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Relating Bridge Analysis for Heat Exchanger Network Retrofit Identification to Retrofit Design

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The aim of the paper is to improve a recently developed automated HEN retrofit targeting method by linking the shapes of the Exchanger Shifted Composite Curve (ESCC) and Exchanger Grand Composite Curve (EGCC) to the required HEN retrofit design measures. The automated HEN retrofit targeting method is based on Bridge Analysis, which identifies new and existing utility paths for energy saving through the enhancement and/or addition of heat exchanger area and the installation of new exchangers. To build the required understanding, generic cases are analysed, one of which is presented. Links between the Exchanger Composite Curves with the required HEN retrofit design are established. The analysis concludes that the Heat Surplus-Deficit Cascade for some recovery exchangers may be divided two sections – Pinched and non-Pinched sections – to better represent and identify the number and type of modifications that a retrofit opportunity will require.

1. Introduction

Increasing industrial process energy efficiency remains a high priority as a key enabler of long-term economic and environmental sustainability. Process Integration (PI) encompasses the systematic engineering knowledge and tools to develop energy efficient process designs (Klemeš, 2013). The PI approach tackles design problems of all scales including individual processes, Total Sites (Tarighaleslami et al., 2017), and regional integration (Perry et al., 2008). In addition, PI analysis can support sustainability improvements for both new and existing sites. Increasing process sustainability provides a key driver to implement retrofit and revamp solutions. Modifications to processes and Heat Exchanger Networks (HEN) aim to lift energy and environmental performance while also debottlenecking throughput (Smith et al., 2010).

In recent years, researchers have applied three approaches for developing HEN retrofit designs. First, the team at The University of Manchester have developed techniques to retrofit HEN without topological change. Heat Transfer Enhancement (HTE) acted as the means to lift heat transfer coefficients and raise overall heat recovery. In general, the approach has applied a UA sensitivity analysis for each exchanger in the network (Jiang et al., 2014) while modelling the entire HEN (Akpomiemie and Smith, 2015). The potential for fouling mitigation and the impact on pressure drop due to HTE have also been considered (Pan et al., 2016).

Second, several new developments for the visualisation of the HEN retrofit have been reported. Lai et al. (Lai et al., 2017) in the previous Conference PRES presented a contribution that applied the STEP – Stream Temperature vs Enthalpy Plot – to HEN retrofit and identifying areas of cross-Pinch heat exchange. Extending the interesting research by Bonhivers et al. (2014), Walmsley et al. (2017) enhanced the graphical Energy Transfer Diagram (ETD) followed by a systematic method by Lal et al. (2018). The key tools arising from these works were the Modified ETD (METD) and the Heat Surplus-Deficit Table (HSDT) as a numerical alternative. Additional HEN retrofit tools also include the Shifted Retrofit Thermodynamic Grid Diagram by Yong et al. (Yong et al., 2015) and the Retrofit Tracing Grid Diagram by Nemet et al. (2015). One significant challenge for visual techniques is scalability to large-scale HENs. As a result, Walmsley et al. (2018) proposed to automate the method of Lal et al. (2018) while attempting to maintain the insights gained from the thermodynamic analysis as well as a user control. One current weakness of the new automated method is an inaccurate estimation of the

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number and type of HEN retrofit changes that implementation of a Retrofit Bridge would require. Resolving this weakness is the focus of the current study.
The third HEN retrofit approach applies Mathematical Programming (MP) to solve a series of equations representing a HEN superstructure model (Čuček and Kravanja, 2016). Application of MP in conjunction with Mixed-Integer Non-linear Programming (MINLP) solvers can tackle large-scale retrofit problems (Čuček et al., 2015). However, such approaches are less user-friendly, lacking the required user interactivity to be applied by the typical engineer in practice. Combining a level of MP with problem visualisation has significant potential for increased user-ability and HEN retrofit performance.
The aim of the paper is to improve Bridge Analysis by linking the shapes of the Exchanger Shifted Composite Curve (ESCC) and Grand Composite Curve (EGCC) to the required HEN retrofit design measures. A generic example is analysed and presented. Composite Curves and grid diagrams are compared to develop new insights. These insights are then proposed to refine a recently developed automated HEN retrofit targeting method based on Bridge Analysis.

2. A brief overview of Bridge Analysis tools, concepts, and recent developments

As underlying tools of Bridge Retrofit analysis (Bonhivers et al., 2017), the ETD, and later the METD (Walmsley et al., 2017), comprise a plot of individual EGCCs, stacked to represent the net heat transfer processes within an existing HEN (Walmsley et al., 2017). Unlike Pinch Analysis, the METD maintains the HEN structure, giving insight into embedded inefficiencies. Applying the METD, Lal et al. (2018) presented three case studies to demonstrate how Retrofit Bridges between coolers and heaters may be identified and quantified. Coupled with this development was the construction of the numerical representation through the HSDT. Figure 1 illustrates the relationship between the ESCC for a recovery unit to its EGCC as well as the Exchanger – Problem Table Algorithm (E-PTA). The ETD and METD combine multiple EGCCs such as the one in Figure 1b. The HSDT (Figure 1d) forms an ordered collection of the net heat surplus-deficit columns of the E-PTA (Column 3 in Figure 1c) for all heat exchangers in the HEN. Where EGCC pockets are large along the vertical axis, it means the driving force significantly exceeds the minimum and presents an opportunity for reintegration through more efficient matching. Bridge Analysis provides a method to identify how to reintegrate heat from less efficient matches through HEN retrofit modifications. A complete Retrofit Bridge defines the set of required modifications to create a new or utilise an existing utility path to achieve energy savings.

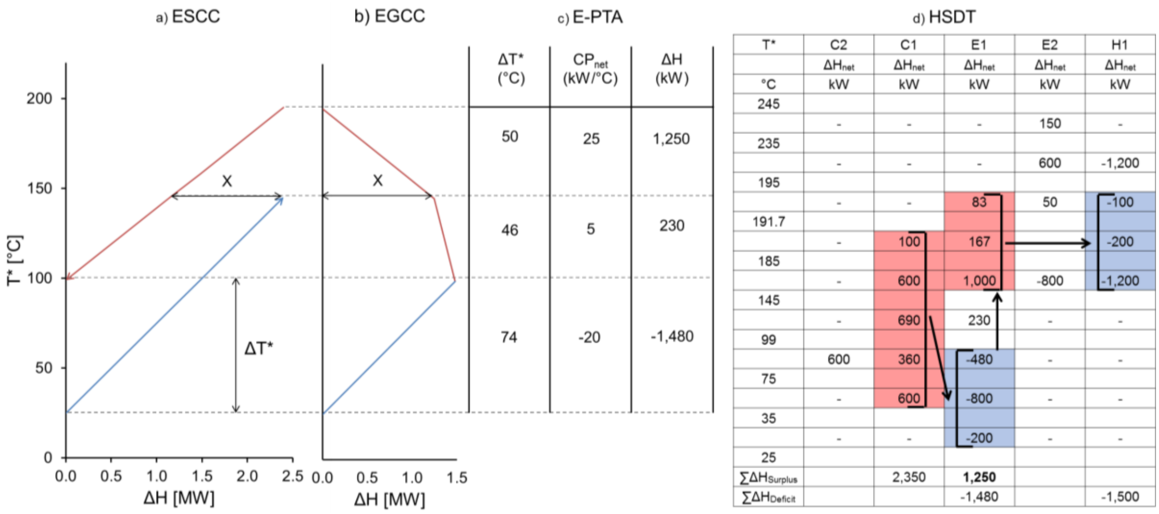

Figure 1: The relationship between the ESCC, EGCC, and E-PTA for recovery exchanger E1 and HSDT for the entire HEN

Using the HSDT, a set of bridges representing modifications can connect a cooler with a heater resulting in energy savings. The Retrofit Bridge identification method is illustrated in Figure 1d. A heat surplus (red) can be transferred to satisfy a heat deficit (blue) in the same or lower temperature interval of the heat surplus. These heat surplus-deficit values correspond to the EGCC. Each pair of cooler-to-recovery exchanger, recovery-to-recovery exchanger, and recovery-to-heater exchanger has a maximum feasible heat transfer, as shown at the bottom of Figure 1d. The minimum of these feasible heat transfer values is the maximum energy savings of the Retrofit Bridge. The procedure for locating a Retrofit Bridge was recently automated by Walmsley et al. (2018)

aiming at tackling large-scale HEN retrofit problems. A key part of the development was the Automated Retrofit Targeting (ART) algorithm. The automation was implemented in Microsoft Excel™ and has shown promise for further development.

3. Method

The purpose of this study is to better understand the connection between a Retrofit Bridge and the required HEN retrofit design. The steps of the analysis method are:
1. A generic problem representing a section of a HEN is considered. For the generic problem, the hot stream heat capacity flow rate - CP_{hot} is assumed greater than the cold stream CP_{cold}.
2. Represent the generic problem using ESCC, EGCC and the grid diagram.
3. Analyse the impact of heat re-integration through a Retrofit Bridge.
4. Correlate the shape of the ESCC and EGCC to the required retrofit design.
5. Extrapolate the results to other cases.
After gaining the insights from the generic analysis, the results are applied to improve the application of Bridge Analysis and its automation to generate better retrofit options.

4. Analysis and linking of Exchanger Composite Curves and retrofit design

Consider the generic case of a recovery exchanger as presented in Figure 2. For this generic case, it is assumed that the hot stream CP is greater than the cold stream CP. Figure 2a shows the ESCC with the right-hand side containing the smaller approach temperature although not Pinched. Next to the ESCC is the EGCC in Figure 2b. Since the outlet temperatures of the hot and cold streams cross-over, an intermediate temperature interval is created with a $CP_{net} = CP_{hot} - CP_{cold}$ where $CP_{hot} > 0$ and $CP_{cold} > 0$. This causes two features of the EGCC. First, the maximum H value for the EGCC is less than the recovery exchanger duty. Second, there is a distinct kink in the heat surplus curve of the EGCC (since $CP_{hot} > CP_{cold}$). In Figure 2c, a section of a HEN is drawn showing the recovery exchanger that is represented in Figures 2a and b, as well as hot and cold streams that currently consume utility. These additional hot and cold streams are assumed to fall within the appropriate temperature ranges to allow a Retrofit Bridge via the focus recovery exchanger.

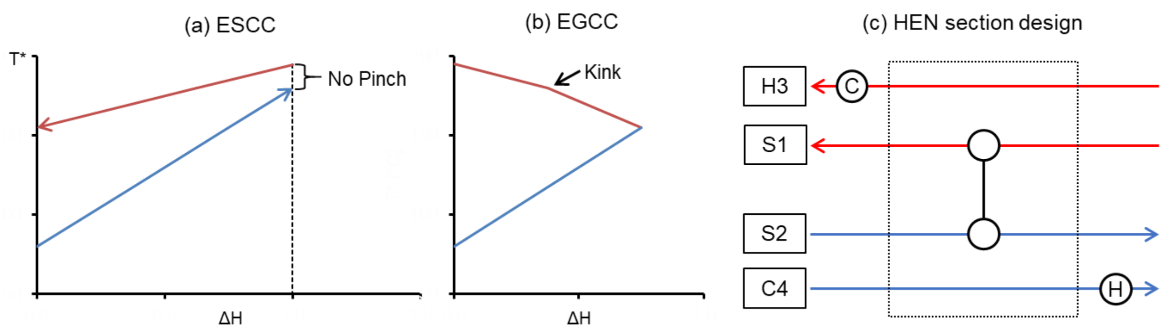

Figure 2: Generic HEN retrofit problem with the focus on one recovery exchanger (before retrofit)

The goal of Bridge Analysis is to identify retrofit heat savings through the reintegration of heat surpluses and deficits. For example, Figure 2b shows a significant temperature gap between the heat surplus at the top and the heat deficit at the bottom. A Retrofit Bridge reintegrates the heat surplus to heat a different cold stream in place of hot utility and the heat deficit to cool a different hot stream in place of cold utility.
Figure 3 presents the case where a Retrofit Bridge is created forming a new path between an existing cooler and heater. In Figure 3a, the hot ESCC is shifted to the right by a duty of x. This shift allows for the improved integration of the hottest and coldest segments of streams S1 and S2. The retrofit design is characterised by two additional matches of duty x in Figure 3c. Often these additional matches represent a need to increase the duty of an existing heat exchanger by increasing its effective heat transfer area (UA) rather than installing a new heat exchanger. After reintegration of duty x, a Pinch on the new ESCC is created as labelled in Figure 3a. This limiting level of reintegration is driven by the outlet temperature of the cold stream (since $CP_{hot} > CP_{cold}$) and corresponds to the upper kink on the EGCC. According to Figure 3b, there may be further opportunity to reintegrate duty y since its driving force is above the minimum. Due to the Pinch in Figure 3b, the reintegration of duty y, and its corresponding heat surplus and deficit segments, through a Retrofit Bridge requires: (1) stream splitting or (2) cyclic matching. These options are presented in Figure 4. Figure 4a shows the hot stream being

split (since $CP_{hot} > CP_{cold}$) with one branch forming a Pinch match where both terminals of the exchanger operate with the minimum approach temperature. The second branch becomes available for reintegration as part of a Retrofit Bridge. The required design with three new recovery matches is illustrated in Figure 4b. Under the stream split scheme, the segments available for reintegration in Figure 4a precisely match the heat surplus-deficit segments in the EGCC of Figure 3b.

As an alternative to splitting stream S1, a cyclic match may be feasible as shown in Figures 4c and d. In this case, the hot stream S1 plays host to a cyclic match with another available cold stream, reducing the associated heater duty. The energy savings (x + y) is the same as the stream splitting approach but it changes the distribution of temperature driving force. The original recovery exchanger's duty decreases to z while one side of the unit is Pinched. The slight increase in temperature driving force of the original recovery exchanger comes from a small reduction in the quality of the heat associated with the cyclic match.

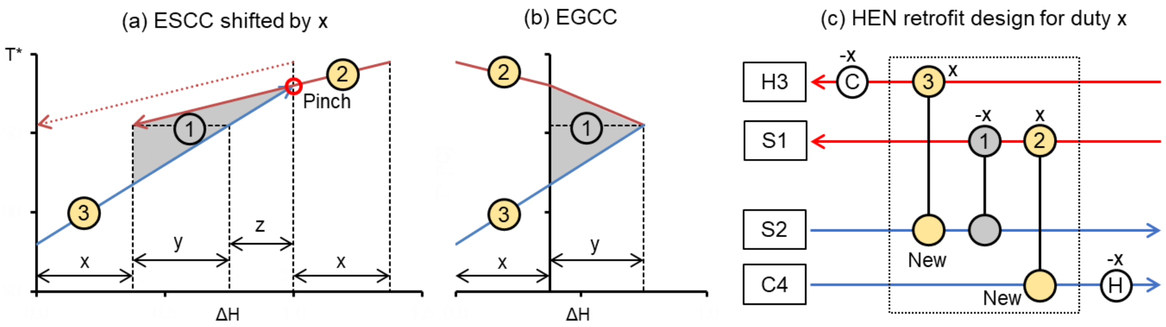

Figure 3: Maximum HEN retrofit with (up to) two new recovery matches as the required HEN retrofit

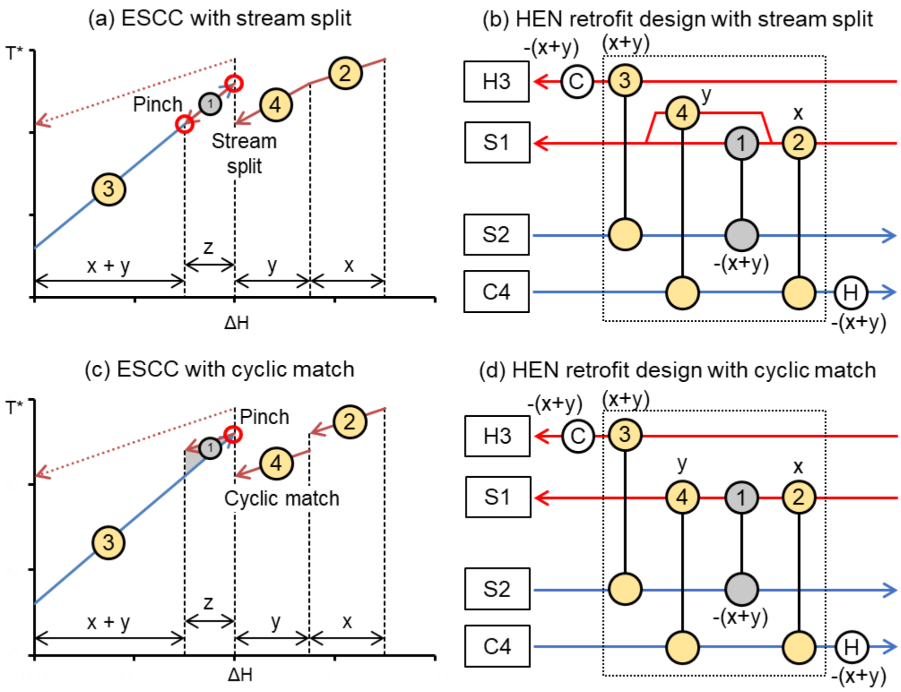

Figure 4: Maximum HEN retrofit with (up to) three new recovery matches including stream splitting and cyclic matching

The learnings from the above analysis can be easily extrapolated to other cases as presented in Table 1. There are nine possible cases. Each case is characterised by the features of the heat profiles of the bridged recovery exchanger: (1) the hot and cold stream outlet temperatures, (2) the hot and cold streams' CPs, and (3) whether the recovery is Pinched or not Pinched.

The previous analysis comprises Case 1A where $T_{h,out} < T_{c,out}$ and $CP_{hot} > CP_{cold}$ with no existing Pinch. For Case 1A, the reintegration of heat surpluses and deficits caused the original recovery exchanger to reach a Pinch point (duty x) beyond which a stream split or cyclic match was required for the hot stream. Case 2 differs from Case 1 in that the recovery exchanger is already Pinched, which means x = 0, as defined in Figure 3a. Case 3 differs again in that $T_{h,out} \geq T_{c,out}$, which means that the reintegration of heat can no longer cause a Pinch and the maximum heat reintegration, ΔH_{max}, is the same as the recovery exchanger duty, Q_{RE}. In all sub-sets of Case 3, there is no requirement for a stream split or cyclic match to achieve maximum reintegration of heat. Likewise, when $CP_{hot} = CP_{cold}$, a stream split or cyclic match is not required for maximum reintegration.

Table 1: Summary of generic Retrofit Bridge analysis

Case	Condition 1: Shifted T_{out}	Condition 2: CP	Condition 3: Existing Pinch	Pinched after Reintegration of x?	Maximum ΔH Reintegration	Stream Split / Cyclic Match?
1A	$T_{h,out} < T_{c,out}$	$CP_{hot} > CP_{cold}$	NO	YES	$\Delta H_{max} < Q_{RE}$	Hot stream
1B	$T_{h,out} < T_{c,out}$	$CP_{hot} < CP_{cold}$	NO	YES	$\Delta H_{max} < Q_{RE}$	Cold stream
1C	$T_{h,out} < T_{c,out}$	$CP_{hot} = CP_{cold}$	NO	YES	$\Delta H_{max} < Q_{RE}$	Not required
2A	$T_{h,out} < T_{c,out}$	$CP_{hot} > CP_{cold}$	YES	N/A (i.e. x = 0)	$\Delta H_{max} < Q_{RE}$	Hot stream
2B	$T_{h,out} < T_{c,out}$	$CP_{hot} < CP_{cold}$	YES	N/A (i.e. x = 0)	$\Delta H_{max} < Q_{RE}$	Cold stream
2C	$T_{h,out} < T_{c,out}$	$CP_{hot} = CP_{cold}$	YES	N/A (i.e. x = 0)	$\Delta H_{max} < Q_{RE}$	Not required
3A	$T_{h,out} \geq T_{c,out}$	$CP_{hot} > CP_{cold}$	NO	NO	$\Delta H_{max} = Q_{RE}$	Not required
3B	$T_{h,out} \geq T_{c,out}$	$CP_{hot} < CP_{cold}$	NO	NO	$\Delta H_{max} = Q_{RE}$	Not required
3C	$T_{h,out} \geq T_{c,out}$	$CP_{hot} = CP_{cold}$	NO	NO	$\Delta H_{max} = Q_{RE}$	Not required

The insights gained from this analysis provides a framework for improving the application of Bridge Analysis. When a recovery exchanger has $T_{h,out} < T_{c,out}$ and $CP_{hot} \neq CP_{cold}$ (Figures 2 - 4), the recovery exchanger may be divided into two sections corresponding to duty x and y as defined in Figure 3. The section corresponding to x will have approaches temperature greater than ΔT_{min} while the section corresponding to y will have one terminal at ΔT_{min}. This second section will require a stream split or cyclic match to be better reintegrated. Using this analysis, it can be known during the Bridge Analysis targeting phase the required features of a retrofit design including the number of heat exchangers as well as whether a stream split or cyclic match is needed. With respect to the HSDT – a key tool to identify Retrofit Bridges, this means that the heat surplus-deficit column for recovery exchangers with $T_{h,out} < T_{c,out}$ is split and represented by two separate cascades. This subtle change has potential to improve help the search for economic reintegration of heat through the Bridge Analysis method.

5. Improved automated Bridge Analysis for Heat Exchanger Network retrofit

The procedure of the improved method compared to Walmsley et al. (2018) is presented in Table 1. Arising from the analysis in this paper is Step 4 where the E-PTA and correspond EGCC is divided into Pinched and non-Pinched sections.

Table 1: Comparison of previous and improved automated HEN retrofit targeting method

Step	Walmsley et al. (2018)	Improved procedure
1	Identify the retrofit problem	Identify the retrofit problem
2	Extract the Retrofit Stream Data	Extract the Retrofit Stream Data
3	Calculate the E-PTA	Calculate the E-PTA
4		Determine Pinched and non-Pinched sections
5	Identify possible Retrofit Bridges (i.e. ART algorithm)	Identify possible Retrofit Bridges (i.e. ART algorithm)
6	Estimate performance metrics: - Number of new or enhanced recovery exchangers - Energy savings - Payback time - Capital investment - Annual profit	Estimate performance metrics: - Number of new or enhanced recovery exchangers (more accurate) - Number of stream splits / cyclic matches - Energy savings - Payback time - Capital investment - Annual profit
7	Select retrofit design (and re-iterate)	Select retrofit design (and re-iterate)
8	Finalise retrofit design	Finalise retrofit design

6. Conclusions

The study analysed a generic case relating to the application of Bridge Analysis, which may be applied to identify HEN retrofit opportunities. Links between the exchanger Composite Curves – ESCC and EGCC – with the required HEN retrofit design were established. Using the lens of Bridge Analysis, the results demonstrated that recovery exchangers can be divided two sections – Pinched and non-Pinched sections – when $T_{h,\,out} < T_{c,out}$ and $CP_{hot} \neq CP_{cold}$. In these cases, Retrofit Bridges often require additional modifications including an extra heat exchanger using a stream split or cyclic match. These results play an important role in refining a recently developed automated HEN retrofit method based on Bridge Analysis. Future work will focus on the application of the refined retrofit method to industrial case studies, evaluating the impacts of a Bridge Retrofit on the heat load of all exchangers, as well as extending the method to Total Site retrofit.

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References

Akpomiemie M.O., Smith R., 2015, Retrofit of heat exchanger networks without topology modifications and additional heat transfer area, Applied Energy, 159, 381–390.

Bonhivers J.-C., Korbel M., Sorin M., Savulescu L., Stuart P.R., 2014, Energy transfer diagram for improving integration of industrial systems, Applied Thermal Engineering, 63(1), 468–479.

Bonhivers J.-C., Srinivasan B., Stuart P.R., 2017, New analysis method to reduce the industrial energy requirements by heat-exchanger network retrofit: Part 1 – Concepts, Applied Thermal Engineering, 119, 659–669.

Čuček L., Kravanja Z., 2016, Retrofit of Total Site Heat Exchanger Networks by Mathematical Programming Approach, Chapter In: Martín M. (Ed.), Alternative Energy Sources and Technologies, Springer International Publishing, New Jersey, USA, 297–340.

Čuček L., Mantelli V., Yong J.Y., Varbanov P.S., Klemeš J.J., Kravanja Z., 2015, A procedure for the retrofitting of large-scale heat exchanger networks for fixed and flexible designs applied to existing refinery total site, Chemical Engineering Transactions, 45, 109–114.

Jiang N., Shelley J.D., Doyle S., Smith R., 2014, Heat exchanger network retrofit with a fixed network structure, Applied Energy, 127, 25–33.

Klemeš J.J. (Ed.), 2013, Handbook of Process Integration (PI): Minimisation of energy and water use, waste and emissions, Woodhead Publishing, Cambridge, UK.

Lai Y.Q., Manan Z.A., Wan Alwi S.R., 2017, Heat exchanger network retrofit using individual stream temperature vs enthalpy plot, Chemical Engineering Transactions, 61, 1651–1656.

Lal N.S., Walmsley T.G., Walmsley M.R.W., Atkins M.J., Neale J.R., 2018, A Novel Heat Exchanger Network Bridge Retrofit Method using the Modified Energy Transfer Diagram, Energy, 155, 190-204.

Nemet A., Klemeš J.J., Varbanov P.S., Mantelli V., 2015, Heat Integration retrofit analysis—an oil refinery case study by Retrofit Tracing Grid Diagram, Frontiers of Chemical Science and Engineering, 9(2), 163–182.

Pan M., Bulatov I., Smith R., 2016, Improving heat recovery in retrofitting heat exchanger networks with heat transfer intensification, pressure drop constraint and fouling mitigation, Applied Energy, 161, 611–626.

Perry S., Klemeš J.J., Bulatov I., 2008, Integrating waste and renewable energy to reduce the carbon footprint of locally integrated energy sectors, Energy, 33(10), 1489–1497.

Smith R., Jobson M., Chen L., 2010, Recent development in the retrofit of heat exchanger networks, Applied Thermal Engineering, 30(16), 2281–2289.

Tarighaleslami A.H., Walmsley T.G., Atkins M.J., Walmsley M.R.W., Neale J.R., 2017, Total Site Heat Integration: Utility selection and optimisation using cost and exergy derivative analysis, Energy, 141, 949–963.

Walmsley M.R.W., Lal N., Walmsley T.G., Atkins M.J., 2017, A Modified Energy Transfer Diagram for Improved Retrofit Bridge Analysis, Chemical Engineering Transactions, 61, 907–912.

Walmsley T.G., Lal N.S., Varbanov P.S., Klemeš J.J., 2018, Automated Retrofit Targeting of Heat Exchanger Networks, Frontiers of Chemical Science and Engineering, DOI: 10.1007/s11705-018-1747-2.

Yong J.Y., Varbanov P.S., Klemeš J.J., 2015, Heat exchanger network retrofit supported by extended Grid Diagram and heat path development, Applied Thermal Engineering, 89, 1033–1045.