−2370.

(6) El-Halwagi, M. M.; Manousiouthakis, V. Synthesis of mass exchange networks. *AIChE J.* **1989**, *35* (8), 1233−1244.

(7) Wang, Y.; Smith, R. Wastewater minimisation. *Chem. Eng. Sci.* **1994**, *49* (7), 981−1006.

(8) Huang, Y. L.; Fan, L. T. Analysis of a work exchanger network. *Ind. Eng. Chem. Res.* **1996**, *35* (10), 3528−3538.

(9) Chen, Z.; Wang, J. Heat, mass, and work exchange networks. *Front. Chem. Sci. Eng.* **2012**, *6* (4), 484−502.

(10) Cheng, C. Y.; Cheng, S. W.; Fan, L. T. Flow work exchanger. *AIChE J.* **1967**, *13* (3), 438−442.

(11) Townsend, D. W.; Linnhoff, B. Heat and Power Networks in Process Design. Part I: Criteria for Placement of Heat Engines and Heat Pumps in Process Networks. *AIChE J.* **1983**, *29* (5), 742−748.

(12) Townsend, D. W.; Linnhoff, B. Heat and Power Networks in Process Design. Part II: Design procedure for equipment selection and process matching. *AIChE J.* **1983**, *29* (5), 748−771.

(13) Colmenares, T. R.; Seider, W. D. Heat and power integration of chemical processes. *AIChE J.* **1987**, *33* (6), 898−915.

(14) Aspelund, A.; Berstad, D. O.; Gundersen, T. An Extended Pinch Analysis and Design procedure utilizing pressure based exergy for subambient cooling. *Appl. Therm. Eng.* **2007**, *27* (16), 2633−2649.

(15) Wechsung, A.; Aspelund, A.; Gundersen, T.; Barton, P. I. Synthesis of heat exchanger networks at subambient conditions with compression and expansion of process streams. *AIChE J.* **2011**, *57* (8), 2090−2108.

(16) Onishi, V. C.; Ravagnani, M. A. S. S.; Caballero, J. A. Simultaneous synthesis of work exchange networks with heat integration. *Chem. Eng. Sci.* **2014**, *112*, 87−107.

(17) Liu, G.; Zhou, H.; Shen, R.; Feng, X. A graphical method for integrating work exchange network. *Appl. Energy* **2014**, *114*, 588−599.

(18) Fu, C.; Gundersen, T. Integrating compressors into heat exchanger networks above ambient temperature. *AIChE J.* **2015**, *61* (11), 3770−3785.

(19) Fu, C.; Gundersen, T. Sub-ambient heat exchanger network design including compressors. *Chem. Eng. Sci.* **2015**, *137*, 631−645.

(20) Fu, C.; Gundersen, T. Integrating expanders into heat exchanger networks above ambient temperature. *AIChE J.* **2015**, *61* (10), 3404−3422.

(21) Fu, C.; Gundersen, T. Sub-ambient heat exchanger network design including expanders. *Chem. Eng. Sci.* **2015**, *138*, 712−729.

(22) Nair, S. K.; Rao, H. N.; Karimi, I. A. Framework for Work-Heat Exchange Network Synthesis (WHENS). *AIChE J.* **2018**, *64* (7), 2472−2485.

(23) Yu, H.; Fu, C.; Vikse, M.; He, C.; Gundersen, T. Identifying optimal thermodynamic paths in work and heat exchange network synthesis. *AIChE J.* **2019**, *65* (2), 549−561.

(24) Zhuang, Y.; Liu, L.; Zhang, L.; Du, J.; Shen, S. An extended superstructure modeling method for simultaneous synthesis of direct work exchanger networks. *Chem. Eng. Res. Des.* **2019**, *144*, 258−271.

(25) Li, J.; Demirel, S. E.; Hasan, M. M. F. Building Block-Based Synthesis and Intensification of Work-Heat Exchanger Networks (WHENS). *Processes* **2019**, *7* (1), 23.

(26) Yu, H.; Fu, C.; Vikse, M.; Gundersen, T. Work and heat integration—A new field in process synthesis and process systems engineering. *AIChE J.* **2019**, *65* (7), No. e16477.

(27) Linnhoff, B.; Flower, J. R. Synthesis of heat exchanger networks: I. Systematic generation of energy optimal networks. *AIChE J.* **1978**, *24* (4), 633−642.

(28) Stover, R. L. Seawater reverse osmosis with isobaric energy recovery devices. *Desalination* **2007**, *203* (1), 168−175.

(29) Razib, M. S.; Hasan, M. M. F.; Karimi, I. A. Preliminary synthesis of work exchange networks. *Comput. Chem. Eng.* **2012**, *37*, 262−277.

(30) Zhao, L.; Riensche, E.; Blum, L.; Stolten, D. Multi-stage gas separation membrane processes used in post-combustion capture: Energetic and economic analyses. *J. Membr. Sci.* **2010**, *359* (1), 160−172.

(31) Fu, C.; Gundersen, T. Heat and work integration: Fundamental insights and applications to carbon dioxide capture processes. *Energy Convers. Manage.* **2016**, *121*, 36−48.

(32) Sun, J.; Feng, X.; Wang, Y.; Deng, C.; Chu, K. H. Pump network optimization for a cooling water system. *Energy* **2014**, *67* (Supplement C), 506−512.

(33) Ma, J.; Wang, Y.; Feng, X. Simultaneous optimization of pump and cooler networks in a cooling water system. *Appl. Therm. Eng.* **2017**, *125* (Supplement C), 377−385.

(34) Ding, Y.; Feng, X.; Chu, K. H. Optimization of hydrogen distribution systems with pressure constraints. *J. Cleaner Prod.* **2011**, *19* (2), 204−211.

(35) Andrews, W. T.; Laker, D. S. A twelve-year history of large scale application of work-exchanger energy recovery technology. *Desalination* **2001**, *138* (1), 201−206.

(36) Deng, J.; Shi, J.; Zhang, Z.; Feng, X. Thermodynamic Analysis on Work Transfer Process of Two Gas Streams. *Ind. Eng. Chem. Res.* **2010**, *49* (24), 12496−12502.

(37) Deng, J.; Ma, L.; Feng, X. Work recovery efficiency of work exchange in chemical process. *Journal of Chemical Industry and Engineering (China)* **2011**, *62* (11), 3017−3023.

(38) Chen, H.; Feng, X. Graphical Approach for Targeting Work Exchange Networks. *International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering* **2012**, *6* (8), 716−720.

(39) Stover, R. L. Development of a fourth generation energy recovery device. A 'CTO's notebook'. *Desalination* **2004**, *165*, 313−321.

(40) Zhou, H.; Liu, G.; Feng, X. Problem table method for work exchange network with efficiency considered. *Journal of Chemical Industry and Engineering (China)* **2011**, *62* (6), 1600−1605.

(41) Zhuang, Y.; Liu, L.; Li, J.; Fan, J.; Teng, J.; Du, J. Synthesis of work exchange network based on transshipment model. *Comput.-Aided Chem. Eng.* **2015**, *37*, 1139−1144.

(42) Zhuang, Y.; Liu, L.; Zhang, L.; Du, J. Direct work exchanger network synthesis of isothermal process based on improved transshipment model. *J. Taiwan Inst. Chem. Eng.* **2017**, *81* (Supplement C), 295−304.

(43) Zhuang, Y.; Liu, L.; Du, J. Direct Work Exchange Networks Synthesis of Isothermal Process Based on Superstructure Method. *Chemical Engineering Transaction* **2017**, *61*, 133−138.

(44) Zhuang, Y.; Liu, L.; Liu, Q.; Du, J. Step-wise synthesis of work exchange networks involving heat integration based on the transshipment model. *Chin. J. Chem. Eng.* **2017**, *25* (8), 1052−1060.

(45) Zhuang, Y.; Liu, L.; Zhang, L.; Du, J. Upgraded graphical method for the synthesis of direct work exchanger networks. *Ind. Eng. Chem. Res.* **2017**, *56* (48), 14304−14315.

(46) Amini-Rankouhi, A.; Huang, Y. L. Prediction of Maximum Recoverable Mechanical Energy via Work Integration: A Thermodynamic Modeling and Analysis Approach. *AIChE J.* **2017**, *63* (11), 4814−4826.

(47) Razib, M. S.; Hasan, M. F.; Karimi, I. Optimal synthesis of compressor network. *Proceeding of the 7th International Conference on the Foundations of Computer-Aided Process Design (FOCAPD 2009), Design for Energy and Environment* **2009**, 263−271.

(48) Du, J.; Zhuang, Y.; Liu, L.; Li, J.; Fan, J.; Meng, Q. Synthesis of indirect work exchanger network based on transshipment model. *Comput.-Aided Chem. Eng.* **2015**, *37*, 1139−1144.

(49) Feng, X.; Chen, H. Optimized work exchange networks with economic consideration. *Journal of Tsinghua University (Science and Technology)* **2012**, *3* (52), 298−302.

(50) Yoon, H.-J. A. Heat and work integration in the synthesis of chemical plants. *Ph.D. thesis*, Massachusetts Institute of Technology, 1990.

(51) Linnhoff, B.; Dhole, V. R. Shaftwork targets for low-temperature process design. *Chem. Eng. Sci.* **1992**, *47* (8), 2081−2091.

(52) Anantharaman, R.; Abbas, O. S.; Gundersen, T. Energy Level Composite Curves—a new graphical methodology for the integration of energy intensive processes. *Appl. Therm. Eng.* **2006**, *26* (13), 1378−1384.

(53) Feng, X.; Zhu, X. X. Combining pinch and exergy analysis for process modifications. *Appl. Therm. Eng.* **1997**, *17* (3), 249−261.

(54) AspenTech. *Aspen HYSYS*; 2013.

(55) Homsak, M.; Glavic, P. Appropriate placement of energors against local pinch temperatures. *Transactions of IChemE* **1995**, *73* (8), 871−879.

(56) Gundersen, T.; Berstad, D. O.; Aspelund, A. Extending pinch analysis and process integration into pressure and fluid phase considerations. *Chem. Eng. Trans.* **2009**, *18*, 33−38.

(57) Aspelund, A.; Gundersen, T. A liquefied energy chain for transport and utilization of natural gas for power production with CO_2 capture and storage-Part 1. *Appl. Energy* **2009**, *86* (6), 781−792.

(58) Aspelund, A.; Gundersen, T. A liquefied energy chain for transport and utilization of natural gas for power production with CO_2 capture and storage-Part 2: the offshore and the onshore processes. *Appl. Energy* **2009**, *86* (6), 793−804.

(59) Aspelund, A.; Tveit, S. P.; Gundersen, T. A liquefied energy chain for transport and utilization of natural gas for power production with CO_2 capture and storage-Part 3: the combined carrier and onshore storage. *Appl. Energy* **2009**, *86* (6), 805−814.

(60) Aspelund, A.; Gundersen, T. A liquefied energy chain for transport and utilization of natural gas for power production with CO_2 capture and storage-Part 4: sensitivity analysis of transport pressures and benchmarking with conventional technology for gas transport. *Appl. Energy* **2009**, *86* (6), 815−825.

(61) Marmolejo-Correa, D.; Gundersen, T. *A new procedure for the design of LNG processes by combining Exergy and Pinch Analyses*; Proceedings of ECOS, Perugia, Italy, 2012.

(62) Marmolejo-Correa, D.; Gundersen, T. New graphical representation of exergy applied to low temperature process design. *Ind. Eng. Chem. Res.* **2013**, *52* (22), 7145−7156.

(63) Fu, C.; Gundersen, T. Appropriate placement of compressors and expanders in above ambient processes. *Comput.-Aided Chem. Eng.* **2016**, *45*, 643−648.

(64) Fu, C.; Gundersen, T. Correct integration of compressors and expanders in above ambient heat exchanger networks. *Energy* **2016**, *116* (Part 2), 1282−1293.

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525

(65) Fu, C.; Gundersen, T. Appropriate placement of compressors and expanders in sub-ambient processes. *Comput.-Aided Chem. Eng.* **2016**, *38*, 1767−1772.
(66) Fu, C.; Uv, P. M.; Nygreen, B.; Gundersen, T. Compression and expansion at the right pinch temperature. *Chemical Engineering Transaction* **2017**, *56*, 1939−1944.
(67) Marmolejo-Correa, D.; Gundersen, T. Process Design Methodology for Energy-Efficient Processes Operating Below and Across Ambient Temperature. *AIChE J.* **2016**, *62* (7), 2324−2340.
(68) Deng, J.; Cao, Z.; Zhang, D.; Feng, X. Integration of energy recovery network including recycling residual pressure energy with pinch technology. *Chin. J. Chem. Eng.* **2017**, *25* (4), 453−462.
(69) Holiastos, K.; Manousiouthakis, V. Minimum hot/cold/electric utility cost for heat exchange networks. *Comput. Chem. Eng.* **2002**, *26* (1), 3−16.
(70) Posada, A.; Manousiouthakis, V. Heat and Power Integration of Methane Reforming Based Hydrogen Production. *Ind. Eng. Chem. Res.* **2005**, *44* (24), 9113−9119.
(71) Fu, C.; Gundersen, T. A Novel Sensible Heat Pump Scheme for Industrial Heat Recovery. *Ind. Eng. Chem. Res.* **2016**, *55* (4), 967−977.
(72) Duran, M. A.; Grossmann, I. E. Simultaneous optimization and heat integration of chemical processes. *AIChE J.* **1986**, *32* (1), 123−138.
(73) Onishi, V. C.; Ravagnani, M. A. S. S.; Caballero, J. A. MINLP Model for the Synthesis of Heat Exchanger Networks with Handling Pressure of Process Streams. *Comput.-Aided Chem. Eng.* **2014**, *33*, 163−168.
(74) Onishi, V. C.; Ravagnani, M. A. S. S.; Caballero, J. A. Simultaneous synthesis of heat exchanger networks with pressure recovery: Optimal integration between heat and work. *AIChE J.* **2014**, *60* (3), 893−908.
(75) Yee, T. F.; Grossmann, I. E. Simultaneous optimization models for heat integration—II. Heat exchanger network synthesis. *Comput. Chem. Eng.* **1990**, *14* (10), 1165−1184.
(76) Onishi, V. C.; Ravagnani, M. A. S. S.; Caballero, J. A. MINLP Optimization Algorithm for the Synthesis of Heat and Work Exchange Networks. *Comput.-Aided Chem. Eng.* **2014**, *33*, 115−120.
(77) Huang, K.; Karimi, I. A. Work-heat exchanger network synthesis (WHENS). *Energy* **2016**, *113*, 1006−1017.
(78) Onishi, V. C.; Ravagnani, M. A. S. S.; Caballero, J. A. Retrofit of heat exchanger networks with pressure recovery of process streams at sub-ambient conditions. *Energy Convers. Manage.* **2015**, *94*, 377−393.
(79) Onishi, V. C.; Ravagnani, M. A. S. S.; Jiménez, L.; Caballero, J. A. Multi-objective synthesis of work and heat exchange networks: Optimal balance between economic and environmental performance. *Energy Convers. Manage.* **2017**, *140*, 192−202.
(80) Onishi, V. C.; Quirante, N.; Ravagnani, M. A. S. S.; Caballero, J. A. Optimal synthesis of work and heat exchangers networks considering unclassified process streams at sub and above-ambient conditions. *Appl. Energy* **2018**, *224*, 567−581.
(81) Pavão, L. V.; Costa, C. B. B.; Ravagnani, M. A. S. S. A new framework for work and heat exchange network synthesis and optimization. *Energy Convers. Manage.* **2019**, *183*, 617−632.
(82) Yu, H.; Vikse, M.; Gundersen, T. Comparison of reformulations of the Duran-Grossmann model for work and heat exchange network (WHEN) synthesis. *Comput.-Aided Chem. Eng.* **2018**, *43*, 489−494.
(83) Yu, H.; Vikse, M.; Anantharaman, R.; Gundersen, T. Model reformulations for Work and Heat Exchange Network (WHEN) synthesis problems. *Comput. Chem. Eng.* **2019**, *125*, 89−97.
(84) Dong, R.; Yu, Y.; Zhang, Z. Simultaneous optimization of integrated heat, mass and pressure exchange network using exergoeconomic method. *Appl. Energy* **2014**, *136*, 1098−1109.
(85) Dong, R.; Yu, Y.; Zhang, Z. Optimization of Hydrogen Distribution Network Considering Pressure and heat recovery. *Energy Procedia* **2015**, *75*, 1147−1152.
(86) Liao, Z.; Tu, G.; Huang, Z.; Jiang, B.; Wang, J.; Yang, Y. Optimal process design for recovering effluent gas at subambient temperature. *J. Cleaner Prod.* **2017**, *144*, 130−141.
(87) Biegler, L. T.; Grossmann, I. E. Retrospective on optimization. *Comput. Chem. Eng.* **2004**, *28* (8), 1169−1192.
(88) Tawarmalani, M.; Sahinidis, N. V. A polyhedral branch-and-cut approach to global optimization. *Mathematical Programming* **2005**, *103* (2), 225−249.
(89) Grossmann, I. E.; Viswanathan, J.; Vecchietti, A.; Raman, R.; Kalvelagen, E. *GAMS/DICOPT: A discrete continuous optimization package*; GAMS Corporation Inc., 2002.
(90) Bussieck, M. R.; Drud, A. *SBB: A new solver for mixed integer nonlinear programming*; GAMS Development Corp., 2001.
(91) Brooke, A.; Kendrick, D.; Meeraus, A.; Raman, R. *GAMS/CPLEX 7.0 User Notes*; 2000.
(92) Gill, P. E.; Murray, W.; Saunders, M. A. SNOPT: An SQP algorithm for large-scale constrained optimization. *SIAM Rev.* **2005**, *47* (1), 99−131.
(93) Fu, C.; Vikse, M.; Gundersen, T. Work and heat integration: An emerging research area. *Energy* **2018**, *158*, 796−806.
(94) Yu, H.; Fu, C.; Gundersen, T. Work and Heat Exchange Networks - Opportunities and Challenges. *Comput.-Aided Chem. Eng.* **2018**, *44*, 481−486.
(95) Gundersen, T.; Aspelund, A.; Barton, P. I. An Overview of New Methodologies for the Design of Cryogenic Processes with an Emphasis on LNG. *Proceedings of 1st Annual Gas Processing Symposium*; Elsevier, 2009; pp 104−112.
(96) Huang, K.; Karimi, I. A. Efficient algorithm for simultaneous synthesis of heat exchanger networks. *Chem. Eng. Sci.* **2014**, *105* (Supplement C), 53−68.
(97) Zhuang, Y. Work exchange network synthesis based on transhipment model. *MSc thesis*, Dalian University of Technology, 2015.
(98) Maurstad Uv, P. Optimal design of heat exchanger networks with pressure changes. *MSc thesis*, NTNU, 2016.
(99) Borge, K. S. H. *Heuristic solution approach to simultaneous optimization of heat and work integration-A two-level optimization model using genetic algorithms to establish the energy target for maximum heat and work recovery*. MSc thesis, NTNU, 2017.
(100) Yu, H.; Gundersen, T. Review of Work Exchange Networks (WENs) and Work and Heat Exchange Networks (WHENs). *Ind. Eng. Chem. Res.* **2017**, *61*, 1345−1350.
(101) Gao, W.; Feng, X. The Optimal Model of a Fluid Machinery Network in a Circulating Water System. *Chem. Eng. Trans.* **2017**, *61*, 91−96.
(102) Gao, W.; Feng, X. The power target of a fluid machinery network in a circulating water system. *Appl. Energy* **2017**, *205* (Supplement C), 847−854.
(103) Le, S. N. T.; Lee, J.-Y.; Chiu, J.-C.; Chen, C.-L. Waste Energy Recovery - Including Pressure and Thermal Energy - From LNG Regasification. *Chem. Eng. Trans.* **2017**, *61*, 1123−1128.
(104) Kansha, Y.; Ishizuka, M.; Tsutsumi, A.; Kambe, Y.; Okamura, T.; Yoshihara, J. Innovative Methanol Synthesis Process by Using Exergy Recuperative Pressure and Heat Circulation Modules. *Chem. Eng. Trans.* **2017**, *61*, 823−828.
(105) Nair, S. K.; Rao, H. N.; Karimi, I. A. Framework for Work-Heat Exchange Network Synthesis. *Chem. Eng. Trans.* **2017**, *61*, 871−876.
(106) Vikse, M.; Fu, C.; Barton, P. I.; Gundersen, T. Towards the Use of Mathematical Optimization for Work and Heat Exchange Networks. *Chem. Eng. Trans.* **2017**, *61*, 1351−1356.
(107) Fu, C.; Vikse, M.; Gundersen, T. Challenges in Work and Heat Integration. *Chem. Eng. Trans.* **2017**, *61*, 601−606.
(108) Demirel, S. E.; Li, J.; Hasan, M. M. F. Systematic process intensification using building blocks. *Comput. Chem. Eng.* **2017**, *105*, 2−38.

DOI: 10.1021/acs.iecr.9b04932
Ind. Eng. Chem. Res. 2020, 59, 507−525