Tools and Methods in Aiding Heat Exchanger Network Retrofit for Better Economic Performance

Abstract for PhD Thesis

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Abstract

This thesis presents novel tools and methods developed specifically to be used during Heat Exchanger Network retrofit for better economic performance. The very first step in starting a retrofit process is collecting and extracting data from measured sets of process data. In the first discovery of this work, a novel method is proposed to ease the process of reconciling data of Heat Exchanger Network for the purpose of Heat Integration analysis. An iterative Method is introduced in the first part of this work differs from conventional data reconciliation method. The method is explained in detail - including its models used and algorithms. Two case studies, an illustrative and an industrial, successfully demonstrate the application of the method. Detailed discussions are given such as the effect of starting parameters to reconcile on the result. A limitation of the Iterative Method was identified and several strategies has been developed to overcome it. In the case studies, the strategies combining the Iterative Method are able to yield satisfying results. This comes at the expense of additional parameters into the models. The scope of data reconciliation is then expended to Total Site. Considering the complexity of Total Site, the model only includes utility systems and equipment, such as heaters, coolers and turbines. Heat exchangers in each individual plant are not considered in the model.

After obtaining the reconciled set of parameters, the next step is to represent them related to the Heat Exchanger Network structure. While the conventional Grid Diagram contains sufficient information for the retrofit process, it does not visualise the data sufficiently well for user interaction and decision making. The second discovery introduces a novel tool to represent all data required for Heat Exchanger Network retrofit in more detail, better supporting the engineer decision during the retrofit process. This tool is the Shifted Retrofit Thermodynamic Diagram. It includes the characteristics of Pinch Analysis. It can be used to easily identify not only the Process Pinch, but also any Network Pinch as well as Utility Pinch occurrences. With better visualisation, several ways are discussed of how to utilise this novel tool for better increase in heat recovery. A case study from the literature is used extensively to demonstrate the use and usefulness of Shifted Retrofit Thermodynamic Diagram.

Although a retrofit action can be thermodynamically feasible, it might not be economically feasible to be implemented. The last chapter is about the discovery of an alternative method to retrofit an existing Heat Exchanger Network, particularly reusing the waste heat. It is demonstrated using a real industrial case study, where it requires a large amount of investment cost to achieve the first retrofit result. In the case study, it is proposed otherwise that the waste heat is reused to heat up some streams. This reduces the utilities consumptions. Although it is similar to the initial proposed retrofit suggestion in terms of utilities saved, performs much better in terms of cost savings and payback.

1. Introduction

It has been four decades since Heat Integration analysis has been introduced for energy recovery in chemical plants (Klemeš and Kravanja, 2013). An important part of physical-insight methods is Process Integration. One of the first works on this has been that of Linnhoff and Flower (1978). The development up to present level has been summarised elsewhere (Klemeš et al., 2014) and specifically for Heat Integration in (Klemeš and Kravanja, 2013). Bakhtiari and Bedard (2013) modified the Network Pinch Approach to handle more complex networks with stream segmentation and splitting, also using heat exchanger specific values for the minimum allowed temperature difference.

While it is important to have Heat Integration in chemical plants, retrofitting an existing HEN is also important (Klemeš, 2013). It is observed that the recent focus of Heat Integration has shifted towards retrofitting existing chemical plants. This is due to existing Heat Exchanger Networks (HEN) have become obsolete after years of service. Chemical, petrochemical, power and other industries are keen to improve the energy efficiency of their plants due to the energy cost (BP, 2013) and increasingly strict environmental regulations (European Commission, 2011). With current fluctuating energy prices, increased production and change in process equipment, retrofitting can reduce operating cost with some capital investment. Various methods have been published for solving the retrofit problem. They are generally based on physical insight, mathematical optimisation or combination of both.

The first step of starting a retrofit process in HEN is data extraction on existing HEN. Design value data maybe obsolete and not accurate after years of adjustment and unit additions. Data reconciliation is an important step in the process of extracting data for retrofitting heat exchanger. Only two types of parameters needed to be reconciled in the process. Of all the constraints used, energy balance constraint causes the non-linearity in the model as it contains two types of parameters. A new method is introduced to solve this non-linearity in section 3.2 that iterates between two linear sub-models. Through case studies iterative method is shown to be able to provide satisfying result with less computational time. In section 3.3, limitation encountered when using iterative method is discussed. To overcome this limitation, three different strategies are developed. Section 3.4 presents a new way to solve data reconciliation problem on Total Site. Model to solve data reconciliation on utility system is presented with demonstration from both illustrative case study and industrial case study. Overall, the iterative method is shown to have less computational effort in the expense of lower accuracy, when compared to simultaneous method. It is suitable to be used in Heat Integration study particularly retrofitting heat exchange network, which does not need high level of accurate data.

After having the reconciled data, the next step is to construct HEN grid diagram for analysis. Using conventional grid diagram is insufficient and inconvenience during the heat integration analysis. An advance visualising tool for HEN is needed to ease the heat integration analysis. Section 4 introduced an extended Grid Diagram – the Shifted Retrofit Thermodynamic Grid Diagram (SRTGD). SRTGD has unique feature set, helping to identify favourable retrofit options. Since it shows in the same view CP (or load), temperatures and the network, it allows the users to simultaneously account for the thermodynamics, stream capacities and the topology as factors. As a result, SRTGD can be efficiently used to incorporate Pinch Technology, identify Process Pinches and Network Pinches. The provided examples and the case study clearly illustrate the advantages offered by the new tool. It has been demonstrated that SRTGD is capable of screening feasible from infeasible solutions, providing visual information in choosing more favourable heat paths. When a heat path is chosen, SRTGD points to the location of potential Network Pinches as well as the maximum heat recovery achievable. However, the main importance comes with the possibility to assess the retrofit options for fluctuating energy prices and forecastles.

A matrix representation of HENs is proposed in section 4 to support synthesis or retrofit tasks. It can be well-organised and can help engineers in analysing the system with preserved accuracy. HENSM records all the temperatures, temperature differences and duties of all heat exchangers in a HEN. Using the temperature differences at heat exchanger ends, the matrix is able to support the location of Process and Network Pinches. During retrofit Path Analysis, the potential of a heat exchanger in becoming a Network Pinch is shown in the matrix. HENSM is demonstrated on a case study. The matrix so far can’t deal stream splitting.

During the process of heat integration analysis, there are some cases where retrofitting HEN for utility consumption reduction is infeasible in other aspect. The proposed HEN retrofit is thermodynamically feasible but might not be economically feasible. Particularly in the low temperature region in HEN where it is generally regarded as waste heat, most of the heat in this region is not recovered. If that is the case, waste heat can be utilised during the HEN retrofication. Section 5 has successfully showed that when utility cannot be reduced due to economic reason, waste heat utilisation can be another option for this. Using an illustrative case study and an industrial case study, it is noted that it is determined that waste heat streams have too low temperature to reduce utilities consumption. Attempt to construct heat path for this purpose in this case study will lead to high investment cost. Therefore, the HEN is then modified to generate hot water from the waste heat streams instead. The section discussed different arrangements of heat exchanger and the effects of its flexibility and complexity under different conditions.

2. Tools and methods proposed

2.1 Iterative Method for Data Reconciliation on Energy System

The iterative method is an alternative to the simultaneous method. The method partitions the model used in the simultaneous method into two sub-models. Iterating between the two sub-models, the method keeps one type of parameters constant (e.g. *T*) while reconciling the parameters of the other type (e.g. *CP*), until satisfactory convergence is achieved. Two types of parameters are reconciled separately while still maintaining the importance of other parameters in the models. Although the iterative method features some inaccuracy, compared to the simultaneous method, it is significantly less computationally intensive and simple to implement. Figure 3.1 shows the models used in iterative method. Figure 3.2 shows the algorithm to deploy these models.

CP Model	T Model
$Min \sum_{i}^{I} \sum_{s}^{S} \sum_{n}^{N} \left(RCP_{i,s} - CP_{i,s,n}\right)^2$ (3.9)	$Min \sum_{i}^{I} \sum_{s}^{S} \sum_{n}^{N} \left(RT_{i,s} - T_{i,s,n}\right)^2$ (3.10)
subject to:	subject to:
Mass balance constraints	
$RCP_{i,HI} = RCP_{i,HO}$ (3.2)	
$RCP_{i,CI} = RCP_{i,CO}$ (3.3)	
Energy balance constraints	Energy balance constraints
$RCP_{i,HI}\left(RT_{i,HI} - RT_{i,HO}\right) = RCP_{i,CI}\left(RT\right.$ (3.4)	$RCP_{i,HI}\left(RT_{i,HI} - RT_{i,HO}\right) = RCP_{i,CI}\left(R\right.$ (3.4)
where RT is set to be constant	where RCP is set to be constant
Constraints from network for example	Constraints from network for example
$RCP_{i1,HO} = RCP_{i2,HI}$ (3.5)	$RT_{i1,HO} = RT_{i2,HI}$ (3.7)
$RCP_{i1,CO} = RCP_{i2,CI}$ (3.6)	$RT_{i1,CO} = RT_{i2,CI}$ (3.8)

Figure 3.1: Equations used in CP model and T model

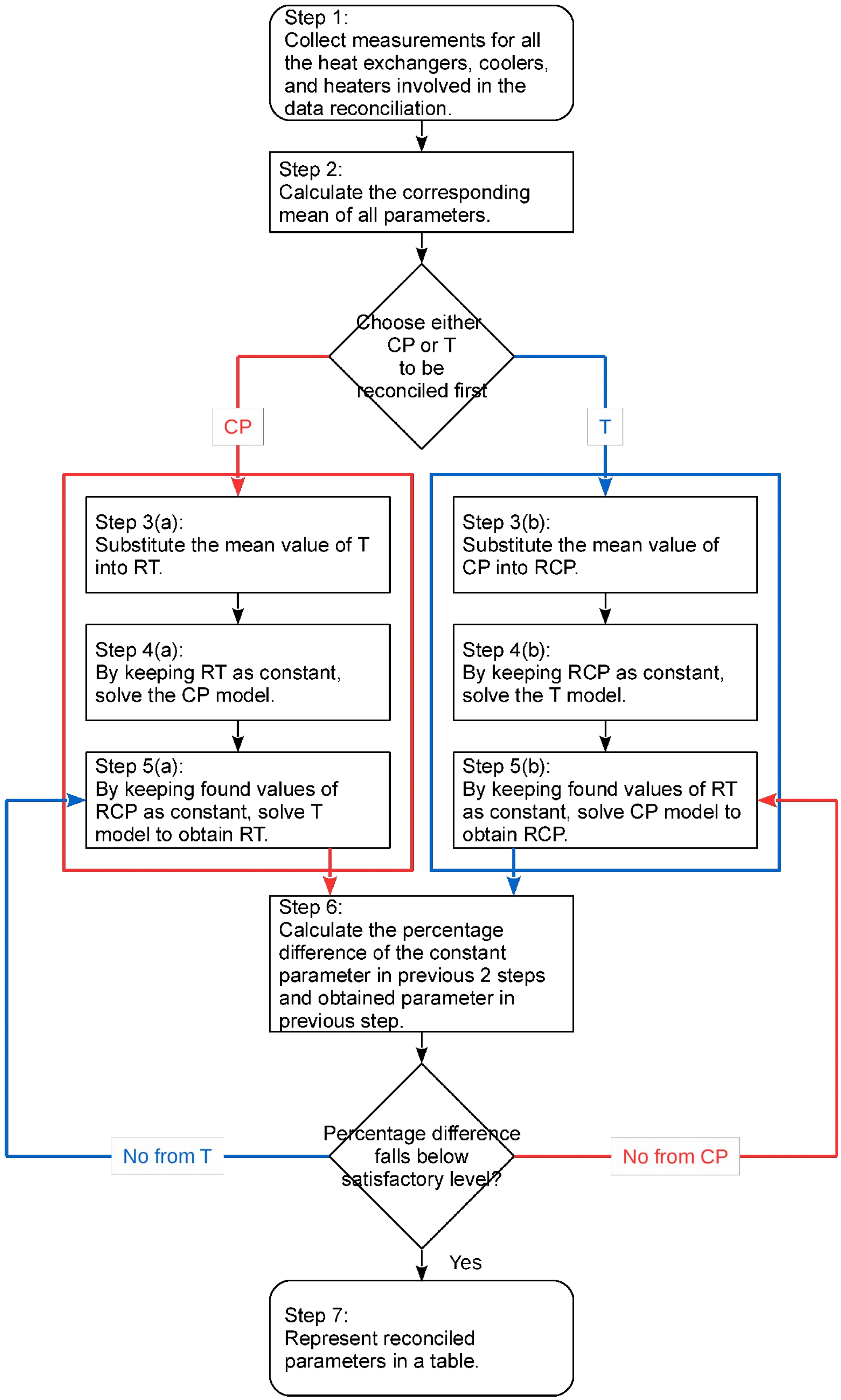

Figure 3.2: Algorithms of proposed iterative method

Within a Total Site there are large amount of heat exchangers, heaters and coolers. Each chemical plant has its own individual sets of chemical equipment and HENs. One common and only characteristic among these chemical plants is they are connected to the same utilities systems. Instead of including all heat exchangers in every plant in the data reconciliation problem, utility system can be reconciled first. After obtaining the reconciled result for utility system, each HEN from each plant can be reconciled using the method introduced in previous sections.

It is assumed that all utilities used in the Total Site do not mix. Each type of utilities used (e.g. steam, hot oil, cooling water) has its own sets of steam headers. All steam headers, coolers and heaters are modelled as black boxes. In Heat Integration analysis, flows in steam header diagram are usually expressed in terms of energy flowrate, such as kW. It should be noted that energy flowrate cannot be measured directly. In data reconciliation process, all flows are measured and expressed in terms of mass flowrate instead. Especially for heaters or coolers using non-isothermal utilities, the supply and return streams are measured in terms of mass flowrates. By doing so the objective function only includes mass flowrates and subject to mass balance constraint around the equipment.

2.2 Advanced Visualisation for Retrofitting Heat Exchanger Network in Heat Integration

To represent a heat exchanger network graphically, conventional Grid Diagram is usually used. However, conventional Grid Diagram is not fully showing certain important features, such as importance of heat capacity and location of Pinch. There is still a need for a suitable visualisation and decision-making tool that would be capable of identifying, using and overcoming HEN bottlenecks, enabling more heat recovery. Such a tool is important as it can help users to make decisions and can also efficiently support formulation of mathematical optimisation models. As such, Shifted Retrofit Thermodynamic Grid Diagram is proposed in this work.

The characteristics of SRTGD are as follows. The horizontal axis tracks the temperature scale, while the vertical axis represents the CP scale. All the streams are represented by rectangles. The width of a rectangle is drawn according to the temperature span of the stream while the height is drawn according to the CP. The area of the bar represents the amount of heat available for exchange. The stream may be divided into segments where each segment represents the stream involvement in a heat exchanger. As shown in Figure 4.3, there are two segments of two streams numbered as 2. These are hot and cold parts of heat exchanger E2 and they belong to streams HS2 and CS1. In heat exchanger E2, the lines labelled ① and ② are called cold end link and hot end link for that heat exchanger.

There are two links at the ends of every recovery heat exchanger, while heaters and coolers are denoted only as segments on the stream rectangles. The links are important because they indicate the thermodynamic feasibility of heat transfer. As the hot stream temperatures are shifted by subtracting ΔT_{min} from their actual temperatures, a vertical link (with zero temperature span) indicates a Pinch Point, be it either Process Pinch (PP) or NP. For feasible heat transfer the heat exchanger links should have positive slope, as this is equivalent to hot streams having higher temperatures than the matched cold streams.

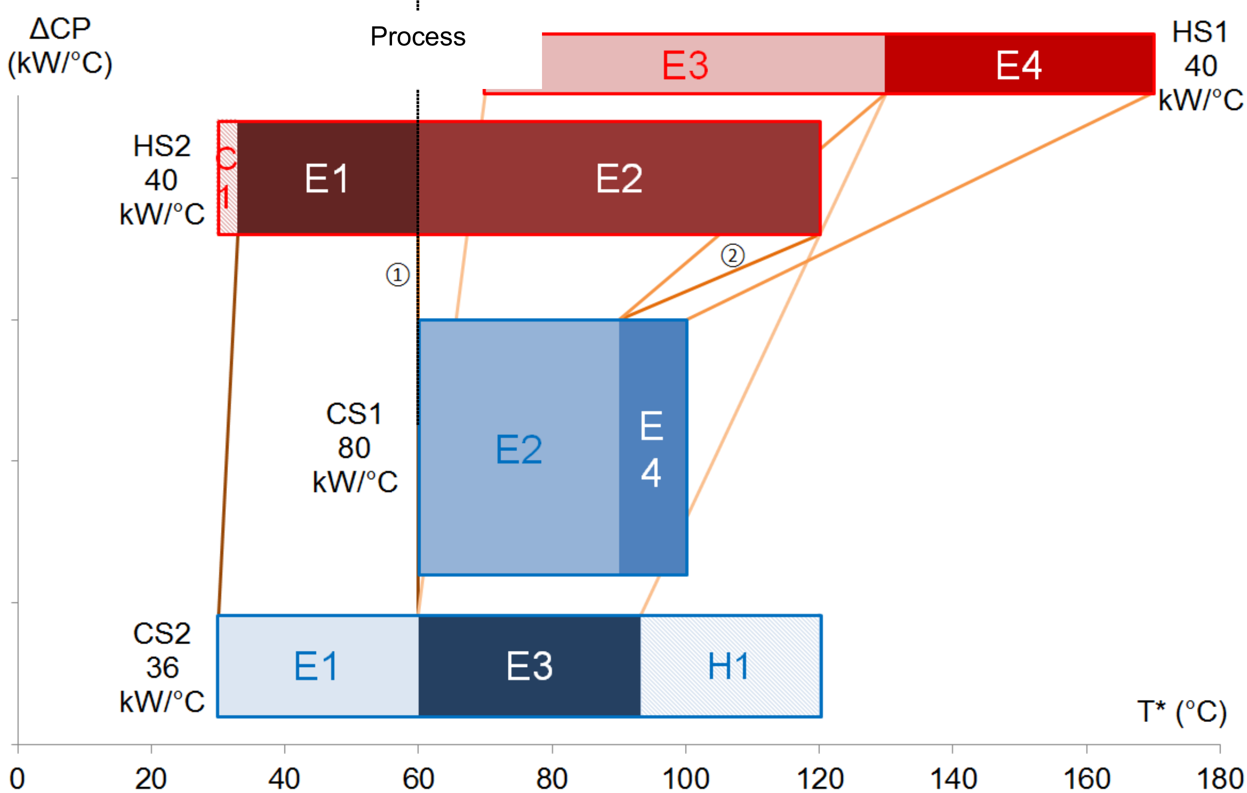

Figure 4.3: An example of a HEN represented using SRTGD

Graphical HEN representations have some limitations. (i) The data accuracy is reduced using graphical representation. Exact values cannot be retrieved directly. (ii) The graphical representation becomes complicated when there are too many heat exchangers in the HEN. (iii) Important data such as temperature differences at the ends of heat exchangers are not able to be directly shown on the graph.

The suggestion to represent HEN numerically in a matrix form is proposed. HEN Stream Matrix (HENSM) is able to improve the discussed limitations faced by graphical representations. However, HENSM doesn't provide the same insight as the graph and should be used in the combination. The data for each heat exchanger are recorded numerically and can be retrieved directly and accurate. This matrix is also able to record a HEN with high number of heat exchangers, as it does not use lines or connectors. This is a well-organised representation and is able to help to process the analysis. Temperature differences can be traced and evaluated directly, which helps in locating Pinches. During heat path tracing in retrofit analysis, the bottleneck heat exchanger limiting the heat recovery can be determined directly. Using the proposed matrix format to represent a HEN helps to increase the clarity.

					Hot Stm	H1	H1	H1	H2	H3	H4	H5			
					CP (kW/°C)	86	86	86	21	185	24	129			
					TS (°C)	310	239	167	299	273	230	206			
					TT (°C)	239	167	103	173	254	133	178			
HEX No.	Cold Stm	CP (kW/°C)	TS (°C)	TT (°C)									Heater Duty (kW)	HETD (°C)	CETD (°C)
3	C1	144	52	91				5,557						66.6	40.6
7	C1	144	91	116								3,623		80.2	77.4
6	C1	144	116	132							2,292			88.3	6.7
4	C1	144	132	150					2,689					138.6	31.6
2	C1	144	150	193			6,135							35.6	6.8
5	C1	144	193	217						3,431				46.1	51.4
1	C1	144	217	260		6,141							14,453	40.4	11.7
					Cooler Duty (kW)			657	1,142	817	881				

Table 4.5: HENSM representation of the case study

2.3 Heat Exchanger Network Modification for Waste Heat Utilisation

For hot water generation, the first step is to determine the supply and required target temperature. The minimum temperature difference between the stream and hot water should be determined as well. Using more advanced graphical HEN representations, such as SRTGD, it is able to locate the temperature region that is capable of producing hot water. The amount of hot water produced can be calculated from the heat load in the temperature region. Preliminary economic analysis can be done by just calculating the capital cost and revenue by selling the hot water generated. Further economic analysis can be done by including the arrangement of the hot water generation circuit and heat exchangers need.

There are three different general arrangement for the hot water circuit:

1. Parallel water heating with splitting the utility generation stream

2. Series water heating with one main stream of water

3. Combination of parallel and series water heating

While they have advantages against each other, the choice of which arrangement is dependent and on case by case basis.

3. Novel Scientific Developments in the Current Thesis

Thesis 1: The first discovery is Data Reconciliation on existing Heat Exchanger Network (HEN) for the purpose of Heat Integration and Pinch Analysis. This is a crucial step before any retrofit process can be commerce. There are only two types of parameters to be reconciled, which is mass flowrate and temperature. As each network having numerous heat exchangers, each heat exchanger is given a set of temperature and flowrate data. The complexity arises when the constraint equations used in the model is highly non-linear. Conventional method that used in the data reconciliation process is too computational effort demanding. Iterative method is introduced in this work to solve the non-linearity occurred during the data reconciliation process. Iterative method provides accurate result with less computational effort. Although Iterative Method has limitations, strategies are also developed in this work to solve these limitations. The scope is then extended to energy and steam system at Total Site level. Without complicating the model, as Total Site has numerous heat exchangers, only equipment involved in the energy and steam system are reconciled first. *(Related Publication: P[4], P[5])*

Thesis 2 : The second discovery derived from HEN Grid Diagram. A new representative diagram is introduced called Shifted Retrofit Thermodynamic Grid Diagram (SRTGD) that is used during retrofit process. Compared to conventional Grid Diagram, SRTGD displays heat capacity of each stream on y-axis, while maintaining temperature differences on x-axis. SRTGD does not only shows heat duty of each heat exchanger according to the area enclosed, but the locations of pinches as well. SRTGD is also shown in the work for retrofitting existing HEN. Early concept of a matrix representation is discussed as well, called HEN Matrix. Such representation reduces the hassle of drawing any graphical representation and can be used to serve as an input for simulation software. *(Related Publication: P[2], P[6], P[8])*

Thesis 3: The third discovery is the waste heat utilisation for utility generation. The general purpose of retrofitting HEN is to reduce the amount of utility consumption. By using various tools such as Pinch Analysis, minimum utility consumption can be targeted and improvement can be made from towards the target. It is noted that there are some cases that although the suggested HEN retrofit options are thermodynamically feasible, it is infeasible in other aspects. Economic feasibility is one of the factors hindering the progress of the HEN retrofit. After Heat Integration Analysis being performed, it may be concluded that although the retrofit is feasible but economic infeasible. Particularly in the low temperature region of the HEN, such low temperature streams are often considered waste heat and generally discarded. In this work discussion is made on how to utilise such waste heat to generate utility for additional revenue. Simple steps in identifying the potential of waste heat in the streams to be utilised are presented. The configuration of hot water generation circuit is discussed and gave a general idea on how to maximise the usage of waste heat that otherwise ignored. *(Related Publication: P[1], P[7], P[12])*

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5. List of Publications

P[1] **Yong J.Y.**, Klemeš J.J., Varbanov P.S., Huisingh D., 2015, Cleaner energy for cleaner production: modelling, simulation, optimisation and waste management, Journal of Cleaner Production, 111, 1-16. (IF: 5.651, citation: 46)

P[2] **Yong J.Y.**, Varbanov P.S., Klemeš J.J., Heat Exchanger Network Retrofit supported by Extended Grid Diagram and Heat Path Development, 2015, Applied Thermal Engineering, 89, 1033-1045. (IF: 3.771, citation: 11)

P[3] Liu Z.-Y., Varbanov P.S., Klemeš J.J., **Yong J.Y.**, 2016, Recent developments in applied thermal engineering: Process integration, heat exchangers, enhanced heat transfer, solar thermal energy, combustion and high temperature processes and thermal process modelling, Applied Thermal Engineering, 105, 755-762. (IF: 3,771, citation: 5)

P[4] **Yong J.Y.**, Nemet A., Varbanov P.S., Kravanja Z., Klemeš J.J., 2016, Data reconciliation for total site integration, Chemical Engineering Transactions, 52, 1045-1050. (citation: 2)

P[5] **Yong J.Y**., Nemet A., Bogataj M., Zore Ž., Varbanov P.S., Kravanja Z., Klemeš J.J., 2016, Data Reconciliation for Energy System Flowsheets, Computer Aided Chemical Engineering, 38, 2277-2282. (citation: 1)

P[6] **Yong J.Y.**, Varbanov P.S., Klemeš J.J., 2015, Matrix representation of the grid diagram for heat exchanger networks, Chemical Engineering Transactions, 45, 103-108. (citation: 1)

P[7] **Yong J.Y.**, Nemet A., Varbanov P.S., Klemeš J.J., Čuček L., Kravanja Z., Mantelli V., 2015, Heat exchanger network modification for waste heat utilisation under varying feed conditions, Chemical Engineering Transactions, 43, 1279-1284.

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P[12] 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, CET, 45, 109-114.

P[13] Čuček L., **Yong J.Y.**, Mantelli V., Vocciante M., Varbanov P.S., Klemeš J.J., Karlopoulos, E., Kravanja, Z., 2014, Data acquisition and analysis of total sites under varying operational conditions, CET, 39, 1819-1824.

6. Reviews Completed

Journals	**Number of Reviews**
Chemical Engineering Transactions (CET)	48
Journal of Clear Production (JCLEPRO)	28
Energy (EGY)	23
Applied Energy (APEN)	5
Computer Aided Chemical Engineering (CACE)	3
TOTAL	**107**