Automated Retrofit

of Heat Exchanger Networks

A thesis

submitted in fulfilment

of the requirements for the degree

of

Doctor of Philosophy in Engineering

at

The University of Waikato

by

NATHAN SANJAY LAL

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

2020

Abstract

In a large industrial processing plant, a significant amount of process heat is generated using fossil fuels, contributing to New Zealand's overall greenhouse gas emissions. While New Zealand's renewable energy sources present potential alternatives to fossil fuels, reducing the process heat demand of industrial processing plants is another critical step for emissions reduction, with multiple long-term economic and environmental benefits. Reducing process heat demand often centres on retrofitting the heat exchanger network to improve heat recovery and lower the hot utility consumption.

This thesis presents a comprehensive automated retrofit design method for heat exchanger networks, fulfilling several gaps in current knowledge. The novel contributions are presented and discussed in four main chapters: (1) two retrofit tools are developed that enable visualisation of the problem – the Modified Energy Transfer Diagram and the Heat Surplus-Deficit Table, (2) an algorithm called Automated Retrofit Targeting that searches for all possible retrofit modifications of the heat exchanger network that unlocks energy savings, (3) a comprehensive energy retrofit planning tool that uses a multi-stage retrofit analysis to provide strategic long-term and cost-effective retrofit plans, and (4) an heat exchanger network simulation method, incorporating using Monte Carlo Simulation, to quantify the effect of variable process flows and temperatures on flexibility and steady state performance.

The developed methods are illustrated using a simple four-stream network and then applied to two industrial case studies that are representative of some of the large industrial energy-users in New Zealand: a paper mill at a Kraft pulp and paper mill cluster and a petrochemical complex. In both case studies, numerous potential retrofit designs have been identified. These options are reduced to those that ranked as the most cost-effective, using thermodynamic and economic constraints with Pareto front analysis. By successive application of the retrofit method, long-term retrofit plans have been proposed, enabling strategic sequencing of modifications and minimising process heat demand. For the petrochemical complex, the hot utility consumption could decrease by 9.58 MW (63% of the total possible savings) using four separate stages of retrofits. The total retrofit profit would reach 1.5 million Euros per year with a simple payback of 1.7 years. The paper mill could achieve its process heat demand reduction target using four retrofit stages, achieving a total retrofit profit of 0.78 million NZD per year. These modifications resulted in an inflexibility of 51.3% (probability of the heat exchanger network failing to meet all target temperatures), but this could be reduced to 4.1% using bypass control.

This thesis provides a novel retrofit method, which uses graphical and numerical tools, in combination with automated analysis, generating and evaluating cost-effective retrofit designs. The retrofit design method has been implemented in Microsoft Excel^{TM} as a critical and functional output that can be rapidly applied to complex industrial heat exchanger networks.

Acknowledgements

Completing a PhD is never easy, and without the support given to me by my supervisors, friends, and family over the last three years, I would have been lost. My biggest thanks go to my chief supervisor Dr Martin Atkins and secondary supervisor Dr Timothy Walmsley. The guidance they have given me over the last three years has been insurmountable. My deepest gratitude to Dr Timothy Walmsley for his vigorous support, despite being on the other side of the planet for most of the time. I also thank my other supervisors, Professor Michael Walmsley, who first introduced me to the Energy Research Group and got the ball rolling, and Dr James Neale, for his support. Thank you very much to the Todd Foundation and the University of Waikato for the financial support that made it all possible.

During my PhD, I have had several opportunities for international collaboration and exchanges. Thank you very much to Professor Jiří Klemeš, Dr Petar Varbanov and the rest of the team in the Sustainable Process Integration Laboratory at Brno University of Technology (Brno, Czechia), as well as Professor Santanu Bandyopadhyay at the Indian Institute of Technology Bombay (Mumbai, India) – I had a wonderful time and learned a lot.

At the University of Waikato, there are also several other people I would like to acknowledge for their support. Big thanks to the Energy Research Group, especially Dr Amir Tarighaleslami (امیر داداش) and Ms Danielle Bertram (D.A.N.I. 2000) for their wisdom and moral support, as we trudged through postgraduate life together, as well as the revolving door of foreign exchange students with whom I found new friends and new people to practice foreign languages with. Gracias, danke, merci. And even though he has moved on to greener Swiss pastures, thank you to Dr Benjamin Ong for being both a thorn in my side and a great friend. I would also like to thank Associate Professor James Carson for being a mentor to me throughout my undergraduate years.

Thank you to my family for all the love and support that you have provided over the years. Thank you, Mum and Dad, for raising me to be the person I am today and giving me the tools I needed to finish a PhD. Thank you too, Chaya, and the rest of my wonderful family, including my uncle Ted, who gave me a place to stay when I needed it, and my grandparents, who are always so proud of me. I love you all, thank you. I hope you enjoy this thesis.

Contributing Publications

The contributions and results presented in this thesis have been published in several international engineering journals over the last three years. The research has also been presented at several national and international conferences (most notably, the PRES conference in 2018 and 2019).

Concerning the chapters of this thesis, significant parts of the literature review in Chapter 2 have been published in Renewable and Sustainable Energy Reviews [1]. Most of the contributions in Chapter 3 have been published in both Chemical Engineering Transactions [8] and Energy [5]. The methods presented in Chapter 6 have been published in Chemical Engineering Transactions [3, 7] and Energy [2]. Most of the work in Chapter 4 has been published in Chemical Engineering Transactions [6] and Frontiers of Chemical Science and Engineering [4]. Two papers have also been published that have been specifically based around the works in this thesis; however, the published work is not presented in the thesis. One of these papers was published in Chemical Engineering Transactions [9] and the other has been published in the ASTFE Digital Library as conference proceedings for the 2019 American Society of Thermal and Fluids Engineers Conference [10]. A final paper, based on the work in Chapter 5, has been submitted to the Journal of Process Integration and Optimization for Sustainability as of July 2020 [11].

Published

[1] Jiri J. Klemes, Qui-Wang Wang, Petar S. Varbanov, Min Zeng, Hon Huin Chin, **Nathan S. Lal**, Nian-Qi Li, Bohong Wang, Xue-Chao Wang, Timothy G. Walmsley. (2020). Heat transfer enhancement, intensification and optimisation in heat exchanger network retrofit operation. *Renewable and Sustainable Energy Reviews.*

[2] **Nathan S. Lal**, Martin J. Atkins, Timothy G. Walmsley, Michael R.W. Walmsley, James R. Neale. (2019). Insightful heat exchanger network retrofit design using Monte Carlo simulation. *Energy*, 181, 1129-1141.

[3] **Nathan S. Lal**, Martin J. Atkins, Timothy G. Walmsley, Michael R.W. Walmsley, James R. Neale. (2019). Flexibility analysis of heat exchanger network retrofit designs using Monte Carlo simulation. *Chemical Engineering Transactions,* 76, 463-468.

[4] Timothy G. Walmsley, **Nathan S. Lal**, Petar S. Varbanov, Jiří J. Klemeš. (2018). Automated retrofit targeting for heat exchanger networks. *Frontiers of Chemical Science and Engineering*, 12(4), 630-642.

[5] **Nathan S. Lal**, Timothy G. Walmsley, Michael R.W. Walmsley, Martin J. Atkins, James R. Neale. (2018). A novel heat exchanger network bridge retrofit method using the modified energy transfer diagram. *Energy*, 155, 190-204.

[6] **Nathan S. Lal**, Timothy G. Walmsley, Martin J. Atkins, Michael R.W. Walmsley, James R. Neale. (2018). Solving complex retrofit problems using constraints and bridge analysis. *Chemical Engineering Transactions,* 70, 1951-1956.

[7] **Nathan S. Lal**, Martin J. Atkins, Michael R.W. Walmsley, James R. Neale, Timothy G. Walmsley. (2018) Accounting for stream variability in retrofit problems using Monte Carlo simulation. *Chemical Engineering Transactions*, 70, 1015-1020.

[8] Michael R.W. Walmsley, **Nathan S. Lal**, Timothy G. Walmsley, Martin J. Atkins. (2017). A modified energy transfer diagram for heat exchanger network retrofit bridge analysis. *Chemical Engineering Transactions*, 61, 907-912.

Supplementary

[9] Timothy G. Walmsley, **Nathan S. Lal**, Petar S. Varbanov, Jiří J. Klemeš. (2018). Relating bridge analysis for heat exchanger network retrofit identification to retrofit design. *Chemical Engineering Transactions,* 70, 295-300.

[10] Timothy G. Walmsley, Petar S. Varbanov, **Nathan S. Lal**, Jiří J. Klemeš. (2019). Visualisation of large-scale heat exchanger networks to support energy retrofit. *ASTFE Digital Library*, Begel House Inc.

Submitted and Awaiting Acceptance

[11] **Nathan S. Lal**, Timothy G. Walmsley, Martin J. Atkins, Michael R.W. Walmsley. (2020) Industrial energy retrofit planning using Automated Retrofit Targeting. *Process Integration and Optimization for Sustainability*

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background

Climate change is one of the biggest threats facing current and future generations, and many countries have recognised that urgent action must be taken to mitigate the adverse effects of rising global temperatures and reduce future impact. The challenge is finding meaningful and cost-effective solutions that can incentivise the necessary reductions in greenhouse gas (GHG) emissions. A great emphasis has been placed on reducing the use of fossil fuels (e.g., natural gas) in industrial processing plants, due to their significant contribution to GHG emissions (MBIE & EECA, 2019). Fuel switching to renewable energy sources, such as hydropower or solar, provides good opportunities for reducing the dependency on fossil fuels. Fortunately, renewable energy sources are abundant in New Zealand and dominate New Zealand's electricity generation (~84% of electricity was generated through renewables in 2018 (MBIE, 2019)); however, the same is not true for the process heating that many of New Zealand's industrial energy-users rely on.

Fuel switching at an industrial processing plant can reduce process heat emissions, but it is often hindered by the availability of cost-effective renewable alternatives, the high cost of investment, and the uncertainty around energy policies and prices. To incentivise GHG emissions reductions and fuel switching, the New Zealand Emissions Trading Scheme has already introduced a carbon price; however, with the relatively low cost of fossil fuels, it is difficult to find economical solutions based around fuel switching. For example, switching away from natural gas does not become economical until the carbon price reaches around 120 NZD/$t_{CO2\text{-}e}$ – a significantly higher price than the current price of ~25 NZD/$t_{CO2\text{-}e}$ (Interim Climate Change Committee, 2019). Instead, energy efficiency improvements have great potential for mitigating climate change and can be economically viable regardless of carbon prices (KBC, 2019). Through energy efficiency improvements, the demand for process heat demand can be reduced, lowering GHG emissions and the overall operating costs. There may also be several long-term benefits as it can decrease the cost of future fuel switching, electrification, or carbon capture.

In an industrial process, process heating is achieved using hot utilities (e.g., coal boiler, steam); however, heat can also be recovered from hot process streams to provide heating to cold process streams. In Figure 1.1a, there is a hot stream coming from a reactor and a cold stream coming from a flash tank. These streams are matched together in a heat exchanger where heat is recovered and exchanged. If the heating, or cooling, requirement is not met, then utilities are required to meet the demand. If more heat can be recovered and used for heating, then less hot utility will be required – providing many benefits regardless of whether the hot utility uses fossil fuels or renewable energy.

Heat recovery is made possible with a heat exchanger network (HEN). A HEN enables the process streams in an industrial processing plant to be heated or cooled to specification using a network of heat exchangers (process-to-process) and utility exchangers (hot and cold) (Figure 1.1b). The amount of heat recovery can be increased by modifying the HEN's operation or structure – this is called retrofitting. Retrofitting is critically important for improving the environmental and economic sustainability of industrial plants, especially as the HENs of existing plants are often less efficient due to the vintage or the technology that was available at the time of commissioning.

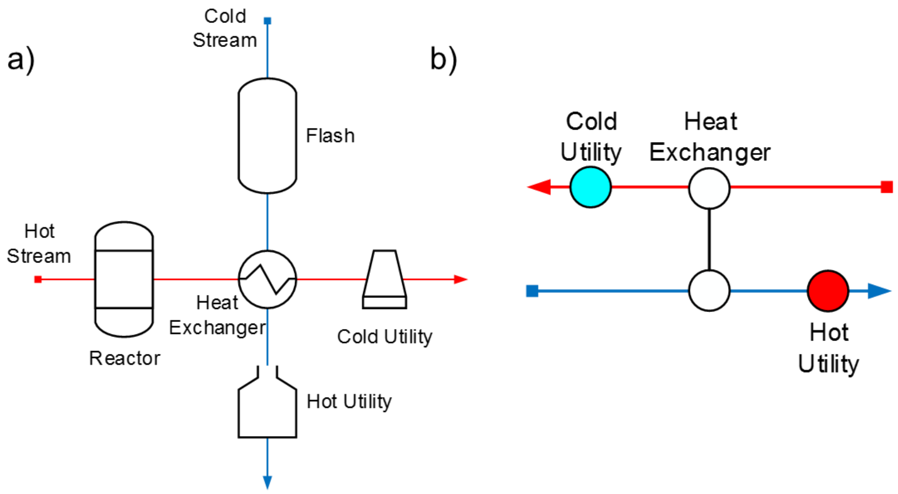


Figure 1.1: a) A simple process flow diagram and b) the corresponding heat exchanger network.

Techniques and methods for increasing the heat recovery and energy efficiency of the HEN have been well-developed, under the umbrella of Process Integration, since the oil crises in the 1970s incentivised cost-reductions. One standout method is Pinch Analysis (PA), which is centred on the concept of a Pinch temperature – a bottleneck in heat transfer (due to temperature driving forces) that is used to guide the design of the HEN towards greater heat recovery and minimal use of utility. PA featured the use of diagrammatical tools such as the Grand Composite Curve to present the fundamental concepts and guide the method. PA has been so successful and applicable that analogues have been developed for water (Y. P. Wang & Smith, 1994), hydrogen (Towler et al., 1996), carbon emissions (Tan & Foo, 2007), and more. However, traditional PA is primarily used for HEN synthesis (i.e., new HENs) and is not as well-suited for the retrofit of existing HENs. PA does not characterise the exchanger units that already exist in the HEN nor utilise this information in a formalised retrofit design method.

Despite these issues, elements of PA have been adapted for the design of retrofit HEN in several – often diagrammatical (graphical) – methods. Graphical retrofit methods typically allow the user to make retrofit design choices based on concepts like the Pinch temperature; however, there is little support for ensuring that retrofit design solutions are even cost-effective. Graphical methods and tools also become cumbersome to use for retrofitting larger HENs. In recent years, there has been a resurgence of graphical retrofit design methods, including Bridge Analysis (Bonhivers, Srinivasan, et al., 2017), which uses a graphical tool known as the Energy Transfer Diagram to represent the existing HEN structure and identify retrofit opportunities (Figure 1.2a). Other recent examples include the STEP (stream temperature and enthalpy plot) method (Lai et al., 2017), which graphically maps hot and cold process streams for a simple retrofit analysis (Figure 1.2b), and the temperature driving force (TDF) plot method (Kamel, Gadalla, Abdelaziz, et al., 2017), which highlights feasibility and efficiency issues in existing heat exchangers (Figure 1.2c). These methods will be covered in more detail in the literature review.

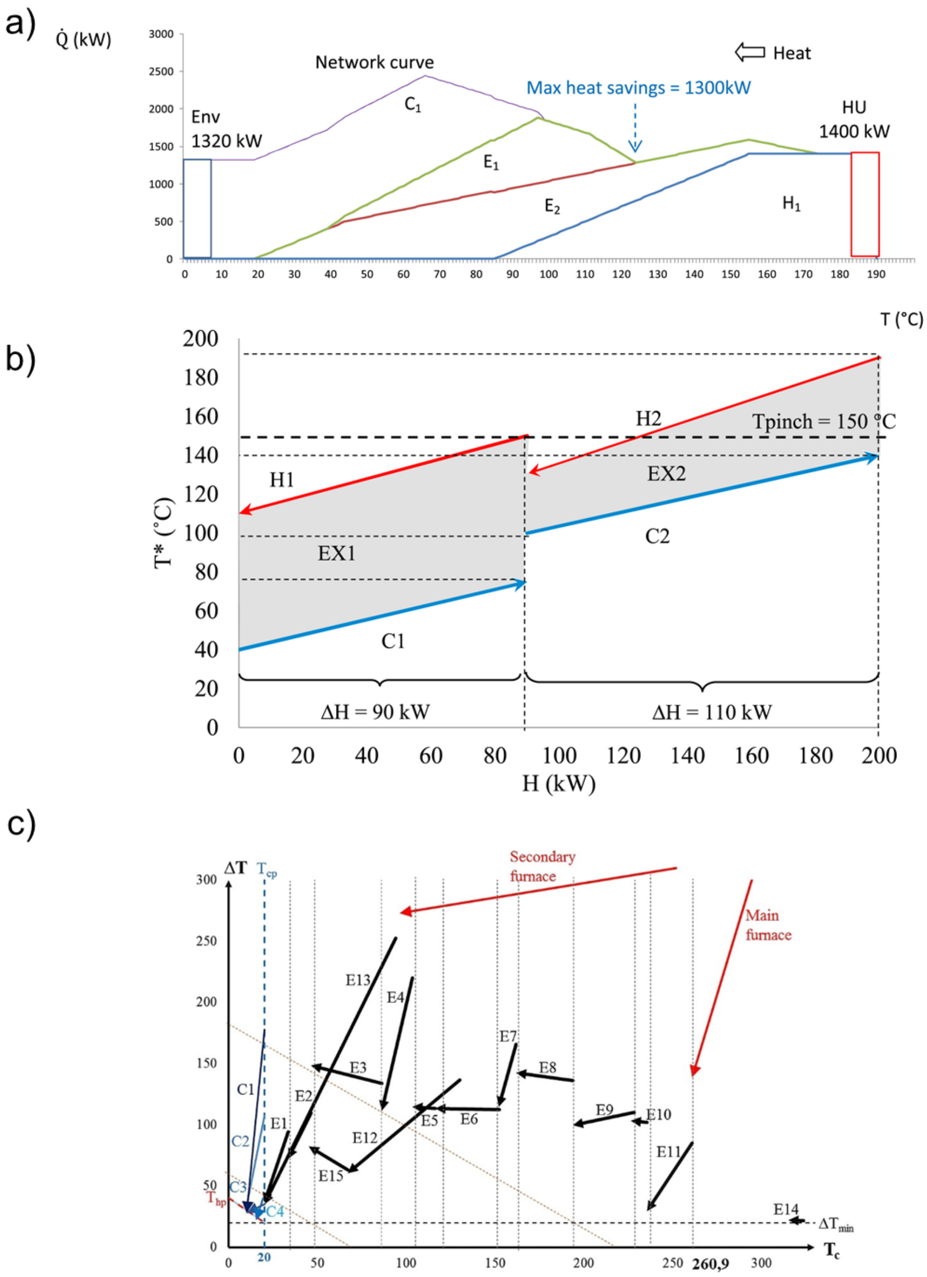


Figure 1.2: Recent graphical retrofit methods: a) the Energy Transfer Diagram (used with permission from Bonhivers et al., 2017), b) STEP (used with permission from Lai et al., 2019), and c) TDF plot (used with permission from Kamel, Gadalla, Abdelaziz, et al., 2017).

Even with these recent developments, it is still difficult to provide confidence that the most cost-effective retrofit modifications have been identified when there are so many different retrofit design options. One possible solution is to pair a graphical design method with an automated procedure so that the manual work required to find all viable designs is minimised and cost-effective solutions can be quickly identified – the graphical tool can still provide insights, but the retrofit analysis is no longer dependent on what can be discerned easily.

Methods that use computation and automation are often categorised as mathematical programming (MP)-based methods. These methods can be deterministic, which usually means solving complex mixed-integer models (Pan, Bulatov, & Smith, 2013), or they can be stochastic, using the randomness of evolutionary algorithms to solve a retrofit problem (Biyanto et al., 2016). These methods have limited graphical representation and often revolve around the rigorous optimisation of HEN superstructures (Figure 1.3). The use of MP-based retrofit methods can be hindered by expensive and excessive computation, as well as difficulty in transferring insights between the engineer and the optimisation process. However, graphical methods such as Bridge Analysis may provide a good basis for automation, without losing all the conceptual information, due to the systematic process used to identify retrofit modifications.

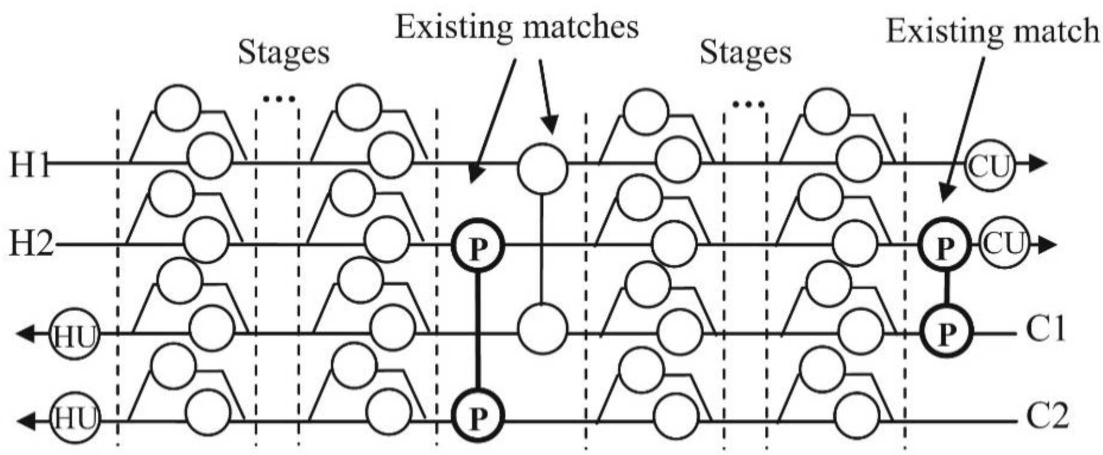


Figure 1.3: Superstructure for a heat exchanger network retrofit design (used with permission from Pan, Bulatov, & Smith, 2013).

1.2 Thesis Aim

The aim of the thesis is to develop a robust retrofit design and analysis methodology that characterises an existing industrial processing plant's heat exchanger network and utilises the heat surpluses and deficits in the total heat cascade to create new heat recovery opportunities for improving energy efficiency and reducing process heat consumption (i.e., hot utility). The research will identify the cost-effective structural HEN modifications that can achieve these retrofit goals, such as the addition of new heat recovery exchangers or heat transfer area (retrofit area).

A primary focus of the thesis will be on the development of a methodology that can provide retrofit design options for HENs with varying sizes and complexities (i.e., number of streams, number of heat exchangers, or stream splitting), addressing a known limitation of graphical methods. Consideration will also be given to the steady state variability of process stream properties (e.g., temperatures and flow rate) so that the performance of a retrofitted HEN design can be evaluated to reduce the likelihood of an inflexible retrofit design – in addition to other insights. A critical output of the research will be the development of a spreadsheet tool that implements the new design and analysis techniques so that they can be widely applied to New Zealand and the rest of the world, using a software platform with a high level of usability and accessibility to help bridge the gap between academia and industrial end-users.

The novel methods will be demonstrated through their application to case studies that represent selected New Zealand industries. Two major case studies will be examined: a paper mill and a petrochemical complex. These case studies represent some of the types of large, complex HENs that may be found in New Zealand. The novel methods could also be applied to HENs belonging to other important industries, such as dairy; however, this thesis has chosen to focus on other industries.

1.3 Structure of the Thesis

The thesis has been organised to reflect the development stages of the research. The thesis begins with Chapter 2, which presents the literature review that has informed and guided the research. One key graphical retrofit method has been identified as having the potential and need for further development: Bridge Analysis. The following chapters of the thesis continue the development of Bridge Analysis, making meaningful improvements to the conceptual presentation of the method and developing the necessary automation.

Chapter 3 discusses the improvements made to the Energy Transfer Diagram and Bridge Analysis. A stronger connection to Pinch Analysis concepts has been established along with the characterisation of surpluses and deficits that enables a higher level of understanding with respect to the flow of heat. Chapter 3 also introduces two new retrofit tools: the Modified Energy Transfer Diagram (METD), and the Heat Surplus-Deficit Table (HSDT). The

METD is an update to the original Energy Transfer Diagram, while the HSDT is a tabular tool (with graphical elements) that helps identify and quantify the retrofit design options.

The next step in the research was to enable these tools to be applied to large, complex HENs. For this purpose, the Automated Retrofit Targeting (ART) algorithm was developed to identify all possible retrofit opportunities automatically – removing the laborious manual solving that was otherwise required. The ART algorithm is presented in Chapter 4, along with strategies for mitigating the large numbers of retrofit design options that can be found for larger HENs. Chapter 5 builds on the ART and develops an algorithm for applying successive retrofit stages (i.e., a multi-stage retrofit analysis) to a single retrofit problem so that energy retrofit plans can be generated for a HEN. Chapter 5 also discusses automated HEN design and the use of Pareto front analysis.

Chapter 6 introduces a novel tool for evaluating potential retrofit designs after they have been found with the ART and Bridge Analysis. The steady state process stream variability in an existing HEN is an oft-overlooked aspect of retrofit analysis, in addition to the dynamic variability and process control. In this chapter, Monte Carlo Simulation (MCS) techniques are used to determine how the variability of inputs to a HEN could affect the outputs of a retrofitted HEN, such as profitability and utility load. MCS techniques also help to analyse the ability of a retrofitted HEN to maintain all targets (i.e., target temperatures), i.e., a retrofitted HEN's ability to maintain feasible operation despite variability in the steady state conditions.

The thesis will culminate with Chapter 7, where the research is summarised, and the overall conclusions are drawn. Chapter 7 also highlights areas within HEN retrofit analysis, where future research could be directed. New opportunities for research, using the spreadsheet tool and developed algorithms, will also be discussed.

Chapter 2

Literature Review

There has been extensive research into the retrofit design of heat exchanger networks (HEN) since the 1970s, and there is a wide range of literature available. For this thesis, there are several key areas of relevant literature. First, a brief introduction to Process Integration (PI) and Pinch Analysis (PA) provides the necessary background for many contemporary HEN retrofit design and analysis methods, many of which are directly adapted from or developed around conventional PA techniques. The bulk of the literature review will cover many of the retrofit design methods that have been developed over the years, which are typically categorised as PA-based methods, mathematical programming (MP)-based methods, or hybrid methods with elements of both PA and MP (Sreepathi & Rangaiah, 2014b). Within these categories, several defining aspects of design will also be analysed including graphical tools, the utilisation of utility paths, heat transfer enhancement, deterministic methods, and stochastic methods. In general, retrofit design approaches tend to either focus on finding the retrofit modifications that either provide the greatest energy reductions or bring the existing HEN closer to the structure of the Minimum Energy Network (determined through PA) (Kemp, 2011). In 2014, a detailed review of HEN retrofit design methods in literature was presented by Sreepathi and Rangaiah (2014b).

The literature review will also analyse other aspects of retrofit HEN performance, such as controllability, flexibility, and the management of process stream variability. For the latter, the literature review will examine the suitability of Monte Carlo Simulation for an analysis of how the variability manifests itself in the HEN performance. The review is concluded by drawing attention to the identified gaps in knowledge and the key methodologies that are relevant to achieving the thesis aim.

2.1 Process Integration and Pinch Analysis

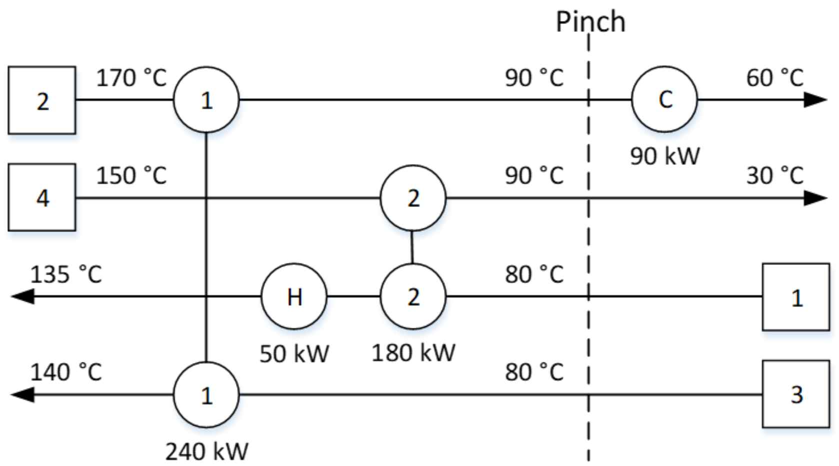
Process Integration found its beginnings during the 1970s energy crisis when conflicts in the Middle East resulted in petroleum shortages that affected many developed countries (Klemeš et al., 2014), including New Zealand. Concerns about the scarcity and cost of energy became a driving force for finding new technologies and methods that would reduce energy usage, such as "Process Integration." Linnhoff and Flower (1978a) introduced Process Integration (PI) in 1978, which has come to be defined as: "Systematic and general methods for designing integrated production systems ranging from individual processes to Total Sites, with special emphasis on the efficient use of energy and reducing environmental effect" (Gundersen, 2000) (Total Sites refers to a group of processes that are linked together by a common utility system).

There are many branches to PI, but the most significant branch (with respect to usage, development, and history) is Heat Integration. In the early days of Heat Integration, the major research was on the synthesis of HENs with optimal energy use. Works by Hohmann (1971), Ponton and Donaldson (1974), Nishida et al. (1977), and Linnhoff and Flower (1978a, 1978b) were all focused on synthesising an optimal HEN design using thermodynamic principles. In 1983, Linnhoff and Hindmarsh (1983) introduced Pinch Analysis (PA), a ground-breaking Heat Integration method that would later find itself adapted for many different types of applications, such as carbon emissions (Tan & Foo, 2007), hydrogen (Towler et al., 1996), and water (Y. P. Wang & Smith, 1994).

2.1.1 Pinch Analysis for Heat Exchanger Network Synthesis

Linnhoff and co-workers pioneered a significant number of Heat Integration and PA concepts, techniques, and tools that have since become synonymous with PA. In 1978, Linnhoff and Flower published a two-part paper in which HENs were synthesis (1978a) and optimised (1978b) based on certain criteria of optimality, also introducing the Problem Table Algorithm (PTA – a tabular method for calculating the net enthalpy in each temperature interval as well as the heat cascade) (Figure 2.1b) and the HEN grid diagram. The grid diagram shows the division of the HEN, by the Pinch temperature, into a hot-end and cold-end that are then designed separately (Figure 2.1a), with any heat exchanged across the Pinch temperature (cross-Pinch heat exchange) being inefficient. Another significant contribution of this work was the use of a minimum temperature difference between streams exchanging heat, ΔT_{min}, as a constraint for heat recovery. Independently, the same conclusions were reached by Hohmann (1971); however, Hohmann also found a relationship between the number of units and the number of streams and utilities. It was later found that the relationship could not be applied to the whole HEN, but rather to each side of the Pinch independently, showing the validity of the Pinch division. PA avoids inefficient cross-Pinch heat exchange which can lead to additional units that the relationship could not account for.

a)



b)

	Interval number *i*	$S_i - S_{i+1}$ (°C)	$\Sigma CP_{HOT} - \Sigma CP_{COLD}$ (kW/°C)	ΔH_i (kW)	Surplus or deficit
S_1 = 165 °C					
	1	20	+ 3.0	+ 60	Surplus
S_2 = 145 °C					
	2	5	+ 0.5	+ 2.5	Surplus
S_3 = 140 °C					
	3	55	- 1.5	- 82.5	Deficit
S_4 = 85 °C					
	4	30	+ 2.5	+ 75	Surplus
S_5 = 55 °C					
	5	30	- 0.5	- 15	Deficit
S_6 = 25 °C					

Figure 2.1: a) Grid diagram for a simple HEN, and b) the corresponding Problem Table Algorithm (using shifted temperatures) (Kemp, 2011).

The Pinch design method was fully presented later by Linnhoff and Hindmarsh (1983), combining ideas from previous works. The Pinch design method was based around dividing the HEN with the Pinch temperature and then solving the hot and cold-side problems separately. Above the Pinch temperature, there is a surplus of heat, while below the Pinch, there is a deficit of heat. As the Pinch is the point of division between the hot-side (surplus) and cold-side (deficit), the Pinch is the most constrained part of the HEN. Hence, the protocol is to start at the Pinch and work outwards, while also treating either side of the Pinch as separate problems. There are three feasibility criteria that are used to assist in the design of a minimum energy network relating to the number of process streams and branches, the heat capacity flow rates of streams in a match, and the difference between heat capacity flow rates of streams in a match. A violation of one of these criteria indicated the need for stream splitting. Linnhoff and Hindmarsh also used a 'tick-off' heuristic for finding matches away from the Pinch that minimised the number of units as well as discussed HEN relaxation in the form of exploiting utility paths and loops.

Linnhoff et al. (1982) introduced Composite Curves (CC) to represent the hot and cold streams (Figure 2.2a). These CCs could be shifted together to create Shifted Composite Curves (SCC) by shifting the temperatures of the streams according to the ΔT_{min} (raising cold temperatures and lowering high temperatures) (Figure 2.2b). Later, Townsend and Linnhoff (1983) combined the hot and cold SCCs to create the Grand Composite Curve (GCC) (Figure 2.2c). The GCC is a useful graphical tool that can be used to determine the energy targets, such as the minimum utility requirements. These energy targets set the limits for what is thermodynamically achievable for the HEN synthesis. These targets are dependent on the stream data and on a specified ΔT_{min} (design value) and can change for different values of ΔT_{min}. There is a significant amount of additional information that the GCCs provide, including the location of Pinch temperature(s), the presence of 'heat recovery pockets' that show the potential for heat recovery, and utility placement options (Klemeš et al., 2014).

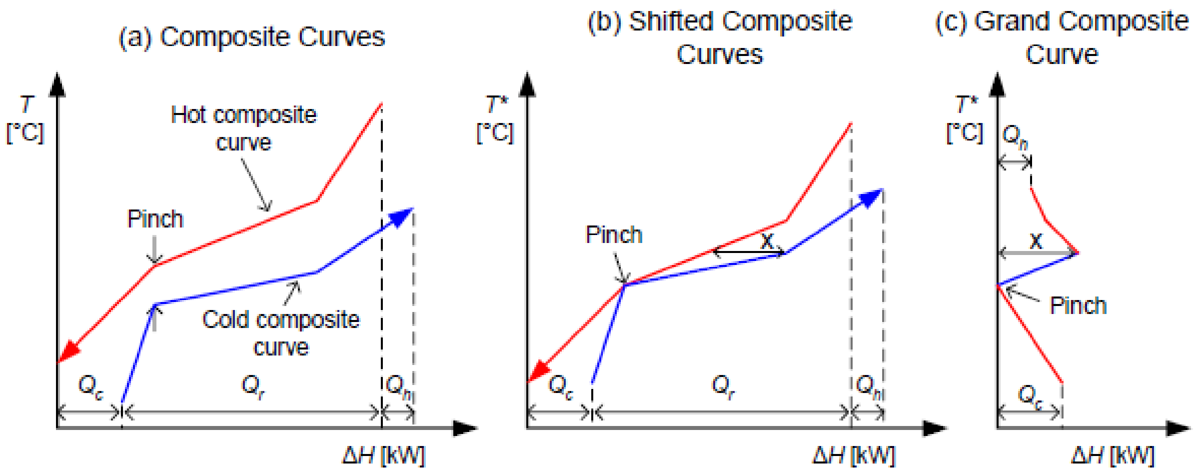


Figure 2.2: Relationship between the a) Composite Curves, b) the Shifted Composite Curves, and c) the Grand Composite Curve (used with permission from Timothy Gordon Walmsley, 2014).

The Pinch design method is a fundamental part of PA and Heat Integration, and should be followed as much as possible to ensure a high level of energy productivity and efficiency; however, in retrofit HEN design, there is often a bigger emphasis on factors that are not as important for grassroots designs. These retrofit-specific factors include optimal utilisation of existing equipment and the constraints of the plant (pressure drop, topology, etc.) The objective of the retrofit design is also significant. Retrofit modifications can be made to improve energy use, debottleneck, increase profit, or to compensate for changes in operation that may have occurred due to ageing or changes to the process specifications (throughput, yield, etc.). The trade-off between capital investment and energy savings can also lead to design choices that would be poor for a new HEN design but acceptable for a retrofit, such as the use of cross-Pinch heat transfer (although many retrofit designs aim to reduce cross-Pinch heat transfer). Additionally, for a HEN to need a retrofit, it is very likely that the HEN was not synthesised using the Pinch design method. It is unlikely that any criteria for optimality have been followed, leading to a sub-optimal design. A complete overhaul of the HEN is almost always not economically feasible, so it is not always effective to modify the HEN such that it meets the grassroots HEN targets. This means that a retrofit design method needs to find other solutions. Additionally, tools such as the GCC proved to be popular and successful as a graphical tool for grassroots HEN design (Townsend & Linnhoff, 1983), but the GCC is not appropriate for retrofit design due to the inability to characterise the existing HEN. Many researchers have developed their own graphical tools, or adapted the GCC, and aim to represent the existing HEN appropriately and provide the needed insights relevant to the constraints of an existing network.

While HEN synthesis design methods are not the focus of this thesis, the early synthesis methods laid the foundations for what would later be developed into HEN retrofit design methods. Furman and Sahinidis (2002) provide a thorough review of methods for HEN synthesis (from the 20^{th} century) that can be referred to for more information in this field of HEN design.

2.2 Pinch Analysis-based Retrofit Design Methods

Pinch Analysis featured many graphical tools such as the Grand Composite Curve and grid diagram – and PA-based retrofit design methods are no different. Many of the PA-based retrofit design methods in the literature involve the use of a diagrammatical tool, often adapted from conventional PA tools. These diagrammatical tools can range from modified versions of Composite Curves to plots relating to the heat exchanger area.

Many retrofit design methods also follow in the footsteps of the Retrofit Pinch Design method proposed by Tjoe and Linnhoff (1986). In one of the earliest developed retrofit design methods, Tjoe and Linnhoff proposed the following procedure: 1) identify and eliminate heat exchangers that transfer heat across the Pinch (a Pinch violation), 2) add new heat exchangers to fill any gaps in heat transfer, and 3) evolve improvements by exploiting utility paths (defined later) and loops. Retrofit targets were also developed based on curves (Figure 2.3) that showed the relationship between heat transfer area and energy requirement – i.e., the trade-off between capital costs and energy savings (which also relates to the chosen ΔT_{min}).

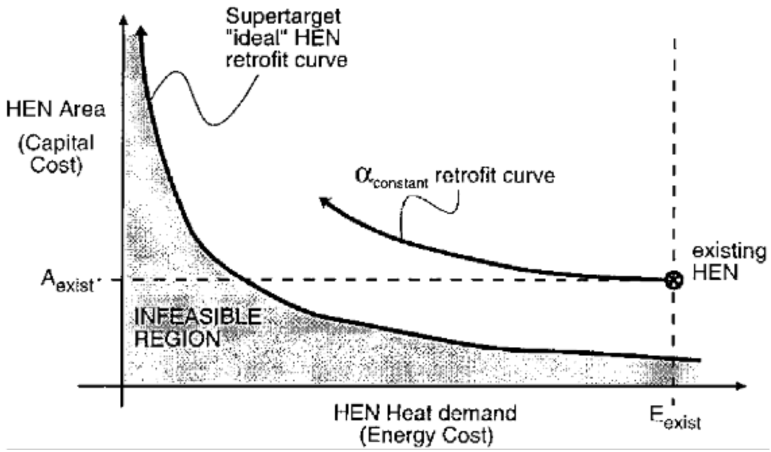


Figure 2.3: Retrofit target curves (used with permission from Asante & Zhu, 1997).

Tjoe and Linnhoff also introduced the concept of area efficiency, which is the ratio between the minimum area requirement and the existing area. Area efficiency takes the constraint of an existing heat exchanger and uses it as a benchmark for retrofit performance. Ideally, the use of area should become more efficient, also ensuring that the existing area is fully utilised before additional heat transfer area is added to the HEN. This PA-based method by Tjoe and Linnhoff is often used in retrofit projects (i.e., an ethylbenzene plant (Yoon et al., 2007), and a crude distillation unit (Cui & Sun, 2017)) and set a standard for the research to come. The retrofit Pinch design method is not without criticisms, and some believe that solutions are not as profitable as they could be and introduce unnecessary complexities to the HEN (i.e., too many stream splits) (Bagajewicz et al., 2013).

2.2.1 Graphical Design Methods and Tools

Graphical design methods and tools are generally based around either the grid diagram (the representation of the process streams and exchangers in a HEN) or the Composite Curves (the representation of process heat in a HEN). Many of the following methods are based around adaptations of these tools for retrofit purposes, providing new insights or allowing for a different type of analysis.

2.2.1.1 Retrofit Grid Diagrams

One of the earliest retrofit-based grid diagrams was developed by Lakshmanan and Bañares-Alćantara (1996). Lakshmanan and Bañares-Alćantara (1996, 1998) proposed a new graphical tool across two papers known as the Retrofit Thermodynamic Diagram (RTD). The RTD was an adaptation of the conventional grid diagram in which the process streams were plotted according to their supply and target temperatures with exchanger matches shown clearly between each stream in such a way that the connecting line was an indicator of the thermodynamic driving force between the two matched streams. The thickness of each stream segment was also a representation of the heat capacity flow rate (kJ/°Cs), the product of the mass flow rate and the specific heat capacity. The RTD was to be used alongside retrofit by inspection, for which several heuristics and guidelines were introduced to find retrofit solutions quickly and simply. However, the authors do not suggest that retrofit by inspection and the RTD could be used instead of more rigorous optimisation methods like MP-based methods, but instead could be used to provide users with simple and time-effective retrofit solutions (that may be sub-optimal).

As an update to the RTD, Yong et al. (2015) posited that the RTD did not adequately consider the ΔT_{min} or the thermodynamic feasibility of the heat exchangers and developed the Shifted Retrofit Thermodynamic Grid Diagram (SRTGD) (Figure 2.4). The main differences between the RTD and the SRTGD were the display of the Pinch temperature and that the lines connecting stream segments in an exchanger match now provided information about the thermodynamic feasibility, based on temperature limits and rules about heat transfer (heat must transfer from a high temperature to a low temperature).

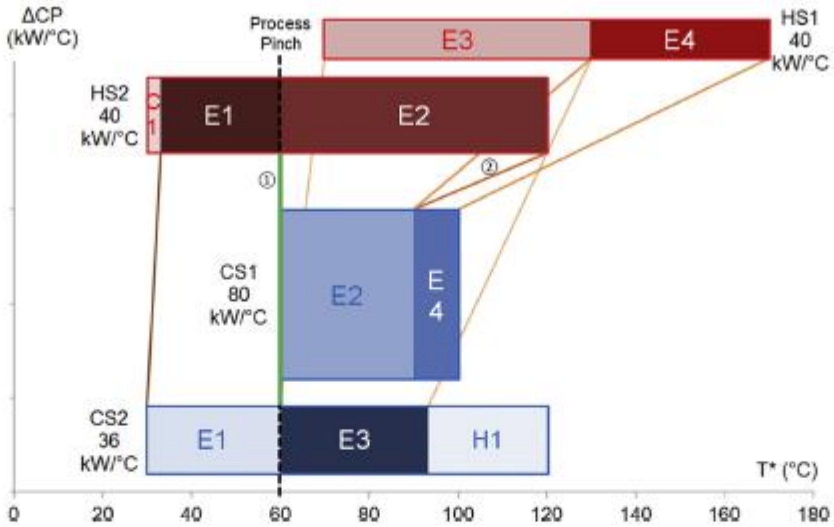


Figure 2.4: Shifted Retrofit Thermodynamic Grid Diagram (used with permission from Yong et al., 2015).

Another graphical method that was introduced as part of developments to the conventional grid diagram was the Retrofit Tracing Grid Diagram (Nemet et al., 2015) (Figure 2.5). Aspects of the RTD and the SRTGD were present in this tool, but differences include the separation of streams from the heat exchangers (which are shown as yellow circles sized based on exchanger duty) and the partitioning of streams and exchangers into three regions: cooling, heat recovery, and heating.

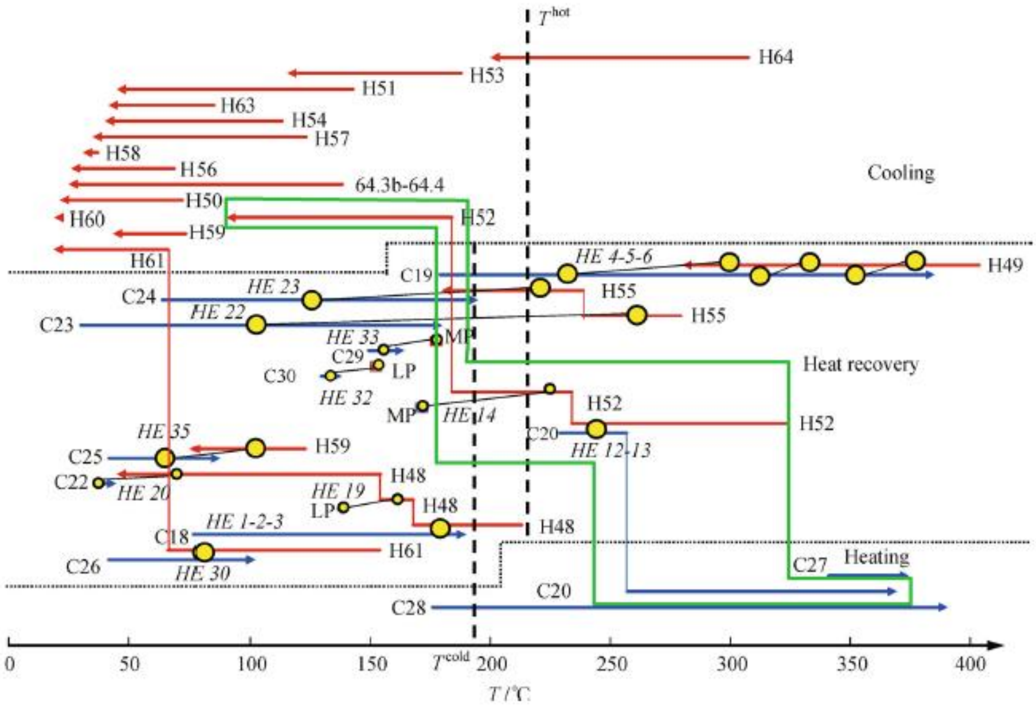


Figure 2.5: Retrofit Tracing Diagram (used with permission from Nemet et al., 2015).

Piacentino (2011) used novel plots such as 'heat load plots' and a spider-type graph showing the factors with the most influence on cost (i.e., exergy destruction, number of shells, and the required heat transfer area) alongside existing techniques such as CCs to produce a comprehensive framework for HEN retrofit design. One of the main features of the heat load plots was the representation of heat surpluses and deficits (areas where there is no overlap between the hot and cold stream temperatures) (Figure 2.6). Large areas of overlap were avoided due to the implication that the heat exchangers would have a high number of shells and complexity. Unlike many retrofit design methods, Piacentino's method also included exergy analysis and HEN relaxation.

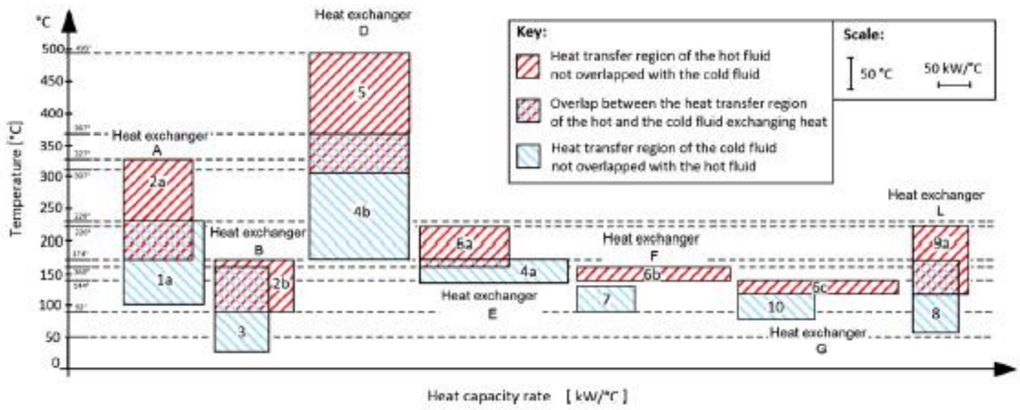
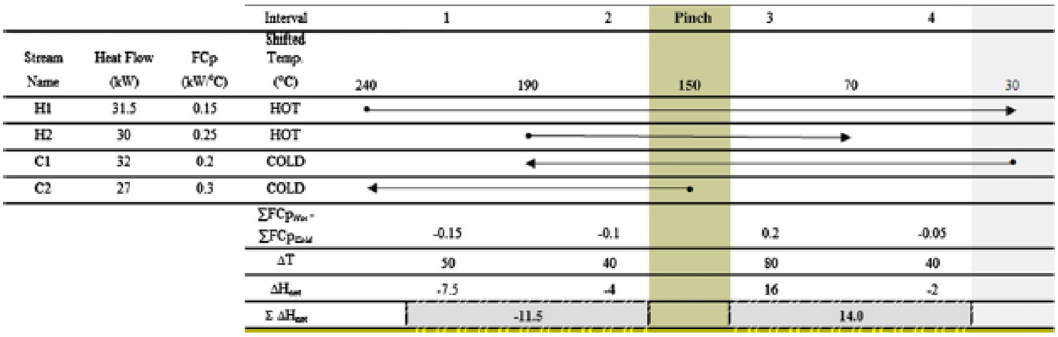


Figure 2.6: Heat load plot (used with permission from Piacentino, 2011).

Abbood et al. (2012) presented the Grid Diagram Table for retrofit design. The Grid Diagram Table is an adaptation of the conventional grid diagram and the Problem Table Algorithm (Figure 2.7). The Problem Table Algorithm was developed as one of the original PA tools for HEN synthesis and is used to generate the GCCs. The purpose of adapting the two tools into one method was so that the numerical and visual elements of the tools could be utilised simultaneously with a single tool.



Stream Name	Heat Flow (kW)	FCp (kW/°C)	Interval / Shifted Temp. (°C)	240	1	190	2	Pinch 150	3	70	4	30
H1	31.5	0.15	HOT									
H2	30	0.25	HOT									
C1	32	0.2	COLD									
C2	27	0.3	COLD									
			ΣFCp_{Hot} - ΣFCp_{Cold}		-0.15		-0.1		0.2		-0.05	
			ΔT		50		40		80		40	
			ΔH_{net}		-7.5		-4		16		-2	
			$\Sigma \Delta H_{net}$		-11.5				14.0			

Figure 2.7: Grid Diagram Table (used with permission from Abbood et al., 2012).

2.2.1.2 Composite Curve-based Tools

Nordman and Berntsson (2001) developed several new CCs to be used above and below the Pinch for describing the HEN in different ways. These new curves were called Advanced Composite Curves (ACC), and a set of four was produced for each side of the Pinch. The total set of ACCs presented the process streams and utilities at their real temperatures and the minimum and maximum temperatures that heat could be supplied at (Figure 2.8). Using ACCs, the relative complexity and improvement cost could be predicted, as well as the potential for increased heat recovery (Nordman & Berntsson, 2009a). Despite these insights, the economic information is only qualitative, therefore, somewhat limiting the ACCs usage to targeting and screening and additional effort would be required to determine the cost-effectiveness of a retrofit design (Nordman & Berntsson, 2009b). The number and complexity of the ACCs also hinder the usability of the method as the concepts are not intuitive to those unfamiliar with the method.

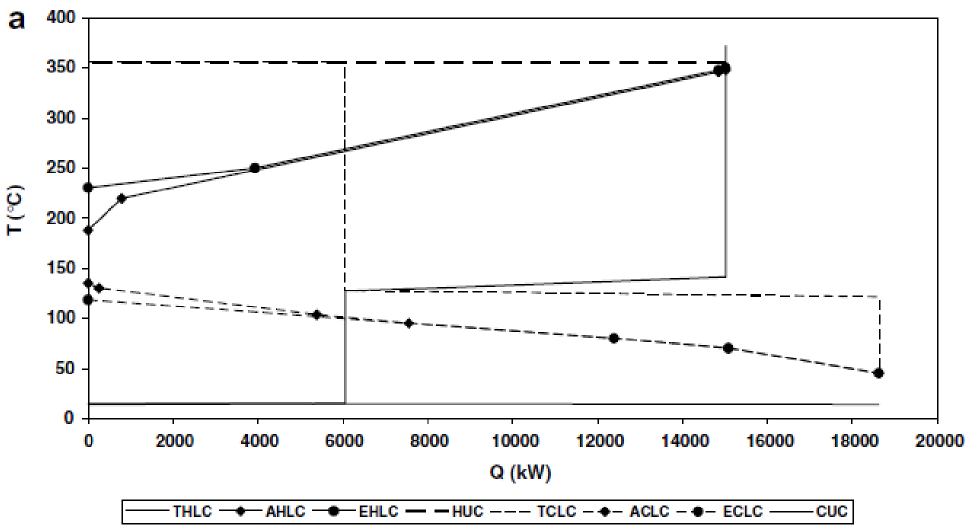


Figure 2.8: Advanced Composite Curves (used with permission from Nordman & Berntsson, 2009).

In a graphical approach proposed by Gadalla (2015), the hot temperatures of the heat exchangers were plotted against the corresponding cold temperatures, with the hot and cold Pinch temperatures dividing the plot into four regions that relate to the feasibility and relative efficiency of the exchangers. Other insights were also derived from the plots, such as the location of utility paths and the relative area and load of each exchanger. The tool was also used to improve heat recovery by making changes to the processes (i.e., temperatures or flow rates) to overcome the Network Pinch (a limitation to heat recovery imposed by the structure of the HEN) (Gadalla et al., 2016). Figure 2.9 shows how the slope of a Pinching exchanger (touching the red Pinch line) can be shifted to overcome the Network Pinch, at the cost of changing process variables or heat exchanger duty.

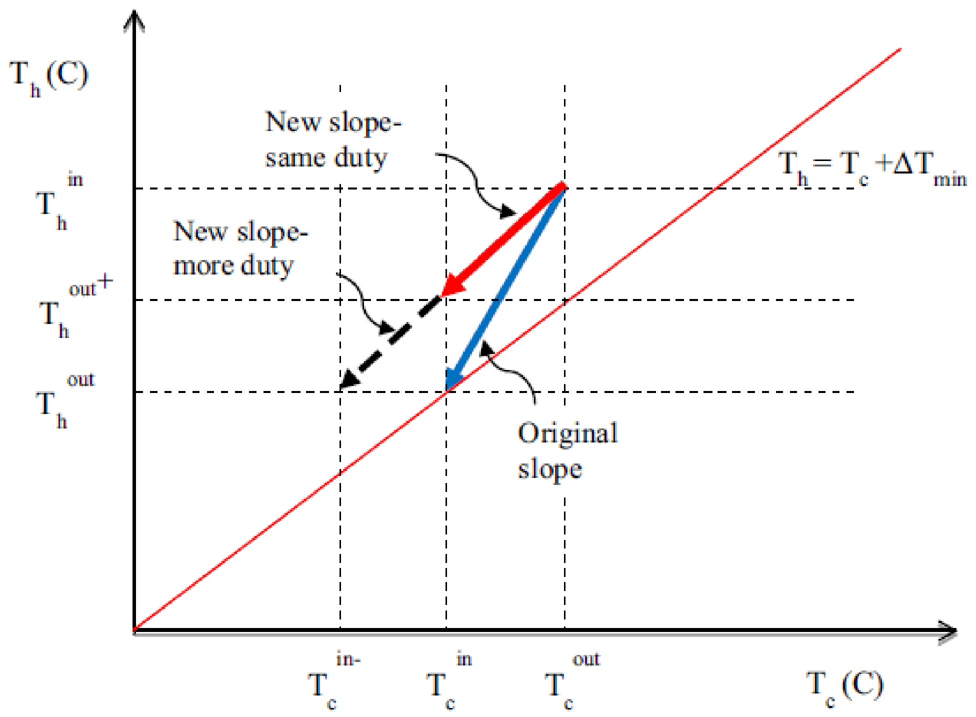


Figure 2.9: Using the new graphical representation to change the slope of a Pinching heat exchanger (used with permission from Gadalla et al., 2016).

Kamel et al. (2017) further developed this work, adding an additional region of infeasibility, and defined the graphical tool as a temperature driving force (TDF) plot. The most recent development of the TDF plot is presented in Figure 2.10. The method was demonstrated with a crude oil refinery case study (Kamel, Gadalla, & Ashour, 2017).

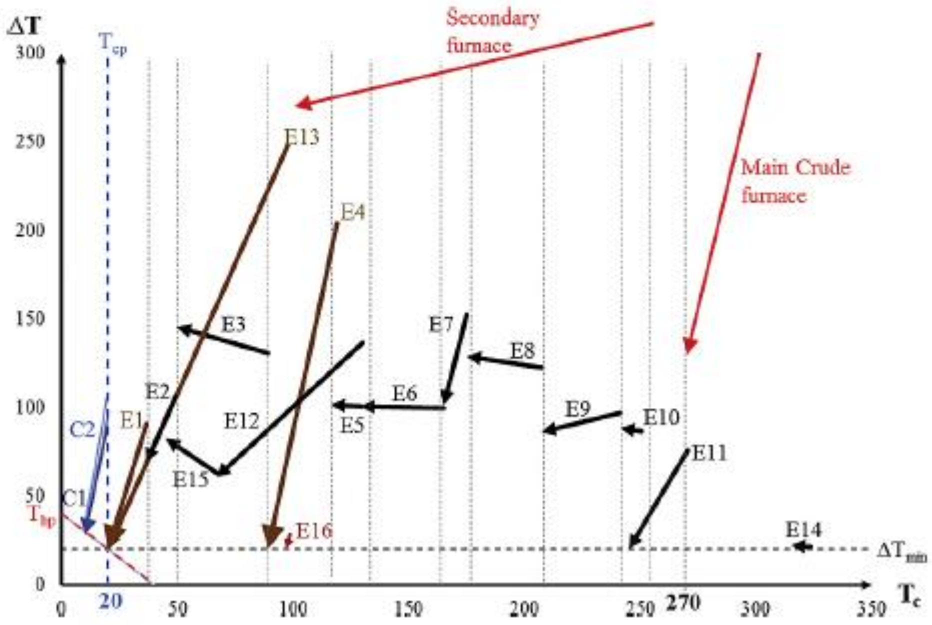


Figure 2.10: Temperature Driving Force plot (used with permission from Kamel, Gadalla, Abdelaziz, et al., 2017).

Another major graphical design method is the Stream Temperature and Enthalpy Plot, or STEP (Wan Alwi & Manan, 2010). STEP is a graphical tool that can be used to diagnose and retrofit existing HENs simultaneously. STEP maintains the individual stream characteristics and enables users to graphically map hot and cold streams and retrofit HENs without performing enthalpy calculations or checking for minimum temperature approach violations (Lai et al., 2017). Originally, STEP was used for the simultaneous targeting and design of grassroots HEN projects but has been since extended for retrofit design (Lai et al., 2018). STEP's usefulness comes from its ability to show the temperature profiles of individual hot and cold streams (like CCs) while showing the heat exchanger matches (Figure 2.11a). Retrofit improvements are achieved by eliminating cross-Pinch heat exchange, like many other methods, which can be identified using STEP. Plots of heat exchanger area versus enthalpy were also used in combination with STEP to minimise the required investment and maximise energy savings (Lai et al., 2019) (Figure 2.11b). STEP has many benefits that are often associated with graphical techniques, such as user interactivity and geometric reasoning; however, the effectiveness of STEP decreases with increasing problem size and complexity, requiring computational implementation. The order that the streams are plotted also affects the ability to identify retrofit solutions.

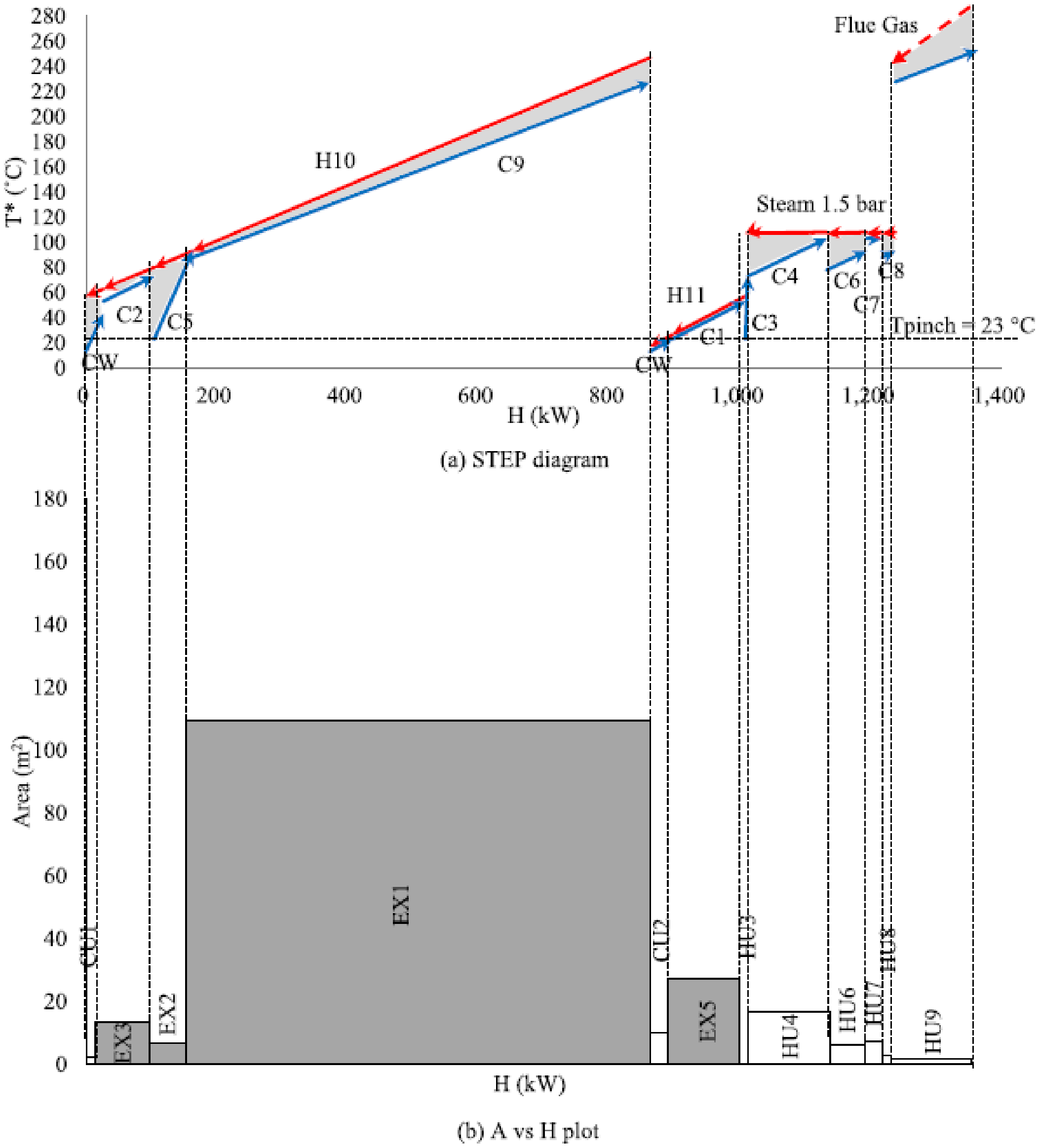


Figure 2.11: Combined graphical tool of STEP and area and enthalpy plots (used with permission from Lai et al., 2019).

2.2.1.3 Bridge Analysis

Bridge Analysis is a HEN retrofit design method that was initially developed by Bonhivers and co-workers (Bonhivers, Srinivasan, et al., 2017; Bonhivers, Alva-Argaez, et al., 2017). The goal of Bridge Analysis is to reduce utility consumption by creating heat recovery pathways between heaters (hot utility exchangers) and coolers (cold utility exchangers). These new heat recovery pathways, or Retrofit Bridges, enable heat recovery to be improved and utility consumption to be lowered. Retrofit Bridges are established with a set of topological modifications that link suppliers of process heat to receptors of process heat.

The first tool for Bridge Analysis was the Energy Transfer Diagram (ETD), a graphical representation of the HEN that consists of several curves similar to the CCs and GCC from conventional PA. The topmost curve represents the total heat flow of the network, while the curves below this curve represent each individual exchanger (including utility) (Figure 2.12). In the same work, a network table was introduced as a tabular tool for evaluating the potential heat flow in each possible match, including matches at different temperature intervals, leading to the evaluation of the energy savings of the Retrofit Bridge itself.

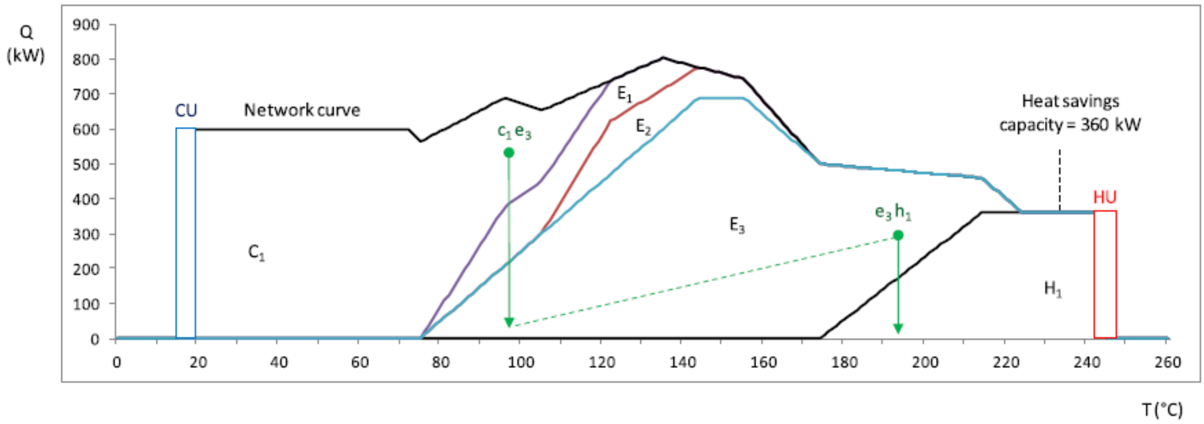


Figure 2.12: Energy Transfer Diagram (used with permission from Bonhivers, Alva-Argaez, et al., 2017).

Since the initial contributions, there has been significant development made to Bridge Analysis by Bonhivers and co-workers, including the introduction of two additional graphical tools: a Heat Exchanger Load Diagram (HELD) that characterises the heat load of the existing exchangers (Figure 2.13a), and a new representation of the HEN as an alternative to the conventional grid diagram (Figure 2.13b) (Bonhivers, Alva-Argaez, et al., 2017). The HELD was introduced to identify exchanger configurations corresponding to retrofit modifications, such as from a Retrofit Bridge, with the new HEN representation as a graphical aid. Like the ETD, the HELD draws on conventional PA, using an adaptation of CCs as the basis for determining exchanger configurations.

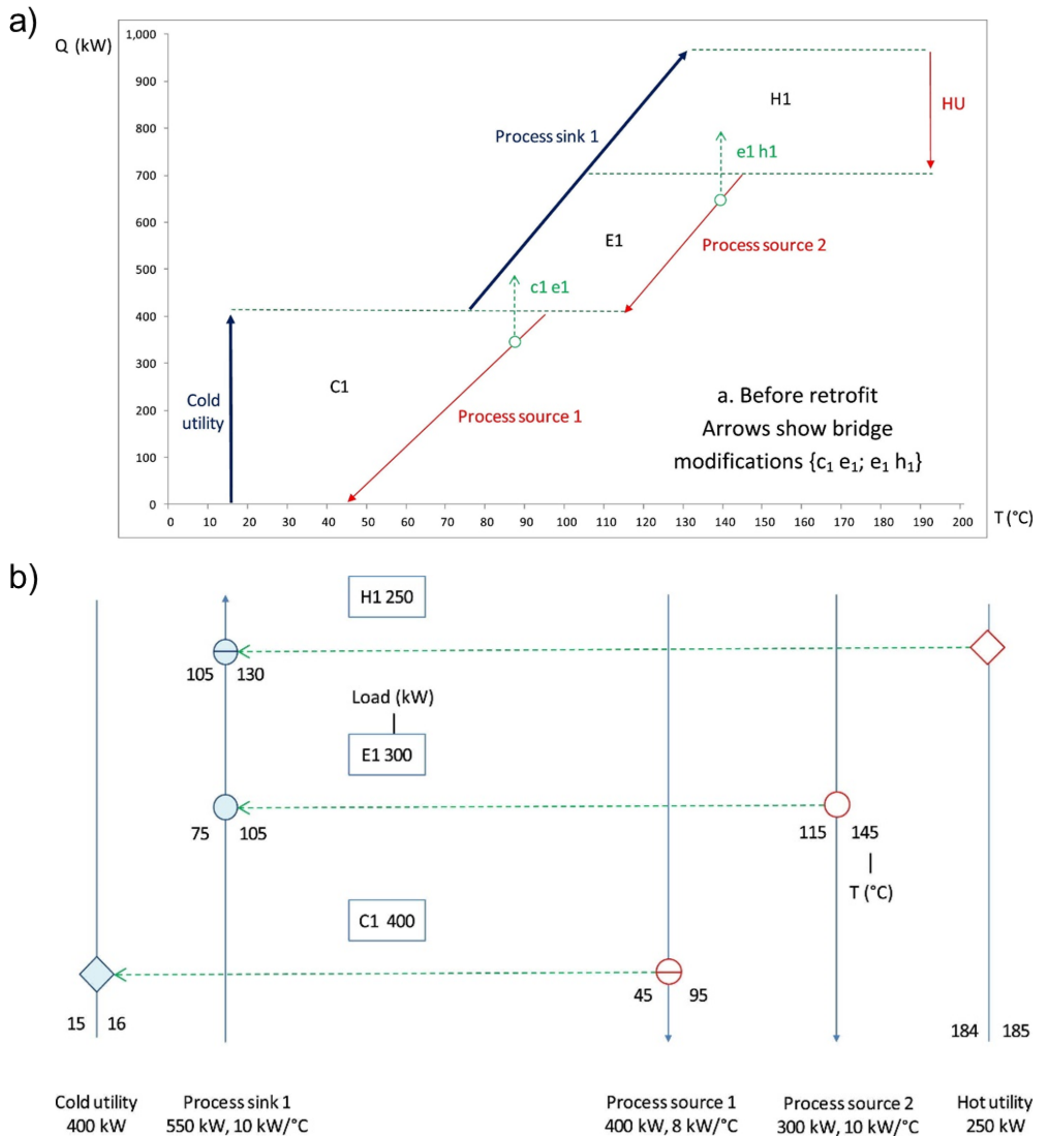


Figure 2.13: a) HELD diagram, and b) new HEN representation for Bridge Analysis (used with permission from Bonhivers, Alva-Argaez, et al., 2017).

To encourage the use of Bridge Analysis and the ETD, Bonhivers and co-workers published two papers to showcase the advantages of Bridge Analysis and how it could be used alongside more conventional PA methods. Bonhivers et al. (2014) presented a paper that compared the ETD against the GCC and ACCs to show the similarities and differences. The similarities, such as the network curve (the uppermost curve on the ETD) and GCC, help to bridge the gap in understanding between the methods, and the differences, such as the detailed characterisation of the existing HEN in the ETD, show the usefulness of the ETD for retrofit HEN analysis. Later, Bonhivers et al. (2016) established further connections to PA, using the HELD, and demonstrated how concepts from both methodologies could be used to improve retrofit analysis and even pave the way for computation. Bonhivers et al. (2019) have also used Bridge Analysis to complement the well-known Network Pinch method by improving the way in which cooler-heater paths can be identified (i.e., bridges), which are used to overcome the Network Pinch.

With regards to application, Bridge Analysis has been applied to a site-wide analysis of a Kraft pulp mill (Bonhivers et al., 2015) and the HEN of a methanol-to-propylene plant by unrelated authors (Sadeghian Jahromi & Beheshti, 2017). Bridge Analysis has also been used alongside several MP-based methods (which will be discussed in more detail in a later section) (Rohani et al., 2016; Chen et al., 2017).

At this point, all Bridge Analysis-oriented graphical tools have been plotted with enthalpy on the vertical axis on the horizontal axis, despite the PA convention of displaying the temperature on the vertical axis. The reason is that enthalpy is a function of temperature and should be displayed as the ordinate/dependent variable (vertical axis) and not the abscissa/independent variable (horizontal axis). Bonhivers et al. (2017) recognise this as a possible reason for Bridge Analysis's low impact on contemporary researchers. However, Bridge Analysis is a graphical retrofit design method with a lot of benefits because of the links that can be made to conventional PA and the insights that it provides regarding the existing HEN. Bridge Analysis has enjoyed a small success in literature but there still room for improvement and further development.

2.2.2 Utility Paths

Some retrofit design methods involve the exploitation of utility paths, also known as heat load paths. A utility path is typically a path between a hot utility exchanger and a cold utility exchanger that allows heat to be shifted from the heat recovery exchangers (that lie on the path) to the utilities, and vice-versa (Figure 2.14). This is called load shifting can be used to either reduce the number of heat exchangers at the cost of higher utility consumption or decrease utility consumption at the cost of increased capital cost. The former is known as network relaxation, while the latter is used by Tjoe and Linnhoff in the retrofit design procedure (Tjoe & Linnhoff, 1986). Previously discussed works, such as Bridge Analysis, create and modify these types of paths to increase heat recovery. While many works focus on exploiting existing utility paths, Bridge Analysis also creates them, often forming complex pathways through multiple heat recovery exchangers.

Osman et al. (2009) proposed that a retrofit could be achieved by exploiting the utility paths and without any need for topological changes to the HEN. The only modification allowed was the addition of area to the existing exchangers. Further development showed that the temperature flexibility in the process streams could also be optimised to provide additional heat recovery and utility reduction (Osman et al., 2016). The recovery was achieved by increasing the temperature of the hot streams and decreasing the temperatures of the cold streams. This type of retrofit analysis is limited to situations where soft temperatures or temperature flexibility can be exploited.

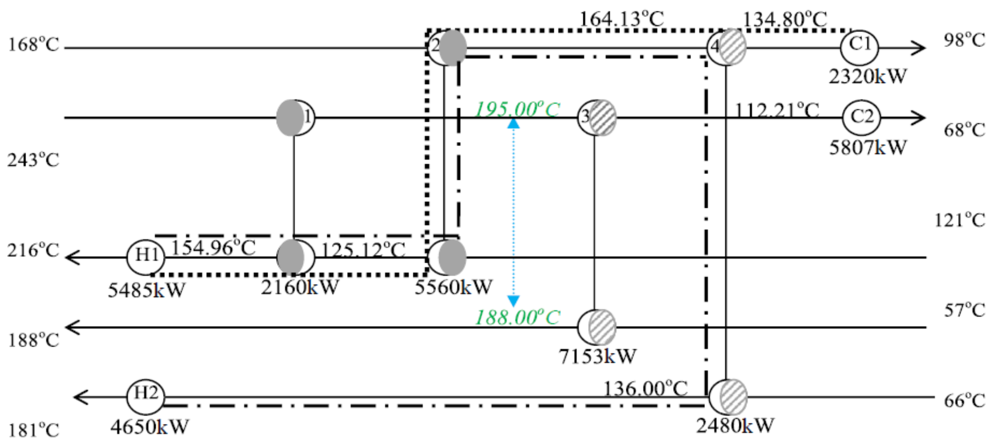


Figure 2.14: Utility paths (used with permission from Osman et al., 2016).

Van Reisen et al. (1995) introduced an approach known as Path Analysis. Path Analysis involved the decomposition of a HEN into subnetworks that were heat balanced and contained at least one heater and one cooler. Ideally, each subnetwork would contain a path, or the possibility of a path, between a heater and a cooler. Subnetworks were then retrofitted using load shifting and evaluated to find the optimal modifications. Path Analysis significantly reduced the design time and effort because only a subsection of the network is considered at a time, rather than the entire network. The trade-off is that the retrofit modifications may result in a sub-optimal HEN. Van Reisen et al. (1998) extended the method by breaking the subnetworks down into zones or structural unities. The accuracy of the method was improved but the computational effort was greatly increased. Path Analysis is like MP-based methods as the breakdown of the HEN into subnetworks and zones allowed for a similar optimisation as what is typically used in MP-based methods with the HEN superstructures.

2.3 Mathematical Programming-based Retrofit Design Methods

Mathematical programming (MP)-based retrofit design methods use mathematical methods to design and optimise HEN retrofits. Information and constraints about the existing HEN are formulated in the model and are used to optimise the HEN according to its objective function. For example, the objective function could be to minimise the investment cost or to maximise energy savings. MP-based methods are effective at finding solutions, but there are still many criticisms of MP-based methods that often result in PA-based methods being favoured. Criticisms of MP-based methods include the lack of user input or insight (concerning the HEN and processes) and the computational time and expense required (Tjoe & Linnhoff, 1986). The lack of user insight and computational expense has limited the use of MP, and it is more common to find PA-based methods in practice than MP-based methods (Briones & Kokossis, 1999b). MP-based methods can also result in the identification of a local optimum rather than the global optimum (Klemeš & Kravanja, 2013). Despite these shortcomings, there is still significant research on MP-based methods, often focusing on overcoming these limitations.

MP-based methods can generally be divided into two subcategories: deterministic and stochastic (Sreepathi & Rangaiah, 2014b). Deterministic methods do not involve any random variation and will always produce the same result each time. Methods such as Mixed-Integer Linear Programming (MILP) and Mixed-Integer Non-Linear Programming (MINLP) are deterministic. Stochastic methods include randomness and can produce different results despite having the same starting conditions. Examples of stochastic methods include simulated annealing and genetic algorithms.

With respect to MP in HEN synthesis, in addition to the review published by Furman and Sahinidis (2002), Grossmann and Guillén-Gosálbez (2010) presented a good review of MP-specific synthesis design methods. Several of the synthesis methods have been adapted into retrofit design methods, and many of the advantages and limitations of MP are still applicable for retrofit design, such as the computational complexity of large HEN problems (Furman & Sahinidis, 2001; Sieniutycz & Jezowski, 2009).

2.3.1 Deterministic Methods

Yee and Grossmann (1986) presented an MINLP model to determine the fewest structural modifications needed for a retrofit design while achieving the minimum utility cost for a specified ΔT_{min}. Essentially, a HEN structure was determined by following three objectives: maximise the use of existing exchangers, assign existing units to new required matches with minimum piping changes, and minimise the number of new stream matches that require the installation and purchase of new units. Yee and Grossmann (1988) also developed a method using an MINLP formulation along with a pre-screening stage and an optimisation stage. The pre-screening stage determines the economic feasibility of the retrofit project using cost information based on area, utility, and structural modifications. The area and utility targets were determined mathematically. One of the shortfalls of the method was that, while the computation of small problems is relatively small, the computation of large problems can be very significant and lengthy. One way of mitigating the complexity of a large problem, due to the large superstructure, is to restrict the superstructure based on the location of pinched exchangers (at ΔT_{min}) (Figure 2.15) (Pan, Bulatov, & Smith, 2013). The smaller superstructure is more manageable but only considers certain configurations, unlike a standard superstructure model that would consider all possible configurations.

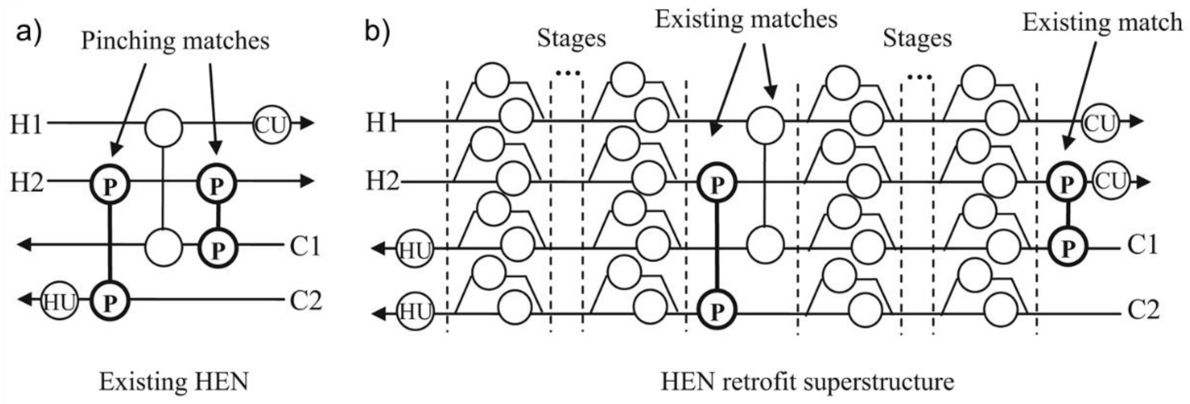


Figure 2.15: a) Existing HEN showing two pinched heat exchangers, and b) the corresponding retrofit superstructure for optimisation (used with permission from Pan, Bulatov, & Smith, 2013).

In a method developed by Isafiade (2018), stream data for the retrofit HEN problem was taken and used as though it was for a grassroots HEN problem. The exchanger matches from the grassroots solution, and the exchanger matches from the existing HEN were then used to construct a reduced superstructure. The reduced superstructure is then solved as an MINLP model. The benefits of this two-step procedure are that the existing exchangers are utilised as much as possible and the computation is relatively less intensive.

Ciric and Floudas (1990) used an MINLP formulation that is decomposed into two sub-problems that are solved simultaneously. The master sub-problem matched streams together and calculated the heat load while the primal sub-problem derived and optimised the HEN and assigned heat exchangers.

Soršak and Kravanja (2004) used an MINLP model with a stage-wise superstructure with an extension allowing different types of heat exchangers to be considered (i.e., shell and tube, plate and frame, double pipe, bypasses). This was achieved using a match superstructure (Figure 2.16). These elements of retrofit design are often neglected to reduce the complexity of the model.

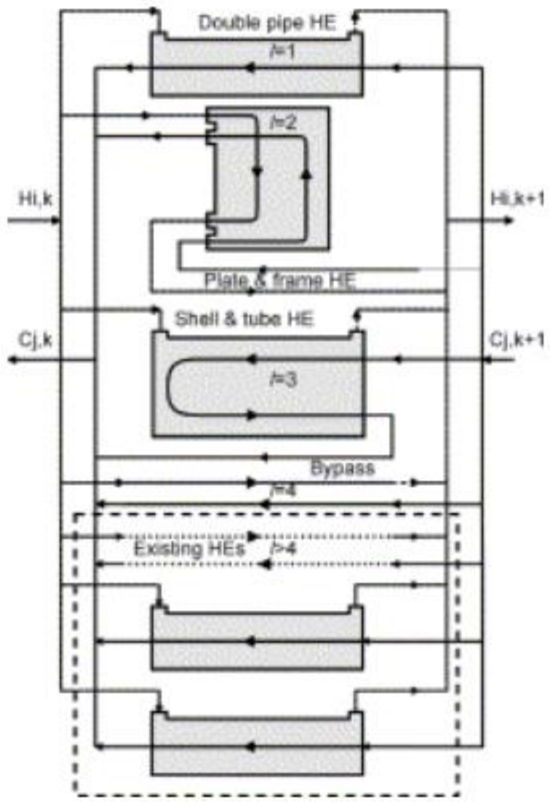


Figure 2.16: Match superstructure (used with permission from Soršak & Kravanja, 2004).

Kang and Liu (2015) used multi-objective optimisation to solve the HEN retrofit problem, optimising the CO_2 emissions and total annual cost. The Pareto front of these objectives was found, and the Pareto-optimal solutions along with it, giving insights into the trade-off between CO_2 emissions and the total annual cost. Interestingly, a key part of Kang and Liu's approach to retrofit was the integration of a heat pump.

Nguyen et al. (2010) used an MILP model (originally formulated by Barbaro and Bagajewicz (2005) for HEN synthesis) for the rigorous one-step retrofit design of HENs. The model accounted for costs that are commonly neglected, such as costs associated with re-piping, area reduction and addition, and stream splitting. The MILP model has been devised for shell and tube heat exchangers and considers many factors relating to the shells. The method does not utilise superstructures like many other deterministic methods; instead, it uses a transhipment/transportation model that regards heat as a commodity to be transported from heat sources to heat sinks.

Abbas et al. (1999) proposed using constraint logic programming to find and optimise retrofit designs. Constraints were added to assist the logic programming in its search for solutions to the retrofit problem. These constraints were based on several heuristics that were previously used by Lakshmanan and Bañares-Alćantara (1998). One of the heuristics was that only one new heat exchanger would be added to create new heat load paths, presenting a limitation as potentially optimal designs that required two exchangers were not considered. Using constraint logic programming, the authors achieved a 70% reduction in retrofit cost compared to Floudas et al. (1989), for the same case study.

2.3.2 Stochastic Methods

Many stochastic MP methods are created because deterministic methods tend to have a large solution space and can get stuck in local optima. Some methods use stochastic algorithms to solve MINLP problems, using the inherent randomness in the algorithm to escape local optima and reach the global optima, such as the work by Liu et al. (2014) which used a hybrid genetic algorithm to minimise the cost of newly added heat exchangers, utilities, and re-piping.

Björk and Nordman (2005) created a hybrid optimisation framework that used a genetic algorithm as well as an MINLP formulation. The genetic algorithm was used to decompose the large HEN retrofit problem into sub-problems, which could then be optimised with the MINLP formulation. The aim of the hybridised MP techniques was to reduce the computational time and effort for large retrofit projects, as large computational times are often needed when solely using MINLP. Rezaei and Shafiei (2009) also coupled a genetic algorithm with linear and non-linear programming (LP and NLP) formulations to find the best structural modifications for a HEN, considering that the genetic algorithm was useful for finding global optima despite its slow computational speed. Evolutionary algorithms like genetic algorithms are typically able to avoid local optima, unlike deterministic methods. There are many types of evolutionary algorithms that have been used in HEN retrofit design including genetic algorithms, integrated differential evolution (IDE) algorithms (Sreepathi & Rangaiah, 2014a), and Particle Swarm Optimisation (Silva et al., 2009).

Biyanto et al. (2016) developed a genetic algorithm to solve the NLP formulation of a HEN retrofit with an emphasis on the increase and optimisation of the overall heat transfer coefficient using heat transfer enhancement. It was found that coiled wire inserts had the greatest improvement out of all examined enhancement devices, although investment cost was not considered. A retrofit design must be justifiable from an economic perspective, so the lack of economic information is a major limitation considering the established trade-off between energy savings and capital investment.

Nielsen et al. (1996) proposed a new framework for HEN synthesis and retrofit design. The framework was built upon object trees with a clear hierarchy for the models and calculations required, depending on the type of stream or network unit needed. A downside to this framework was that it created more complex problems due to the lack of assumptions and simplifications that other methods often use. Simulated annealing was used to solve the resulting complex HEN problem, at the cost of expensive computation. Athier et al. (1998) also used simulated annealing as part of a two-level procedure based on an existing grassroots design procedure. The modifications allowed by the simulated annealing included the addition of a new exchanger (randomly selected) and the deletion of a previously added exchanger. The method involved multiple iterations and modifications would persist in each iteration.

Ochoa-Estopier et al. (2015) developed a two-level retrofit approach for HENs in heat-integrated crude oil distillation systems. The first level used simulated annealing to determine potential topological modifications to the HEN (Figure 2.17), while the second level used a repair algorithm (NLP model formulated as a non-linear least-squares problem) to identify constraint violations and rectify the HEN. The constraints that were considered include the ΔT_{min} and the area of the existing exchangers. An extension to the method included a decomposition of the HEN into two smaller HENs, in the second level, to reduce computational complexity and simplify the optimisation (Ochoa-Estopier et al., 2018).

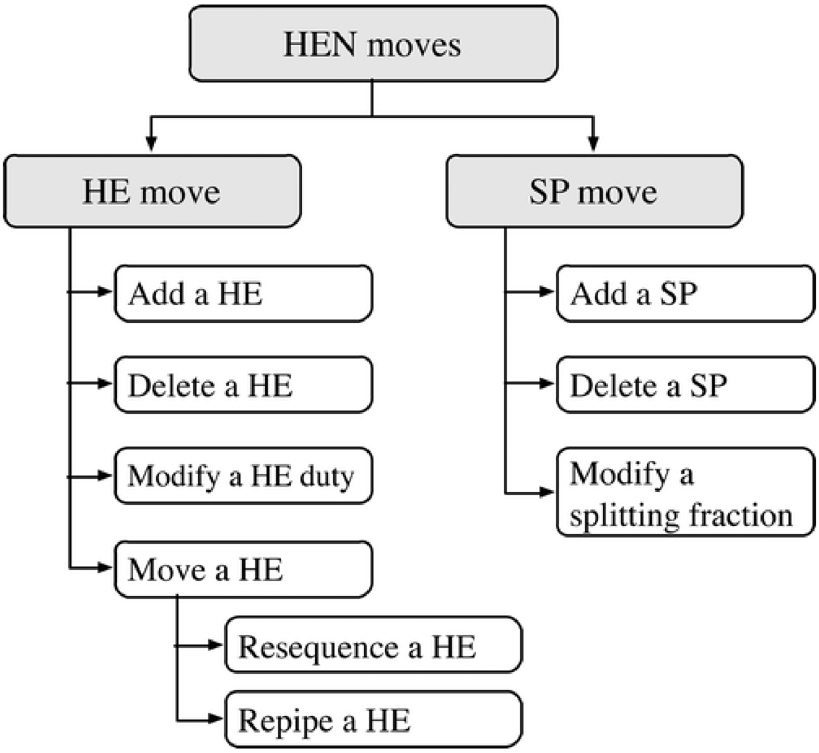


Figure 2.17: Simulated annealing move tree for HEN retrofit design (used with permission from Ochoa-Estopier et al., 2015).

Recognising that many MP-based methods that use stochastic algorithms also use deterministic methods, Zhang and Rangaiah (2013) opted to use a stochastic algorithm for the global optimisation. In this work, an IDE algorithm was used to handle the simultaneous optimisation of the HEN structure and model parameters. The stochastic algorithm helps avoid local optimums in favour of the global optimum and helps to reduce the computational effort required. Sreepathi and Rangaiah (2014a) used IDE in a similar method. First, different retrofit reassignment strategies were tested using IDE to perform the single-objective optimisation. Then, a genetic algorithm was used to solve the multi-objective optimisation (MOO) with utility cost and investment cost as the objectives. MOO had not yet been used in retrofit HEN design ((Kang & Liu, 2015) would later use MOO alongside MINLP methods) and can be advantageous over single objective optimisation as objectives can often be conflicting (i.e., the trade-off between utility cost and investment cost) (Rangaiah et al., 2015). Results from the multi-objective optimisation include the Pareto-optimal solutions (based on the Pareto front) which reflect the trade-off in HEN retrofit design and help with the design selection process. The method was further extended to account for streams with variable heat capacities (Sreepathi & Rangaiah, 2015).

2.4 Hybrid Retrofit Design Methods

Hybrid methods are the special cases where certain aspects of PA-based methods are combined with aspects of MP-based methods, usually done to overcome any shortcomings that one type of method may have. Often, these hybrid methods use PA-based techniques for targeting and preliminary design before using MP-based techniques to optimise the retrofitted HENs. One criticism, at least for hybrid synthesis design methods, is that the computational effort is still considerable, and the methods are largely inefficient and ineffective for large problems (Pettersson, 2005).

Briones and Kokossis (1996) acknowledged that MP-based methods are typically less used than PA-based methods due to the lack of input from the engineer during the design process and developed a hybrid method that would allow for engineers to make decisions between each automated stage. Three stages were used: targeting area and modifications (PA), structural optimisation (MP), and network optimisation (MP). This research led to a hybrid method known as conceptual programming, featuring 'hypertargets' for optimising ΔT_{min}, the number of units, and cost (Figure 2.18). Briones and Kokossis developed conceptual programming for grassroots HEN design (Briones & Kokossis, 1999b) as well as retrofit HEN design (Briones & Kokossis, 1999a). The networks that resulted from hypertargeting and conceptual programming provide significant information but needed further optimisation. A paper presenting industrial applications of the method, as well as modifications made to enhance the method further, was later published (Briones & Kokossis, 1999c).

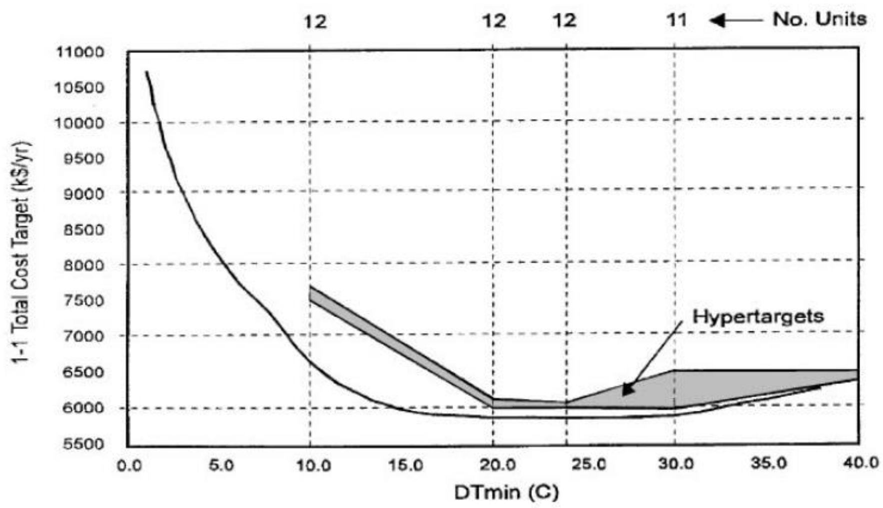


Figure 2.18: Hypertargets (used with permission from Briones & Kokossis, 1999).

Ayotte-Sauvé et al. (2017) used thermodynamic criteria, such as the concept of a heat load path, to build algorithms to reduce the size of the HEN retrofit superstructure and the computational time of the MINLP optimisation. Similarly, to conceptual programming, the novel method allowed for user intervention at each step of the procedure.

The work of Asante and Zhu (1997) in the field of retrofit design is well-known and is another good example of a hybrid method. The method was based around the concept of a Network Pinch, the location of exchanger matches that are 'pinched' (constrained at the ΔT_{min}) (Figure 2.19). The effect of a Network Pinch is that it divides the HEN into a heat surplus source and a heat deficit sink and limits the overall heat recovery of the HEN. The Network Pinch is a bottleneck that must be overcome through topological changes to the HEN. The retrofit was achieved in two steps: the diagnosis stage and the optimisation stage. A sequential search strategy was used for the optimisation, and this allowed for user interaction. The method was limited by the lack of cost consideration and the simplifying assumption that the thermal properties of the process streams were constant. These limitations were later addressed by Smith et al. (2010). Non-constant thermal properties were handled by segmenting the streams to intervals where it could be assumed that the thermal properties were constant, cost estimation was included, and the targeting and optimisation stages were combined. The Network Pinch method was also extended by Varbanov and Klemeš (2000) to provide guidance in cases where the Network Pinch cannot be identified in the HEN.

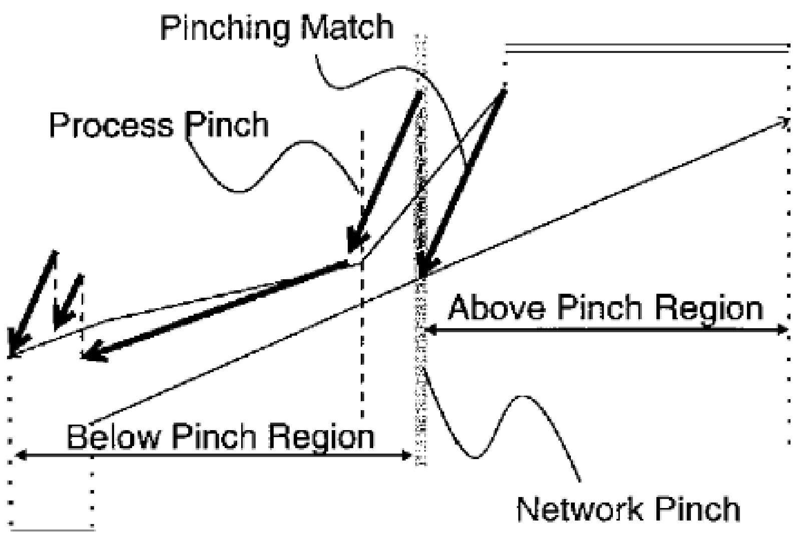


Figure 2.19: Network Pinch and the identification of pinching matches (used with permission from Asante & Zhu, 1997).

The Network Pinch method was modified further by Bakhtiari and Bedard (2013) so that it could handle complex HEN configurations (i.e., inclusive of stream splits), flexibility in the supply and target temperatures, effluent streams, and different ΔT_{min} values for different heat exchangers. The modified Network Pinch method also used a Match Penalty concept to mitigate the risk that a retrofit modification selected in the first step is preventing the optimal solution from being identified in the subsequent steps. The concept of a Network Pinch has permeated through the retrofit HEN design space with many practitioners using the method, including some of its extensions (Al-Riyami et al., 2001). Although, as with the analysis of cross-Pinch, the retrofit analysis should not be limited to the identification of Network Pinches. Piacentino (2011) suggested that retrofit analysis should focus on all sub-optimal uses of the available temperature driving forces, which encompasses many aspects of retrofit HEN design.

As previously mentioned, there are several works that utilise Bridge Analysis in the retrofit design process before optimising the HENs with mathematical formulations. Rohani et al. (2016) devised superstructures based on the concept of a bridge and then optimised the superstructure using an MINLP model. Chen et al. (2017) used the Energy Transfer Diagram to provide the retrofit solutions to an ammonia-water absorption refrigeration system (Figure 2.20) before optimising the solutions with a linear programming model. These are examples of hybrid methods and showcase how PA-based techniques are often paired with MP.

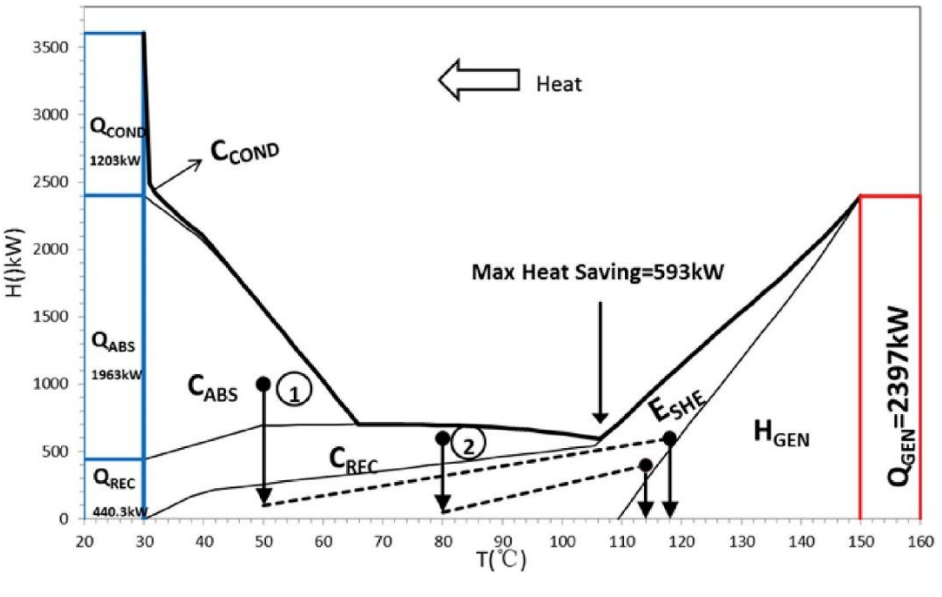


Figure 2.20: Energy Transfer Diagram with bridges for an ammonia-water absorption refrigeration system (used with permission from Chen et al., 2017).

2.5 Other Retrofit Design Methods

2.5.1 Heat Transfer Enhancement

Another major part of HEN retrofit, which does not necessarily fall within the previous sections, is the use of heat transfer enhancement (HTE) for cost-effective retrofitting. The investment cost for adding HTE to an existing heat exchanger is usually an order of magnitude lower than the costs for structural modifications (Akpomiemie & Smith, 2015). The HTE approach to HEN retrofit recently precipitated a line of research where the focus was on the identification of the best heat exchanger in a HEN to apply HTE and the practical issues that surround the change. Please note that some previously discussed works of literature may have also included the use of HTE, most specifically the work of Biyanto et al. (2016), who used an MP-based retrofit method that utilised HTE for the improvement of the overall heat transfer coefficients of exchangers.

Akpomiemie and Smith (2015) opted for a retrofit approach that would not include any topological modifications, as they can be costly and complex. Instead, Akpomiemie and Smith improved the heat recovery of the HEN by enhancing the heat transfer coefficient (HTC) of selected exchangers along a heat load path. This is achieved through HTE and involves adding specifically designed devices to a heat exchanger, typically a shell and tube heat exchanger. Examples of tube-side enhancements include fins, twisted tapes, and coiled wires (Figure 2.21); examples of shell-side enhancements include helical baffles. In the case of some tube-inserts, these can be cheap and easy to install.

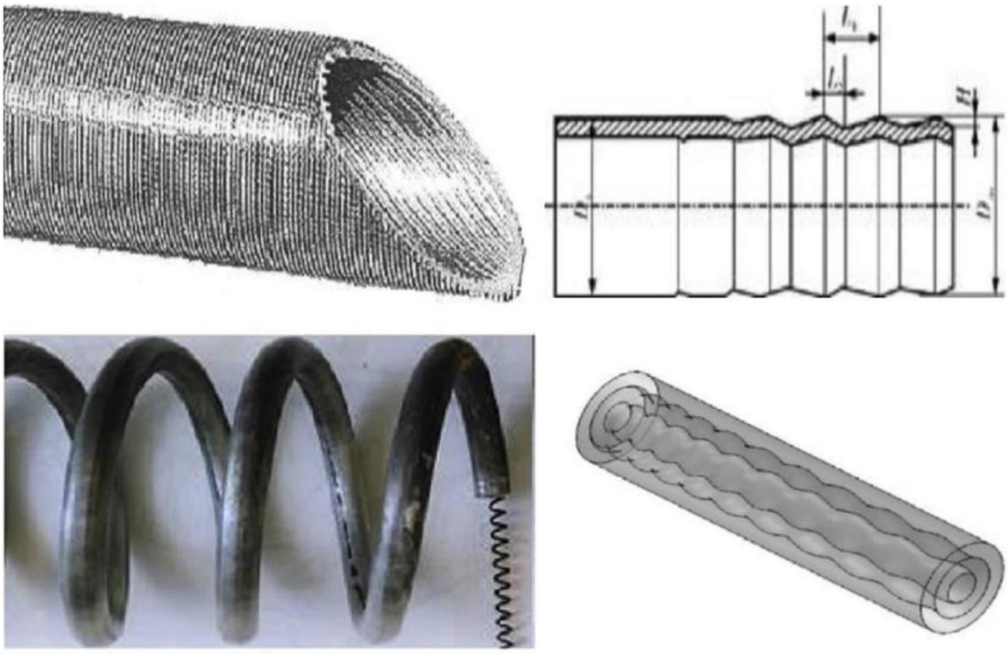


Figure 2.21: Examples of tube-side devices for heat transfer enhancement (used with permission from Klemeš et al., 2020).

The novel method involved identifying the heat exchangers suitable for HTE and then selecting the best candidate with a sensitivity analysis. The method is iteratively applied, updating the HEN each time, until the maximum retrofit profit is less than the initial profit. Further work by Akpomiemie and Smith saw the use of an area ratio, rather than a sensitivity analysis, for determining the best exchanger to enhance (Akpomiemie & Smith, 2016), as well as a hierarchy for the order in which exchangers should be enhanced and the inclusion of pressure drop considerations (Akpomiemie & Smith, 2017). Similar work was carried out by Jiang et al. (2014) and Wang et al. (2012). An improved method for modelling the performance of heat exchangers with HTE was also proposed by Jiang et al. (2014) so that HTE retrofit analysis could be more accurate. Much of these developments combined to form a cost-effective strategy for the HTE retrofit in HENs (Akpomiemie & Smith, 2018), selecting which heat exchangers to enhance optimally.

Pan et al. (2013) used an MILP-based method to find a feasible retrofit solution using HTE only. Like other MP-based methods, the formulation utilised two iterative loops to handle the search for feasible solutions as well as the maximisation of retrofit profit. Heat transfer enhancement was considered for the shell-side and the tube-side. Later developments included considerations of fouling and pressure drop (Pan et al., 2016), as well as the geometrical elements of shell and tube heat exchangers (Pan, Smith, & Bulatov, 2013). Pan et al. (2018) later extended their MILP-based iterative approach, applying it to an illustrative example and an industrial scale problem to show the efficacy and efficiency of the method. These developments targeted several gaps in the literature that the authors had identified, as these aspects of retrofit design are not prioritised often.

Another way of handling HTE is to determine the additional area required by the existing exchangers and then apply HTE as a way of reducing the amount of area needed. Zhu et al. (2000) applied this strategy when developing a targeting strategy for tube-side enhancements. The proposed method used an enhancement ratio to determine the required HTE as well as a pressure drop index. Pressure drop is an important part of HTE as the use of enhancements can increase the pressure drop. The pressure drop index helped to evaluate these changes.

Understanding how HTE can be used is also important as many retrofit design methods determine how much retrofit area is needed but do not propose how that area will be implemented. Nie and Zhu (1999) extended the Network Pinch method to handle HTE implementation for the reduction of retrofit area while ensuring that pressure drop constraints (i.e., based on existing pumps) were maintained.

Substituting HTE for the additional area can be a valuable retrofit strategy in cases where major topological changes to the heat transfer area can be impractical or expensive. HTE is a potential option that significantly reduces the effort and cost of any retrofit project.

2.5.2 Other

In terms of optimisation of a selected retrofit design, methods such as the Cost Derivative Method could be used to optimise the allocation of retrofit area (Timothy G. Walmsley, Walmsley, Morrison, et al., 2014). The method accounted for several key characteristics of a heat exchanger, including film coefficients and flow arrangements. Applying the Cost Derivative Method to a simple distillation process and a milk powder plant resulted in annual cost reductions of 7.1% and 5.8%, respectively. The Cost Derivative Method also introduced a flow-on factor to show how changes to the area of exchangers could propagate effects downstream (Figure 2.22), such as lowering utility load or causing temperatures to be off-target. The propagation of changes through the HEN is an important consideration.

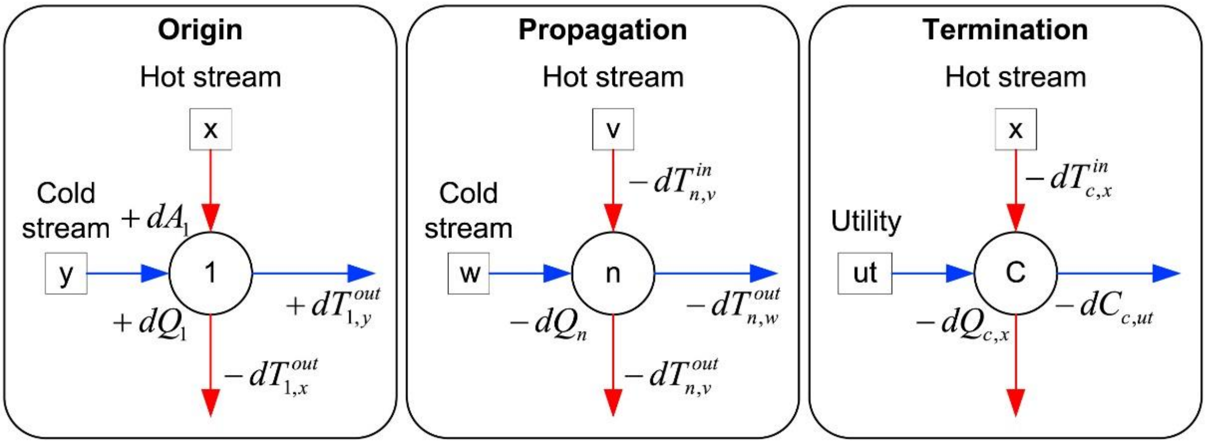


Figure 2.22: Effect of flow-on factors on utility load and cost (used with permission from Timothy G. Walmsley, Walmsley, Morrison, et al., 2014).

Many retrofit design methods that are focused on specific heat exchangers are based on shell and tube heat exchangers. This is due to the prevalence of shell and tube heat exchangers in industry. With respect to the Network Pinch, remedying the HEN with conventional methodology may not be possible for a HEN consisting of plate heat exchangers due to the different topology, especially if the plate heat exchangers have been brazed or welded. Bulatov (2005) developed a retrofit framework specifically for plate HENs, building on the grassroots design method and the retrofit area matrix method.

In a different approach to other retrofit design methods, Pouransari and Maréchal (2014) considered the location of units in the plant layout so that the distance between matched streams could be accounted for in an MILP problem. The layout of the HEN and units was presented as a 3D diagram with a detailed coordinate system (Figure 2.23). The MILP problem in the original work related to the synthesis of a HEN; however, the authors claim that the method is practical for retrofit design as well. As an existing HEN is heavily constrained by the spatial arrangement of the process streams and exchanger units, a similar distance-based analysis would be very useful for a retrofit analysis, in which new exchanger units that matched streams in proximity may be favoured over exchanger units that matched streams that were far apart. The cost of piping infrastructure would need to be considered to add weight to these decisions.

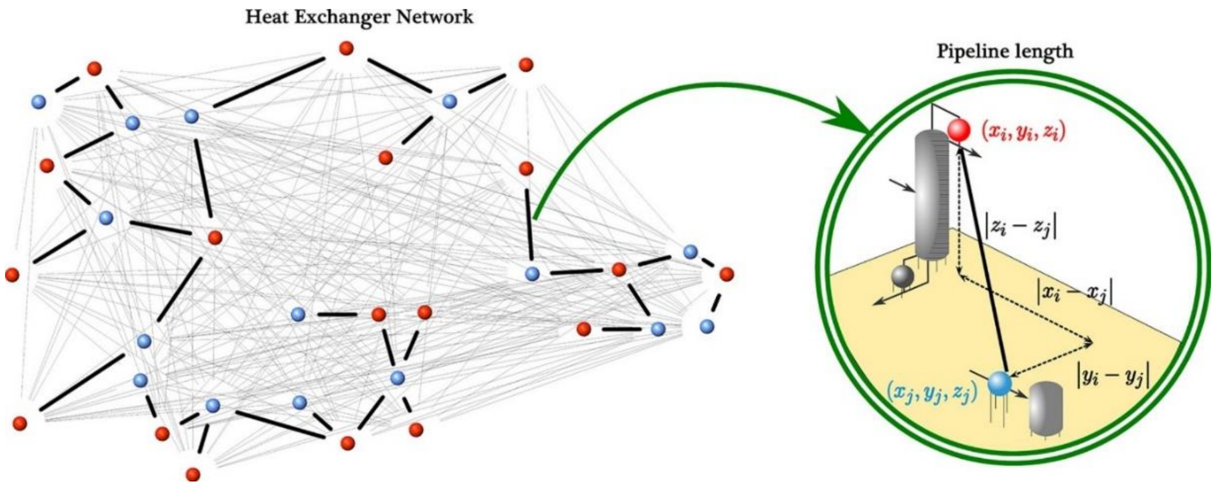


Figure 2.23: Representation of the spatial distance between heat exchangers in a HEN (used with permission from Pouransari & Maréchal, 2014).

2.6 Heat Exchanger Network Performance

2.6.1 Heat Exchanger Network Flexibility

An often-overlooked aspect of retrofit HEN is the effect of retrofit modifications on the operability of the HEN, which encompasses the controllability, resiliency, and flexibility of the HEN. If these aspects of HEN design are not considered, the HEN may become uncontrollable without undoing some of the design choices that made the retrofitted HEN optimal originally (Oliveira et al., 2001). While the exact definitions of flexibility, resiliency, and controllability can vary in the literature, they each relate to the ability of a HEN to function at steady state. In this thesis, controllability can be considered to relate to the dynamic ability of a HEN to respond to changes in operation, while flexibility and resiliency relate to the ability of the HEN to operate within a feasible region (Figure 2.24). The difference between these two terms is that resiliency refers to the ability of the HEN to return to steady state (i.e., nominal values or setpoints) after a disturbance (Grossmann & Morari, 1983) (although, some works also define this as flexibility). In this thesis, flexibility is defined as the ability of a HEN to remain at steady state despite changes in operation – which may include completely different operating conditions, in addition to other changes. As Verheyen and Zhang (2006) state, "a good HEN should be optimal for a set of nominal conditions as well as provide the flexibility to handle a range of operating conditions." Verheyen and Zhang also defined there to be two major causes of variation in HEN parameters: 1) variations around a nominal value due to environmental changes or poor control, and 2) variations due to seasonal changes or periodical changes to the operating conditions.

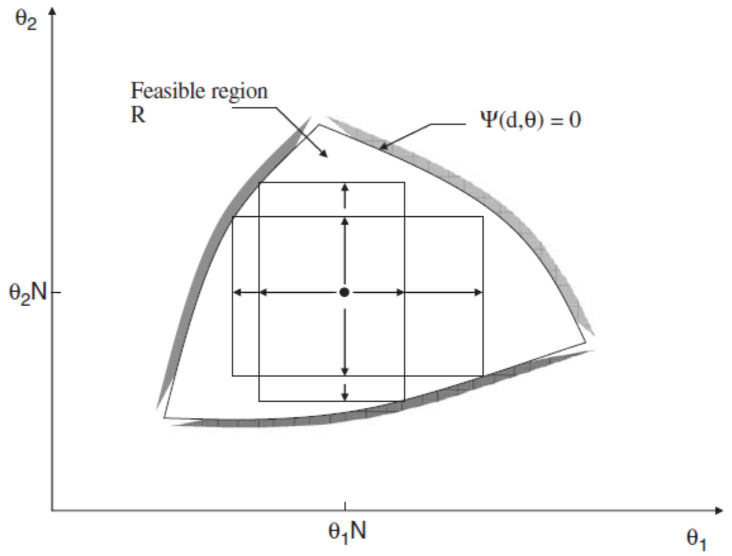


Figure 2.24: The feasible region of HEN operation (used with permission from Verheyen & Zhang, 2006).

Flexibility issues can arise when there is variation in the process stream parameters. In HEN design, synthesis and retrofit, the analysis is based on nominal values for these process stream parameters. In some cases, the use of nominal values is a simplification that neglects the variability that is sometimes present (Grossmann & Guillén-Gosálbez, 2010). By not considering the uncertainty, there exists the chance that a HEN design will not perform to expectations in certain conditions and could even lead to safety issues.

One of the main methods of controlling a HEN and increasing its flexibility is the use of bypasses on the heat recovery exchangers (the other method is utility control) (Figure 2.25). Bypasses are needed for control of heat recovery exchangers, especially when there are no utility exchangers present on the same process stream (Young et al., 2006). Mathisen et al.

(1992) presented a methodology for determining the optimal bypass selection for control of the HEN. Several heuristics for bypass control were outlined, including bypasses over several exchangers in series may enhance the controllability, bypasses with direct effects should be preferred for the control of critical targets, and bypasses with multiple downstream paths to a single critical target should be avoided. Sun et al. (2018) developed a methodology for considering the bypass control and economics of a HEN simultaneously. This is significant as there is a trade-off between bypass control and the capital investment required – bypasses result in increased flexibility but increase the capital cost, too.

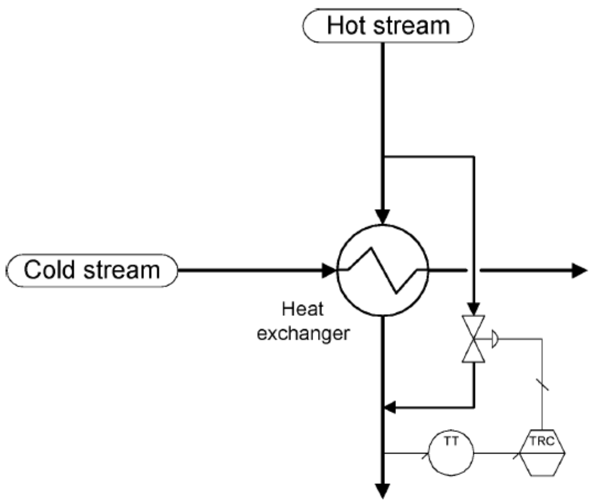


Figure 2.25: Bypass for the control of a heat recovery exchanger (used with permission from Westphalen et al., 2003).

There is significant research on HEN controllability and flexibility for grassroots HEN projects. Westphalen et al. (2003) proposed a controllability index as a means of measuring the controllability of the HEN. The controllability index could be calculated during HEN design and used to identify trade-offs between energy savings and controllability. Young et al. (2006) used dynamic simulations, as opposed to steady state simulations, to develop and design control structures, also proposing heuristics for identifying strategies. Escobar et al. (2013) developed a framework for integrating flexibility and controllability into HEN synthesis. Heggs and Vizcaíno (2002) used a disturbance propagation model to show which heat exchangers in a HEN should be controlled to achieve the greatest level of temperature controllability. Tellez et al. (2006) proposed that design reliability theory could be used to identify control systems that would be controllable, resilient, and able to prevent constraint violations in the HEN.

Deterministic mathematical programming methods are commonplace when dealing with controllability during HEN synthesis. Verheyen and Zhang (2006) used MINLP models to design and optimise HENs with multiple periods of operation. Novak Pintarič and Kravanja (2004) developed an MINLP-based method for HEN synthesis that determined the optimal flexible network structure as well as the optimal oversizing of heat exchangers that were required to achieve a flexible and feasible HEN and later developed a flexibility index based on the deviation of uncertain parameters from their nominal values (Novak Pintarič & Kravanja, 2015). A similar flexibility index was also developed by Swaney and Grossmann (1985). Gu et al. (2018) incorporated flexibility and controllability design into the HEN synthesis (by MINLP optimisation), using optimised bypass fractions to handle potential disturbances. Payet et al. (2018) synthesised HENs using MILP to design and optimise the network before analysing the HENs flexible behaviour and robustness.

Bakar et al. (2015) related the flexibility of a HEN to PA, more specifically, the ΔT_{min} selection. In Pinch design, the ΔT_{min} constrains the design and dictates how the HEN can be synthesised. The work by Bakar et al. sought to optimise the ΔT_{min} such that the economics and controllability were both maximised. A trade-off plot was proposed by Bakar et al. (2016) to assist in the optimal selection of the ΔT_{min}. The trade-off plot was an extension of an early plot that was used for the trade-off between energy savings and capital cost. The new trade-off plot retains this information but now also includes the operation cost and controllability (Figure 2.26). There are obvious implications for controllability, as a higher ΔT_{min} means lower energy savings but better controllability. While the trade-off plot was developed for HEN synthesis, it is still an important tool for retrofit projects.

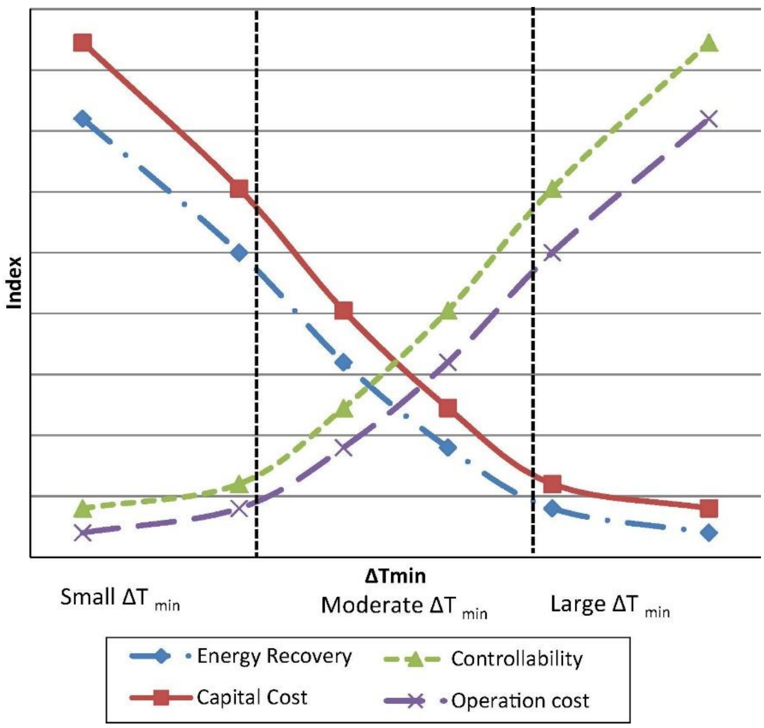


Figure 2.26: Trade-off plot for controllability considerations (used with permission from Bakar et al., 2016).

In retrofit HEN design literature, there are fewer examples of flexibility analyses. Many of the previously discussed methods are conducted post-design; therefore, these methods can still be applicable to retrofit designs after they have been designed. It is important to verify the controllability and flexibility of a retrofitted HEN as a once-flexible HEN may no longer perform to the same standard once modifications have been applied. In a similar sense, there has been some research into improving the flexibility of existing HENs; however, the distinction must be made that the goal of these works is to improve flexibility and controllability and not necessarily to improve heat recovery while improving or maintaining flexible performance. For example, Papalexandri and Pistikopoulos (1993, 1994) developed an MINLP model for retrofitting HENs to improve their flexibility. A specified set of operating conditions was paired with a superstructure representing possible retrofit modifications to find the most cost-effective, and energy-efficient flexible retrofit HEN designs. There is still a gap in the literature for retrofit HEN design methods that incorporate flexibility and controllability considerations into the initial retrofit design stages.

2.6.2 Monte Carlo Simulation

In literature, Monte Carlo Simulation (MCS) is often used as a stochastic tool for the analysis of a system's performance. MCS is an analysis method based on artificially recreating a chance process, running it many times, and then directly observing the results (Barreto & Howland, 2005). Because of the randomness that is incorporated into the modelling, MCS is a stochastic mathematical method and elements of MCS-type sampling have been used in stochastic MP techniques (for HEN retrofit design) such as simulated annealing (Athier et al., 1998). In a real-life process, temperature and flow rates can often have a distribution of possible values. MCS can effectively represent these distributions and characterise the variation and uncertainty that is present in a real process.

MCS has also been used in Process Integration in areas other than Heat Integration. Tan et al. (2007) used MCS to assess the sensitivity and robustness of water networks (analogous to HENs). The analysis was used to identify the network configurations that could appropriately handle any mass load fluctuations while rejecting the configurations that would fail. Later, Tan et al. (2017) used MCS to test the robustness of carbon management networks, and Benjamin et al. (2017) used MCS to assess the vulnerability of bioenergy parks to variable disturbances. Other examples include using MCS to optimise process flow sheets (Zore et al., 2017) and to verify the reliability of resource allocation networks (Arya & Bandyopadhyay, 2018), as well as investigating the effect of unsteady parameters on the design of an internal combustion engine using convergence values, frequency distributions, and cumulative probability distributions (T. Zhang et al., 2016). MCS can also be applied to financial projects, such as risk analysis of investment in renewable technology projects, which showed advantages over standard methods and sensitivity analyses (Arnold & Yildiz, 2015).

Some authors have used MCS in the design of heat exchanger units. Sieres and Campo (2018), who used MCS for the determination of heat transfer coefficients, remarked that MCS is useful for propagating the uncertainties that are introduced by measured values. Similarly, Badar et al. (1993) used MCS techniques for determining the thermal properties of a heat exchanger, while Clarke et al. (2001) used the techniques for sensitivity analysis of heat exchanger designs based on uncertain physical properties, such as air temperature and overall heat transfer coefficient (Figure 2.27).

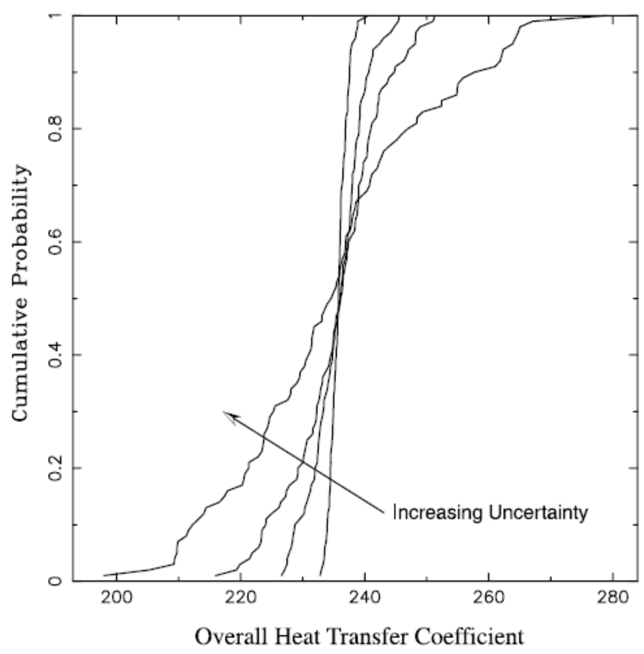


Figure 2.27: Analysis of the uncertainty in the overall heat transfer coefficient of a heat exchanger (used with permission from Clarke et al., 2001).

In terms of MCS usage for HENs, there no literature on MCS and retrofit HEN design. There is also little literature on MCS and HEN synthesis; however, one notable example is the work by Novak Pintarič and Kravanja (2015) where MCS was used to test the flexibility of an optimal HEN synthesis design, assuming Normal distributions for all temperatures and heat capacity flow rates. In all cases, the usefulness of MCS with respect to uncertainty was affirmed, and MCS has yet to be applied to HEN design in a retrofit sense. There is potential for success with MCS as the historical plant data introduces uncertainty to the retrofit design and MCS will be able to use this data to inform the design.

2.7 Conclusion

The literature review shows that there are many retrofit design methods that offer solutions to the retrofit Heat Exchanger Network problem; however, these retrofit design methods are often lacking in usability, simplicity, and relevance to established Pinch Analysis techniques from where many insights can be derived. Mathematical programming (MP) methods offer rigorous optimisation of a HEN but are hindered by a reliance on expensive computational software, excessive computational effort, and lack of user input outside of design selection. Graphical methods are useful tools for presenting important concepts and incorporating a user's insights, but there is a clear need for a graphical HEN retrofit design method that is capable of handling large, complex industrial HEN problems. This can be achieved by computation, a lack of which is a weakness of graphical methods. Computation alongside graphical methods is often achieved by hybrid methods which combine advantages of both types of methods, even if some hybrid methods rely heavily on the MP side and often fall into the same problems as pure MP methods. There is also a considerable gap in the literature for how to deal with the uncertainty that is introduced by variable process stream data in terms of the economics, performance, and flexibility of the HEN.

The review has identified key areas in the literature where there is a gap, particularly in the computation of useful graphical methods and analysis of retrofitted HEN performance. Bridge Analysis and Monte Carlo Simulation have been identified as candidates for development to address these gaps in line with the thesis aim.

Chapter 3

Improved Bridge Analysis and the Modified Energy Transfer Diagram

3.1 Introduction

The heat exchanger network (HEN) can be retrofitted using Bridge Analysis to improve heat recovery and reduce the demand for process heat. Bridge Analysis identifies retrofit modifications in the form of 'bridges' between heat sinks and sources. These bridges are found using the Energy Transfer Diagram (ETD), developed by Bonhivers et al. (2017) as the primary tool for Bridge Analysis. The aim of this chapter is to develop new, or modified, retrofit tools that address some of the shortcomings of the ETD and Bridge Analysis, helping to strengthen the concept of Bridge Analysis and improve the characterisation of the HEN. These novel graphical and tabular tools more effectively support the identification of bridges that can achieve energy savings through heat recovery improvement. First, the Modified ETD (METD) more appropriately represents the cascade and distribution of process heat from the hot utilities to the cold utilities (and then environment) through the classification and graphical representation of heat surpluses and heat deficits (within the process streams) in the HEN. Second, the Heat Surplus-Deficit Table (HSDT) is a numerical counterpart to the METD, adapted primarily from the Problem Table Algorithm traditionally used in Pinch Analysis, and is also used to identify bridges tabularly. More importantly, the HSDT is a useful tool for enumerating the energy savings that a bridge can achieve through the corresponding retrofit modifications.

The novel developments to Bridge Analysis provide a deeper understanding and connection to fundamental Pinch Analysis concepts and tools such as the Pinch temperature and Grand Composite Curve. These developments also improve the overall implementation of Bridge Analysis. The use of the METD and HSDT is demonstrated with an illustrative example. Two industrial HEN case studies, relevant to New Zealand, are also analysed. The first case study is based on a Kraft pulp and paper mill and the second case study is based on a petrochemical complex.

3.2 The Original Energy Transfer Diagram

The Energy Transfer Diagram (ETD) (Figure 3.1) is the primary tool that has been developed for Bridge Analysis – a novel retrofit design method that finds retrofit modifications for heat recovery improvement. It was introduced in the first published papers on Bridge Analysis (Bonhivers, Korbel, et al., 2014) and has since been extended to other aspects of the industrial process (Bonhivers et al., 2015). The ETD for Bridge Analysis of HENs has remained largely unchanged and undeveloped since its introduction; however, there are some weaknesses – some of which have been acknowledged by the original authors. The authors recognised that having the temperature on the horizontal axis and enthalpy on the vertical axis – the opposite of standard Pinch Analysis graphical tools such as the Grand Composite Curve – might have led to confusion and a lack of discussion among Pinch Analysis practitioners (Bonhivers et al., 2016). Two papers were published to compare and link the ETD to other Pinch Analysis-based tools and methods such as the Grand Composite Curve and Advanced Composite Curves to bridge the gap in understanding (Bonhivers et al., 2016; Bonhivers, Svensson, et al., 2014), but there have been no meaningful developments to the ETD to address this problem otherwise.

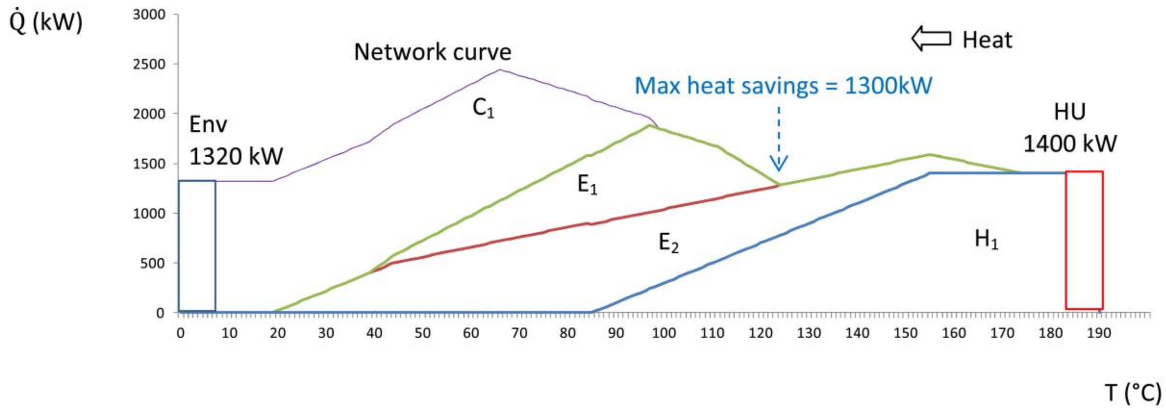


Figure 3.1: The Energy Transfer Diagram (used with permission from Bonhivers, Srinivasan, et al., 2017).

Bridge Analysis and the ETD have many similarities and connections with traditional Pinch Analysis, but key concepts such as the Pinch temperature are not given significance. Many PA-based retrofit analysis methods make modifications to the HEN based on the presence of cross-Pinch heat exchange, relying on the identification of the Pinch temperature. The Pinch temperature can be easily identified using the ETD; however, no attempt has been made to conceptually involve the Pinch temperature in Bridge Analysis. In a similar way, equation-based methods are used to create the Energy Transfer Curves that make up the ETD; however, many other traditional PA techniques (i.e., the Problem Table Algorithm) can also be used to create the exact same ETD. The connection between the two methods is not made – missing the insights that those techniques could provide to Bridge Analysis. For a graphical tool that is founded in PA, there appears to be a disconnect between ETD and PA as the relationships between ETD and PA are used to compare and differentiate rather than improve the understanding behind the thermodynamic concepts presented in the ETD.

There are also some issues with the identification of bridges (the set of modifications used to improve heat recovery) when using the ETD. There are two main issues: 1) the savings potential of a bridge cannot be determined using the ETD, requiring the use of additional tools, and 2) there is no information about the actual process streams in the HEN and the corresponding heat that can be recovered from them (hot streams). However, the ETD is perfectly capable of enumerating the savings potential as well as representing the heat available in process streams. This chapter addresses these issues and makes several modifications to the ETD and overall Bridge Analysis method. By changing the representation of the ETD, its use in Bridge Analysis is greatly improved, enabling additional insight into the retrofit problem. To summarise the developments:

1. The ETD is constructed using the Problem Table Algorithm and Composite Curves to improve the understanding of how heat is cascaded through the HEN.
2. Temperature is plotted on the vertical axis while enthalpy is plotted on the horizontal axis, keeping with the standard conventions used in PA.
3. The importance of the Pinch temperature for Bridge Analysis is established, and the Pinch temperature is highlighted on the ETD.
4. Each Energy Transfer Curve is redefined as an Exchanger Grand Composite Curve, allowing the identification of specific process streams as well as the heat surpluses or deficits that are present.
5. The classification of heat surpluses and deficits in the ETD allows the savings potential (heat recovery improvement) of a Retrofit Bridge to now be quantified. Heat surpluses are indicated by red lines while heat deficits are indicated by blue lines. Black lines are used to show zero net enthalpies.

These modifications improve the use of Bridge Analysis and assist the user in generating different retrofit design options, Retrofit Bridges. The developed ETD is called the Modified Energy Transfer Diagram (METD) and has been modified specifically for the retrofit analysis of HENs. The Problem Table Algorithm has also been adapted into a retrofit tool called the Heat Surplus-Deficit Table (HDST), which serves as a numerical companion to the METD (like the network table in the original Bridge Analysis); however, both retrofit tools can be used independently to identify and quantify Retrofit Bridges.

In this thesis, the following notation is used for the different types of heat exchanger units: C for coolers/cold utility, H for heaters/hot utility, and E for heat recovery exchangers.

3.3 Modified Energy Transfer Diagram

In this section, significant detail is provided on the novel contributions based around the METD, its construction, and the way in which retrofit opportunities are identified and quantified (i.e., Retrofit Bridges). The connection to Pinch Analysis is discussed in each section, and an illustrative example is used to demonstrate the METD's use in Bridge Analysis.

3.3.1 Illustrative Example

Throughout this section, a four-stream illustrative example is used to demonstrate the different features of the METD. The four-stream HEN has been adapted using stream data from Klemeš et al. (2014) (Figure 3.2a). There are two recovery exchangers (E1 and E2), two coolers (C1 and C2) with a total cold utility (CU) load of 2,950 kW, and one heater (H1) with a hot utility (HU) load of 2,700 kW. A global ΔT_{min} of 10 °C is used for the retrofit analysis. This corresponds to a ΔT_{cont} of 5 °C for each of the four process streams. ΔT_{cont} refers to the contribution to the minimum approach temperature and can be used to differentiate streams with different thermal characteristics and requirements.

The corresponding METD for the HEN is presented in Figure 3.2b. Each of the exchanger units (C1, E1, H1, etc.) are represented on the METD.

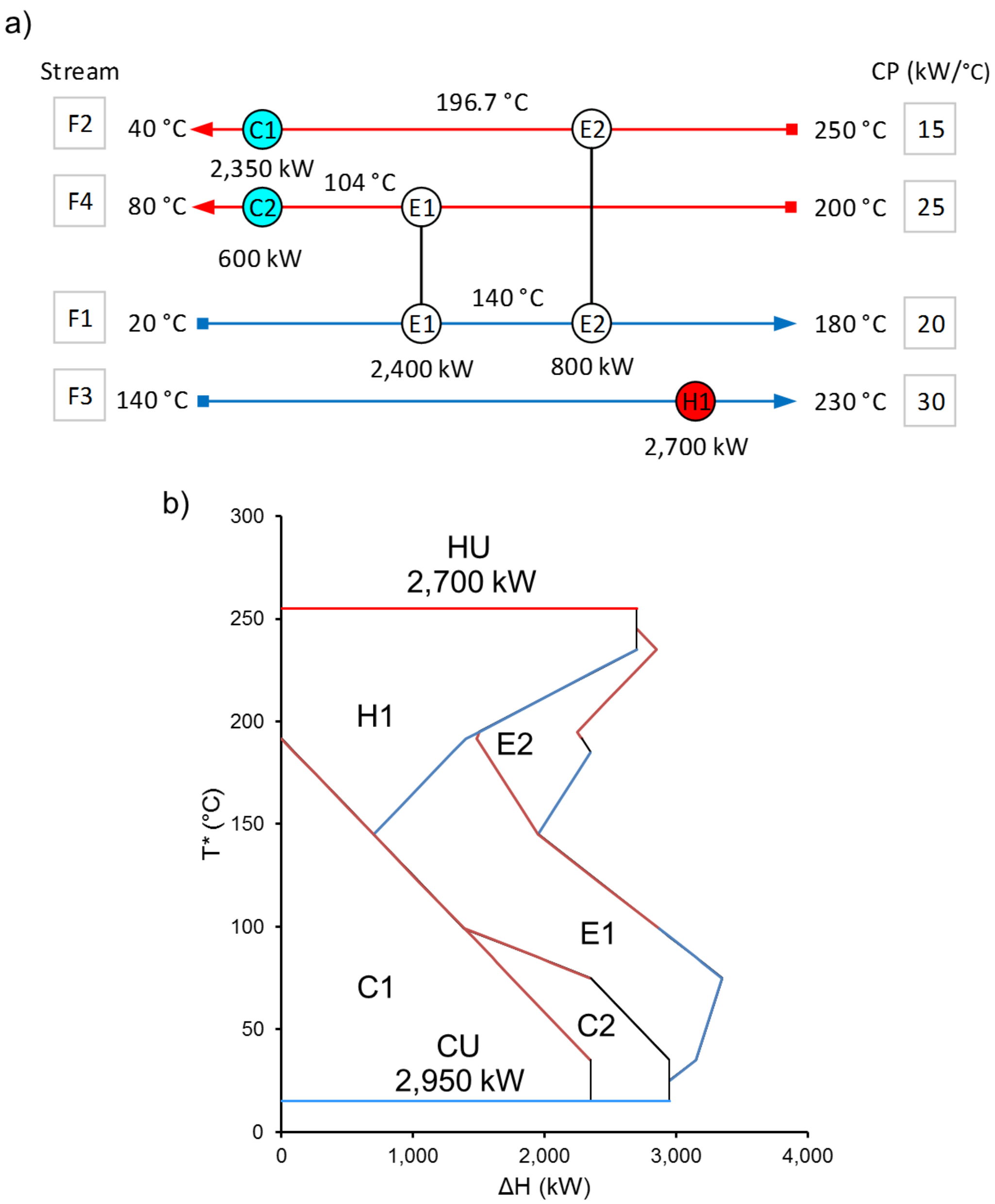


Figure 3.2: a) Heat exchanger network grid diagram and b) Modified Energy Transfer Diagram for the four-stream illustrative example.

3.3.2 Constructing the Modified Energy Transfer Diagram

The construction of the original ETD was based around the calculation of Energy Transfer Curves (ETC) and a network curve (explained later) using Equations 3.1 and 3.2 (Bonhivers, Alva-Argaez, et al., 2017).

$$\mathrm{ETC}_i\ (T) = \mathrm{ETC}_i\ (T+1) + FCp_i^S\ (T) - FCp_i^r\ (T) \tag{3.1}$$

$$\text{Network curve}\ (T) = \sum_{i=1}^{\text{Exchangers}} \text{ETC}_i\ (T) \qquad (3.2)$$

Where FCp_i^S and FCp_i^r refer to the heat capacity of the supplier and the receptor in a heat exchanger, or more simply, the hot stream and cold stream in a heat exchanger. The ETC is calculated for each individual heat exchanger (recovery and utility), at each temperature *T*. Equation 3.1 says that the heat flow at temperature *T* is equal to the heat flow at temperature (*T* + 1) plus the net heat flow between the supplier and receptor. The ETC is generated by calculating these heat flows at all relevant temperatures, for a given heat exchanger. Following Equation 3.2, the network curve is the sum of these ETCs.

The same ETD can be generated using the Problem Table Algorithm and Composite Curves; however, Energy Transfer Curves are redefined as Exchanger Grand Composite Curves (EGCC) due to their method of construction and the thermodynamic concepts they represent. Like the Grand Composite Curve (GCC) (of the whole HEN), the EGCCs represent the overall heat surpluses and deficits in the process streams; however, the GCC is constructed from the entire set of stream data while the EGCC is constructed from a single heat exchanger match (or utility match). In other words, each EGCC is created using the temperature and flow rate data of the process stream segments matched in a heat exchanger. As with the GCC, the EGCCs are also dependent on the ΔT_{min} or ΔT_{cont} of the matched streams. Hot temperatures are shifted down by the corresponding ΔT_{cont} ($\Delta T_{min}/2$, if a global ΔT_{min} is used) while cold temperatures are shifted up by the ΔT_{cont} (the original ETD also used shifted temperatures). The progression from an individual heat exchanger to an EGCC is presented in Figure 3.3, featuring the development from stream data to Exchanger Shifted Composite Curves (ESCC), to the Exchanger Problem Table Algorithm (EPTA), and finally to the EGCC.

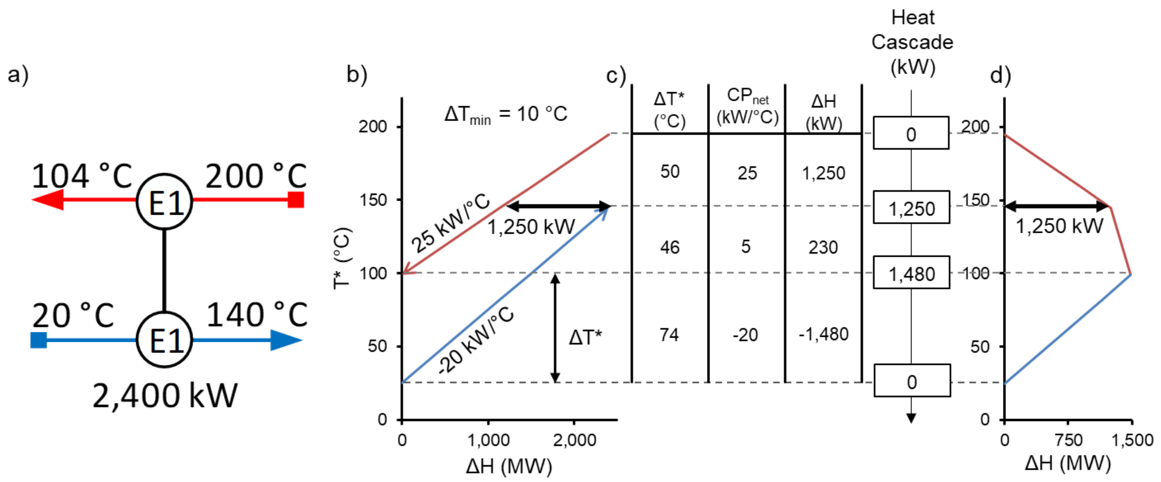


Figure 3.3: Relationship between a) heat exchanger stream data and the b) ESCC, c) EPTA, and d) EGCC for the recovery exchanger E1.

The heat exchanger data (Figure 3.3a) is first used to create an ESCC (Figure 3.3b) (with temperatures shifted based on ΔT_{min}), which show the temperature intervals in which the process streams are present. The total heat flow in each interval can then be calculated, providing either a net heat surplus or a net heat deficit. The total heat flow, or net change in enthalpy, is calculated in each temperature interval using Equation 3.3:

$$\Delta H_{ij} = (CP_h - CP_c) * (T_i^* - T_j^*) = CP_{net}\Delta T_{ij}^* \tag{3.3}$$

Where *ΔH* is the total heat flow (kW) in the temperature interval defined by *i* and *j*, and *CP* is the heat capacity flow rate of the hot (*h*) or cold (*c*) stream (product of the specific heat capacity and mass flow rate) (kW/°C). To assist with the calculation of the heat flows, the Problem Table Algorithm is used – modified for individual heat exchangers and aptly named the Exchanger Problem Table Algorithm (EPTA)(Figure 3.3c). Like the EGCC, the EPTA considers each exchanger as a separate problem with only one hot stream and one cold stream (including utility streams), whereas the Problem Table Algorithm considers the entire set of hot and cold streams. The general formula of the EPTA is presented in Table 3.1.

Table 3.1: Exchanger Problem Table Algorithm.

T^* (°C)	ΔT^* (°C)	CP_{net} (kW/°C)	ΔH (kW)	Heat Cascade (kW)
T_1				$H_1 = \Delta H_{HU,E}$
	$T_1 - T_2$	$(CP_h - CP_c)_{1-2}$	$(\Delta T \cdot CP_{net})_{1-2}$	
T_2				$H_1 + \Delta H_{1-2}$
	$T_2 - T_3$	$(CP_h - CP_c)_{2-3}$	$(\Delta T \cdot CP_{net})_{2-3}$	
⋮	⋮	⋮	⋮	⋮
	$T_{n-1} - T_n$	$(CP_h - CP_c)_{[n-1]-n}$	$(\Delta T \cdot CP_{net})_{[n-1]-n}$	
T_n				$H_{n-1} + \Delta H_{[n-1]-n}$

Each EGCC is drawn using the heat cascade from the EPTA, as seen in Figure 3.3. The heat cascade is the cumulative flow of heat surpluses (positive values) and heat deficits (negative) in the EGCC. Once all EGCCs have been determined (Figure 3.4a), they are ‘stacked’ against the vertical axis of the METD (Figure 3.4b). When an EGCC would overlap with another, the curve is instead shifted along the horizontal axis (to the right) while retaining the same temperature and change in enthalpy values (e.g., the 800 kW surplus and deficit in E2 are preserved during the stacking) (Figure 3.4c). In the example, the EGCC of E2 is distorted from its original shape without affecting any of the EGCCs that had already been stacked in the METD. The shape of other EGCCs may cause several ‘points’ to appear in the EGCC, such as the 150-kW surplus in E2 that results in a peak due to the EGCC of H1. In general, it is recommended that heater EGCCs are stacked first, followed by cooler EGCCs, and then finally recovery EGCCs, for clarity. When plotting the METD, the stacking effect is achieved by adding the enthalpy of the EGCC (from its EPTA) onto the current total enthalpy for the same temperature interval.

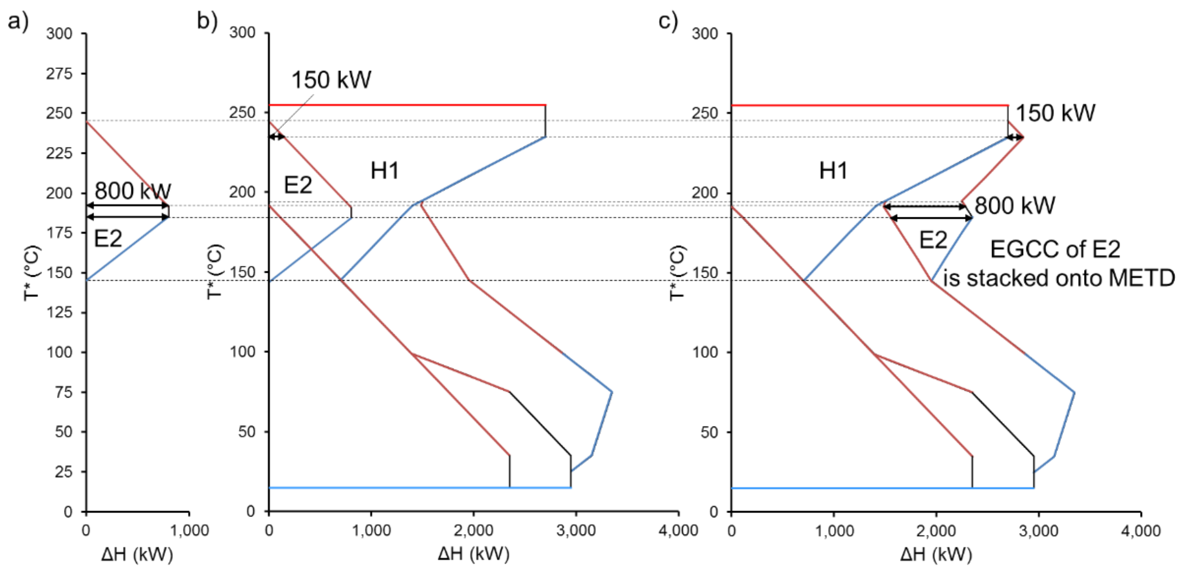


Figure 3.4: The construction of the METD through the stacking of EGCCs. The EGCC of exchanger E2 (a) overlaps with other curves in the METD (b) and is shifted and stacked, preserving temperatures and enthalpies (c).

3.3.3 Targeting Energy Savings and Heat Recovery Improvement

The METD does not show the heat recovery of the existing heat exchangers, instead it focuses on the information that the EGCC provides – the available heat surpluses and deficits. The existing heat recovery is typically already known, prior to the start of the retrofit analysis, and does not provide information that is as immediately meaningful as the available heat surpluses and deficits. For example, an existing heat exchanger may recovery a large amount of heat between two streams, but this does not guarantee that there is a large available heat surplus or deficit that can be used in a retrofit. The goal of Bridge Analysis and the METD is to target these opportunities. The following section will explain how energy savings and heat recovery improvements can be achieved.

One of the main features of the ETD and METD is the network curve. The network curve is the outermost curve (overall outline of the EGCCs) of the METD which represents the total heat cascade in the HEN. In fact, the network curve, especially apparent in the METD, is equivalent to the GCC for the same stream data (and same ΔT_{min}), displaced along the enthalpy axis. The displacement of the network curve from the normal position of the GCC (against the vertical axis) is proportionate to the retrofit energy target or maximum energy savings (Figure 3.5a). When the heat recovery of an existing HEN is improved, the displacement of the network curve is reduced. If the network curve reaches the normal position of the GCC, then no further improvements to heat recovery can be made. This is because the GCC provides minimum utility targets (Figure 3.5b), i.e., the absolute minimum amount of utility required to service the process streams (for a given ΔT_{min}). Once these targets are reached, there are no more energy savings that can be gained.

The displacement, and therefore, the retrofit energy target, can be quickly determined by locating the Pinch temperature along the network curve at the point with the minimum enthalpy. For the illustrative example presented in Figure 3.5, the Pinch temperature is found to be 145 °C (Pinch temperature is dependent on the ΔT_{min}, multiple Pinch temperatures may also exist). At this point, the displacement of the network curve from the GCC position can be quickly determined to be 1,950 kW. Given a minimum hot utility target of 750 kW (from the GCC), it is theoretically possible to achieve a 72% reduction in the hot utility through Bridge Analysis (based on the selected ΔT_{min} – this has an effect on targets).

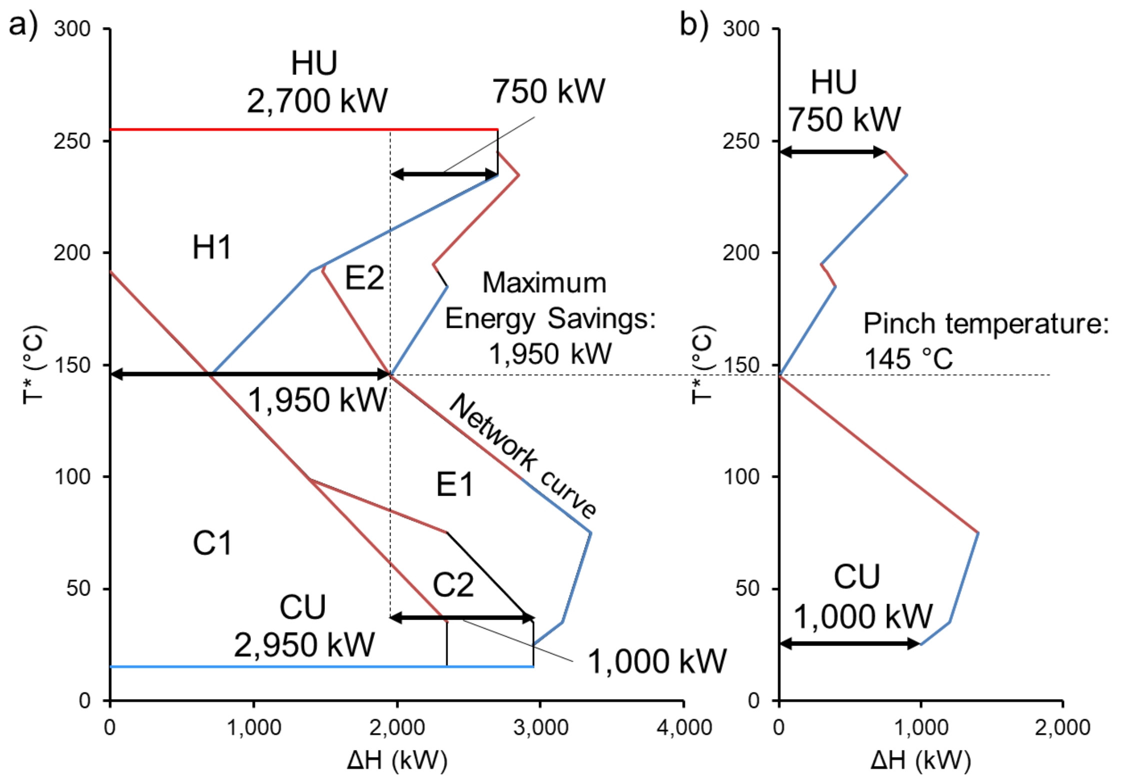


Figure 3.5: Comparison of a) the Modified Energy Transfer Diagram with b) the Grand Composite Curve for the illustrative example.

Retrofit modifications through Bridge Analysis will increase the heat recovery and push the network curve closer to the GCC position on the enthalpy axis, reducing the displacement and providing a lower reduction target for additional retrofitting. If the retrofit energy target can be achieved, then a Minimum Energy Network will have been achieved. Knowing the retrofit energy target assists with Bridge Analysis; however, the goal of a retrofit is not to achieve a Minimum Energy Network as it is seldom cost-effective to do so. Still, the retrofit energy target helps guide Bridge Analysis by setting a limit to what is achievable. Understanding the reason for the displacement that leads to the retrofit energy target can also help to guide the retrofit analysis.

In a HEN, there are energy penalties for improper use of utilities and for cross-Pinch heat exchange (simply, heat transferred across the Pinch temperature) which result in lower heat recovery. These penalties create the displacement of the network curve and the deviation from the minimum utility targets. Accordingly, there are three “golden” rules for Pinch Analysis (for achieving the minimum utility targets) (Kemp, 2011) that can also apply to a retrofit design:

1. Do not transfer heat across the Pinch (temperature).
2. Do not use cold utilities above the Pinch.
3. Do not use hot utilities below the Pinch.

The retrofit energy target is equal to the sum of the energy penalties (from Pinch violations), so by following these rules and reducing cross-Pinch heat exchange and correcting utility placement, heat recovery can be improved. Indirectly, this is how Bridge Analysis achieves energy savings (ETD does not utilise the Pinch temperature); however, using the Pinch temperature explicitly with the METD allows Bridge Analysis to target and rectify any heat transfer that violates the golden rules of Pinch Analysis. This is also how many other retrofit design methods, such as the early method developed by Tjoe and Linnhoff (1986), achieve retrofit savings – what differs is the approach for correcting cross-Pinch heat transfer.

As the METD represents each individual heat exchanger in the HEN, identification of cross-Pinch heat transfer (and its magnitude) and improper placement of utilities is effortless. In Figure 3.6, cooler C1 and (recovery) exchanger E1 both transfer heat across the Pinch temperature of 145 °C and contribute to the amount of additional heat that can be recovered to reduce process heat demand. In cooler C1, there is 2,350 kW of cold utility used to cool a heat surplus – with 700 kW used to cool the surplus from a temperature that is above the

Pinch (determined with the EGCC of cooler C1). This is cross-Pinch heat transfer, represented by the yellow shading in Figure 3.6, as well as use of cold utility above the Pinch. Recovery exchanger E1 also involves 1,250 kW of cross-Pinch heat transfer, bringing the total cross-Pinch heat transfer to 1,950 kW – the same as the retrofit energy target. Generally, if there are exchangers with significant cross-Pinch heat transfer, then these may present opportunities for retrofitting, and any retrofit modifications, or Retrofit Bridges, that affect these exchangers could be highlighted in the analysis. Other savings opportunities can be found when utilities are entirely located on the wrong side of the Pinch, i.e., hot utility used below the Pinch. Improper utility placement (with respect to the Pinch temperature) can be identified with the METD in the same manner as cross-Pinch heat transfer; however, there are no such cases in the illustrative example. Identifying these Pinch violations is the key to finding Retrofit Bridges that provide the greatest improvements in heat recovery, and therefore, the greatest reductions in process heat demand.

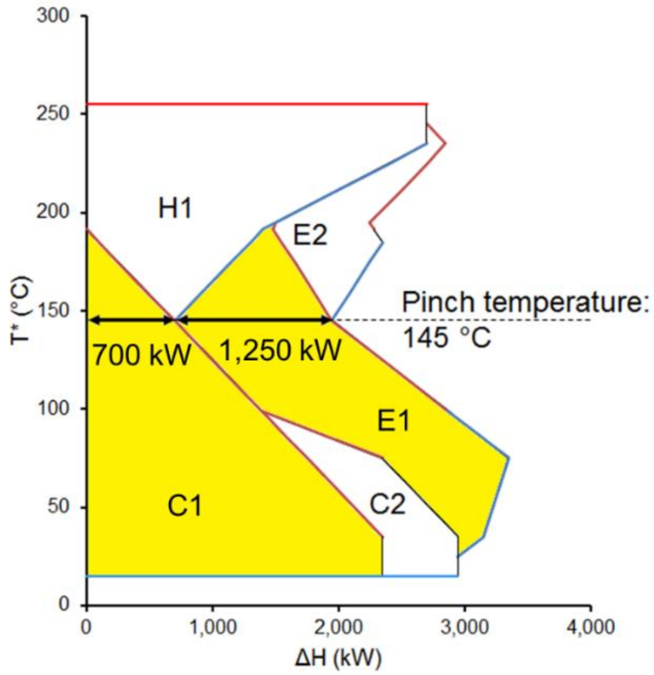


Figure 3.6: Identification of cross-Pinch heat transfer in the METD of the illustrative example.

3.3.4 Using Retrofit Bridges

In a HEN, a cooler (i.e., a cold utility exchanger) is used to reduce the temperature of a hot process stream by rejecting process heat to the environment (a heat sink). Equally, a heater (i.e., a hot utility exchanger such as a boiler) is used to raise the temperature of a cold process stream by supplying heat from a hot utility such as steam. If heat could be recovered from the hot process stream and transferred to the cold process stream, then the temperature of the hot process stream would decrease and the temperature of the cold process stream would increase; therefore, less cold and hot utility would be required as the process streams are now closer to their temperature targets. Bridge Analysis aims to increase the level of heat recovery in the HEN with retrofit modifications so that the overall utility demand can be reduced, particularly hot utility which is expensive and often requires fossil fuels. Modifications for a HEN are identified using Retrofit Bridges.

Retrofit Bridges are a series of matches that are used to create pathways between coolers and heaters, like a utility path. However, utility paths are typically used in network relaxation to eliminate small heat exchangers from a HEN (taking an energy penalty but decreasing capital costs) by shifting the heat duty onto the utilities at either end of the path (Kemp, 2011). Bridge Analysis achieves the opposite as new exchangers are added to reduce utility duties. If utility paths already exist in the HEN, the utility duty is shifted onto recovery exchangers by increasing the heat transfer area of those recovery exchangers. To avoid confusion with utility paths and network relaxation (which serves a different purpose), for Bridge Analysis, these paths are known as heat recovery pathways, and heat recovery pathways are created and exploited with Retrofit Bridges.

Each match in a Retrofit Bridge is a match between a heat surplus (or a portion of a heat surplus) and a heat deficit (or a portion of a heat deficit) (Figure 3.7a). A heat surplus is a section of a hot process stream that needs to be cooled (through recovery or cold utility), and a heat deficit is a section of a cold process stream that needs to be heated (through recovery or hot utility). Surpluses and deficits are only available in certain temperature intervals, depending on the temperatures of the stream segments that are matched together in heat recovery exchangers. A surplus (or portion of a surplus) cannot be used to heat a deficit (or portion of a deficit) that is at a higher temperature than the surplus (heat only transfers from a high temperature to a lower temperature). The matches in a Retrofit Bridge allow a heat surplus to be recovered and used to supply heat to a deficit. Through a series of matches that start with a cooler's heat surplus and end with a heater's heat deficit, heat can be supplied to the heater deficit and removed from the cooler heat surplus – achieving process heat demand reductions (Figure 3.7b). A Retrofit Bridge will also reduce cross-Pinch heat transfer or reduce the amount of utility used on the wrong side of the Pinch (discussed in the previous section), as matching between a cooler heat surplus and heater deficit is only possible if heat is being transferred across the Pinch. All Retrofit Bridges will contain a surplus-deficit match (not necessarily directly between a cooler and a heater) that contains Pinch-violating heat transfer. Generally, each surplus-deficit match required by a Retrofit Bridge relates to a retrofit modification, which can be either an increase in the heat transfer area of an existing heat recovery exchanger or the addition of a recovery exchanger.

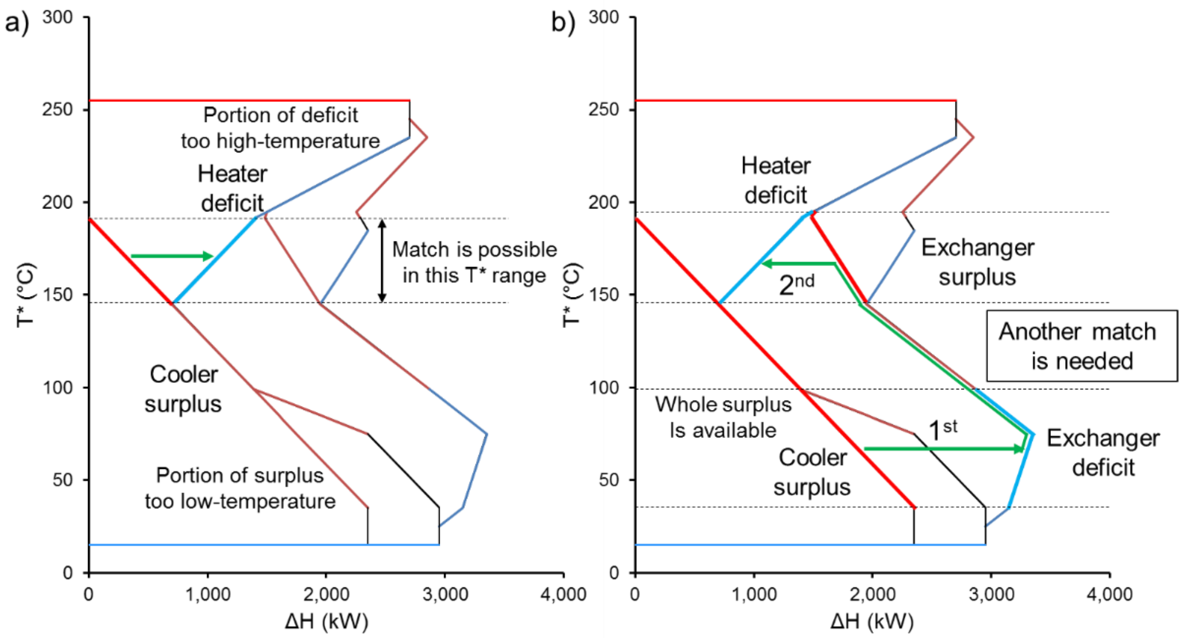


Figure 3.7: Identification of feasible surplus-deficit matches and Retrofit Bridges, including a) direct matches between a cooler heat surplus and a heater deficit, or b) matches including heat recovery exchangers. Matched surpluses and deficits are highlighted in the METD.

For a given HEN (and ΔT_{min}), there can be many possible Retrofit Bridges, depending on the number of heat exchanger units and the (shifted) temperature intervals at which heat surpluses and deficits are available. Retrofit Bridges are identified using the METD, using the surpluses and deficits that are represented as red and blue lines. The following rules must be followed to find a feasible Retrofit Bridge:

1. The first match in a Retrofit Bridge must begin with a cooler heat surplus; the last match must end with a heater deficit. These can be the same match.
2. If a cooler heat surplus is matched to a recovery exchanger deficit (a heat deficit in a recovery exchanger), then the recovery exchanger surplus (or a portion depending on

the amount of heat that can be matched) becomes available and must be used in the next surplus-deficit match (Figure 3.7b).

3. A match is only possible if the heat surplus is within an equal or higher temperature interval than the heat deficit so that heat may be transferred without violating the Second Law of Thermodynamics or ΔT_{min} (temperature intervals are shifted).
4. A Retrofit Bridge must be a unique sequence of matches; however, a specific match can be used in multiple different Retrofit Bridges and Retrofit Bridges may have the same matches in a different sequence.

After identification, the energy savings that each Retrofit Bridge can achieve is determined. Each surplus-deficit match has a maximum amount of heat that can be transferred, based on the amount of heat that can be supplied or received within the matched temperatures (i.e., a surplus cannot supply a deficit with more heat than it is thermodynamically able to receive while remaining within feasible temperatures). The match in a Retrofit Bridge that allows the least amount of heat transfer acts as a bottleneck to heat recovery and limits the energy savings of the Retrofit Bridge; therefore, a Retrofit Bridge's energy savings are equal to the minimum allowable heat transfer of any match in the Retrofit Bridge. Enthalpies are obtained using the EGCCs, the available surpluses or deficits, and the horizontal axis of the METD.

For each surplus-deficit match in a Retrofit Bridge, a new heat recovery exchanger is added to the HEN matching the corresponding process streams in the matched temperature intervals. The duty of the new heat exchanger is equivalent to the energy savings of the Retrofit Bridge, which is also subtracted from the involved utility exchangers. If the match already exists, then the duty of the existing exchanger can be increased, usually at the cost of increased heat transfer area. Retrofit Bridges can also affect the inlet temperatures of existing exchangers involved in the Retrofit Bridge (i.e., the surplus and deficit of a heat recovery exchanger are used in the set of matches), causing a reduction in temperature driving forces that must be compensated for with increased heat transfer area.

The three main steps of Bridge Analysis are explained using the illustrative example. First, a Retrofit Bridge is identified, starting with the cooler heat surplus of C1. With this surplus, three possible matches can be made to the heat deficits in exchangers E1 or E2 or to the heater deficit in H1 (Figure 3.8a). If the match is made to the heater deficit in H1, then a complete Retrofit Bridge will have been found. As Bridge Analysis helps to create new pathways between coolers and heaters, the Retrofit Bridge C1-H1 would be the most obvious. However, Bridge Analysis also helps to identify the less obvious pathways – the ones that require extra steps. For this demonstration, at least one heat recovery exchanger is involved, and the C1-E1 surplus-deficit match is used as the first step. As the heat deficit in E1 has been used, the heat surplus in E1 must also be used to find another match. The heat deficits in heater H1 and exchanger E2 can both be matched to the surplus in E1, though, the E1-H1 match will be used to complete the Retrofit Bridge. In the second step, the quantification of energy savings, the allowable heat transfer in each match is determined using the heat flow (ΔH) values from the METD. These ΔH values represent the net surplus or deficit available in that temperature interval, as they are determined using the EPTA and EGCC. In the first match, C1-E1, within the matching feasible temperature ranges, the surplus in C1 can transfer 2,350 kW; however, the deficit can only receive 1,480 kW (Figure 3.8b). In the second match, E1-H1, the surplus has 1,250 kW of process heat that can be transferred to the deficit in H1. This value is less than the deficit of 1,480 kW from within the same exchanger because there is 230 kW of heat surplus that is not at a high enough temperature to supply heat to the H1 deficit. The H1 deficit can receive 1,500 kW from the E1 surplus. The result is that the Retrofit Bridge, C1-E1-H1, can only recover 1,250 kW – achieving 64% of the retrofit savings target.

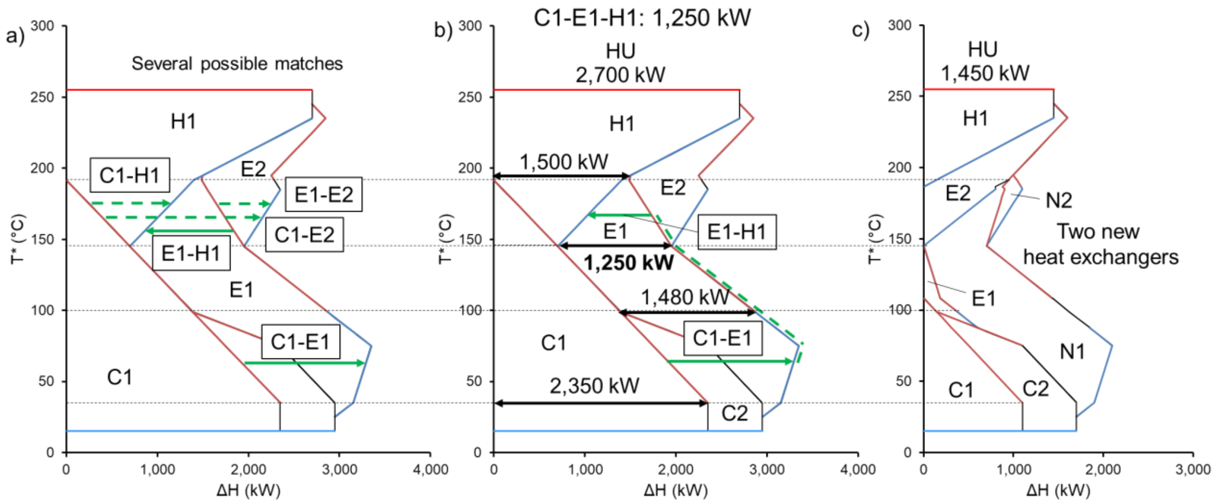


Figure 3.8: a) Identification, b) quantification and c) implementation of Retrofit Bridge C1-E1-H1.

Bridge Analysis suggests that two new heat recovery exchangers are added to the HEN to create the surplus-deficit matches identified by the Retrofit Bridge. These matches are shown on the HEN grid diagram, with each match depicted as a match between the hot side (inlet) of an exchanger unit on a hot stream and the cold side (inlet) of an exchanger on a cold stream

(Figure 3.9a). The two new heat exchangers, N1 and N2 (N for new), are placed in these positions, and both have a heat exchanger duty of 1,250 kW – equal to the amount of heat to be recovered. The placement of the new exchangers has also resulted in the heat exchanger duty of E1 being reduced from 2,400 kW to 1,150 kW (which could require an increase in heat transfer area due to new temperature driving forces and negatively impact the overall effectiveness of the retrofit), as well as a 1,250-kW reduction in both cold utility (C1) and hot utility (H1). Exchanger E2 and cooler C2 are unaffected by the retrofit modifications resulting from the Retrofit Bridge C1-E1-H1. The resulting retrofitted HEN is presented in Figure 3.9b. The changes to the HEN are also reflected in the METD. The EGCCs for C1, E1, and H1 have been reduced in size and new EGCCs have been added for each of the new exchangers. When comparing the METD before the retrofit (Figure 3.8a) and after (Figure 3.8c), it can be seen that the network curve retains the same shape; however, the displacement from the GCC has been reduced by 1,250 kW.

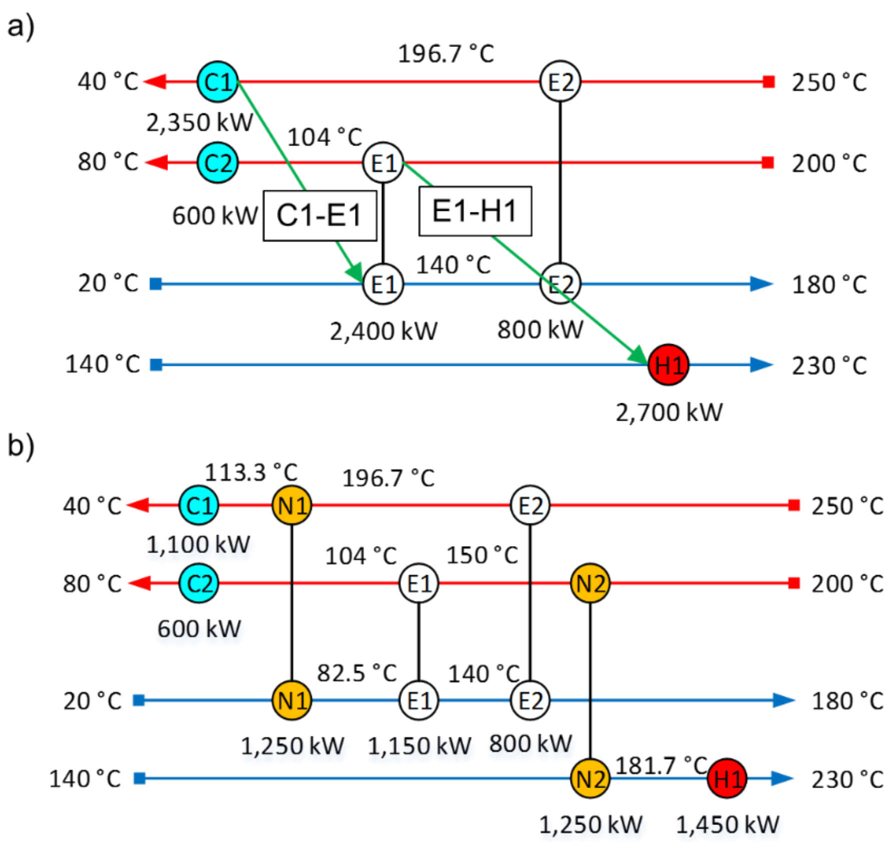


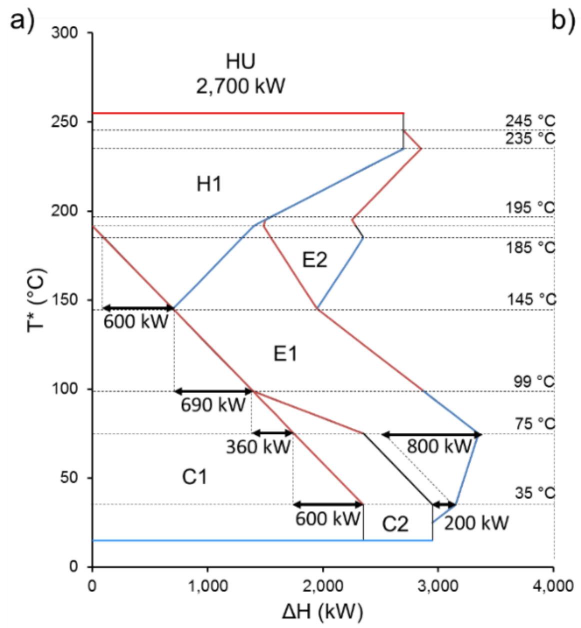
Figure 3.9: a) The matches in a Retrofit Bridge can be represented on the grid diagram, leading to b) the final retrofitted HEN for Retrofit Bridge C1-E1-H1.

The placement of new exchangers can have several effects, not just the reduction of utility duty. If the match already exists in similar temperature ranges, the duty of the new exchanger can be added to the duty of the existing exchanger – heat transfer area of the existing exchanger is increased instead of adding an entirely new heat exchanger. As seen in the above example, new exchangers can also affect the duty of other exchangers in the Retrofit Bridge (E1 was affected, but E2 was not). The effect may not be known until the mass and energy balances are completed. Several different scenarios will be examined in Section 3.4.

In this thesis, Retrofit Bridges are noted and described based on the exchangers involved. For example, for a Retrofit Bridge that uses the surplus in cooler C1, matches with a deficit in recovery exchanger E1, and then uses the corresponding available surplus to match with a deficit in heater H1, the corresponding Retrofit Bridge would be recorded as C1-E1-H1 (as in Figure 3.8). This notation helps show the pathway that is created. If multiple recovery exchangers are involved, they each will be referred to in the order that they are used. For example, C1-E1-E2-H1 implies that the surplus of E1 is being matched to a deficit in E2 first before the surplus of E2 is used to match the heater. In the original work by Bonhivers et al. (2017), the same Retrofit Bridge would be represented as {$c^s{}_1e^r{}_1$, $e^s{}_1e^r{}_2$, $e^s{}_2h^r{}_1$} or, as simplified in a subsequent paper), {c_1e_1; e_1e_2; e_2h_1} (Bonhivers, Alva-Argaez, et al., 2017). This notation shows that each match had a supplier of heat and a receptor of heat, or a surplus and deficit; however, the notation in this thesis is much simpler as the surpluses and deficits do not need to be explicitly acknowledged when it is implied by the type of heat exchanger unit.

3.4 Heat Surplus-Deficit Table

The second tool that has been developed for Bridge Analysis (in this thesis) is the Heat Surplus-Deficit Table (HSDT), a numerical counterpart to the METD. The HSDT is a tabular retrofit tool (also adapted from the Problem Table Algorithm) with minor graphical elements that allow for the quick identification and quantification (of energy savings) of Retrofit Bridges (Figure 3.10b). The METD and HSDT are different representations of the same data (Figure 3.10) and can be used independently – they do not need to be used simultaneously. The net enthalpy changes, or net surplus or deficit, in each EGCC in each temperature interval are displayed numerically in the HSDT. The main strength of the HSDT is the improved quantification of Retrofit Bridge energy savings when compared to the METD.



b)

T* (°C)	C1 ΔH (kW)	C2 ΔH (kW)	E1 ΔH (kW)	E2 ΔH (kW)	H1 ΔH (kW)
245					
				150	
235					
				600	-1,200
195					
			83	50	-100
191.7					
	100		167		-200
185					
	600		1,000	-800	-1,200
145					
	690		230		
99					
	360	600	-480		
75					
	600		-800		
35					
			-200		
25					

Figure 3.10: The relationship between the Modified Energy Transfer Diagram (a) and the Heat Surplus-Deficit Table (b).

The HSDT is the collection of the ΔH columns from the EPTAs of each exchanger unit in the HEN, typically presented in the following order: coolers, heat recovery exchangers, and heaters. In the HSDT, positive ΔH values refer to heat surpluses, while negative ΔH values refer to heat deficits. The surpluses and deficits are also coloured light red/orange and blue for visualisation. A general formula for the HSDT is presented in Table 3.2.

Table 3.2: General structure and formula for the Heat Surplus-Deficit Table.

T^* (°C)	$\Delta H_{(C)}$ (kW)	⋯	$\Delta H_{(E)}$ (kW)	⋯	$\Delta H_{(H)}$ (kW)
T_1					
	$\Delta H_{1\text{-}2(C)}$	⋯	$\Delta H_{1\text{-}2(E)}$	⋯	$\Delta H_{1\text{-}2(H)}$
T_2					
	$\Delta H_{2\text{-}3(C)}$	⋯	$\Delta H_{2\text{-}3(E)}$		$\Delta H_{2\text{-}3(H)}$
⋮	⋮		⋮		⋮
	$\Delta H_{[n-1]\text{-}n(C)}$	⋯	$\Delta H_{[n-1]\text{-}n(E)}$	⋯	$\Delta H_{[n-1]\text{-}n(H)}$
T_n					

Retrofit Bridges can be identified and easily quantified using the HSDT. The same rules for identifying Retrofit Bridges in METD also apply to the HSDT. Figure 3.11a demonstrates how the HDST can be used to find the Retrofit Bridge C1-E1-H1 (previously identified with the

METD in Figure 3.8). Figure 3.11a shows the Retrofit Bridge created by matching C1 to E1 and E1 to H1. Quantification of the Retrofit Bridge is achieved by summing the enthalpy values in each matched surplus and deficit, in the feasible temperature ranges. In the first match, the entirety of the C1 surplus (2,350 kW) can be matched to the entirety of the E1 deficit (1,480 kW). In the second match, between E1 and H1, there is 230 kW of surplus that cannot be used in the match because it is at a lower temperature than the deficit receiving heat. Similarly, there is 1,200 kW of heat deficit in H1 that requires heat at a higher temperature than the E1 surplus; therefore, it is also excluded. The E1 surplus can supply up to 1,250 kW of heat, while the H1 deficit can receive up to 1,500 kW of heat. The total flow of process heat in this Retrofit Bridge is limited by the 1,250-kW surplus in E1; therefore, the total energy savings that this Retrofit Bridge can achieve is 1,250 kW. The resulting HSDT of the retrofitted HEN (presented in Figure 3.11b) shows how the two new heat exchangers have been introduced to transfer heat in the temperature intervals where the surplus-deficit matches were found. The utility consumption has been reduced by 1,250 kW. Note that the net surplus and deficit in N2 are relatively low (208.3 kW) despite the exchanger load being 1,250 kW. This means that there is significant overlap in the temperature profiles of the streams. Neither the METD nor the HSDT can be easily used to determine heat exchanger duty when the matched streams are present in the same temperature interval (as only the net enthalpy is presented), but this is not necessary if the grid diagram is used.

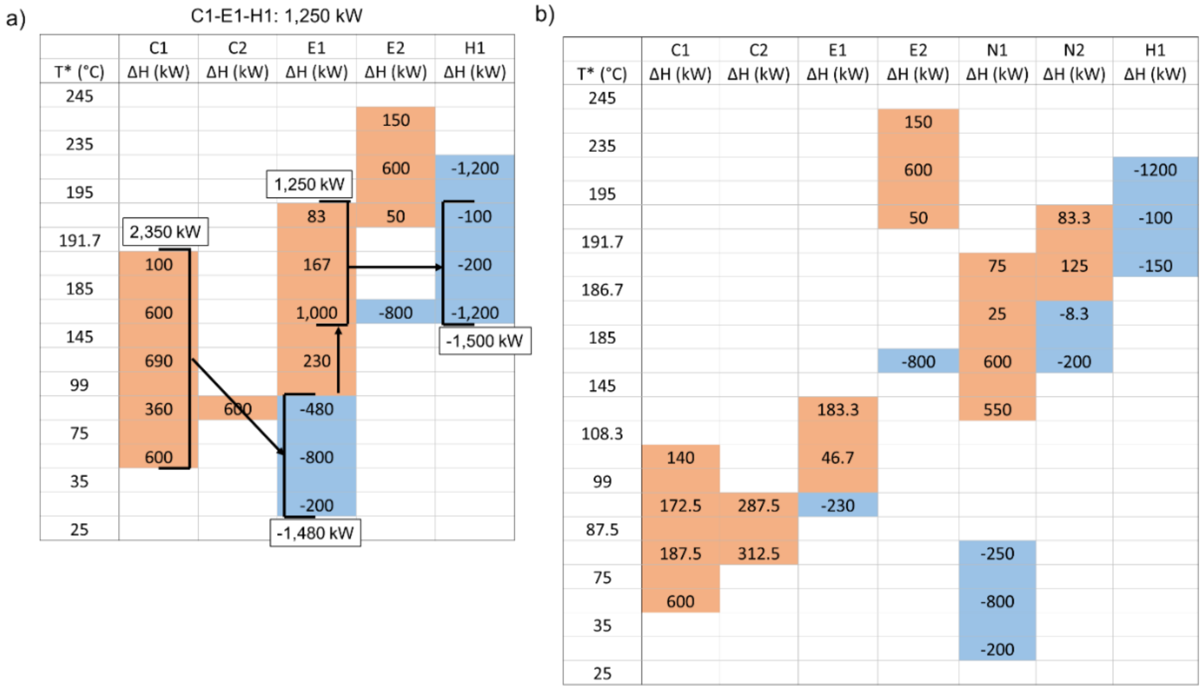


Figure 3.11: Using the HSDT to find Retrofit Bridges (a) and the resulting HSDT from retrofitting (b).

3.5 Additional Results for the Illustrative Example

In addition to the Retrofit Bridge identified in the previous section, there are six other Retrofit Bridges that can be found using the METD and HSDT. This section provides additional examples of how the METD and HSDT can be used, as well as a brief discussion on how Retrofit Bridges are implemented. The first three Retrofit Bridges will be explained using the METD, while the remaining three will be explained using the HSDT. For a discussion around finding the same Retrofit Bridge with both tools, please refer to the above section. This section simply provides additional examples of the use of these tools. The Retrofit Bridge results are summarised in Table 3.3.

Table 3.3: Summary of Retrofit Bridges.

#	Retrofit Bridge	Energy Savings (kW)	New Heat Exchangers	Identification	Retrofitted HEN
1	C1-E1-H1	1,250	2	Figure 3.8	Figure 3.9b
2	C1-H1	700	1	Figure 3.12a	Figure 3.14a
3	C2-E1-E2-H1	600	1	Figure 3.12b	Figure 3.14b
4	C1-E2-H1	700	1	Figure 3.12c	Figure 3.14c
5	C1-E1-E2-H1	800	1	Figure 3.13a	Figure 3.14d
6	C1-E2-E1-H1	700	2	Figure 3.13b	Figure 3.14e
7	C2-E1-H1	600	1	Figure 3.13c	Figure 3.14f

The three Retrofit Bridges identified and quantified using the METD are presented in Figure 3.12. The first is Retrofit Bridge C1-H1 (Figure 3.12b) – only one match is needed to create a cooler heat surplus-heater deficit pathway. There is a large amount of surplus process heat available in C1, but because heat can only be transferred from a high temperature to a low temperature, only 700 kW of the original 2,350 k can be recovered in a new match. Similarly, there is a large heat deficit in H1, but it is only possible for the deficit to receive 1,400 kW within the available temperature range. Therefore, the overall savings for the Retrofit Bridge are 700 kW, limited by the minimum allowable heat transfer in the match. Figure 3.12d presents the METD of the retrofitted network, showing a new exchanger N1, matching a surplus and deficit in the identified temperature range. The hot utility has been reduced by the 700 kW energy savings.

The next Retrofit Bridge is denoted as C2-E1-E2-H1 and needs three matches to complete the pathway between the cooler and the heater. Figure 3.12b shows the matches and the available surpluses and deficits in each available temperature range. The cooler C2 is the limiting factor, restricting the energy savings to 600 kW; however, the entire cooler heat surplus can be used for heat recovery, rendering the cooler redundant in the retrofitted HEN (it may still be kept for control purposes). The final METD of the retrofitted HEN is presented in Figure 3.12e. The EGCC of cooler C2 is removed, with the duty shifted to exchanger E1 which has a change in EGCC shape accordingly. The final METD demonstration involves the identification of Retrofit Bridge C1-E2-H1 (Figure 3.12c). Here, the match between C1-E2 limits the overall heat recovery improvement to 700 kW. Because the C1-E2 match already exists (as exchanger E2), only one new heat exchanger is added. The resulting METD is presented in Figure 3.12f.

In all METDs of the retrofitted HENs, it is important to see that the network curve (GCC) maintains its shape but is now positioned closer to the vertical axis. Utility demand has also been lowered according to the energy savings of each Retrofit Bridge.

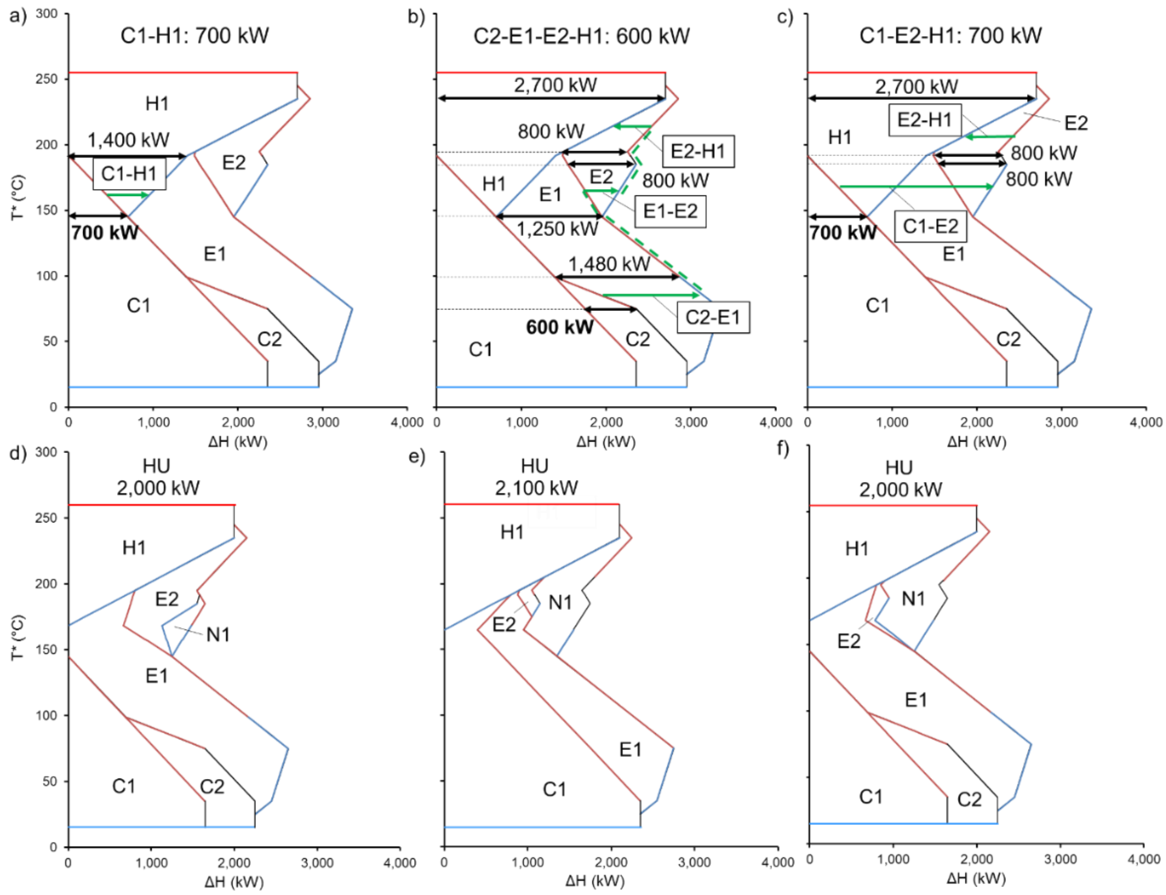


Figure 3.12: Three Retrofit Bridges found using the METD (a, b, c) and the final METD showing changes, including new exchangers (d, e, f), for each Retrofit Bridge.

Figure 3.13 shows how the final three Retrofit Bridges are identified and quantified using the HSDT, rather than the METD. Initially, the numerical ΔH values are not needed for the identification, and the only thing that is important is the temperature and sign of the heat flow (i.e., positive or negative). In Figure 3.13a, the Retrofit Bridge C1-E1-E2-H1 is found. The pathway is found by matching the red surplus blocks with blue deficit blocks with an equal or lower temperature. If the entirety of a block cannot be matched, then only a portion may be used, as is the case with the match E1-E2. There is 230 kW that is unusable, so this is left out of the identified pathway. Quantification is then achieved by summing the ΔH values in each surplus or deficit block. As with the METD, the minimum of these blocks limits heat recovery and therefore is the quantity of process heat that can be saved by the Retrofit Bridge. In the Retrofit Bridge C1-E1-E2-H1, this is 800 kW.

Interestingly, the Retrofit Bridge in Figure 3.13b involves the exact same exchanger units, but the heat recovery pathway is made in a different way leading to different matches and lower retrofit savings. This shows that Retrofit Bridges are not just dependent on the exchanger units involved (more specifically the surpluses and deficits involved), but also on the order of the matches. An implication is that the number of possible combinations of Retrofit Bridges exponentially increases as the number of heat recovery exchangers increases.

The final Retrofit Bridge of the illustrative example is C2-E1-H1, which has two matches with a maximum allowable heat transfer of 600 kW (Figure 3.13c); however, just like the Retrofit Bridge C2-E1-E2-H1, the entire surplus of C2 can be recovered rather than be rejected to the environment.

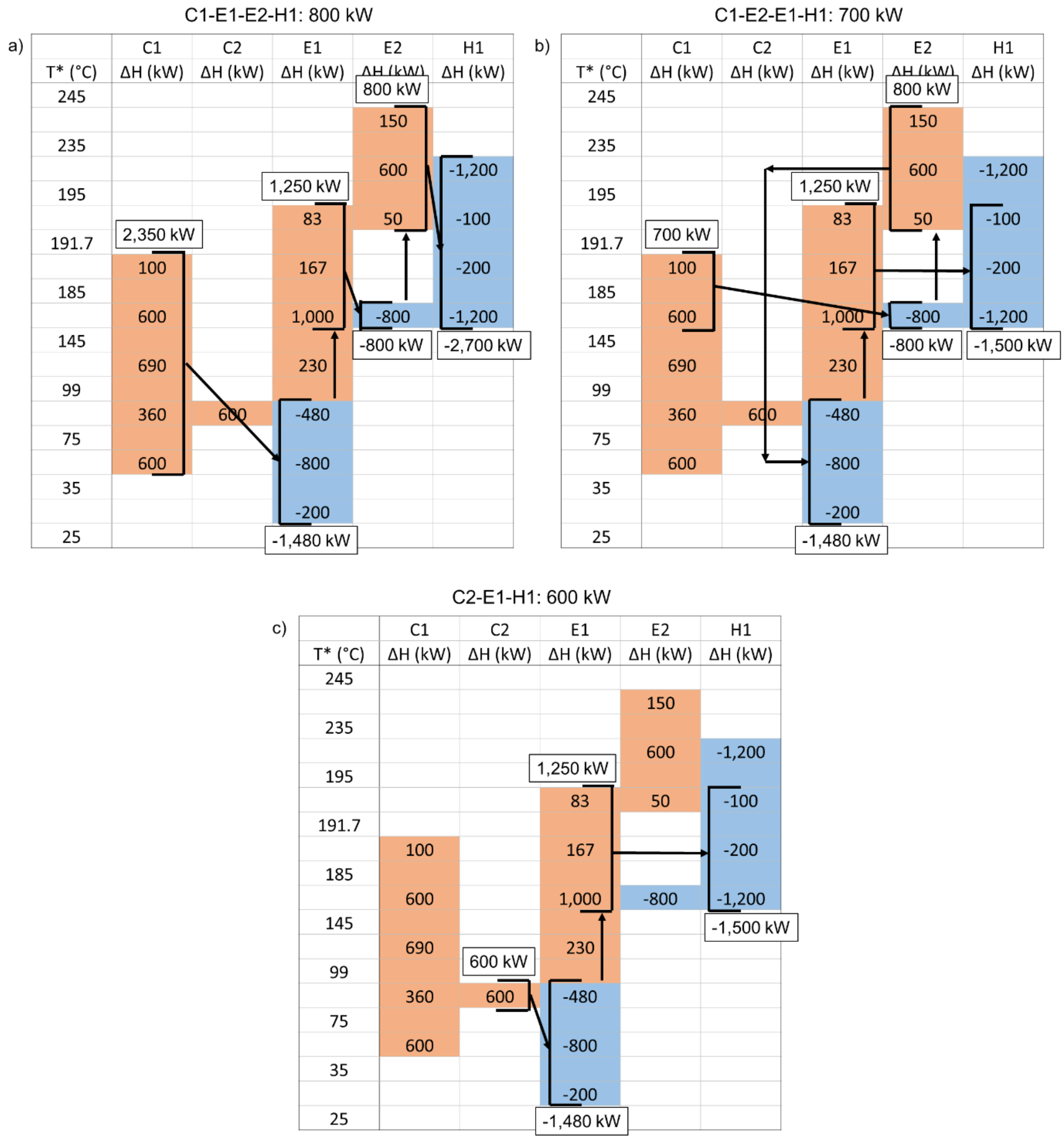


Figure 3.13: Three Retrofit Bridges found using the HSDT: a) C1-E1-E2-H1, b) C1-E2-E1-H1, and c) C2-E1-H1.

Each Retrofit Bridge provides a retrofit design option that can be represented by a grid diagram. Generally, each match relates to a new heat exchanger. However, matches C2-E1, C1-E2, and E1-E2 already exist, and E1 or E2 are modified instead of adding a new heat exchanger. A modification does not necessarily mean that the duty is increased or decreased, the duty can remain the same, but it is likely that retrofit area (additional heat transfer area) will be needed due to reduced temperature driving forces. Unfortunately, this amount of retrofit area required could counteract any energy savings from the Retrofit Bridge. The economics of a Retrofit Bridge will be analysed in Chapter 5, with this chapter focusing more on the methodology used to identify a Retrofit Bridge.

In both Figure 3.14b and Figure 3.14c, the first match already exists, although only in Figure 3.14b is the duty of the existing exchanger affected. In Figure 3.14b and Figure 3.14f, the Retrofit Bridges allow the cooler C2 to be removed from the HEN. Recovery exchangers can also be made redundant in similar ways. In Figure 3.14d, an exchanger (represented with dotted lines) is placed to create the match corresponding with C1-E1, resulting in a cyclic match with exchanger E2 (represented by the dashed lines). This creates a loop with E2 and allows one of the exchangers to be removed in favour of the other (otherwise there is 800 kW of heat transfer split between the two). As E2 is the existing exchanger, E2 is kept and the new match can be ignored. While Retrofit Bridges provide the guidelines for a retrofit design, there are often practical decisions such as these that an engineer can make to improve the design of the HEN.

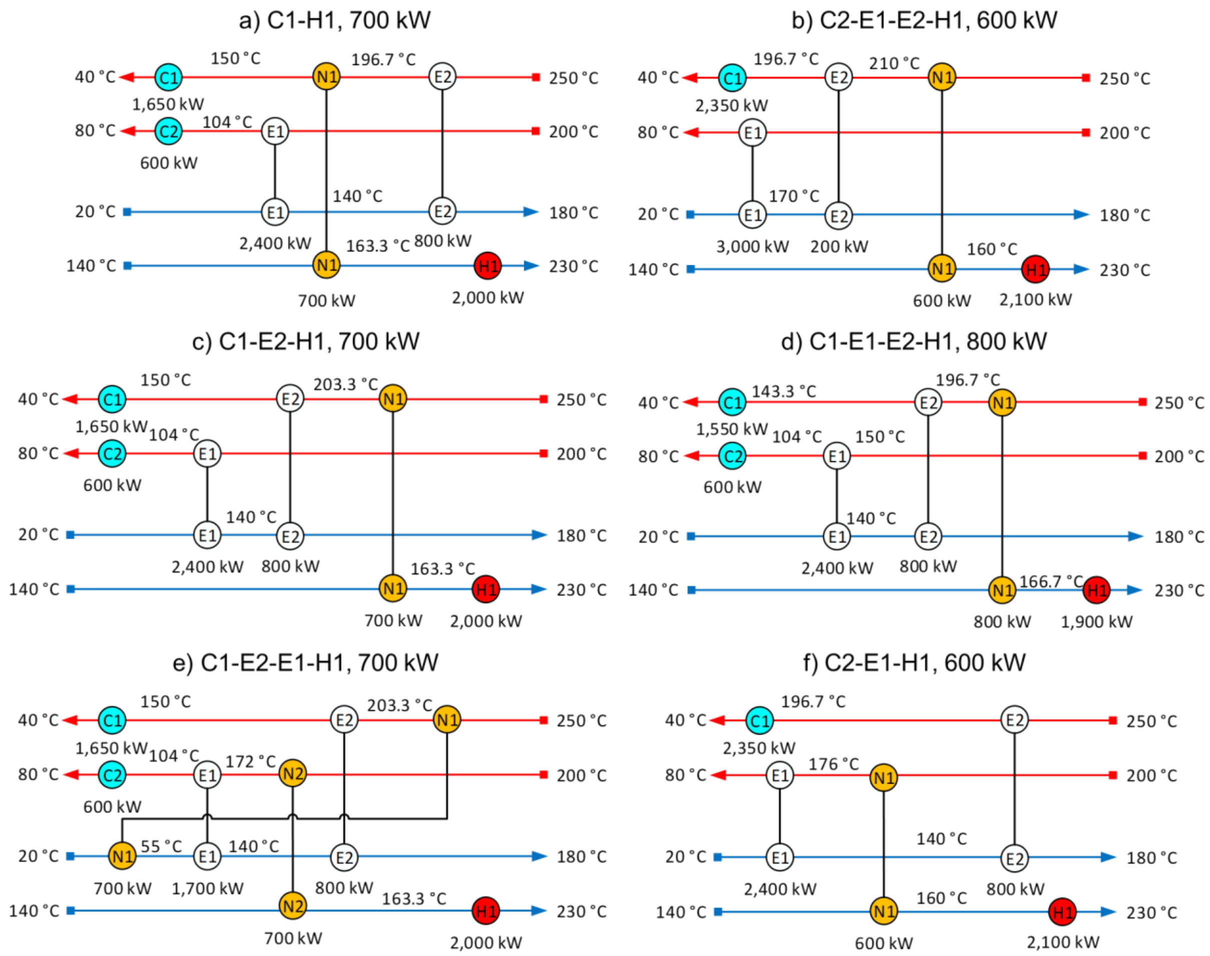


Figure 3.14: Retrofitted HENs for the remaining six possible Retrofit Bridges for the illustrative example (a-f).

3.6 Industrial Case Studies

Many of the graphical methods in recent literature are demonstrated using relatively simple HEN retrofit problems or only present one possible solution – and not necessarily a profitable solution, as the retrofit design that achieves the greatest energy savings may require an uneconomic amount of capital investment. Illustrative examples, such as the one above, effectively demonstrate how the METD and HSDT can be used to conduct Bridge Analysis, but a successful graphical method needs to be capable of handling larger HEN problems. In these cases, it is still important to provide more than one or two solutions so that retrofit design selection is an informed decision. The following section introduces two industrial case studies that are relevant to New Zealand's own processing industries. The primary goal of these case studies is to demonstrate how the methodologies developed in the thesis can be applied to large, complex HENs. These case studies are a paper mill based at a Kraft pulp and paper mill cluster and a petrochemical complex. The case studies have different levels of complexity and size, testing the capability of the developed Bridge Analysis tools. However, the methodology presented in the thesis is not limited to these types of case studies.

3.6.1 Paper Mill

The first case study is based on the HEN of a paper mill at a Kraft pulp and paper mill cluster. The paper mill HEN has been adapted from Atkins et al. (2008). The stream data is presented in Appendix A. The scope of the paper mill includes the paper machine and recycling plant. Currently, heat is distributed around the processes with five coolers, five recovery exchangers, and four heaters. The process streams are either liquid water streams or air streams with all existing matches being either water-to-water or air-to-air. The goal of the retrofit project is to explore options for heat integration between the water and air streams, while also reducing the process heat demand of 9.14 MW. All water streams are assumed to have a ΔT_{cont} of 5 °C and a heat transfer coefficient of 2,555 W/m^2°C, while all air streams are assumed to have a ΔT_{cont} of 10 °C and a heat transfer coefficient of 111 W/m^2°C. Therefore, the ΔT_{min} of water-to-air exchanger matches will be 15 °C. In this study and subsequent studies of the same case study in the thesis, it is assumed that all heat transfer coefficients, flow rates, and specific heat capacities remain constant for a given stream. The grid diagram for the paper mill HEN, along with the heat capacity flow rates (product of mass flow rate and specific heat capacity) of each stream, is presented in Figure 3.15. Two of the coolers, C3 and C4, are cooling exhaust streams (EX 1 and EX 2). In reality, these coolers would not be used but it helps to represent the heat surplus that is available in the air streams. These coolers are presented with dashed lines.

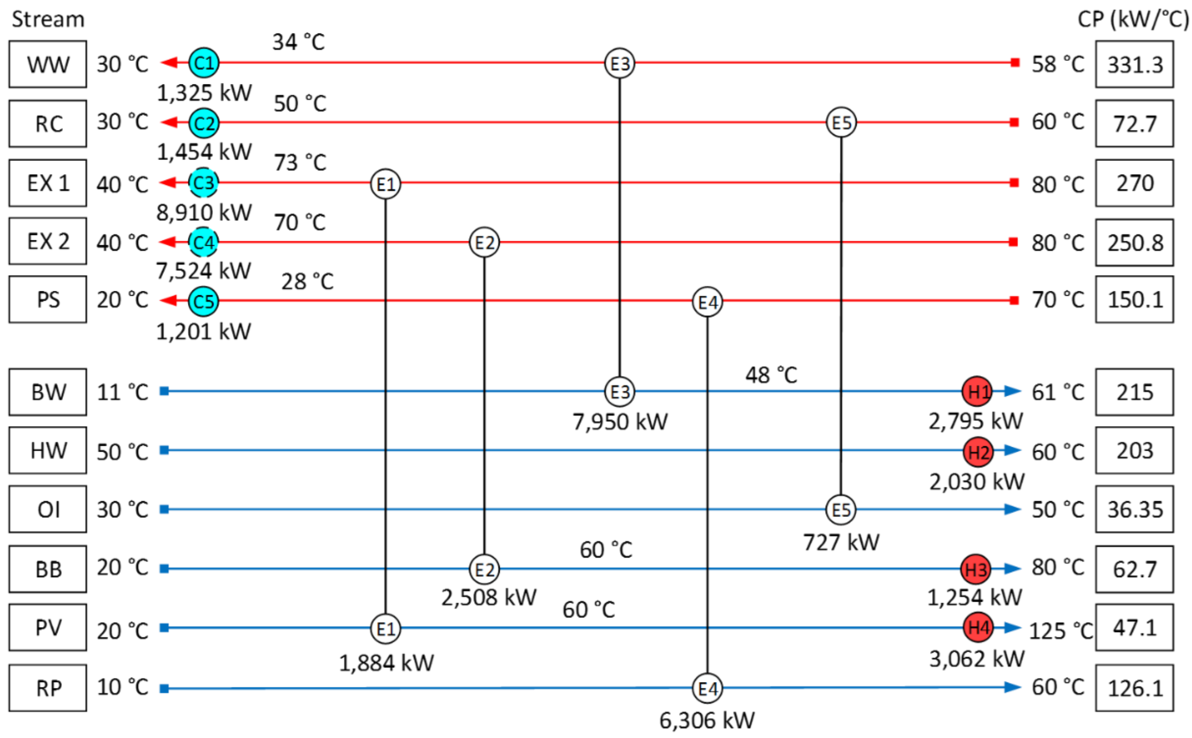


Figure 3.15: Grid diagram of the paper mill HEN.

The METD for the paper mill is generated using the extracted retrofit stream data from the HEN (Figure 3.16a). The METD features several prominent EGCCs (which have been highlighted for discussion). H1 and H4 both have large heat deficits; however, H1 (and H2) is entirely below the Pinch. These are the only exchangers with inefficient heat transfer and no exchanger units transfer heat across the Pinch of 70 °C. The sum of the heat deficits in H1 and H2 is equal to the maximum retrofit energy savings achievable for this HEN, for the selected values of ΔT_{cont}, which was determined to be 4.83 MW. As H4 and H3 are above the Pinch and no exchanger units transfer across the Pinch, the process heat demand of these heaters is unable to be lowered through Bridge Analysis.

One of the simplest Retrofit Bridges that can be identified in the METD is a direct match between cooler C3 and heater H1. The identification of this match is illustrated in Figure 3.16b. In the available temperature ranges, there is a surplus of 2.7 MW in C3 and a deficit of 2.15

MW; therefore, the energy savings that this Retrofit Bridge can provide are equal to 2.15 MW. Implementing this Retrofit Bridge results in the addition of one new heat exchanger, N1, and a new hot utility load of 6.99 MW and a new cold utility load of 18.26 MW (Figure 3.16c). The heater H1 is still supplying some heat below the Pinch, meaning that there are still retrofit opportunities involving this utility. The new retrofit savings target for the updated METD is 2.68 MW and can be further reduced by other Retrofit Bridges (other Retrofit Bridges may also achieve greater energy savings in the first stage).

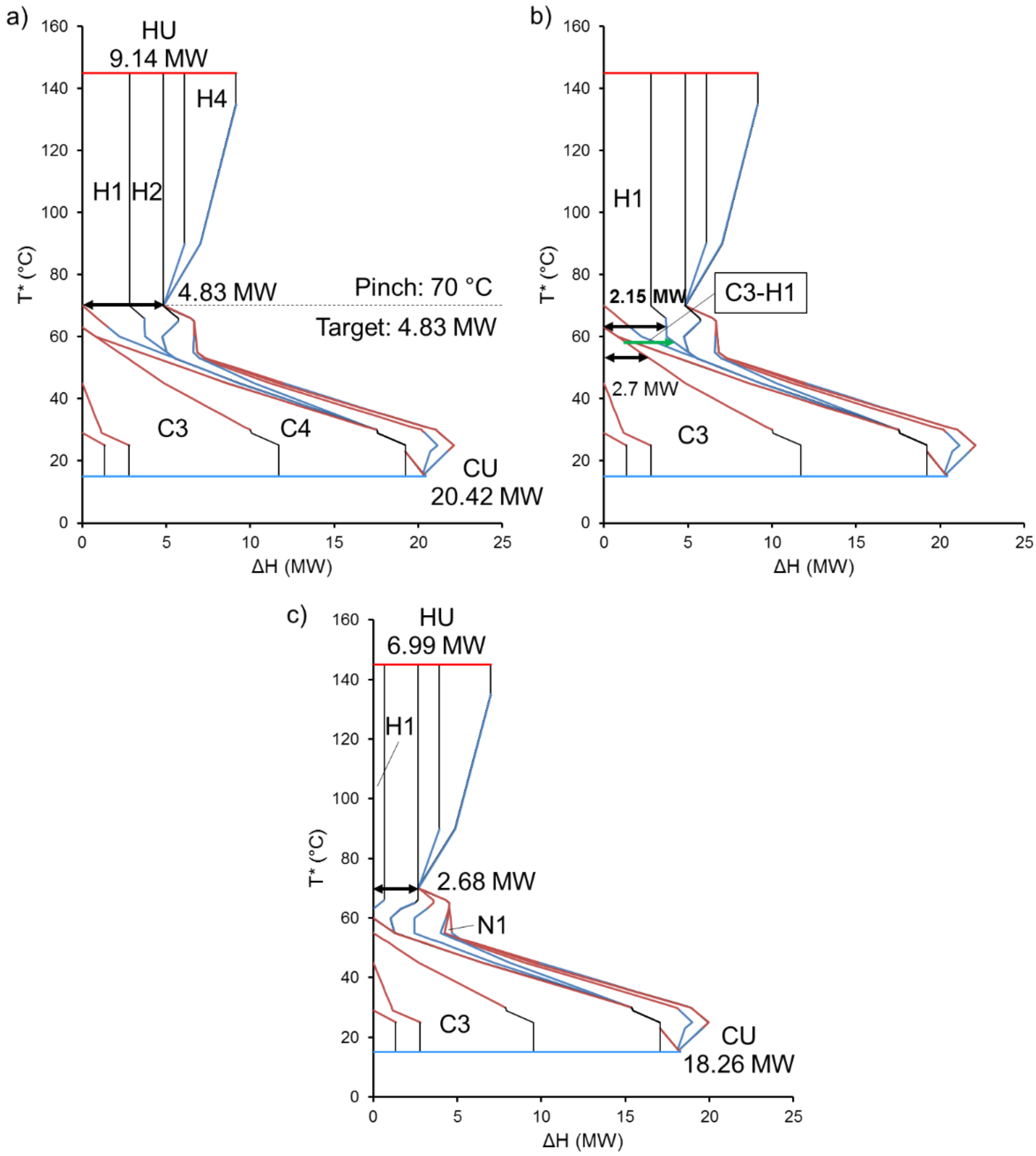


Figure 3.16: a) METD for the paper mill HEN, b) using the METD to find a Retrofit Bridge, and c) the resulting METD from the retrofitted HEN.

Even though the Retrofit Bridge C3-H1 could be easily identified, it does not necessarily mean that C3-H1 will be the most profitable or achieve the greatest reductions in process heat utility demand. There are many other Retrofit Bridges that can be identified by sight using the METD, including several direct matches between heaters and coolers. For example, C4-H2 and C4-H1 are also Retrofit Bridges with direct matches. However, there are many more Retrofit Bridges that can be found using the heat recovery exchangers, and these options should be explored to ensure that the best Retrofit Bridge can be identified. Manually processing the Retrofit Bridges is impractical as even with a handful of coolers, heaters, and recovery exchangers, there can still be hundreds or thousands of potential Retrofit Bridges. The inability to find all possible Retrofit Bridges easily is a significant limitation.

3.6.2 Petrochemical Complex

The second case study is based on a petrochemical complex from an anonymous source. The HEN features many coolers and two cold streams with significant pre-heating (with recovery exchangers). There are also several stream splits present in the HEN. The petrochemical complex HEN contains many exchanger units and represents the next level in complexity and size. The grid diagram for this network is presented in Figure 3.17. Bridge Analysis of the petrochemical complex HEN uses a ΔT_{min} of 10 °C and assumes that all streams have constant flow rates and specific heat capacities. It is also assumed, for simplicity, that all streams have a constant heat transfer coefficient of 1,000 W/m^2°C.

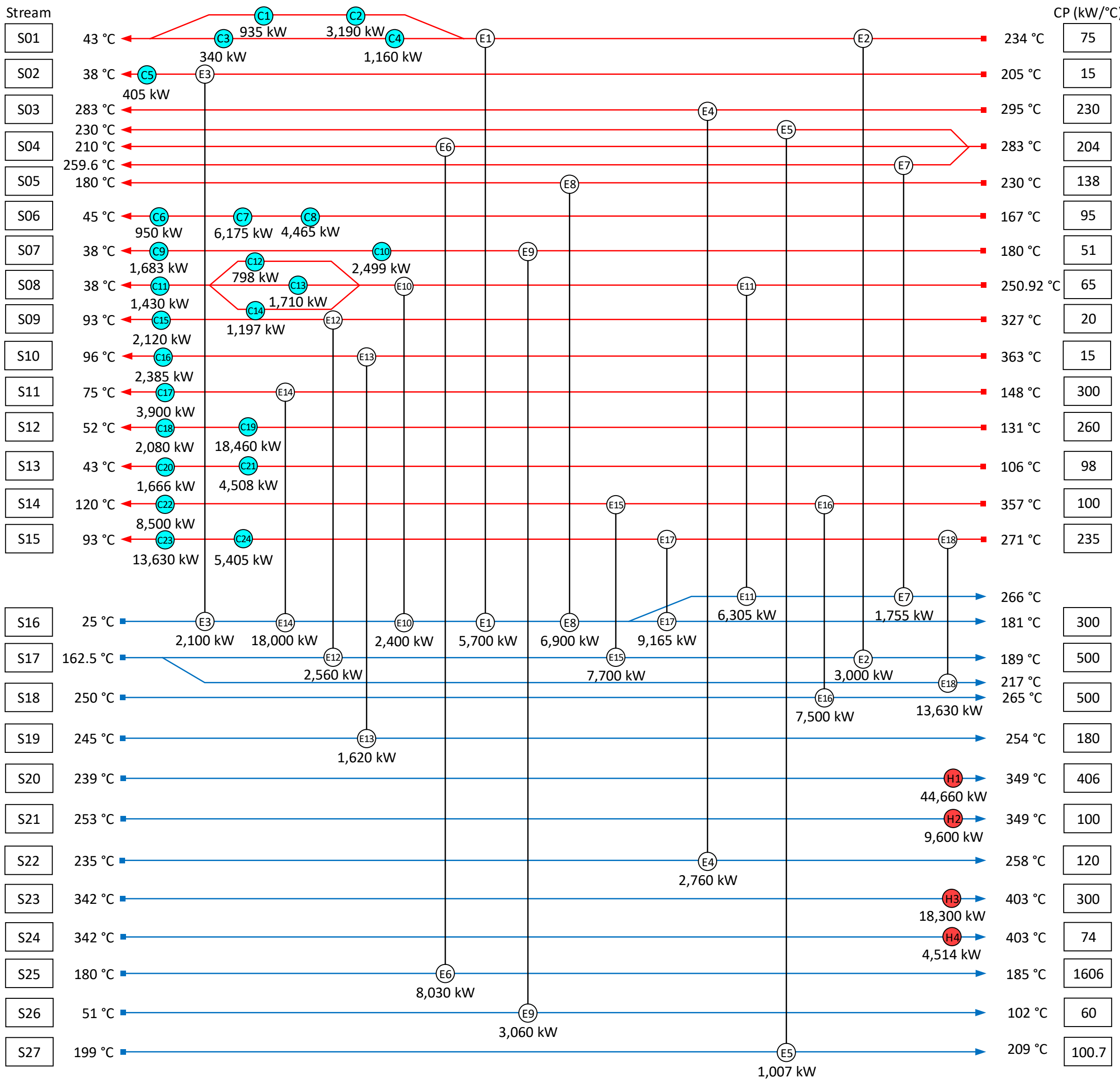


Figure 3.17: Grid diagram of the petrochemical complex HEN.

The METD presented in Figure 3.18a shows that the current hot utility demand of 77.1 MW can be reduced by 15.1 MW (based on the network curve). Furthermore, based on the Pinch temperature of 244 °C, there is significant cross-Pinch heat transfer, particularly in recovery exchangers E6, E15, and E18. Additionally, the deficits in heaters H1 and H2 have high heating demands. As hot utility is the major factor in determining total utility costs, Retrofit Bridges that reduce the heating demand of these two heaters are more likely to have greater environmental and economic potential.

Further analysis of the METD becomes more difficult due to the complexity and considerable clutter of EGCCs (especially coolers and recovery exchangers). With 46 different heat exchanger units, it becomes significantly harder to identify complete Retrofit Bridges due to the lack of clarity. Normally, direct matches between streams in coolers and heaters can be exploited for easier and generally cheaper retrofit projects; however, there are no apparent direct matches. A Retrofit Bridge can be found using C22, E15, and H1, but it is still difficult to determine the energy savings (Figure 3.18b). For specific elements of a HEN – such as C22, E15, and H1 – a sub-problem can be analysed, only accounting for those exchanger units that are affected by an identified Retrofit Bridge or are to be targeted by a Retrofit Bridge. In Figure 3.18c, an METD is presented for the sub-problem, only using the EGCCs of the involved exchanger units. The clarity of the METD is improved, and the energy savings for Retrofit Bridge C22-E15-H1 can be identified (2.74 MW). After applying this Retrofit Bridge, one new heat exchanger is needed – the match between C22 and E15 already exists so E15 is modified instead of placing a new heat exchanger. The METD for the retrofitted HEN sub-problem (Figure 3.18d) shows that the new retrofit savings target (following the sub-Pinch) for that arrangement of exchangers is zero, C22 and E15 can no longer be matched in a future Retrofit Bridge. Analysis of sub-problems can be a possible solution to the clarity issue of larger HEN problems, but it still relies on knowledge of which exchangers to target in a Retrofit Bridge.

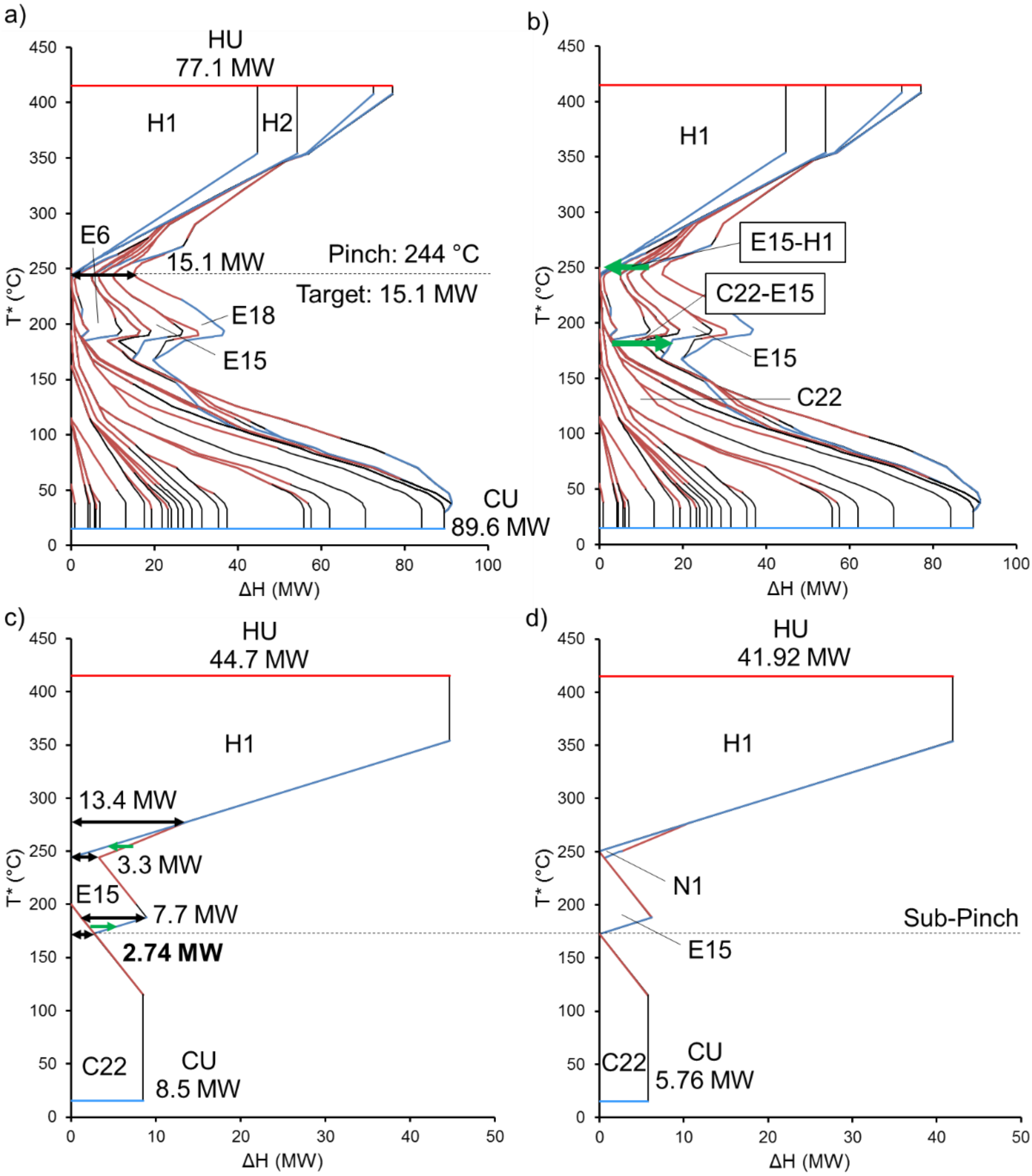


Figure 3.18: a) METD of the petrochemical complex HEN, b) identifying a Retrofit Bridge with the METD, c) quantifying a Retrofit Bridge using the METD of the sub-problem, and d) final retrofitted METD of the sub-problem.

Even with the HSDT, it is difficult to identify a range of Retrofit Bridges that would provide confidence to any decision-making process. A simplified version of the HSDT is presented in Figure 3.19 to show the large number of surpluses and deficits that will lead to hundreds of thousands of Retrofit Bridges. Retrofit Bridges can be found easily enough with the HSDT, but even finding the Retrofit Bridge that provides the greatest energy savings is not an easy task (and greatest energy savings does not mean greatest economic viability). With retrofit problems such as the petrochemical complex HEN, it is difficult to find Retrofit Bridges, let alone find all economic Retrofit Bridges. However, the HSDT can be automated, due to its tabular nature, so that identifying Retrofit Bridges and solving the retrofit problem is more manageable and practical.

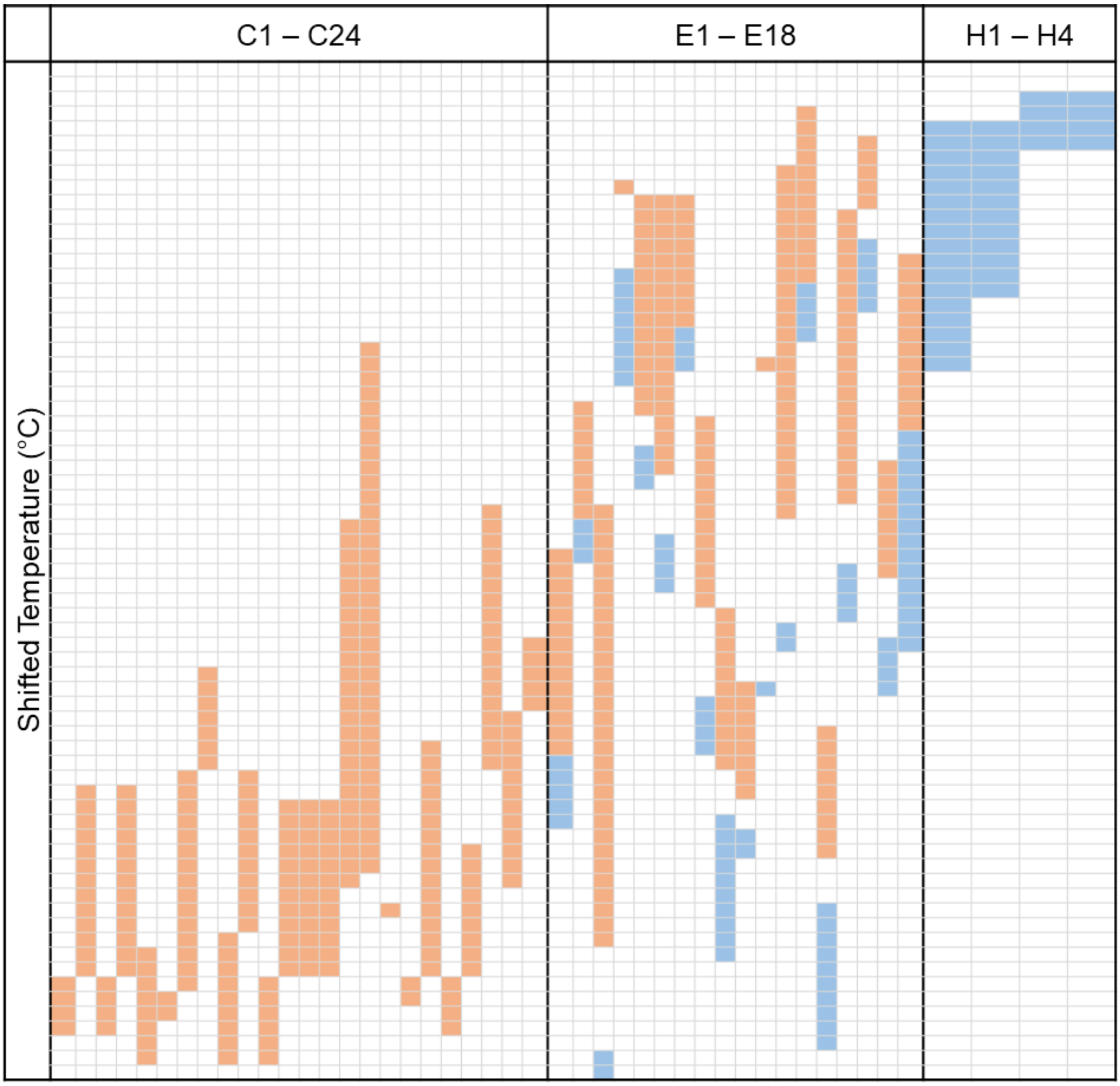


Figure 3.19: A simplified HSDT for the petrochemical complex HEN.

3.7 Advantages and Limitations

The advantage of the METD over the ETD is the improved connection to conventional Pinch Analysis through meaningful developments to the ETD representation. For example, directly strengthening the relationship between the ETD and GCC (rather than identifying the similarities and differences) may enable the METD to have an increased degree of familiarity with practitioners of Pinch Analysis. The identification of heat surpluses and deficits on the METD also allows the determination of energy savings, which was not possible with the original ETD. This allows the METD, as well as the HSDT, to be used independently to conduct Bridge Analysis – other Bridge Analysis tools such as the network table are not needed. However, the strengths and weaknesses of the METD and HSDT mean that there are certain situations where one will work better than the other to perform Bridge Analysis.

The advantage of the METD over other major graphical retrofit design methods, such as STEP (Lai et al., 2017) and Advanced Composite Curves (Nordman & Berntsson, 2009a), is that METD and Bridge Analysis can be used to generate many different retrofit design options in a clear procedure, while other tools such as STEP tend to guide the engineer towards a singular retrofit design. It is beneficial to have a range of options so that any decisions for the retrofit project are more informed. A small range of solutions allow for comparisons as well as allowing an engineer to determine the best fit for a specific project (the retrofit design that saves the most energy might not be the most economic). Considering these methods further, graphical methods such as the Advanced Composite Curves are somewhat limited to targeting and require many different plots for the same problem. STEP is similar to METD in that both attempt to correct cross-Pinch heat transfer and other Pinch violations; however, these Pinch violations are much clearer on the METD than on a STEP plot as the METD represents the EGCCs of each unit exchanging heat while STEP represents the streams. A stream may not cross the Pinch but may transfer heat across the Pinch, and this is not readily apparent in STEP.

Like many graphical methods, the METD is limited by what can be ascertained visually – this was apparent with the case studies. It can become difficult to identify the different curves (EGCCs) in the METD, which affects the identification of Retrofit Bridges. Issues are likely to arise when small EGCCs (in terms of ΔH) are stacked close to each other or when there are many existing exchangers in the HEN. The authors of the STEP tool reported a similar limitation with their graphical tool (Wan Alwi & Manan, 2010). Larger problems may also have many different possible retrofit solutions and it is difficult to locate them all by hand. Another limitation of the METD and Bridge Analysis is that a Retrofit Bridge only explicitly identifies where new heat exchanger matches can be added (to a HEN) or where heat transfer area can be added to existing heat exchangers (i.e., if the match already exists, although, this is not always the case). There are many other types of retrofit modifications, including heat transfer enhancement, that are not considered (but could be possible with additional analysis, or separate analyses). Similar limitations are faced by the HSDT, although, the HSDT is more capable of handling a larger number of streams and heat exchanger units.

Despite the increased ease of use and improved conceptual representation, it will still take significant time to conduct a thorough analysis of a large, complex retrofit HEN problem using the METD or HSDT, as there can be multitudes of possible combinations for a Retrofit Bridge. Automating the method will help overcome this limitation and will address the gaps in literature where there are viable graphical methods hindered by a lack of computation and automation. Automation allows the method to consider many different retrofit opportunities and handle larger HEN problems.

3.8 Conclusions

Bridge Analysis is a useful graphical retrofit method that utilises several different tools for identifying and quantifying Retrofit Bridges, a set of modifications used to create or exploit a heat recovery pathway. The Energy Transfer Diagram (ETD) is currently used as the primary tool for Bridge Analysis (Bonhivers, Srinivasan, et al., 2017); however, this chapter has introduced several major improvements to the ETD that focus on its usability and conceptual foundations. The Modified Energy Transfer Diagram focuses more on the concept of heat surpluses and heat deficits and establishes itself as a 'retrofit design' replacement for conventional PA tools such as the Grand Composite Curve, owing to the similarity between the two tools – with the METD being more appropriate for retrofit HEN design. Another tool known as the Heat Surplus-Deficit Table was introduced to provide a numerical and graphical tool to accompany the METD. Both tools can be used to identify Retrofit Bridges and retrofit designs quickly; however, the strengths of the METD related to understanding the HEN problem and providing targeting information while the strengths of the HSDT related to the ability to perform numerical calculations while creating a heat recovery pathway. One major limitation of the improved Bridge Analysis method, and a limitation of many graphical methods, is that large complex HEN problems can become difficult to solve. Fortunately, the HSDT can be readily automated through computation. The next chapter will discuss the automation of the HSDT and the overall improved Bridge Analysis method.

Chapter 4

Automation of Bridge Analysis

4.1 Introduction

The previous chapter proposed new developments to Bridge Analysis and introduced two new retrofit tools: the Modified Energy Transfer Diagram (METD) and the Heat Surplus-Deficit Table (HSDT). These tools help to identify Retrofit Bridges within a heat exchanger network (HEN) to reduce process heat demand and improve heat recovery. A retrofit analysis relies on an engineer making informed decisions about the different options for retrofit modifications; however, due to the size and complexity of some HENs, it can become difficult and impractical to conduct Bridge Analysis manually and analyse the numerous unique Retrofit Bridges that can be applied to retrofit a HEN. These limitations are shared by many diagrammatical retrofit design methods and are especially apparent in the two industrial case studies introduced in Chapter 3. The current chapter discusses the further developments that enable the improved Bridge Analysis method to be applied to a range of retrofit problems.

In the literature review of Chapter 2, automation was identified as a possible solution to these limitations and a necessary element for a successful Pinch Analysis-based method. An algorithm called Automated Retrofit Targeting (ART) is developed and implemented in Microsoft Excel™ using Visual Basic for Applications, allowing the automatic identification and quantification of all feasible Retrofit Bridge options for a given HEN. ART uses the HSDT as the basis for the automated Retrofit Bridge search due to its tabular structure that allows for systematic procedures.

This chapter presents the ART algorithm and provides details into how Retrofit Bridges can be identified and quantified (in terms of heat recovery improvement or energy savings) rapidly and automatically, while also using constraints to focus the search towards the retrofit options that are more likely to be economical. The performance of ART is demonstrated using the two case studies, showing how ART allows Bridge Analysis to be conducted for otherwise difficult HEN problems. These contributions are a major step towards creating an automation tool for undertaking a retrofit analysis of large industrial HENs.

4.2 Problem Definition

The goal of ART is to automatically find and quantify Retrofit Bridges that can be applied to a HEN to reduce process heat demand, as per Bridge Analysis. Following the definition in the previous chapter, a Retrofit Bridge is a unique series of matches between heat surpluses and heat deficits that increases the heat recovery within the HEN. A Retrofit Bridge must begin with a surplus being cooled with cold utility (cooler heat surplus) and end with a deficit being heated with hot utility (heater deficit), with any number of matches in between (including direct matches between the cooler heat surplus and heater deficit). All matches must be thermodynamically feasible and have approach temperatures that do not violate the selected ΔT_{min}. Thermodynamic feasibility is checked by comparing the maximum shifted temperature of the surplus against the minimum shifted temperature of the deficit. The expression for checking thermodynamic feasibility is presented in Equation 4.1:

$$T^*_{S,\text{max}} \geq T^*_{D,\text{min}} \tag{4.1}$$

Where subscripts *S* and *D* refer to the heat surplus and heat deficit, and *T** is the temperature (°C) shifted according to the global ΔT_{min} or ΔT_{cont}. Guidance for ΔT_{min} selection is not discussed in this thesis; however, selection affects the Retrofit Bridges that can be found, the capital cost required, and the energy savings that they provide.

Each surplus-deficit match in a Retrofit Bridge has a maximum amount of heat that can be transferred, based on the (shifted) temperatures at which the heat is available to be supplied or received. The match that allows the least amount of heat transfer acts a heat recovery bottleneck and limits the total energy savings of the Retrofit Bridge, even if other matches allow a greater amount of heat transfer. The amount of heat transfer provided by the bottlenecking match is equivalent to the maximum energy savings or heat recovery improvement (Q_{RB}) that a Retrofit Bridge can provide. The expression for determining the current maximum energy savings is given in Equation 4.2:

$$Q_{RB,\,\text{max}} = \min\left(Q_{\min(n-1)}, Q_n\right) \tag{4.2}$$

Where Q_{min} is the current energy savings based on previous matches in the Retrofit Bridge, and Q_n is the allowable heat transfer in the most recent match.

The ART search will consider all possible combinations for a Retrofit Bridge – although, some may be quickly discarded if they are entirely infeasible. The total number of possible combinations for Retrofit Bridges can be extraordinarily high, especially if there is a large number of heat exchanger units (including utilities). Equation 4.3 can be used to estimate the total number of Retrofit Bridge combinations (including thermodynamically infeasible combinations) that can be found for a given HEN:

$$n_{\mathrm{RB,max}} = n_C n_H \left(1 + \sum_{k=1}^{n_E} \frac{n_E!}{(n_E - k)!} \right) \tag{4.3}$$

Where $n_{RB,max}$ is the maximum number of Retrofit Bridge combinations, n_C is the total number of coolers, n_H is the total number of heaters, and n_E is the total number of heat recovery exchangers. For larger HENs, $n_{RB,max}$ can quickly reach millions or billions, requiring significant computational effort. While many of these may be infeasible, a large number of feasible Retrofit Bridges may offer very little energy savings or economic benefit. For the automation of Bridge Analysis to be successful and useful, it is important that an engineer is provided with economic retrofit options.

4.3 Automated Retrofit Targeting

The Automating Retrofit Targeting (ART) algorithm and overall method, has three main parts: 1) the search for Retrofit Bridges, 2) the use of constraints to target performance and reduce computational effort, and 3) the estimation of the total retrofit area required for a Retrofit Bridge. A flow chart of the overall ART procedure is presented in Figure 4.1, and the following section details the method with specifics regarding each of the three main parts.

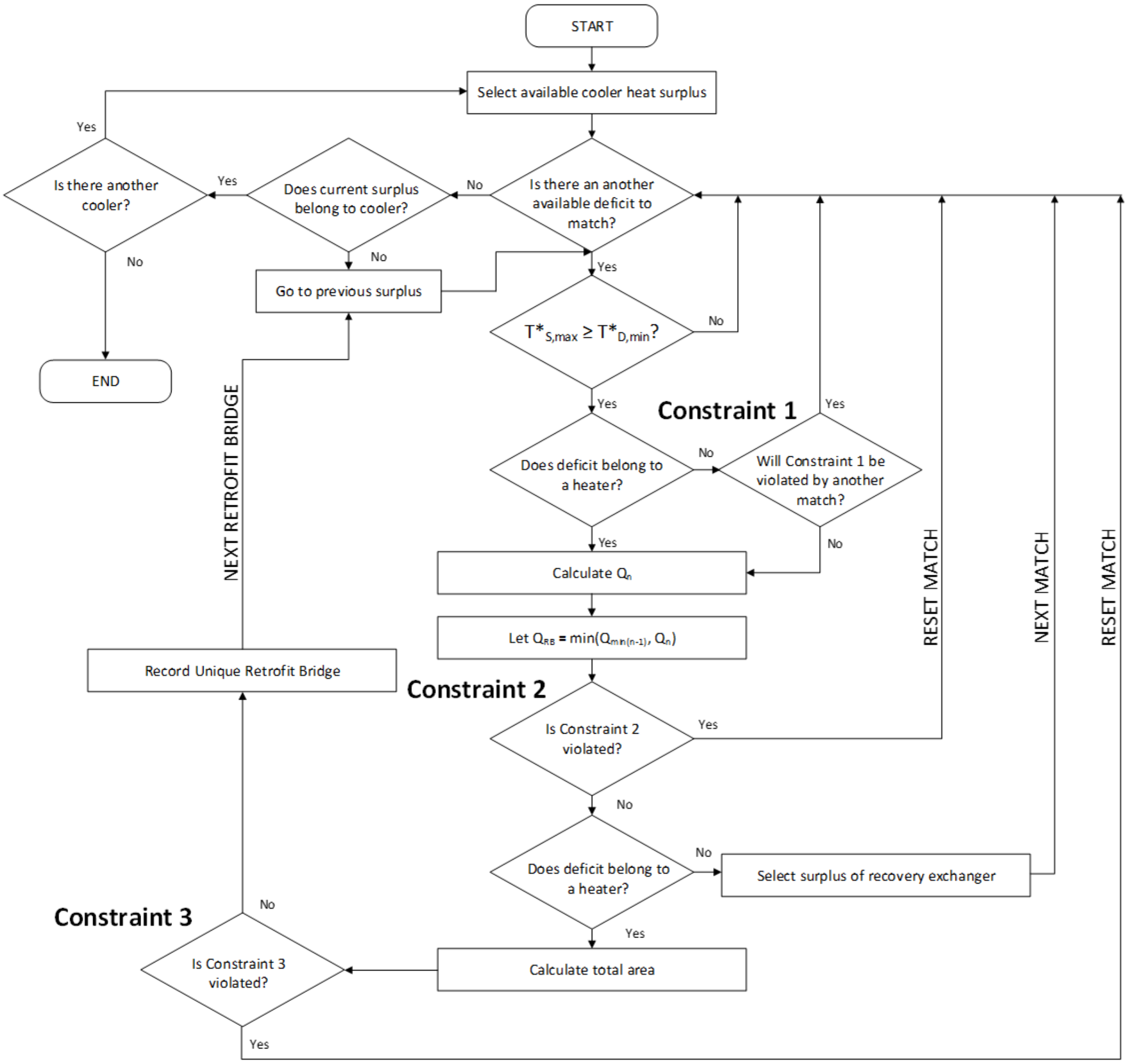


Figure 4.1: Overview of the Automated Retrofit Targeting algorithm.

4.3.1 Retrofit Bridge Search

The search for Retrofit Bridges utilises a recursive multi-loop algorithm to determine feasible and unique Retrofit Bridges for a HEN, automated within Microsoft Excel. Microsoft Excel, and Visual Basic for Applications (VBA – a programming language within Excel), have been used because the high level of use, familiarity, and accessibility that Excel has with everyday people. This allows the automation to be developed within a spreadsheet tool that most users will already be familiar with. The output from the Excel spreadsheet tool is easy to interpret and further analyse. An example of a typical output from the tool is presented in Appendix B (inclusive of developments covered in subsequent chapters, too).

The search algorithm, ART, systematically cycles through all possible combinations of matches until all feasible Retrofit Bridges have been determined. Figure 4.2 presents an illustration of the search that the ART performs using the HSDT. The search begins with a cooler heat surplus, such as the surplus in cooler C2, which is then checked against all deficits. If a match is infeasible (red arrows), the match is undone, and the surplus is re-matched with the next available deficit (in a different exchanger unit). If the match is valid and a heater deficit has not been reached, then the search continues with the surplus that corresponds to the previously matched deficit (if the deficit in exchanger E1 is matched with the surplus in cooler C1, the next match will begin with the surplus in exchanger E1). Every deficit is a potential match, adding to a series of matches that must be followed until a heater has been reached. When a Retrofit Bridge is found, the search resumes from the last position, albeit with the next surplus-deficit match.

	C1	C2	E1	E2	H1
T* (°C)	ΔH (kW)	ΔH (kW)	ΔH (kW)	ΔH (kW)	ΔH (kW)
245					
				150	
235					
				600	-1,200
195					
			83	50	-100
191.7					
	100		167		-200
185					
	600		1,000	-800	-1,200
145					
	690		230		
99					
	360	600	-480		
75					
	600		-800		
35					
			-200		
25					

Figure 4.2: Illustration of ART searching through the HSDT of the four-stream HEN.

The ART algorithm itself is complex with several checks and loops to ensure that matches are feasible and that the search will resume from the correct position when needed. ART has been built using two sub-algorithms. The first sub-algorithm, or sub-routine, initialises ART and begins the search (with another sub-algorithm named "Find_Retrofit_Bridge") with a cooler heat surplus. Pseudocode (simplified programming language) for the first part of the algorithm is presented in Figure 4.3. This sub-routine is simple, but it allows the search to work through all possible starting points (coolers). Once ART has found all Retrofit Bridges for a cooler, it moves on to the next cooler, and so on, until all Retrofit Bridges have been found and the search is exhausted.

```
Algorithm: Automated_Retrofit_Targeting
Input: Heat Surplus-Deficit Table
for each cooler in the HEN do
    Find_Retrofit_Bridge (cooler surplus, next deficit, energy savings
      Q_RB = 1 × 10^10, number of matches N_m = 1)
end
```

Figure 4.3: First sub-algorithm of Automated Retrofit Targeting, for initialising the method and cycling through all coolers.

Figure 4.4 presents pseudocode for the second part of the algorithm and corresponds to the main search that uses recursion to step through the possible surplus-deficit matches continuously. The estimated energy savings are initialised with an exponentially large number (i.e., $Q_{RB} = 1 \times 10^{10}$, as seen in Figure 4.3). As each match is added to a Retrofit Bridge, the overall energy savings will be minimised based on the allowable heat transfer in each match, eventually reaching its minimum value once the bottleneck of the Retrofit Bridge has been located (using Equation 4.2) – restricting heat recovery. In addition to the energy savings, the search also keeps track of the current surplus and deficit being matched and the total number of surplus-deficit matches in the Retrofit Bridge.

The actual search of ART begins by matching the active heat surplus (initially from a cooler) with the next available deficit (availability refers to whether it has already been matched in the current Retrofit Bridge), either from a heat recovery exchanger or from a heater. At this step, it is necessary to confirm the thermodynamic feasibility of the match using Equation 4.1. If the match is feasible, the estimated energy savings of the Retrofit Bridge are updated using

Equation 4.2 again. Next, the Retrofit Bridge is checked to see if the latest match has reached a heater deficit. If not, at least one more match will be needed, and the search continues. The method is called again, recursively, with updated references to the surplus and deficit, the current energy savings, and the current number of matches (incremented accordingly). If the Retrofit Bridge is complete, the estimated total retrofit area required for the retrofit will be calculated and the Retrofit Bridge is recorded. If at any time a Retrofit Bridge is rejected or a match is rejected, then the ART simply resumes with the last used surplus and creates a match with the next available heat deficit. ART only stops once all possible combinations of Retrofit Bridges have been analysed.

Algorithm: Find_Retrofit_Bridges

Input: Current heat surplus position, heat deficit start position, current energy savings Q_{RB}, number of matches N_m

```
In first instance, surplus is from cooler
for each HX unit with an available deficit do
    if T_Smax ≥ T_Dmin then
        if N_m + 1 ≤ N_m_max or deficit belongs to a heater then          (1)
            Calculate Q_RB
            if Q_RB ≥ (Q/N_m)_min × N_m then                             (2)
                if deficit belongs to a heater then
                    Calculate A_total
                    if Q_RB ≥ (Q/A)_min × A_total then                   (3)
                        Record Retrofit Bridge
                    end
                else
                    Find_Retrofit_Bridges(next surplus, next deficit, Q_RB,
                     N_m + 1)
                end
            end
        end
    end
end
```

Figure 4.4: Second sub-algorithm of the Automated Retrofit Targeting method for finding Retrofit Bridges and applying constraints.

During ART, three constraints are applied based on the performance of the Retrofit Bridge (including incomplete Retrofit Bridges). The constraints are used at different stages in the algorithm (represented by (1), (2), and (3) in Figure 4.4) and help prevent computational effort being spent on uneconomic Retrofit Bridges. If a constraint is violated, the Retrofit Bridge is rejected. If a Retrofit Bridge passes all three constraints, it is recorded, and the search resumes for the next possible retrofit option.

4.3.2 Performance Constraints

Constraints are used for two main reasons: 1) to eliminate and reject Retrofit Bridges that are unlikely to provide any reasonable economic benefit, and 2) to reduce the computational effort. Three performance constraints are used to provide a quick analysis of the Retrofit Bridges without necessitating the complete HEN retrofit design. If a constraint is violated, then the current Retrofit Bridge is discarded, and the search begins looking for another Retrofit Bridge. The three constraints used in this chapter are:

Constraint 1: A maximum number of matches in a Retrofit Bridge.

Constraint 2: A minimum amount of energy savings per match in a Retrofit Bridge.

Constraint 3: A minimum amount of energy savings per unit of estimated retrofit area in a Retrofit Bridge.

Other constraints can be used (as demonstrated in Chapter 5), but these constraints have been selected as they directly relate to the ART search and are indicative of the capital costs and utility cost savings of a Retrofit Bridge.

To prevent searching for Retrofit Bridges with an unrealistic number of matches (e.g., 10 matches in a single Retrofit Bridge), Constraint 1 limits the number of allowable matches (N_m) in a Retrofit Bridge. The number of matches is generally indicative of the number of retrofit modifications, although, discrepancies can occur when a match already exists in the HEN (Retrofit Bridges can make use of existing matches) or stream splitting is required, for example. Regardless, the number of matches is a good indication of the magnitude of capital investment that a corresponding retrofit HEN design may require – the fixed cost of heat exchangers. In this work, a maximum of four matches is applied; however, five, six, or even three could also be used depending on the needs of the retrofit project. Retrofit Bridges requiring more than the value of Constraint 1 are more likely to incur greater capital costs and retrofit effort without necessarily achieving enough energy savings to justify the extra expense. Constraint 1 is represented by Equation 4.4:

$$N_m \leq N_{m,\text{max}} \tag{4.4}$$

Constraint 2 considers the ratio between energy savings and number of matches (Q/N_m), iterating the principle that the Retrofit Bridge should provide enough energy savings to justify the additional investment cost of each match (which usually results in a new heat exchanger or new heat transfer area). In practice, the energy savings (Q_{RB}) should at least account for the fixed costs of each new heat exchanger. HEN cost functions (sum cost of individual heat exchangers) are generally in the format of Equation 4.5:

$$CC = FC \times N_E + \sum_{i=1}^{N_E} (VC \times A_i^n) \tag{4.5}$$

Where *CC* is the capital cost, *FC* is the fixed cost component, *VC* is the variable cost component, N_E is the total number of heat exchangers, A_i is the total heat transfer area for each heat recovery exchanger (ranging from *i* to N_E), and *n* is an exponent that is dependent on the cost function. The number of matches relates to the number of heat exchangers, and therefore, affects the fixed cost component. Setting a minimum ratio of energy savings per match helps to ensure that a Retrofit Bridge achieves a level of process heat reduction that is relative to the capital investment. The expression for Constraint 2 is presented in Equation 4.6:

$$\left(\frac{Q}{N_m}\right)_{\text{min}} \leq \frac{Q_{RB}}{N_m} \tag{4.6}$$

As Constraint 2 relates to the fixed cost of a heat exchanger, Constraint 3 relates to the variable cost of a heat exchanger. The third constraint is a minimum ratio between the energy savings and the estimated retrofit area required (Q/A). This area is estimated based on the matches created by the Retrofit Bridges. There should be a good balance between the energy savings and required heat transfer area, echoing the well-known trade-off between energy savings and capital cost. The expression for Constraint 3 is presented in Equation 4.7:

$$\left(\frac{Q}{A}\right)_{\text{min}} \leq \frac{Q_{RB}}{A_{\text{total}}}, \quad \text{where } A_{\text{total}} = \sum_{i}^{N_m - 1} A_{ij}, \quad j = i + 1 \leq N_m \tag{4.7}$$

Where *i* and *j* are integers that represent the heat exchanger providing the heat surplus and the heat exchanger with the heat deficit. The heat transfer area is calculated for each new match in the Retrofit Bridge.

There is a progression to these constraints as each constraint requires a greater level of detail regarding the indicative costs and tightens the trade-off between the energy savings and capital costs. The first constraint is applied during the initial Retrofit Bridge search using only the number of matches. Then, the second constraint is applied once the allowable heat recovery savings have been calculated for a match, and then finally, the third constraint is applied when the Retrofit Bridge has been completed and the area can be estimated.

Constraints can be added or modified depending on the needs of the retrofit project. For example, if a project requires a short payback period (PB), then the ART algorithm can be adapted to constrain the PB. This constraint was demonstrated in Lal et al. (2018). Constraints such as pressure drop constraints or match constraints (i.e., forbidden matches) can also be in future with the right information and analyses. Retrofit HEN design is complex, but ART has been developed to allow additional constraints to be implemented in the future. Information about each process stream and each heat exchanger can also be held within the algorithm and used to conduct other analyses.

4.3.3 Heat Transfer Area Estimation

Heat transfer area is estimated using the ε-NTU method, where ε is the effectiveness and NTU is the number of transfer units. The following equations outline the method and the steps taken. First, the minimum and maximum heat capacity flow rates (CP_{min}, CP_{max}) (kW/°C) are determined using Equation 4.8, based on the heat surplus and heat deficit matched in the heat exchanger:

$$CP_{\min} = \min(CP_S\,, CP_D), \quad CP_{\max} = \max(CP_S, CP_D) \tag{4.8}$$

Where CP is the product of the mass flow rate, $\dot{m}$ (kg/s), and the specific heat capacity, c_p (kJ/kg°C). Then, the maximum possible heat exchanger duty (Q_{max}) is calculated using Equation 4.9:

$$Q_{\max} = CP_{\min}\left(T_{S,\max} - T_{D,\min}\right) \tag{4.9}$$

Where $T_{S,\max}$ is the highest available temperature of the heat surplus and $T_{D,\min}$ is the lowest available temperature of the heat deficit (neither temperature is shifted). With the maximum heat exchanger duty calculated, the effectiveness (ε) of the heat exchanger can be calculated with Equation 4.10:

$$\varepsilon = \frac{Q_{RB}}{Q_{\max}} \tag{4.10}$$

Once effectiveness has been calculated, the chosen NTU correlation can be used; in this case, the correlation for a double-pipe counter-flow heat exchanger has been used. Different NTU correlations can be easily used for different types of heat exchanger arrangements (e.g., cross-flow or shell and tube), when needed (Çengel, 2007). All ε-NTU correlations are based around c and ε; therefore, no additional information is required to use different correlations. The chosen correlation is presented in Equation 4.11:

$$NTU = \frac{1}{c-1}\ln\left(\frac{\varepsilon - 1}{\varepsilon \cdot c - 1}\right), \text{where } c = \frac{CP_{\min}}{CP_{\max}} \tag{4.11}$$

Next, the overall heat transfer coefficient (U) can be determined based on the individual heat transfer coefficients (h) of the streams containing the surplus and deficit. The overall heat transfer coefficient (kW/m^2°C) is calculated using Equation 4.12:

$$\frac{1}{U} = \frac{1}{h_S} - \frac{1}{h_D} \tag{4.12}$$

Finally, the heat transfer area can be estimated with Equation 4.13:

$$A = \frac{CP_{\min} NTU}{U} \tag{4.13}$$

The total heat transfer area (A) is the sum of the heat transfer area needed for each match in the Retrofit Bridge. Once the total retrofit area has been estimated, Constraint 3 can be used to eliminate the Retrofit Bridges that require excessive retrofit area, i.e., high capital investment.

Each match in the Retrofit Bridge is initially treated as though it is a new heat exchanger match. Retrofit Bridges generally create new pathways; however, there may be times when a match already exists, and the retrofit area is not estimated correctly. This is a disadvantage of the current implementation of the method, but the targeting can be applied without requiring the full retrofit HEN design.

4.3.4 Method Validation

With respect to validation of the method and algorithm, manual use of the Bridge Analysis tools – METD and HSDT – has been used extensively to verify that the results from ART are correct. The manual calculations (i.e., mass and energy balances) and retrofit HEN design were compared against the results from ART to ensure that the automated calculations and procedures were correct.

4.4 Case Study: Paper Mill

In the previous chapter, a paper mill case study was introduced (grid diagram shown in Figure 4.5). It was shown that Bridge Analysis tools such as the METD and HSDT could be used to find Retrofit Bridges; however, it was difficult to be confident that an identified Retrofit Bridge was the best choice, let alone confirm that all feasible Retrofit Bridges had been found and considered. Many Retrofit Bridges could be identified by sight, particularly several Retrofit Bridges with a direct match between a cooler heater surplus and heater deficit; however, even with only a handful each of coolers, heaters, and heat recovery exchangers, there are still hundreds or thousands of potential Retrofit Bridges. Equation 4.3 estimates that there are 6,520 possible combinations (including infeasible combinations) of Retrofit Bridges, though this number will be reduced when the infeasible combinations are excluded. The retrofit analysis with ART was conducted using a computer with an Intel® Core™ i7-4770 CPU @ 3.4 GHz.

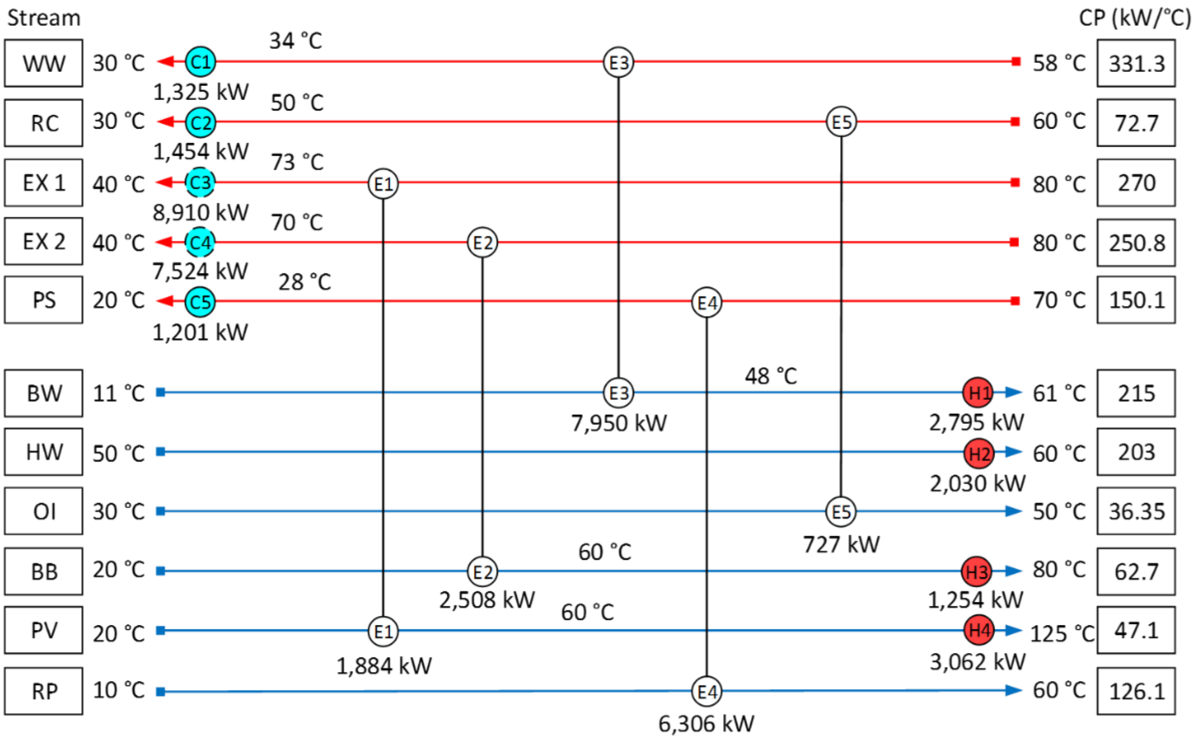


Figure 4.5: Grid diagram of the paper mill HEN.

4.4.1 Constraint Analysis

Due to the relatively small size of the paper mill HEN, the ART algorithm can find all 1,757 feasible Retrofit Bridges in approximately 5.7 seconds without needing to use constraints (down from 6,520 possible combinations). Finding all 1,757 retrofit options is not manageable by hand, emphasising that even a smaller HEN needs a degree of automation to find the best retrofit solutions. Despite finding all possible solutions, constraints can be applied to remove the uneconomic Retrofit Bridges and return a set of economically viable solutions from which a single solution can be selected.

The effect that different values for the constraints have on the Retrofit Bridge results is examined in this section. Figure 4.6a shows the effect of decreasing the maximum number of matches from six (the absolute maximum based on the number of heat exchangers) to one (with no other constraints applied). Interestingly, the Retrofit Bridges with direct matches between cooler heat surpluses and heater deficits (one match) are shown to have higher energy savings than most other Retrofit Bridges and require less retrofit area – reinforcing the importance of these direct matches. Retrofit Bridges tend to suffer low economic performance when a larger number of matches is needed (more than four). As the majority of Retrofit Bridges appear to have three or four matches, the maximum of four matches is a conservative choice for Constraint 1. Figure 4.6b shows the effect of ranging Constraint 2 between 0-800 kW per match and show that the majority of Retrofit Bridges provide at least 200 kW per match. A similar trend is seen in both figures; with the more heavily constrained Retrofit Bridges appearing on fronts that appear to edge towards the upper left corner of the plots, where the trade-off between energy savings and retrofit area improves.

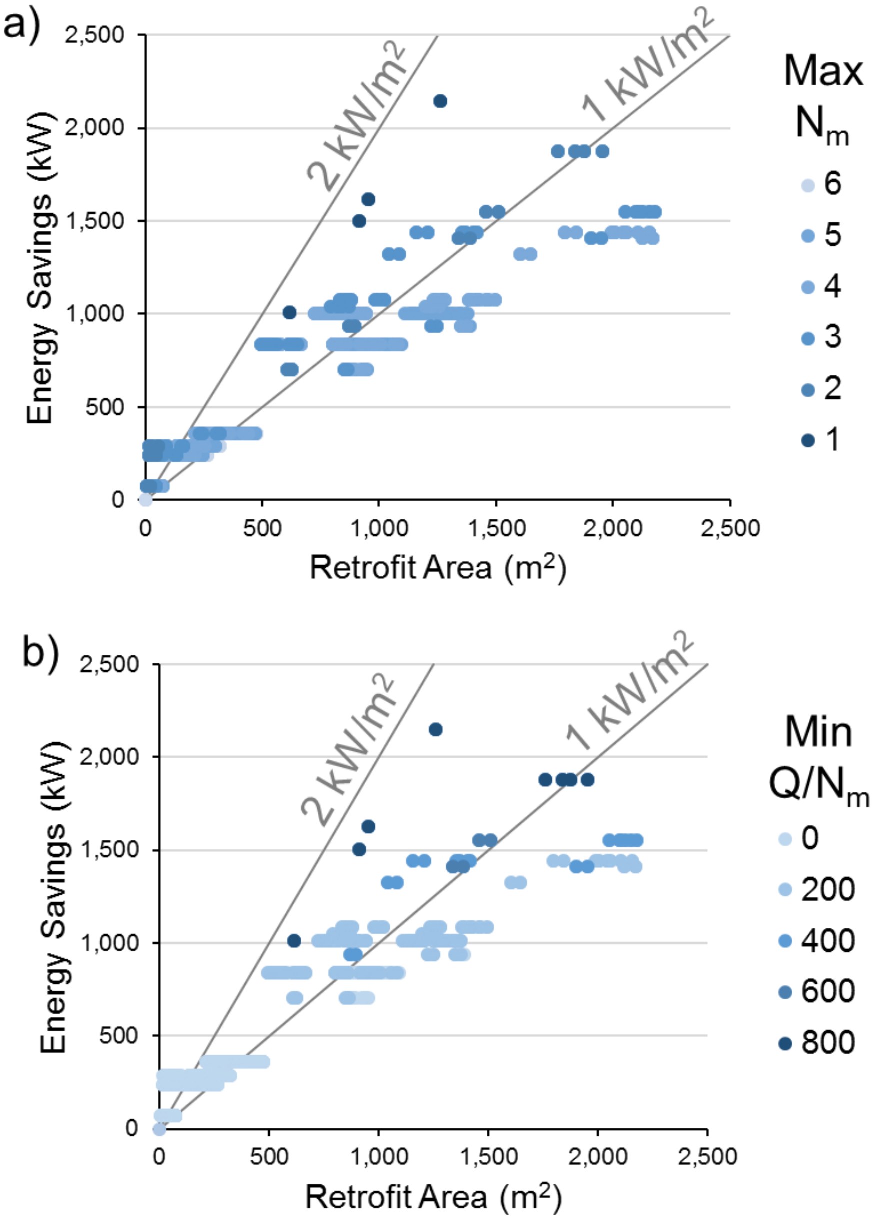


Figure 4.6: The effect of varying constraints on the Retrofit Bridge search: a) varying Constraint 1 from six to one matches, and b) varying Constraint 2 from 0-800 kW/match.

When examining the effect of varying Constraint 3, most Retrofit Bridges only have a ratio of energy savings to retrofit area of 0-1 kW/m^2 (Figure 4.7a). Retrofit Bridges with ratios of at 2-

10 kW/m^2 do not achieve great improvements in heat recovery and therefore do not reduce utility costs significantly (Figure 4.7b), although, there could be potential for cheaper retrofit projects due to the relatively low amount of area (less than 200 m^2). Due to the low ratio of energy savings to the number of matches, these Retrofit Bridges are quickly rejected by the other constraints (shown in Figure 4.6 with the use of 1 kW/m^{2}and 2 kW/m^2 guidelines). The Retrofit Bridges with a ratio of energy savings to retrofit area between 1-2 kW/m^2 are likely to be the most economical Retrofit Bridges as they typically provide enough energy savings to justify the area investment.

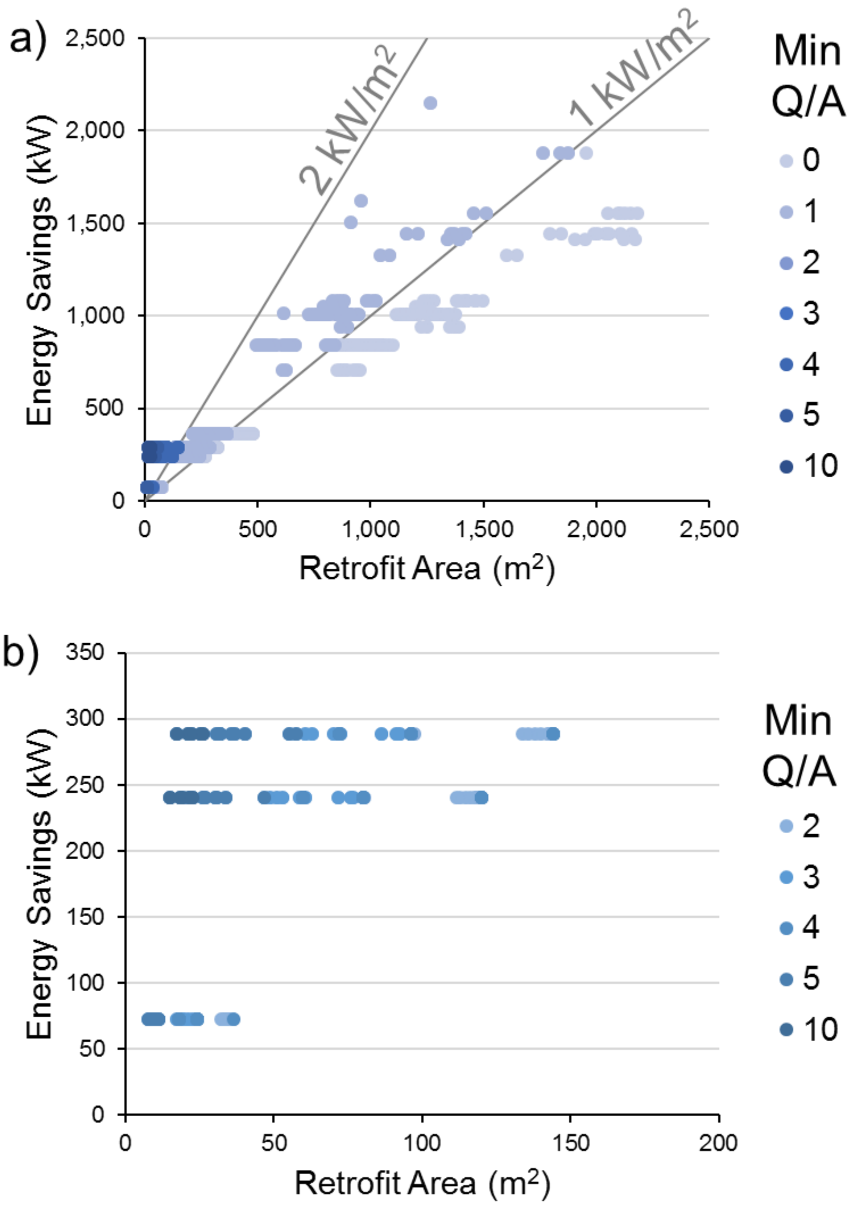


Figure 4.7: The effect of varying Constraint 3 on the Retrofit Bridge search: a) varying Constraint 3 from 0-10 kW/m^2 and b) all Retrofit Bridges with ≥ 2 kW/m^2.

Considering the entire set of Retrofit Bridges (all 1,757), Figure 4.8 shows that Retrofit Bridges with a higher ratio of energy savings to the number of matches will have a lower ratio of energy savings to retrofit area, and vice-versa, indicating a trade-off between Constraint 2 and Constraint 3. However, Retrofit Bridges with a high Q/N_m were more likely to outperform the Retrofit Bridges with a high Q/A (10-15 kW/m^2). A higher Constraint 2 is more likely to have a greater capacity for finding economic Retrofit Bridges (and reducing computational effort) than Constraint 3; however, implementation of a low Constraint 3 (1-2 kW/m^2 minimum) is effective at finding the Retrofit Bridges with the better economic potential (after Constraint 2 has been applied). Therefore, it is important to select constraints that best represent the type of retrofit project. A brief validation can also be conducted to ensure that the most appropriate constraints (in terms of magnitude of threshold) have been selected (an example is presented in Chapter 5). This validation can be achieved by comparing the economic results of Retrofit Bridge searches with different levels of constraints to show how the chosen constraints capture solutions without excluding the more profitable solutions. This validation is an important step in the constraint selection process.

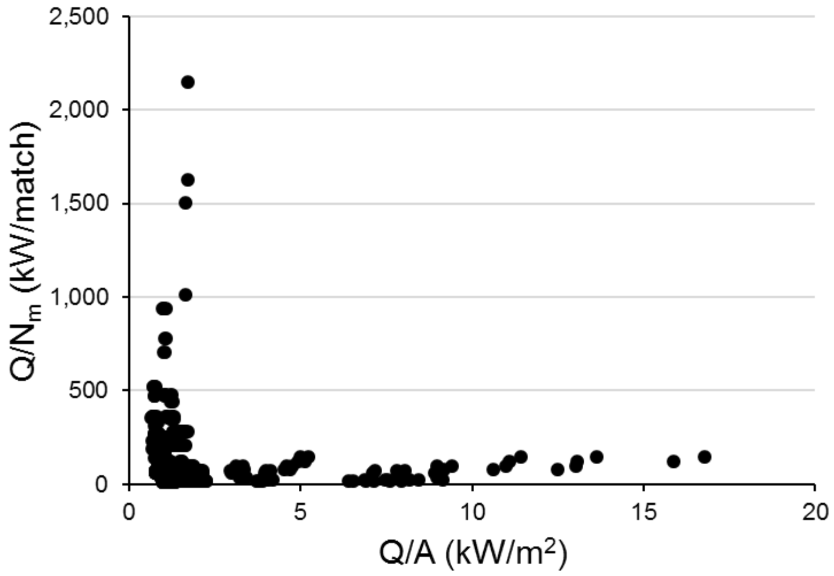


Figure 4.8: Representation of the trade-off between Q/N_m and Q/A.

4.4.2 Retrofit Analysis

For the retrofit analysis of the paper mill, the following constraints were applied, after being validated in the above section:

Constraint 1: A maximum of four matches.

Constraint 2: A minimum of 200 kW of energy savings per match.

Constraint 3: A minimum of 1 kW of energy savings per unit area.

With these constraints, the number of Retrofit Bridges is reduced to 105. Ideally, the constraints help to filter out uneconomic retrofit options. The following figures compare the 105 Retrofit Bridges against the total 1,757 Retrofit Bridges using the estimated energy savings they provide along with the number of matches and the total retrofit area. The effect of applying each constraint is also examined, although the effect of Constraint 1 and Constraint 2 are shown together.

Figure 4.9a shows a smaller distribution of Retrofit Bridges than Figure 4.9b, because Retrofit Bridges often use the same matches resulting in similar heat transfer bottlenecks and overall energy savings and because there are only six possible values on the horizontal axis (which is later constrained to four). Figure 4.9b shows a wider range of Retrofit Bridges, as the required retrofit area is often unique to a Retrofit Bridge. In Figure 4.9a, the effect of Constraint 2 (Q/N_m) is evident, and many Retrofit Bridges with low savings and a high number of matches are excluded. In both figures, there are several excluded Retrofit Bridges with a ratio of either Q/N_m or Q/A that is similar to other Retrofit Bridges that have not passed both constraints. For example, there are several options that all have the same energy savings (1,881 kW) and number of matches (two); however, once the area is estimated and constrained, some of the options are excluded for having a low ratio of savings to area (Figure 4.9b). Furthermore, Figure 4.9a shows several Retrofit Bridges that achieve higher savings than other options with the same number of matches that are later excluded by Constraint 3. This illustrates the importance of considering both the number of matches (i.e., fixed cost of a heat exchanger) and the area (i.e., the variable cost of a heat exchanger) – and not just accepting a Retrofit Bridge if it passes only one constraint. A Retrofit Bridge with a single match could need a large heat exchanger.

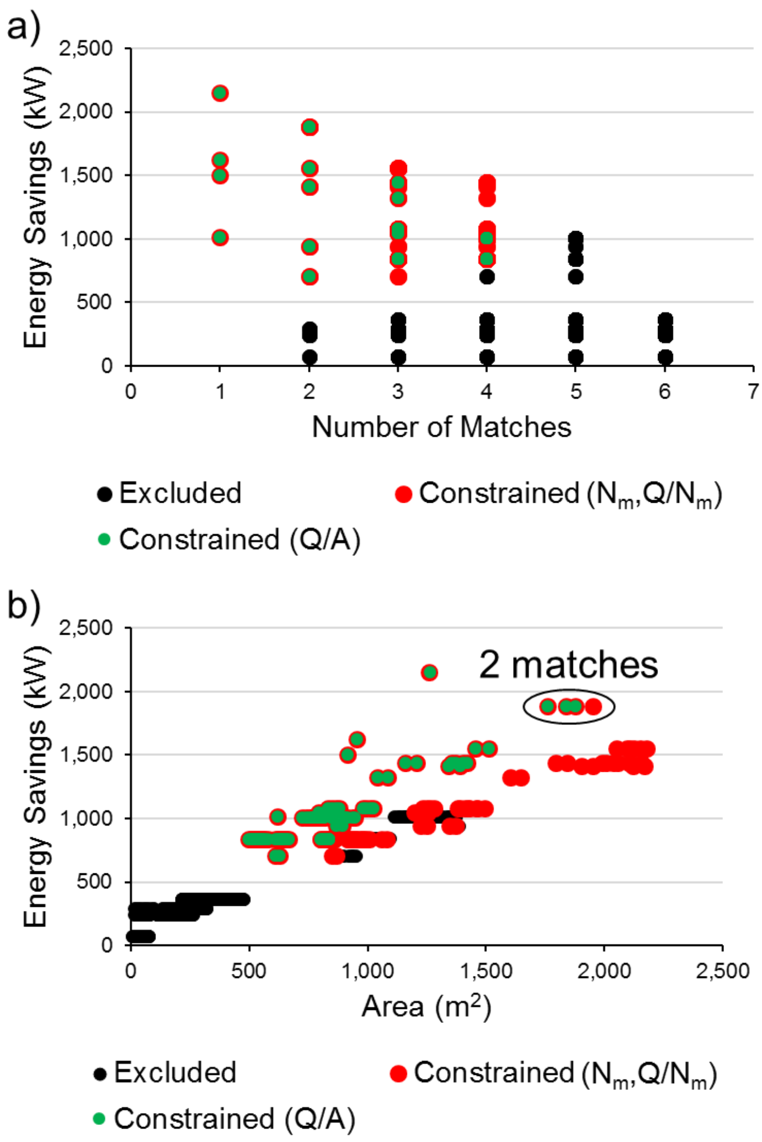


Figure 4.9: Retrofit Bridge search results for the paper mill with constraints: a) energy savings against the number of matches and b) energy savings against the total retrofit area.

4.5 Case Study: Petrochemical Complex

The second major case study is the HEN from a petrochemical complex, which features a cold stream with significant preheating. The existing HEN has 24 coolers, 18 recovery exchangers, 4 heaters, and several stream splits. Due to the large number of heat exchanger units and process streams, the METD and HSDT could not be easily used manually to find good retrofit solutions (it is possible with the HSDT, it is just more cumbersome). It is necessary to automate the process with ART. The grid diagram for the HEN is provided in Figure 4.10. Prior to the analysis, the total number of possible combinations (including infeasible Retrofit Bridges) was determined to be 1.67 x 10^{18} Retrofit Bridges, using Equation 4.3. The retrofit analysis with ART was conducted using a computer with an Intel® Core™ i7-4770 CPU @ 3.4 GHz.

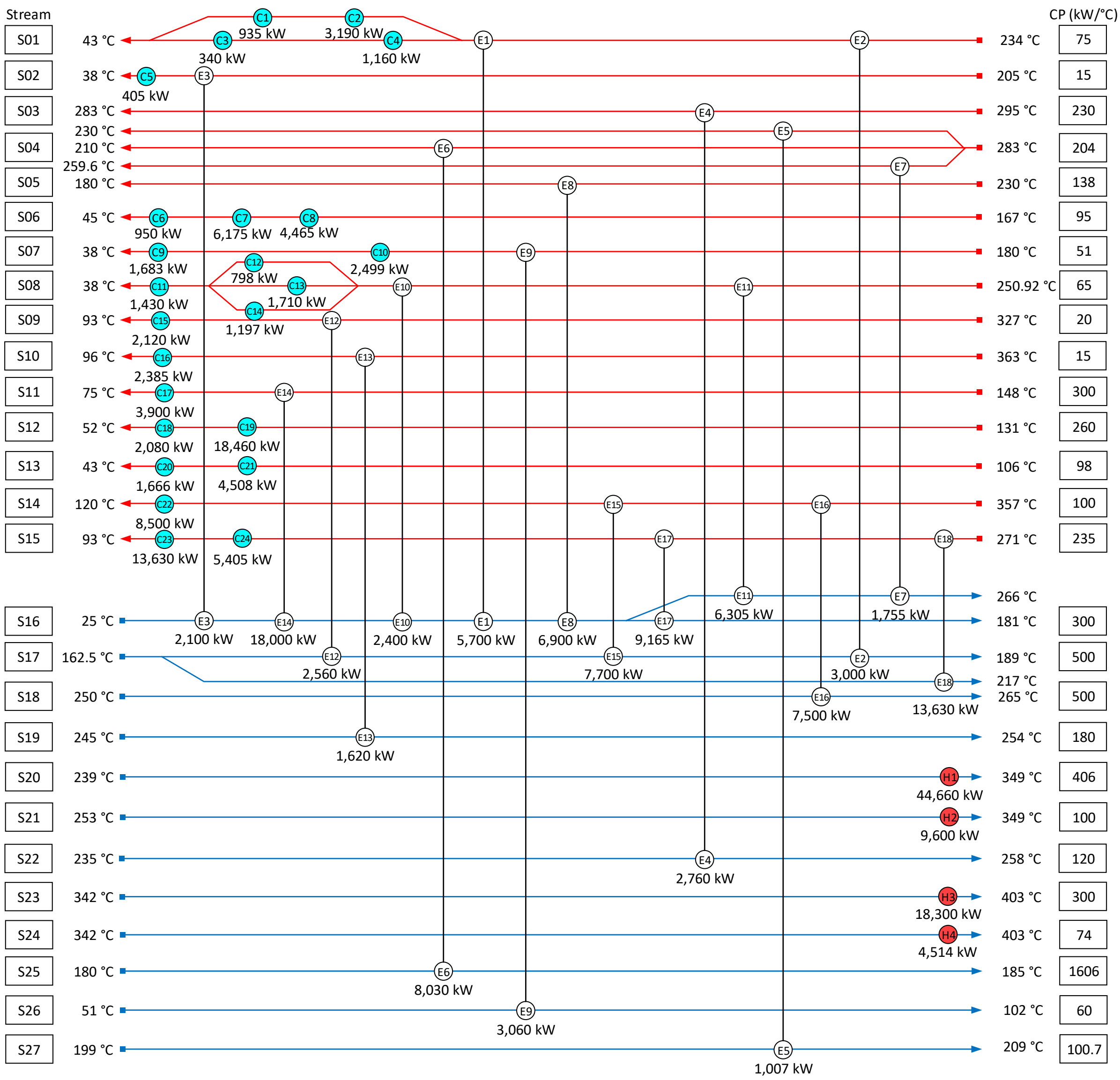


Figure 4.10: Grid diagram of the petrochemical complex HEN.

4.5.1 Constraint Analysis

For each of the three constraints used in this chapter, a plot has been provided showing how the threshold of the constraints can affect the results of the ART search for the petrochemical complex. In each figure, one constraint is varied while the other two constraints are kept constant (constraints are required for a HEN of this size).

In Figure 4.11a, the effect of varying Constraint 1 (maximum number of matches) is examined, with an initial Constraint 2 of 600 kW/match. It was found that, under these conditions, a

Retrofit Bridge could have up to eight matches; however, as the maximum number of matches was decreased to make Constraint 1 more restrictive, the recorded Retrofit Bridges were more likely to have a good ratio of energy savings to area.

This trend was also observed in Figure 4.11b and Figure 4.11c (increasing the minimum threshold rather than decreasing the maximum threshold). In Figure 4.11b, Constraint 2 was varied with a constant maximum of four matches, while in Figure 4.11c, Constraint 3 was varied with a constant maximum of four matches and Constraint 2 of 200 kW/match. For this HEN, it was found that a lower Constraint 3 should be used to avoid returning Retrofit Bridges that provide little benefit for a low amount of heat transfer area, while Constraint 2 could be set at a high level without necessarily rejecting potentially economic retrofit options – reaffirming conclusions made during the paper mill case study.

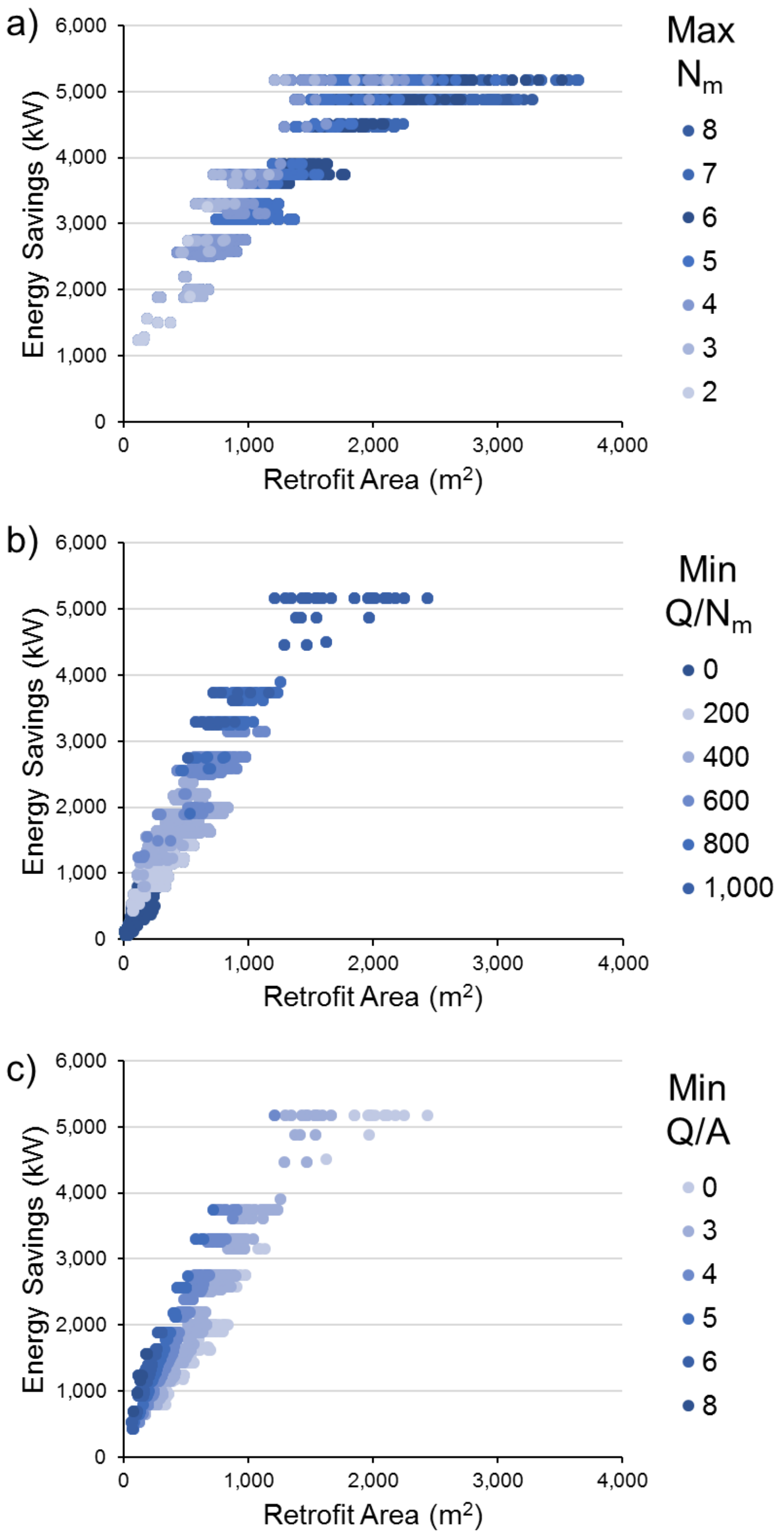


Figure 4.11: The effect of varying constraints on the Retrofit Bridge search: a) varying Constraint 1 from 2-8 matches (with Constraint 2: 600 kW/match), b) varying Constraint 2 from 0-1,000 kW/match (with Constraint 1: four matches), and c) varying Constraint 3 from 0-8 kW/m^2 (with Constraint 1: four matches and Constraint 2: 200 kW/match).

4.5.2 Retrofit Analysis

Unlike the paper mill case study, it is not practical to identify all Retrofit Bridges for the petrochemical complex case study due to the very large number of Retrofit Bridge combinations that are possible because of the size of the HEN. For this reason, constraints are applied straight away. The ART search was conducted using the following constraints:

Constraint 1: A maximum of four matches (of a possible 19).

Constraint 2: A minimum of 450 kW of energy savings per match.

Constraint 3: A minimum of 3 kW of energy savings per unit area.

Using ART, 386 Retrofit Bridges were found in less than one second (computer specifications provided in Section 4.6 where computational efficiency is discussed in more detail). The effect of Constraint 3 on the number of Retrofit Bridges is more apparent in Figure 4.12b than in Figure 4.12a; however, the Retrofit Bridges excluded by Constraint 2 are more obviously uneconomic (low energy savings compared to other Retrofit Bridges with similar numbers of matches or area).

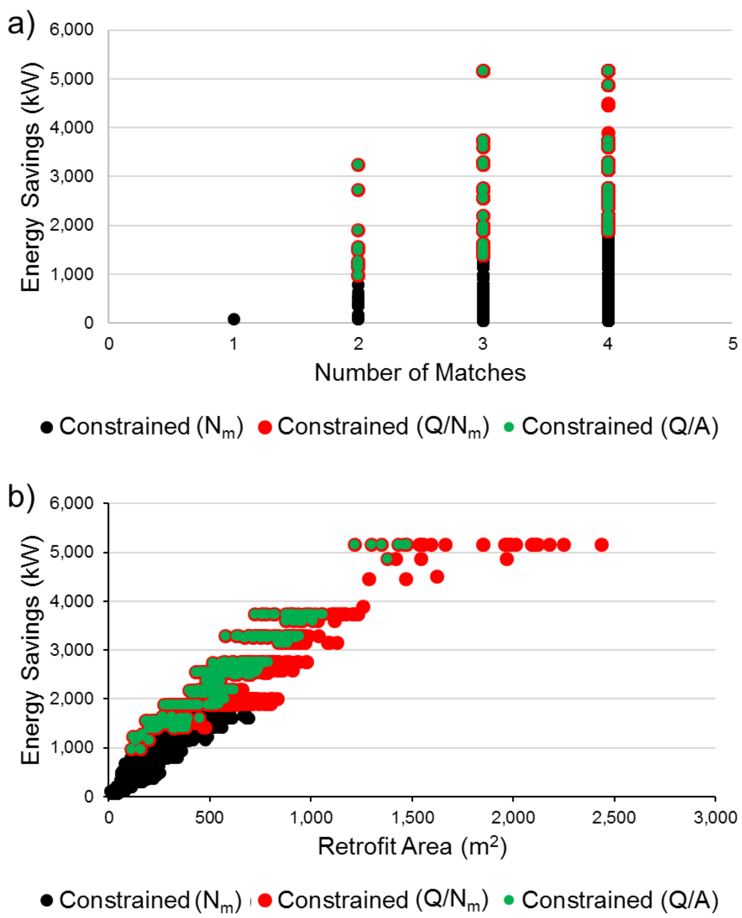


Figure 4.12: Retrofit Bridge search results for the petrochemical complex with constraints: a) energy savings against the number of matches and b) energy savings against the total retrofit area.

4.6 Automated Retrofit Targeting Performance Analysis

Automating the retrofit analysis does not remove user-interaction or engineering judgement from the retrofit design process as the user selects the constraints, analyses the constraints, and then performs the evaluation of the Retrofit Bridges. The ART handles the time-consuming procedure of identifying and quantifying Retrofit Bridges. To demonstrate the computational performance,

Table 4.1 presents the computational time required to determine all possible (and feasible) Retrofit Bridges for the petrochemical complex HEN, for a given set of constraints. Results were obtained using a computer with an Intel® Core™ i7-4770 CPU @ 3.4 GHz.

In this analysis, the petrochemical complex HEN is used due to the greater computational effort to find all Retrofit Bridges compared to the paper mill (all Retrofit Bridges can be easily found for the paper mill). In this study, Constraint 2 is varied from 200-1,723 kW/match (1,723 kW/match is the maximum value and search times for >200 kW/match require too much memory and time). Constraint 1 is set to a maximum of 10 matches, and Constraint 3 is not used at all. Additionally, the computational time, or solution time, is solely based on the time taken for ART to compute the Retrofit Bridges and pass them through the constraints. All other automation, such as problem initialisation and writing to spreadsheet was excluded from the solution time. Solution time was averaged based on five trials with the same constraints and determined using Excel-based timers. Each trial will result in the identification of the same Retrofit Bridges.

The initial implementation of constraints, 200 kW/match, reduced the number of unique Retrofit Bridges to 7,134,348 – a 99.9% reduction in the number of Retrofit Bridges (from the total number of possible combinations, 1.67 x 10^{18}). Increasing the threshold further continued to dramatically reduce the number of feasible Retrofit Bridges as well as the solution time. With a threshold of 400 kW/match, the 18,880 feasible Retrofit Bridges could be found in 1.77 seconds, rather than the many minutes needed for a higher threshold. At higher thresholds, the solution time becomes less than a second. There is a point where increasing the values of the constraints provides no reduction of computational effort and reduces the number of Retrofit Bridges.

Table 4.1: Automated Retrofit Targeting search statistics.

Constraint 2 (kW/match)	Average Solution Time (s)	Number of Retrofit Bridges
Equation 4.3	-	1.67 x 10^{18} [b]
≥ 200	724	7,134,348
≥ 300	34.5	340,408
≥ 350	6.53	72,312
≥ 400	1.77	18,880
≥ 450	0.70	7,224
≥ 500	0.43	4,283
≥ 600	0.21	1,434
≥ 700	0.14	540
≥ 800	0.11	346
≥ 900	0.08	165
≥ 1,000	0.07	96
≥ 1,200	>0.06	38
≥ 1,400	>0.06	6
≥ 1,600	>0.06	6
≥ 1,723	>0.06	5

It is critical to reiterate that all identified Retrofit Bridges are unique but not always independent. In this context, independence requires that implementation of two Retrofit Bridges can be simultaneously applied to a HEN. However, this is not always the case as Retrofit Bridges may involve some of the same matches and exchanger units. This means that the application of one Retrofit Bridge could change the existing exchanger units in such a way that another Retrofit Bridge would no longer achieve the previously estimated savings or may no longer be feasible at all. Targeting combinations of multiple Retrofit Bridges and pushing towards the maximum retrofit energy savings will be examined in the next chapter. ART will continue to be used to determine Retrofit Bridges; however, to enable this type of analysis and handle the exponential increase in retrofit possibilities, it will be necessary to automate the retrofit design and conduct an economic evaluation. Improved constraints and optimisation are also needed. These aspects of retrofit design will be covered in Chapter 5.

4.7 Conclusions

Application of the ART algorithm has enabled identification and quantification of feasible and economically viable Retrofit Bridges in a matter of seconds. Retrofit Bridges are checked against several performance constraints that represent the trade-off between energy savings and the fixed and variable capital costs (indirectly through estimations of the number of matches and the heat transfer area). These constraints provided effective ways of rejecting uneconomic Retrofit Bridges and reducing the search space and computational effort. Using ART, Bridge Analysis can be conducted for large and complex HEN retrofit projects. ART also provides a good starting point for further development of Bridge Analysis, including cost estimation and other constraints (i.e., pressure drop or spatial limitations) as it has enabled the quick identification and quantification of Retrofit Bridges, so that these Retrofit Bridges may be analysed in more detail later. The next chapter will discuss a new algorithm that uses ART to produce long-term retrofit design plans that can consider combinations of Retrofit Bridges and their effect on the profitability of the retrofit project.

Chapter 5

Industrial Energy Retrofit Design Planning

The automation of Bridge Analysis opens several new opportunities for further development. The next step in the development of Bridge Analysis and Automated Retrofit Targeting (ART) is the analysis of the cumulative effect of multiple Retrofit Bridges on a single Heat Exchanger Network (HEN). Due to the large number of possible Retrofit Bridges that can be discovered with ART, it is likely that several unique Retrofit Bridges can be combined to achieve even greater reductions in process heat demand while remaining cost-effective. It is also possible that entirely new retrofit opportunities may be possible once a HEN has been retrofitted – if the maximum retrofit energy savings (as determined with the Modified Energy Transfer Diagram) has not been reached. The application of successive Retrofit Bridges creates an industrial energy retrofit design plan, or a retrofit plan, that details several retrofit stages that can be applied either simultaneously as a larger capital project or sequentially over a longer period. This is achieved through a multi-stage retrofit analysis.

A multi-stage retrofit analysis is not often considered in many recent retrofit design methods – especially not on the same scale as what is possible with ART. Mathematical programming methods may be able to implement multiple unique retrofit modifications through the optimisation of HEN superstructures, but it is difficult to consider the additional retrofit opportunities that may arise after an initial retrofit design has been implemented without using another optimisation procedure. There is also no guarantee that the most economical first stage will lead to the most economical overall retrofit HEN design. This is a complex issue; however, by analysing a wider range of possible retrofit plans, there is an increased chance of finding the most economical overall retrofit HEN design.

The significant increase in retrofit design options is a consequence of multi-stage retrofitting, and while constraints were introduced in Chapter 4 to help address the sheer number of possible Retrofit Bridges, multi-stage retrofitting results in an exponential increase in retrofit options. Improvements have been made to the ART search to accommodate the increase in retrofit options, including the use of constraints that utilise more detailed design information (although, this is still a high level retrofit HEN design method) and a Pareto front analysis. The multi-stage retrofit analysis is enabled due to automated HEN design that allows heat exchangers to be more accurately sized and HEN features such as a stream splitting to be included, in addition to the mass and energy balances that are required after retrofit modifications are applied to the HEN.

The aim of this chapter is to build the Automated Retrofit Targeting method into an easy-to-use industrial energy retrofit design planning tool. The major developments include an algorithm for multi-stage retrofit analysis, automated HEN design, and the use of a Pareto front analysis to guide the search for viable Retrofit Bridges. The industrial energy retrofit design planning tool is demonstrated using the paper mill and petrochemical complex case studies, showing how the improved method provides greater energy savings and economic benefits over single-stage Bridge Analysis.

5.1 The Multi-Stage Retrofit Analysis Method

The method presented in this chapter has been developed as an extension to Automated Retrofit Targeting (ART) and Bridge Analysis. The major improvement to Bridge Analysis is the implementation of an algorithm for solving multiple retrofit stages, resulting in the output of retrofit plans that can be used to guide the energy retrofit planning. The overall method is presented in Figure 5.1 and builds upon the methods from the previous two chapters.

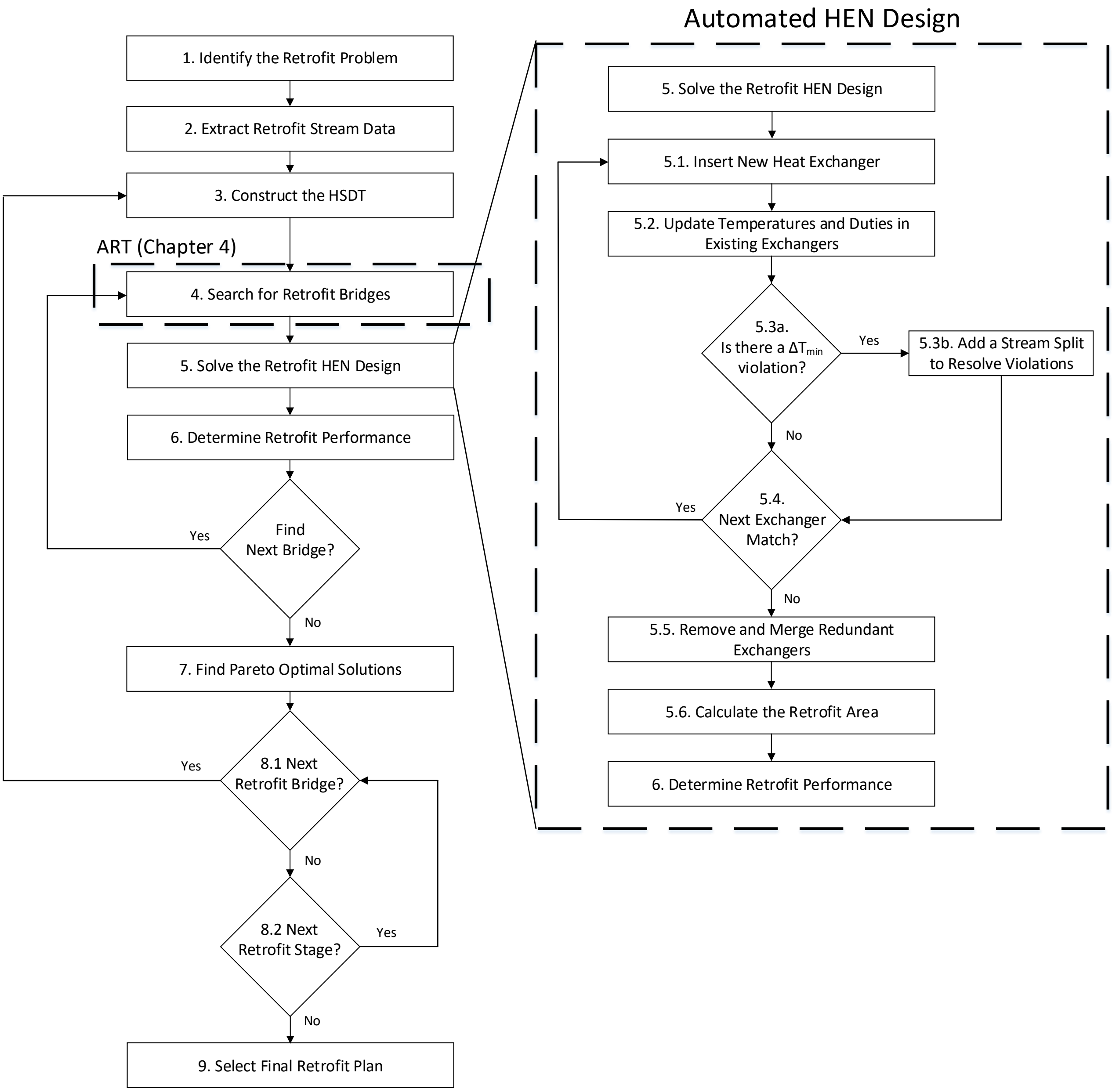


Figure 5.1: Overview of the multi-stage retrofit analysis method, including automated HEN design and ART.

5.1.1 Step 1: Identify the Retrofit Problem

As with every retrofit analysis, the method begins with the formal identification of the retrofit problem. The retrofit problem focuses on a HEN, or subnetwork of a larger HEN, where the primary goal is to reduce the utility demand and, by extension, operating costs. Part of the problem identification and definition is the measurement, collection, and reconciliation of material and fluid flows within the targeted HEN, as part of a mass and energy balance around critical heat transfer components.

5.1.2 Step 2: Extract Retrofit Stream Data

Retrofit stream data is based on the existing heat recovery exchangers and utility exchangers in the HEN. The necessary retrofit stream data includes the supply and target temperatures of each stream within an exchanger, as well as each stream's heat capacity flow rate (CP – not to be confused with c_p which represents a specific heat capacity), heat transfer coefficient (HTC), and specification of ΔT_{cont} (or global ΔT_{min}). The retrofit problem and stream data can also be summarised as a conventional grid diagram to show the HEN's topological structure. The retrofit stream data is input into a Microsoft Excel-based spreadsheet tool where it can be used to complete the rest of the retrofit analysis.

Later in the method, Retrofit Bridges, or more generally, retrofit modifications, are used to make upgrades to the HEN. As part of the energy retrofit planning analysis, new retrofit stream data is extracted from these retrofitted HENs and used to find additional Retrofit Bridges, allowing for the successive retrofit stages by 'redefining' the retrofit problem and the HEN being targeted by a retrofit.

5.1.3 Step 3: Construct the HSDT and METD

Based on the retrofit stream data, the HSDT and METD are generated. The HSDT is used as the basis for the retrofit analysis and algorithms, while the METD is used to provide insights such as retrofit energy savings target and the presence of cross-Pinch heat transfer or improper use of utility. While a significant part of Bridge Analysis, the METD is not used in the automation and computation of the method and is used solely for targeting and to help guide users towards large reductions in process heat use. For further information about the generation and use of these retrofit tools, please refer to Chapter 3.

5.1.4 Step 4: Search for Retrofit Bridges

The Automated Retrofit Targeting (ART) algorithm applies an exhaustive branching method to search the given HSDT for all feasible Retrofit Bridges. The basic search for a Retrofit Bridge remains the same as in Chapter 4. Once a Retrofit Bridge has been identified, it is quantified in terms of the estimated energy savings it will achieve, it will then be assessed based on constraints as well as a Pareto front analysis. New developments to the method also include the estimation of capital cost and profitability and the design of the retrofitted HEN. These developments are covered in the following sections but are applied once a Retrofit Bridge has been identified. Constraints are still applied, as in Chapter 4; however, the steps in which they are applied may be different.

5.1.5 Step 5: Solve the Heat Exchanger Network Retrofit Design

To facilitate multi-stage retrofit analysis, and improve the use of constraints and economic evaluation, the retrofit HEN must be solved for each Retrofit Bridge. The solving of retrofit HEN designs refers to the implementation of retrofit modifications based on the matches suggested by the Retrofit Bridge. Retrofit modifications include the placement of new heat exchangers, additional heat transfer area retrofitted to existing exchangers (which is calculated as the positive difference between the calculated heat transfer area of the existing exchanger in the initial HEN and the retrofitted HEN), and stream splitting. The retrofit HEN design also includes the identification of redundant exchangers (including utilities) and recovery exchangers that can be 'merged' together. Merging occurs when a new heat recovery exchanger matches the same streams as an existing recovery exchanger and is in a position where the inlet stream conditions of one exchanger are equal to the outlet stream conditions of the other, on both the hot and cold sides. Other modifications, such as re-piping or heat transfer enhancement, may also be possible but are not explicitly considered in this retrofit analysis. An engineer with intimate knowledge of the HEN may be able to implement a retrofit design using techniques such as heat transfer enhancement instead of increased heat transfer area, but this level of detail is outside the scope of this thesis.

The solving of a retrofit design for a given set of Retrofit Bridges is handled by the automated retrofit tool. If a Retrofit Bridge identifies a necessary match, a new recovery exchanger is added to the HEN to complete that match. It is assumed that each new exchanger initially has a duty equal to the estimated retrofit savings, using the surpluses and deficits that have been shifted away from the relevant exchangers. Existing exchangers are then adjusted based on mass and energy balances. If there is a ΔT_{min} violation in an existing exchanger due to the changes to the HEN, stream splitting will be used to correct the violation. Once all heat exchangers have been added, some exchangers may duplicate the same match as an existing exchanger and may be merged into one match with the possible need for additional heat transfer area. Likewise, some existing exchangers may become redundant, allowing them to be re-purposed potentially. In practice, utility exchangers that become redundant because of increased heat recovery will not necessarily be removed because they may be essential for start-up or operation control of the network; however, these considerations are outside the scope of the thesis.

Each heat recovery exchanger in the retrofitted HEN is sized to determine the required heat transfer area (utility exchangers are assumed to be oversized and are ignored in this step). Recovery exchangers are sized based on a ε-NTU correlation that assumes counter flow heat transfer, where ε is the effectiveness of the heat transfer, and NTU is the number of transfer units (other correlations are possible).

Stream Splitting

In retrofit design, stream splitting is needed when a new heat exchanger match would cause an existing exchanger to no longer be feasible due to ΔT_{min} or Second Law violations. If the approach temperature on either side of an existing heat exchanger violates ΔT_{min}, splitting is required to balance the HEN and maintain feasibility. In this chapter, two main techniques are used to split a stream and can be applied to either a surplus stream or a deficit stream. In this thesis, the techniques are known as a Type A split and a Type B split and are based on the temperatures of the surplus or deficit requiring splitting as well as the position of the violating exchanger relative to the branches of the stream split (Figure 5.2).

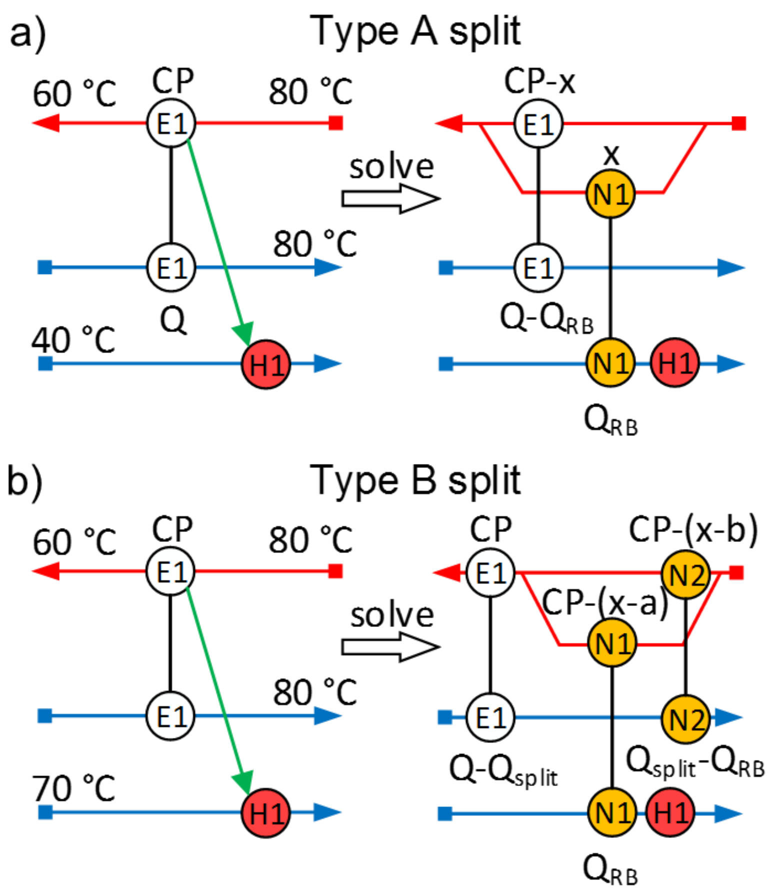


Figure 5.2: The two stream splitting techniques used in the automated HEN design: a) a Type A split and b) a Type B split (using shifted temperatures).

Considering a heat surplus: if the entirety of the surplus in the violating exchanger is at a high enough temperature to supply heat to the matched deficit (in another exchanger), then the entire surplus can be split, as seen in Figure 5.2a (surplus in E1 is available between 60-80 °C and can heat the 40 °C deficit in H1). If only a portion of the surplus is hot enough temperature to supply heat, then only that portion can be split, as seen in Figure 5.2b (the surplus in E1 cannot supply heat in the temperature range of 60-70 °C as the deficit in H1 is at 70 °C).

In the first scenario, the entire surplus is split, and the existing exchanger and the new exchanger are positioned on opposite branches of the stream split – this is a Type A split. In the second scenario, a Type B split must be implemented, which requires an additional heat exchanger. The portion of the surplus that can be used is split into two branches, with the two new heat exchangers on opposite branches. The first new heat exchanger represents the new match determined by the Retrofit Bridge, while the second heat exchanger matches the same streams as the violating existing exchanger (N2 in Figure 5.2b). The existing exchanger is downstream to the split and transfers the remaining surplus (that was not split) to the originally matched deficit. If a deficit requires stream splitting, then the entire deficit must be at a low enough temperature to receive heat to use a Type A split; otherwise, a Type B split will be required. Once ΔT_{min} has been violated (approach temperature less than ΔT_{min}) and a stream split is needed, Equations 5.1 and 5.2 can be used to determine the type of split for a surplus or a deficit:

$$\text{surplus : if } T^*_{S,out} < T^*_{D,in}\text{, use a Type B split} \tag{5.1}$$

$$\text{deficit : if } T^*_{D,out} > T^*_{S,in}\text{, use a Type B split} \tag{5.2}$$

Where all temperatures (*T*)* are shifted according to ΔT_{min} or ΔT_{cont}, and subscripts *S* and *D* refer to surplus and deficit. The split ratio (on a CP basis) is also dependent on the type of stream split used in the automated HEN design. For a Type A split, Equation 5.3 can be used, and for a Type B split, Equation 5.4 can be used:

$$\text{Type A :} \quad \text{split ratio} = \frac{Q_{RB}}{Q_{EX}} \tag{5.3}$$

$$\text{Type B :} \quad \text{split ratio} = \frac{Q_{RB}}{Q_{split}} \tag{5.4}$$

Where Q_{RB} is the estimated energy savings (kW) of the Retrofit Bridge, Q_{EX} is the duty of the existing exchanger (kW) that is violating ΔT_{min}, and Q_{split} is the amount of heat surplus or deficit (kW) that has been removed from the original violating exchanger and split. Q_{split} is calculated for Type B splits with Equation 5.5 for a surplus split or Equation 5.6 for a deficit split:

$$\text{surplus : } Q_{split} = CP_S \cdot \left(T^*_{S,in} - T^*_{D,in}\right) \tag{5.5}$$

$$\text{deficit : } Q_{split} = CP_D \cdot \left(T^*_{S,in} - T^*_{D,in}\right) \tag{5.6}$$

With these checks and equations, the automated HEN design can quickly determine if a stream split is needed and then provide the correct solution to maintain feasibility in the HEN.

5.1.6 Step 6: Determine Retrofit Performance

Performance of the retrofit designs (and therefore Retrofit Bridges) is determined with performance constraints and an economic analysis. The constraints that were introduced in Chapter 4 have been updated for the improved method and are applied at different stages of Bridge Analysis as the retrofit HENs can now be automatically designed. With the HEN designs, a simple economic analysis can also be conducted.

Performance Constraints

For larger HENs, there may be an impractically large number of possible Retrofit Bridges due to the countless combinations. There is a need to reduce and constrain the Retrofit Bridges to a more manageable number. In the previous chapter, the performance of Retrofit Bridges was constrained using three criteria: a maximum number of matches (N_m) in a Retrofit Bridge (Constraint 1), a minimum amount of energy savings per number of matches (Q/N_m; Constraint 2), and a minimum amount of energy savings per unit of area (Q/A; Constraint 3). These constraints filtered out Retrofit Bridges that were unlikely to be economically viable. The number of Retrofit Bridges was greatly reduced without compromising on the potential of the remaining options. A fourth constraint, a maximum payback period, was also used in a paper that first explored the use of constraints with ART (Lal et al., 2018) and will be used in this chapter necessitating the economic estimation prior to the Pareto front analysis. The economic estimation also enables constraints on Net Present Value (NPV) and Internal Rate of Return (IRR); however, the calculation of these metrics and their use in constraints is not considered in this thesis. In future, implementing them, and other constraints, into the ART algorithm would not be difficult. The priority of constraints is also determined by the point at which they are applied in the algorithm.

As the number of Retrofit Bridges increases exponentially with successive retrofit stages, especially as multi-stage retrofitting leads to many new branches to explore, there is a greater need to be able to focus the ART, and the overall retrofit method, on the Retrofit Bridges with the greatest economic potential.

The constraints used within the ART search algorithm are based on a preliminary analysis of the Retrofit Bridges, but some form of optimisation is needed to improve the retrofit analysis. One major development has also been the automated solving of the Retrofit Bridges into retrofit HEN designs providing more detailed information that can be used to improve the use of constraints (i.e., use number of modifications rather than number of matches) and allow an economic evaluation (which can be affected by stream splitting, particularly Type B splits). Each successive stage must meet the constraints; however, the constraints are not applied to the overall retrofit HEN design. For example, the retrofitted HEN can have more modifications than allowed by Constraint 1 if each individual Retrofit Bridge met the constraints.

Prior to the HEN design, for the initial Retrofit Bridge search, Constraints 1 and 2 are still applied in the same manner as Chapter 4. However, once the HEN has been solved, these constraints are updated to consider the number of modifications rather than the number of matches in the Retrofit Bridge. In this analysis, retrofit modifications include new heat exchangers and any additional heat transfer area required for the existing heat exchangers. Stream splitting is not considered as the modification relates to piping infrastructure rather than the heat exchanger units. However, any retrofit area or exchangers necessitated by a stream split are considered retrofit modifications.

Constraints 1 and 2 are applied twice (once in the preliminary search, and once after the HEN has been designed). Constraint 3 is only applied after the HEN has been designed. Constraint 4, the payback period restriction, is applied after the simple economic evaluation has been conducted. The overall objective of these constraints is to reduce the number of uneconomic or impractical Retrofit Bridges and push the retrofit analysis towards a more optimal retrofit solution.

Estimation of Economic Performance

After each HEN retrofit design has been solved, the design is evaluated based on its estimated economic performance. The economic evaluation of each retrofit design involves determining the capital cost (CC) of the retrofit, the utility cost savings (ΔS), the simple payback period (PB), and total retrofit profit (TRP).

The capital cost is typically calculated using a cost function that considers the fixed cost of a heat exchanger and the variable cost, which is based on the heat transfer area. This cost function is dependent on the type of heat exchangers and the specific HEN project (presented in each case study). Similarly, utility cost savings are based on the types of utility and specific prices, but a general function can be used, such as Equation 5.7:

$$\Delta S = UC_{\text{initial}} - UC_{\text{final}} = \sum_{i=1}^{n} \left(p_{h,i} \Delta Q_{hu,i}\right) + \sum_{j=1}^{m} \left(p_{c,j} \Delta Q_{cu,j}\right) \tag{5.7}$$

Where *UC* is the utility cost, *p* is the utility price, and *n* and *m* are the numbers of heaters and coolers. Different prices for different utility types are possible. The PB is calculated with Equation 5.8 (in years):

$$\text{PB} = \frac{\text{CC}}{\Delta \text{S}} \tag{5.8}$$

The yearly TRP is calculated using Equation 5.9:

$$\text{TRP} = \Delta \text{S} - \text{CC} \cdot \text{AF} \tag{5.9}$$

Where *AF* is an annualization factor based on a given equipment lifetime in years, *n*, and a discount rate, *i*. The formula used to determine AF is given in Equation 5.10:

$$AF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{5.10}$$

With the TRP and PB calculated, Constraint 4 can be used if required (restriction to PB) and the overall profitability of each Retrofit Bridge and retrofit plan can be evaluated.

5.1.7 Step 7: Find Pareto Optimal Solutions

To further assist in the determination of an optimal retrofit plan, this step applies a Pareto front analysis to narrow the Retrofit Bridges to focus on the most promising modifications and help minimise computational effort. Minimising computational effort is especially important when considering how the number of possible Retrofit Bridges exponentially increases with each added heat exchanger and successive retrofit stage. The Pareto front algorithm searches for the Pareto optimal solutions, and a selected number of near-Pareto optimal solutions (set at 2 for this work), based on three performance metrics. These performance metrics are the energy savings (Q), energy savings per modification (Q/N_{mod}), and energy savings per unit of retrofit area (Q/A) – the first three constraints. Equation 5.11 outlines the Pareto optimisation objective:

$$max\left\{k\frac{Q_j}{Q_{max}}+j\frac{(Q/A)_j}{(Q/A)_{max}}+(1-j-k)\frac{\left(\frac{Q}{N_{mod}}\right)_j}{\left(\frac{Q}{N_{mod}}\right)_{max}}\right\}, \tag{5.11}$$

$$0<j<1, \qquad 0<k<1, \qquad j+k\leq 1$$

Where *Q* is the energy savings of the Retrofit Bridge, *A* is the required retrofit area, N_{mod} is the number of modifications (new heat exchangers and increased area), and *k* and *j* are arbitrary values, which are varied in increments of 0.05. The approach is based on three performance metrics (Q, Q/N_{mod}, Q/A), which are indicative of the overall economics of the Retrofit Bridge and are roughly proportionate to the costs. For each combination of *k* and *j*, the Pareto optimisation returns the top three ranked Retrofit Bridges – the Pareto optimal solution and two nearest-Pareto optimal solutions. This means that the minimum number of Pareto optimal solutions will be 3^r, where r is the number of retrofit stages.

5.1.8 Step 8: Multi-Stage Retrofitting

After step 7, each Retrofit Bridge in the set of viable Retrofit Bridges is then carried forward to a multi-stage retrofit analysis. Each additional stage increases the number of potential retrofit plans that can be evaluated and further analysed. The only limitation to the number of retrofit stages is the retrofit energy target determined using the METD. Once the target has been reached, the HEN cannot be retrofitted further using Bridge Analysis. Applying a second retrofit stage does not remove the first stage as an option from the set of possible retrofit plans, resulting in a large set of possible solutions.

The multi-stage retrofitting algorithm is demonstrated in Figure 5.3. Each box represents a set of Retrofit Bridges which have been found during the same retrofit stage using the same retrofit stream data. The Retrofit Bridges in each box are the remaining solutions after the constraints and Pareto front analysis have been applied. The multi-stage retrofit analysis begins by exploring the successive retrofit opportunities that stem from Retrofit Bridge 1. New retrofit stream data is extracted from the HEN designed by Retrofit Bridge 1 and used to conduct Steps 2 to 8. This pattern is repeated until the maximum number of retrofit stages has been reached or the retrofit savings target has been achieved. In Figure 5.3, a maximum of three retrofit stages have been explored conceptually; therefore, this current retrofit plan will finish with Retrofit Bridge 1.1.1. Because the number of retrofit stages has reached a predefined maximum, the algorithm returns to the previous set and continues down a new path based on the next ranked Retrofit Bridge (i.e., Retrofit Bridge 1.2 can be solved, and so on). Eventually, the algorithm returns to the first set and the successive retrofit stages can be applied to Retrofit Bridge 2. Once all possible search pathways have been exhausted, the multi-stage algorithm ends, and a single set of retrofit plans (comprised of Retrofit Bridges) remains. Some Retrofit Bridges can be applied independently to each other (i.e., without affecting the same heat exchangers), which can lead to retrofit plans with the same costs, savings, and modifications but with the retrofit stages applied in a different order. These plans are identified and removed to ensure that all reported retrofit designs are unique. The multi-stage retrofitting algorithm is achieved with several recursive loops in Microsoft Excel using Visual Basic for Applications (VBA). The retrofit analysis will then move onto the final step in the method: the design selection.

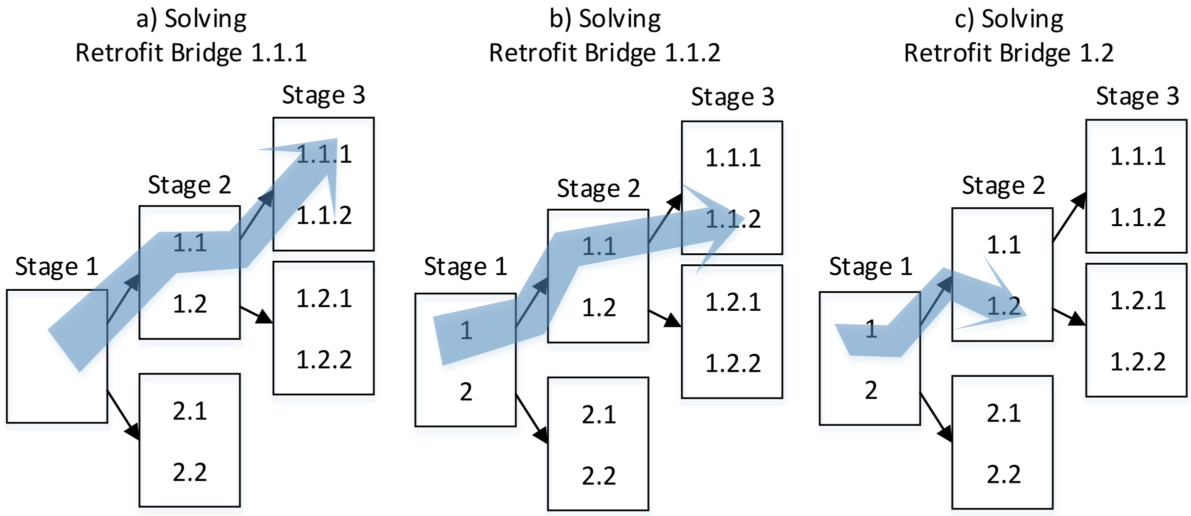


Figure 5.3: Conceptual illustration of the multi-stage algorithm.

5.1.9 Step 9: Select Final Retrofit Plan

The final step is to select the most suitable retrofit plan. TRP and PB give insights into the economic success of a retrofit plan. Some projects may prioritise shorter PBs over a larger TRP to recuperate the investment quicker, which may favour retrofit plans with fewer stages. These factors should be considered when determining the best retrofit plan. The sequence of Retrofit Bridges in retrofit plans identified by the multi-stage retrofit analysis can be analysed cumulatively or one-by-one. Analysing the cumulative effect reveals the long-term benefit of the entire retrofit plan, often including many modifications and high capital investment.

Analysing each Retrofit Bridge (retrofit stage) one-by-one highlights the incremental benefits that occur during the process of the implementation plan. Capital constraints often force factories to implement energy retrofit solutions incrementally. As a result, both perspectives – the long-term and the incremental solutions – provide a lens to view the retrofit plan, where for specific industrial cases, one can look for synergistic decision-making at the various stages of implementation to maximise asset cost efficiency.

Business case development may also include a study on the environmental impacts in addition to detailed costing of the main plant items and auxiliary equipment, e.g., piping requirements and control systems.

5.2 Illustrative Example

The illustrative four-stream example from Chapter 3 is revisited to provide a simple example of energy retrofit planning using the multi-stage retrofit analysis. The four-stream HEN is again presented in Figure 5.4. From the previous analysis in Chapter 3, the maximum retrofit savings target is 1,950 kW. One of the Retrofit Bridges from the previous retrofit analysis reduced the heating demand by 1,250 kW, meaning that future Retrofit Bridges can only reduce the heating demand by an additional 700 kW. In this illustrative example of multi-stage retrofitting, four retrofit stages are analysed and only Constraint 1 is applied, constraining the number of modifications to a maximum of four. Additional constraints are unnecessary considering the small size of the HEN. The Pareto front analysis is conducted normally and includes up to two near-Pareto optimal solutions.

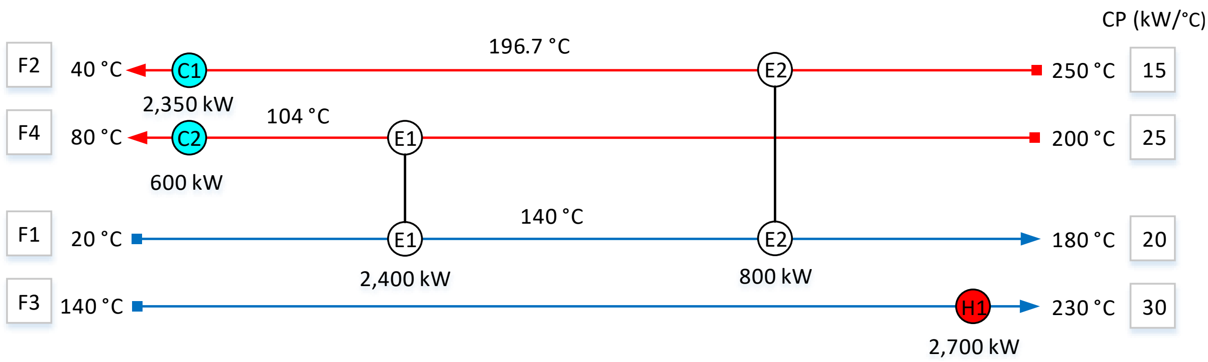


Figure 5.4: Grid diagram for the heat exchanger network of the four-stream illustrative example.

The economic evaluation of each retrofit design is based around the capital cost of each new exchanger or modified exchanger as well as the utility cost savings. The utility cost savings are based on a hot utility price of 35 NZD/MWh (New Zealand Dollars) and a yearly operation of 8,400 hours. For the capital cost (in NZD), the following two equations are used, Equation 5.12 for the cost of a new heat exchanger (CC_{new}) and Equation 5.13 for the cost of retrofit area for an existing exchanger ($CC_{existing}$):

$$CC_{\text{new}} = 24{,}578 + 3{,}072\ A^{0.83} \tag{5.12}$$

$$CC_{\text{existing}} = 12{,}289 + 3{,}072\ A^{0.83} \tag{5.13}$$

Where A is the retrofit area for that exchanger (m^2) (new or existing). The capital costs are later annualised based on an equipment lifetime of 10 years and a discount rate of 10%. Following these calculations, the PB and TRP are calculated. These calculations are repeated for each Retrofit Bridge in each retrofit plan.

The energy retrofit planning analysis returns 71 different retrofit plans that have between one and four applied Retrofit Bridges. While the option exists to analyse each Retrofit Bridge individually, the cumulative effect of each successive Retrofit Bridge has been analysed – this has implications on heat exchanger area as exchangers can be re-sized based on the overall retrofitted HEN. Of the 71 retrofit plans, only 17 reduce the hot utility demand by the targeted 1,950 kW – all but one requiring more than two retrofit stages. (Figure 5.5 shows the overall energy savings, the number of modifications, required area, total retrofit profit (TRP), and payback for each of the 71 returned retrofit plans. Figure 5.5b shows that the retrofit plans that achieve 1,950 kW in energy savings also require at least 400 m^2; however, Figure 5.5a shows that this area can be distributed across five to nine modifications (i.e., new exchangers). Due to fixed costs of heat exchanger units, having more exchanger units for the same area is generally going to result in a higher capital cost. This is reflected in Figure 5.5c as a retrofit plan with only two stages had the greatest profitability out of all plans. This specific plan has been highlighted with a cross in each of the three figures. Another interesting observation, for this illustrative example problem, is that the profitability of the plans with two retrofit stages is almost twice that of the single-stage plans (excluding the 1,250 kW Retrofit Bridge). This increase demonstrates the importance of using an energy retrofit plan to ensure that capital investment can be used effectively to reduce hot utility demand.

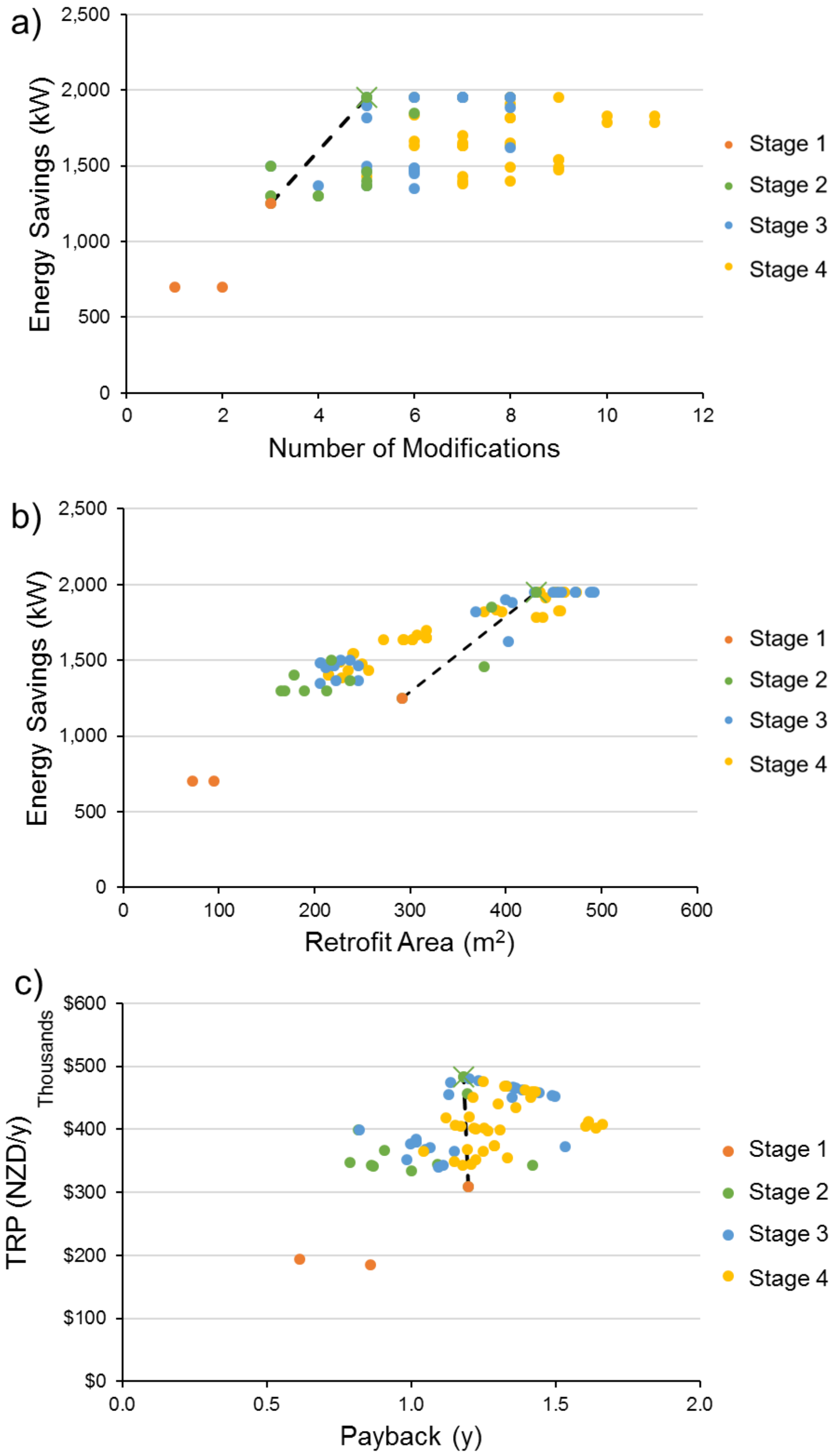


Figure 5.5: Energy retrofit plans from the multi-stage retrofit analysis of the illustrative example, showing the a) energy savings against the number of modifications, b) energy savings against the retrofit area required, and c) total retrofit profit against payback.

Having reached the target with a high TRP and low PB, the retrofit plan with the highest TRP is recommended for development into an industrial retrofit plan and business case. This plan is highlighted in Figure 5.5 with a green cross, and a dotted black line is used to show the progression from stage 1 to stage 2. The first point is a retrofit plan featuring the same first Retrofit Bridge and three retrofit modifications. Adding the second Retrofit Bridge to the retrofit plan increases the total retrofit area required as well as the total number of modifications (to five) but achieves greater energy savings and greater TRP for the same PB – a significant advantage of applying multiple Retrofit Bridges.

In this retrofit plan, first, C1-E1-H1 is applied; then, C1-N1-E2-H1 is applied, affecting one of the new heat exchangers that were introduced by the first Retrofit Bridge. The progressive effect of the two Retrofit Bridges on the METD and HEN grid diagram is demonstrated in Figure 5.6. The METD for the first Retrofit Bridge is shown in Figure 5.6a and shows the presence of two new heat exchangers. This is the same retrofit solution as the first Retrofit Bridge shown in the illustrative example in Chapter 3. After the first Retrofit Bridge is applied, exchanger E1 needs a heat transfer area increase of 18.5 m^2 and two new heat exchangers are added with areas of 24.2 m^2 and 181.8 m^2 (Figure 5.6b). After the second Retrofit Bridge is applied, exchanger E2 needs 50.9 m^2 of additional heat transfer (Figure 5.6d) and the new exchanger N1 needs an additional 20.1 m^2 of heat transfer area. Setting a strategic retrofit plan can avoid the expense making successive modifications to the same heat exchanger over many years. In this case, the first stage of the retrofit would be to install N1 (44.3 m^2), N2 (181.8 m^2), and modify E1, and then, in the second stage, install N3 (43.9 m^2) and modify E2. The implementation plan must be tailored to suit the specific process and capital constraints of the project.

The overall HEN has three new heat exchangers and has reached the minimum utility targets of 750 kW hot utility and 1,000 kW cold utility. The final METD, which represents the Minimum Energy Network, is shown in Figure 5.6c.

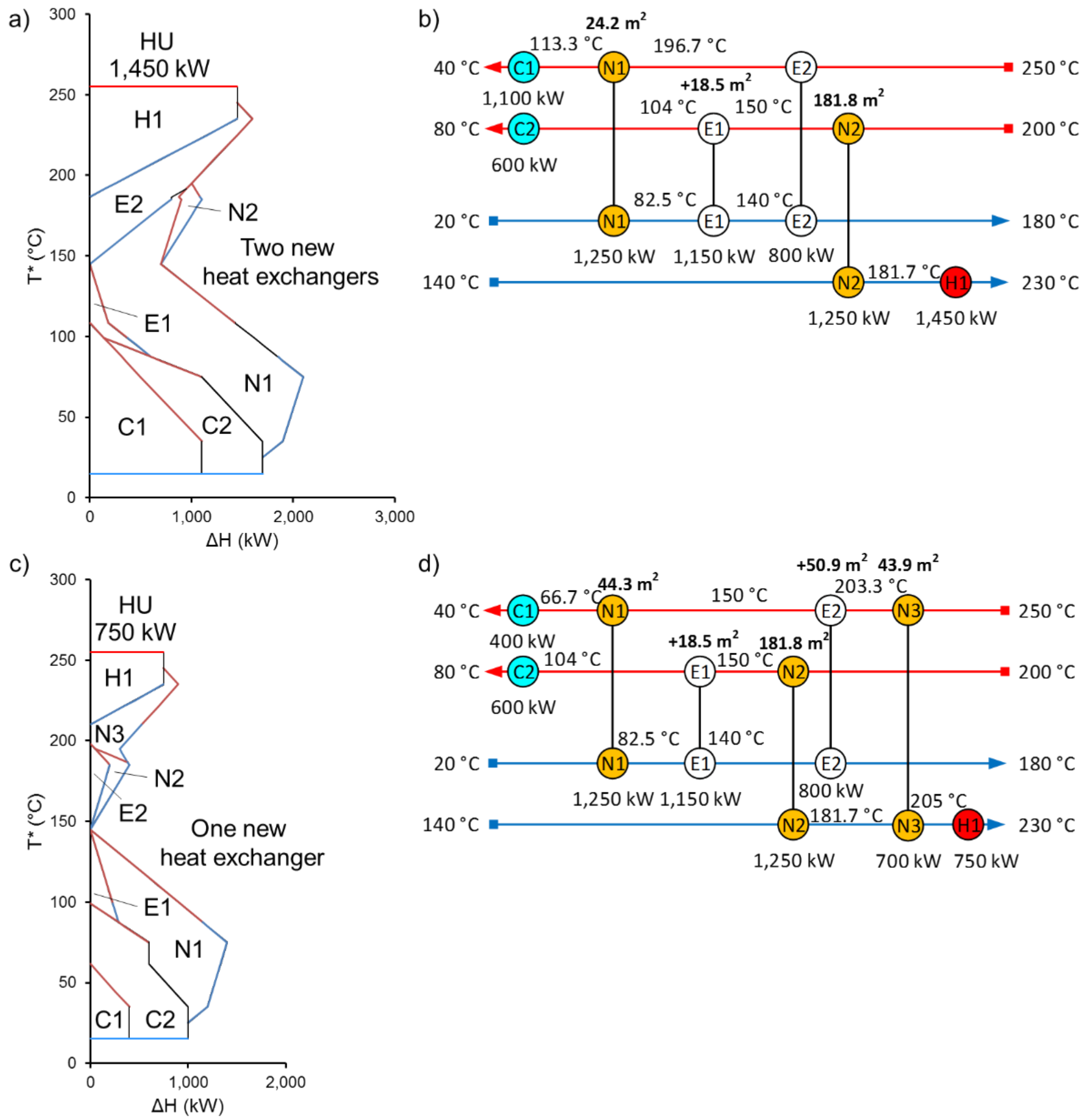


Figure 5.6: Retrofitted METD and HEN for each Retrofit Bridge identified in the energy retrofit plan: a) METD and b) HEN for Retrofit Bridge C1-E1-H1, and c) METD and d) HEN for Retrofit Bridge C1-N1-E2-H1.

Each successive Retrofit Bridge, or retrofit stage, in a retrofit plan, will reduce the energy savings and push the network curve of the METD towards the GCC position – towards the minimum utility targets (Figure 5.7). The shape of the network curve is retained after each stage; however, new exchanger units are introduced meaning that new EGCCs are drawn on the METD, and existing EGCCs are altered.

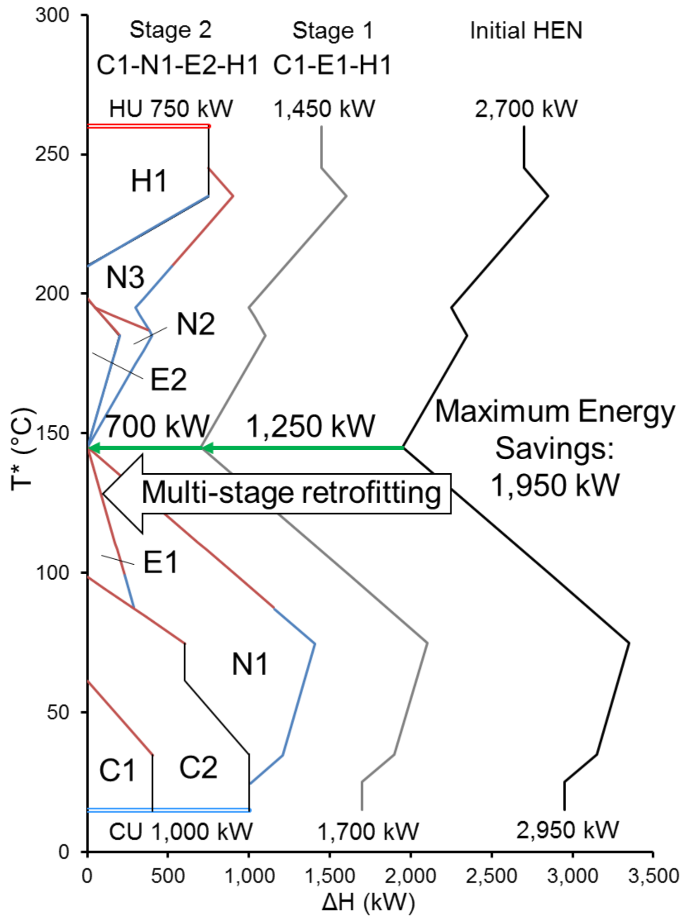


Figure 5.7: Movement of the METD network curve as a result of the multi-stage retrofit analysis.

5.3 Case Study: Paper Mill

The paper mill case study is used again to demonstrate the novel method (please refer to previous chapters for more information). The goal of this retrofit project is to explore options for further heat integration, using multiple retrofit stages to get closer to a Minimum Energy Network. From the METD analysis in Chapter 3, the retrofit savings target is known to be 4.825 MW. The project will determine if there is an economical solution for integration the air streams with the water streams, using a maximum of four retrofit stages (i.e., up to four

Retrofit Bridges in a retrofit plan). From a brief study of the grid diagram (Figure 5.8), the approach temperatures in all heat recovery exchangers are currently equal to the corresponding ΔT_{min} (not a global ΔT_{min} due to the presence of ΔT_{cont} values for each stream), meaning that any changes to the heat recovery exchangers will result in a violation and inefficient heat transfer, and stream splitting will be required.

The following constraints were applied to the multi-stage retrofit analysis of the paper mill:

Constraint 1: A maximum of four retrofit modifications per retrofit stage (stream splitting is not considered a modification; however, any additional heat exchanger units or area required by splitting is counted). In the preliminary search, Constraint 1 is applied on a per match basis.

Constraint 2: A minimum of 200 kW of energy savings per modification per retrofit stage. In the preliminary search, Constraint 2 is applied on a per match basis.

Constraint 3: A minimum of 0.5 kW of energy savings per unit area per retrofit stage.

Constraint 4: No constraint applied to the payback period.

A Pareto front analysis was conducted as per the method.

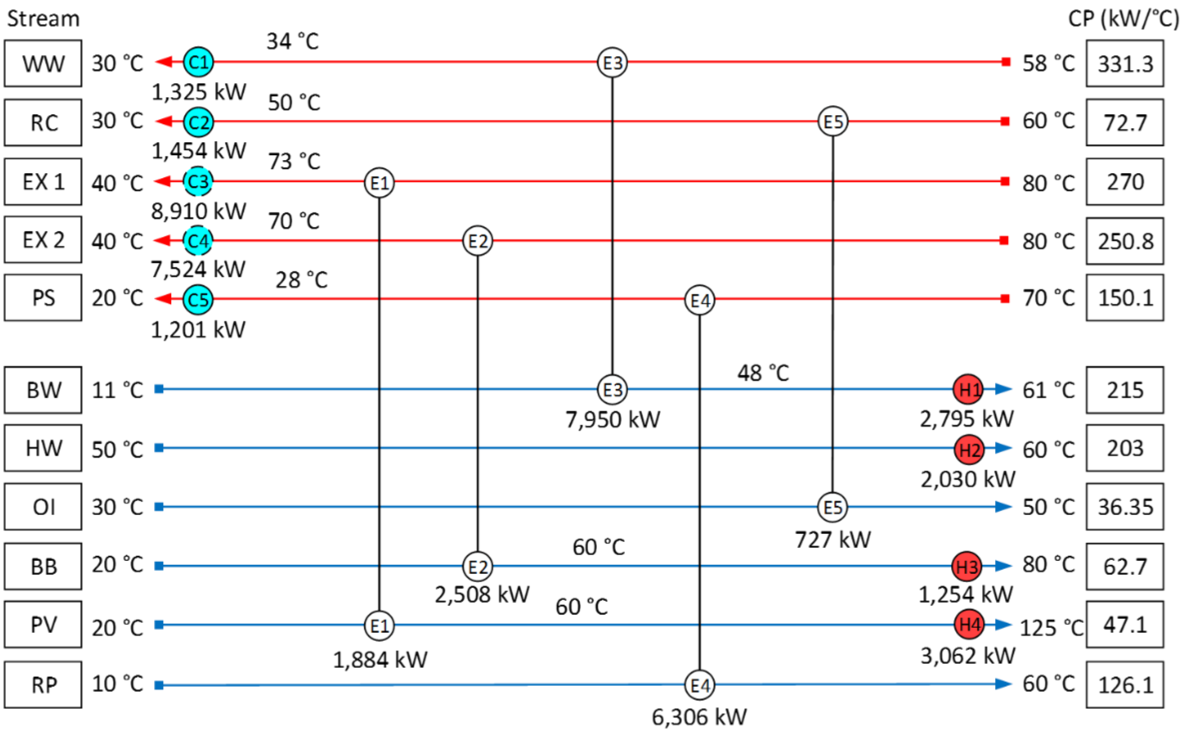


Figure 5.8: Grid diagram of the paper mill HEN.

5.3.1 Retrofit Bridge Evaluation

To calculate the utility cost savings, the hot utility was costed based on a steam price of 35 NZD/MWh and an annual operation of 8,400 hours. The cost of cold utility was negligible due to significantly low cooling water prices (no chilled water is needed). The capital cost (CC) of the retrofit area for existing exchangers and new exchangers was costed using Equation 5.14 and Equation 5.15 (Timothy Gordon Walmsley, 2014):

$$CC_{water} = 69{,}620 + 7{,}740\ A \tag{5.14}$$

$$\mathrm{CC_{air}} = 19{,}340\ \mathrm{A}^{0.815} \tag{5.15}$$

Where A is the retrofit area in each recovery exchanger (costed individually) (m^2), CC_{water} refers to a heat exchanger that matches only liquid water streams, and CC_{air} refers to a heat exchanger that matches an air stream with either another air stream or a water stream. These capital cost equations are annualised based on a discount rate of 10% and a lifetime of 10 years. The PB and TRP were then calculated using Equation 5.8 and Equation 5.9.

5.3.2 Design Selection

The energy retrofit planning analysis concludes with the identification and quantification of 80 unique retrofit plans. These 80 retrofit plans can be analysed based on the trade-offs between energy savings and the number of modifications (Figure 5.9a) or retrofit area (Figure 5.9b), as well as the comparison between the TRP and the simple payback (Figure 5.9c). As Figure 5.9a and Figure 5.9b both relate to the ratios of Q/N_m (Constraint 2) and Q/A (Constraint 3), a curve forms from the plot of the 80 retrofit plans that resembles a Pareto front, showing that the solutions tended to have good economic potential and a good trade-off between energy savings and capital cost. Furthermore, the Pareto solutions have been highlighted in red to emphasise their position relative to the near-Pareto solutions. To summarise these three figures: the retrofit savings target of 4.825 MW was achieved by many retrofit plans but required at least six modifications and 3,600 m^2 of retrofit area; in fact, all retrofit plans required significant amounts of retrofit area leading to long PBs ranging from approximately 2.4 to 3.3 years.

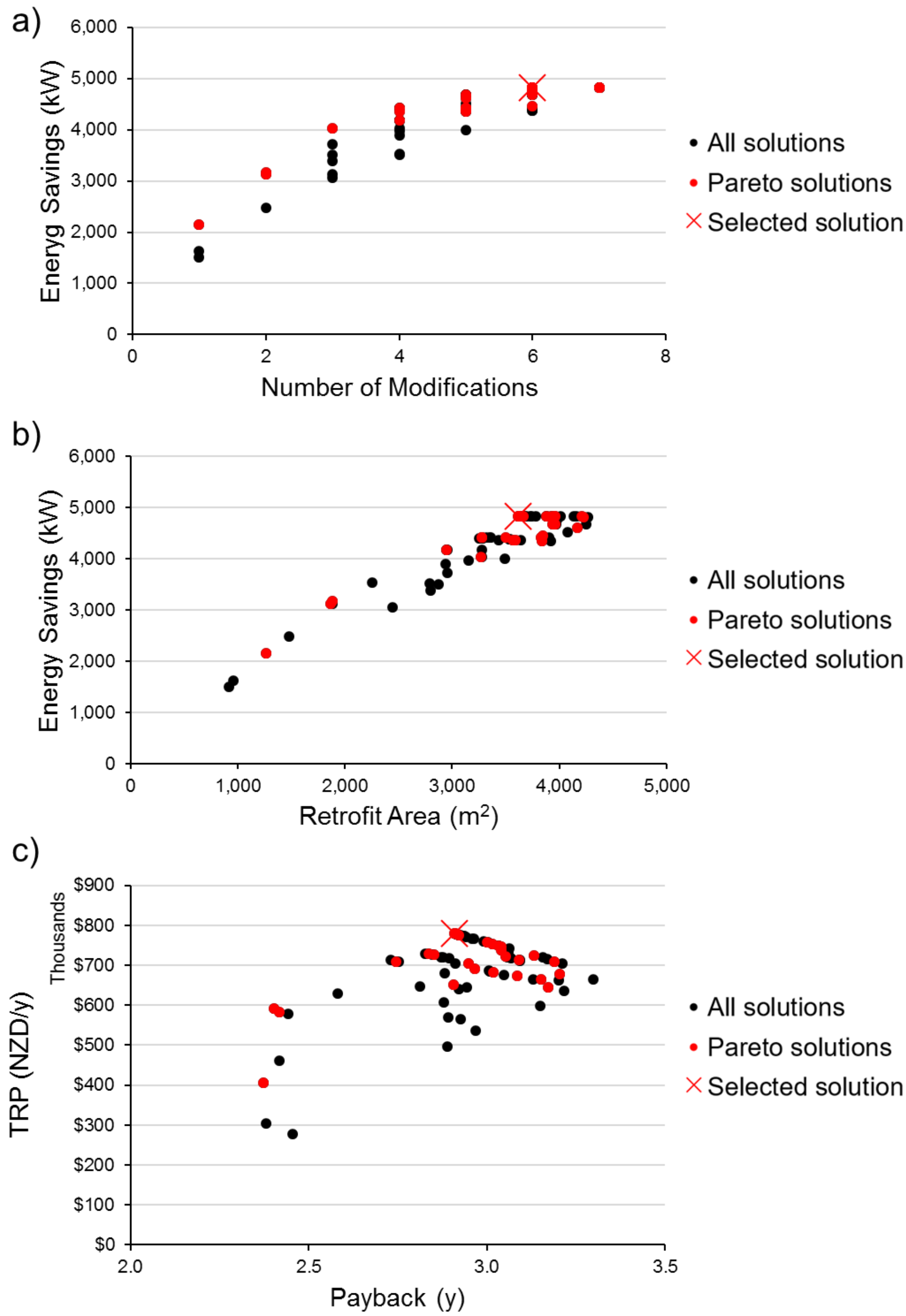


Figure 5.9: Analysis of retrofit plans for the paper mill HEN: a) energy savings against retrofit modifications, b) energy savings against the retrofit area, and c) total retrofit profit against payback.

One of these designs has been identified as the most suitable for the paper mill (indicated by a red cross in Figure 5.9) as it has the highest TRP out of all possible retrofit designs. To compare the top-ranked plan with those that stem from the same original retrofit stage, Figure 5.10 is presented, showing the same trade-offs as Figure 5.9b and Figure 5.9c. These figures show that each successive retrofit stage increased the total retrofit area, total energy savings, profitability, and payback. The comparison between the retrofit design after four retrofit stages and the retrofit design after one shows how important it is to be able to evaluate the new retrofit opportunities that are made possible through previous retrofitting, as well as those that come from applying several independent modifications simultaneously. The top-ranked retrofit plan is represented by a cross on each figure, and the specific stages that reach this design solution are shown by a bold line, with a relatively large positive gradient (compared to the other retrofit plans). Evidently, the branch of retrofit plans from the first stage that leads to the top-ranked design maintains a higher economic and thermodynamic performance than the other second stage branches (green).

To compare the chosen plan with those that stem from the same original retrofit stage (i.e., same first Retrofit Bridge), Figure 5.10 is presented, showing the same relationships (trade-offs) as Figure 5.9b and Figure 5.9c. These figures show that each successive retrofit stage increased the total retrofit area, total energy savings, TRP, and PB. The chosen retrofit plan is represented by a cross on each figure, and the specific stages that reach this design solution are shown by a bold line, with a relatively large positive gradient (compared to other plans). Figure 5.10a and Figure 5.10b both show that the most important retrofit stage was the second stage, with Retrofit Bridge C4-H2. In Figure 5.10b, a large increase in TRP was achieved with very little increase in PB, showing better utilisation of the invested capital. All retrofit stages that follow this Retrofit Bridge have higher energy savings and higher profitability.

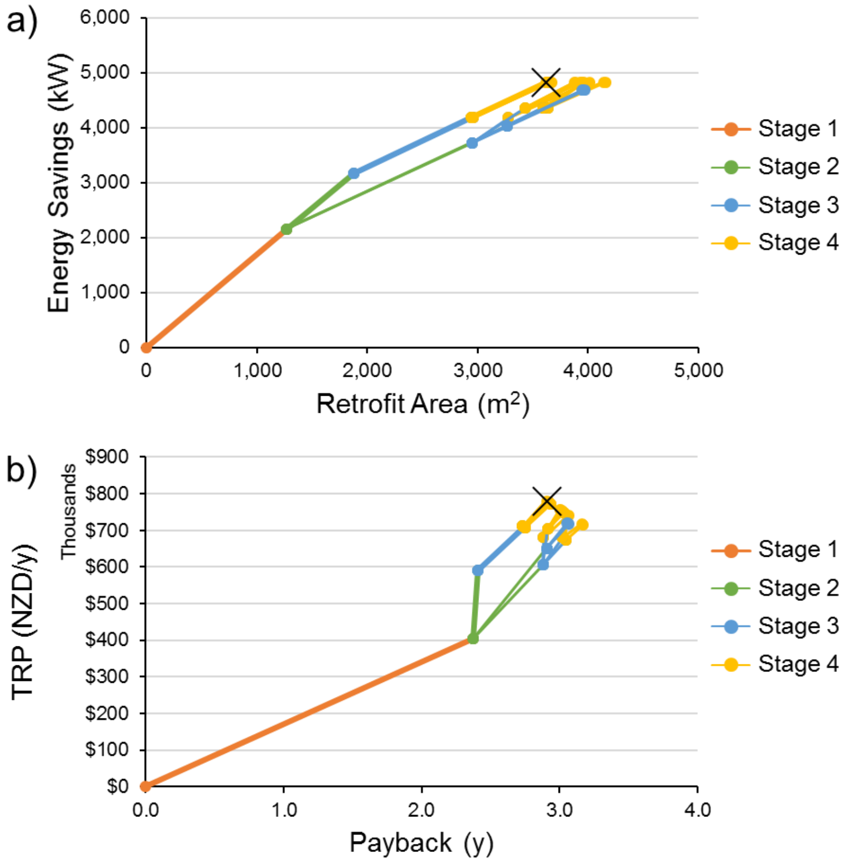


Figure 5.10: Analysis of the incremental effect of energy retrofit planning for the paper mill: a) energy savings against retrofit area, and b) total retrofit profit against payback.

The top-ranked retrofit plan consists of four Retrofit Bridge stages, six retrofit modifications, and two stream splits. The Retrofit Bridges comprising the design are C3-H1, C4-H2, C4-E2-H2, and C3-E1-H1. As none of the Retrofit Bridges involve the new heat recovery exchangers in Retrofit Bridges (i.e., in a match), the stages can be performed in any order. A summary table of the individual stages is presented in Table 5.1, which shows that the first stage is the most profitable and most significant. C3-H1 also has the shortest PB, recuperating the investment in only 2.37 years while the Retrofit Bridges in stages 3 and 4 have large PBs and low profitability. The overall design (considering the cumulative effect of all Retrofit Bridges) will have a capital investment cost of 4.3 million NZD, PB of 2.91 years (not much longer than the PB of the first stage), a TRP of 778,943 NZD/y, and meet the retrofit savings target of 4.825 MW.

Table 5.1: Summary of the retrofit stages in the top-ranked retrofit plan.

Stage	Retrofit Bridge	Savings (kW)	Retrofit Area (m^2)	Capital Cost (NZD)	Payback (y)	Profit (NZD/y)
1	C3-H1	2,150	1,263	1,563,697	2.37	404,705
2	C4-H2	1,015	617	768,937	2.47	186,058
3	C4-E2-H2	1,015	1,064	1,184,358	3.81	118,450
4	C3-E1-H1	645	675	786,959	3.98	69,729
Overall	N/A	4,825	3,619	4,303,670	2.91	778,943

The HEN based on the top-ranked retrofit plan is presented in Figure 5.11. The existing exchangers remain unchanged in terms of area, despite the flow rates through E1 and E2 being split, while the new exchangers require large heat exchanger areas ranging from 317 to 1,263 m^2. These large areas are the result of the low heat transfer coefficients of air, which is involved in all new heat exchangers. The final METD is presented in Figure 5.11b, where the network curve of the METD has been shifted back to the GCC position, indicating that the minimum utility targets have been met. As the target of 4.285 MW was reached, the heaters H1 and H2 have had their duties reduced to zero and have been removed from the HEN. In reality, these heaters may be left as trimmers to ensure that target temperatures are met. With heaters H1 and H2 removed (in theory), all Pinch violations have been corrected and there are no more retrofit opportunities that can be found using Bridge Analysis. The process heat demand has been reduced to its minimum, for the given ΔT_{min} values.

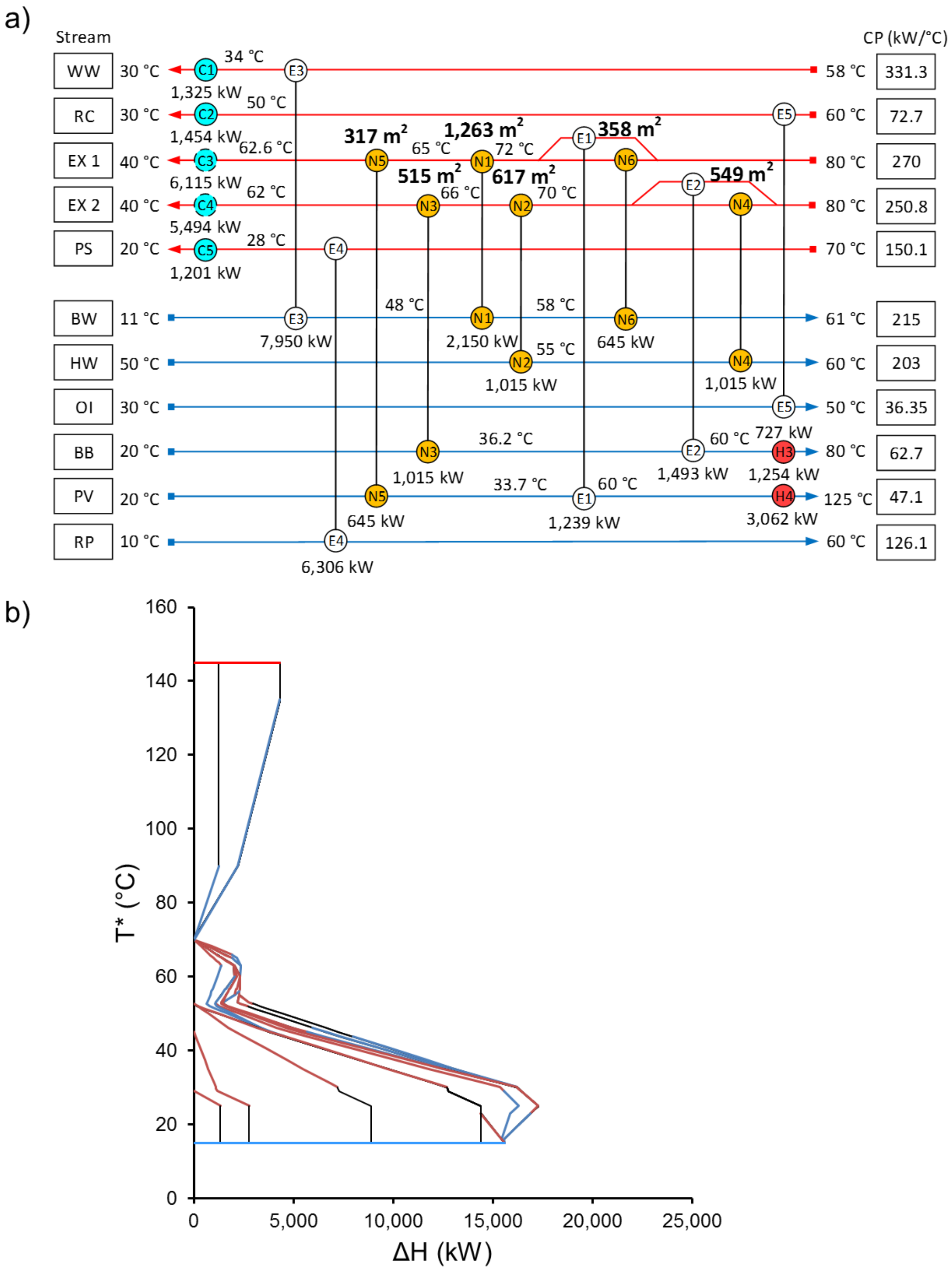


Figure 5.11: a) Retrofitted HEN for the paper mill based on the top-ranked retrofit plan and b) the METD for the retrofitted HEN.

5.4 Case Study: Petrochemical Complex

The aim of this retrofit project is to determine an optimal retrofit HEN design for the petrochemical complex, considering successive retrofit stages to allow for greater energy savings when compared to the petrochemical complex retrofit analysis in Chapter 4. Several stream splits exist in the HEN currently, but new stream splits will be required for Retrofit Bridges that involve the recovery exchanger E13, due to the current exchanger approach temperature. The other recovery exchangers are unlikely to necessitate stream splitting. The multi-stage retrofit analysis is based on a global ΔT_{min} of 10 °C, and it is assumed that all streams have a constant CP and a heat transfer coefficient of 1,000 W/m^2°C. The multi-stage retrofit analysis will consider a maximum of four retrofit stages and aim to achieve the retrofit savings target of 15.1 MW. The HEN is presented in Figure 5.12.

The following constraints were applied to the Retrofit Bridge search and subsequent evaluation:

Constraint 1: A maximum of four retrofit modifications per retrofit stage. In the preliminary search, Constraint 1 is applied on a per match basis.

Constraint 2: A minimum of 350 kW of energy savings per modification per retrofit stage. In the preliminary search, Constraint 2 is applied on a per match basis.

Constraint 3: A minimum of 3 kW of energy savings per unit area per retrofit stage.

Constraint 4: A maximum payback period of 2 years applied to the overall retrofit project.

A Pareto front analysis was then conducted on each set of Retrofit Bridges.

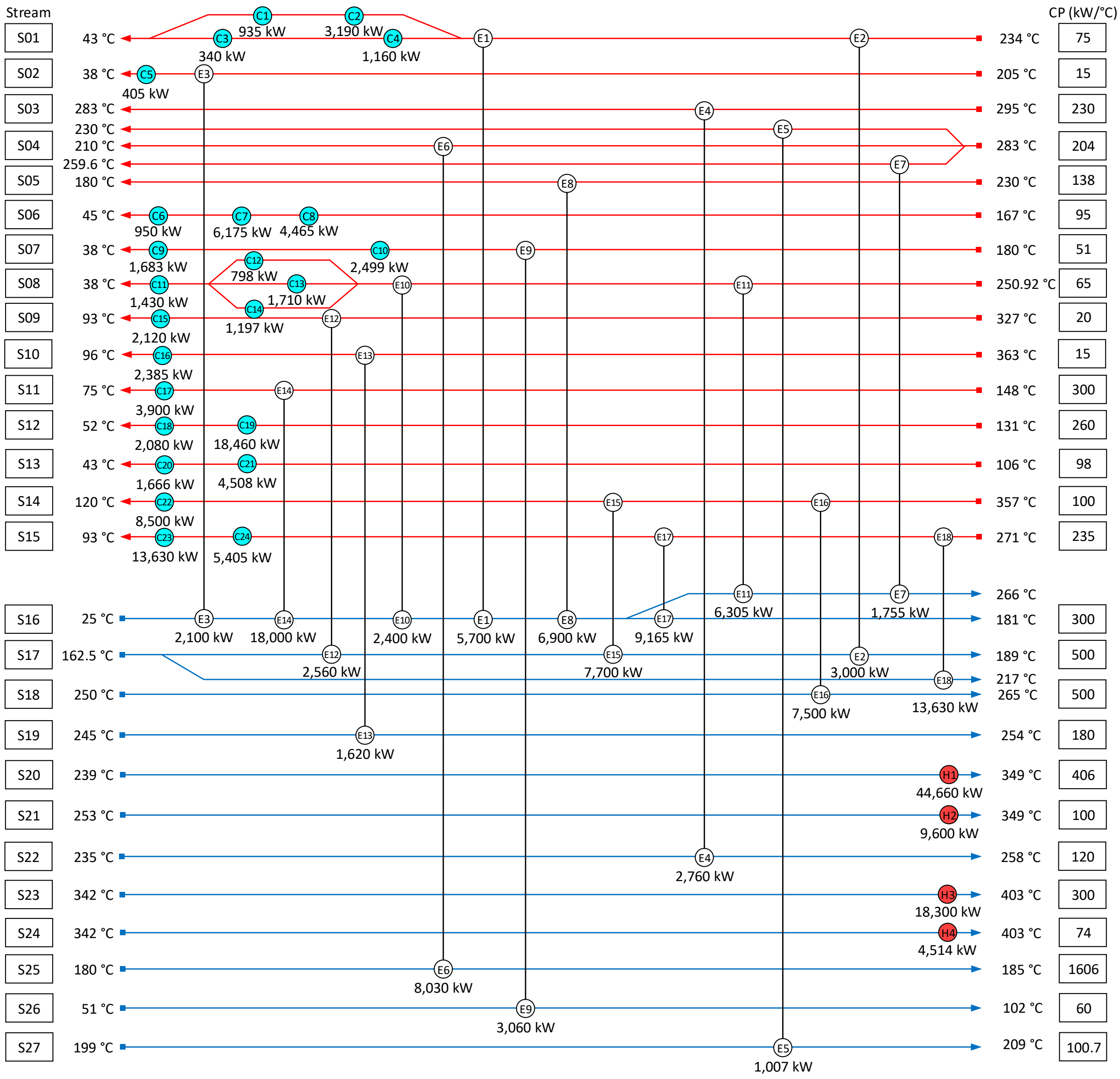


Figure 5.12: Grid diagram of the petrochemical complex HEN.

5.4.1 Retrofit Bridge Evaluation

The Retrofit Bridge evaluation of the petrochemical case study differs from the paper mill due to the different location and project type. The utility cost savings were determined with a hot utility price of 25 EUR/MWh (Euro) and an annual operation of 8,600 hours. Cost of cold utility was assumed negligible (as cooling water around ambient conditions can be used). The capital cost (in Euro) of new heat exchangers and new retrofit area is given Equation 5.16:

$$CC = 30{,}000 + 3{,}500\ A^{0.85} \tag{5.16}$$

Where *A* is the estimated retrofit area for each new or retrofitted exchanger (m^2). With the utility cost savings (in Euro) and capital cost estimations, the TRP and PB are calculated using Equations 5.8 and 5.9. Capital cost was annualised based on a lifetime of 15 years and a discount rate of 7%.

5.4.2 Design Selection

From the energy retrofit planning analysis, 108 Retrofit Bridges were returned. Figures showing the relationship between the energy savings and the number of modifications (Figure 5.13a) and retrofit area (Figure 5.13b) for each retrofit plan have been provided as well as a figure showing the relationship between TRP and PB (Figure 5.13c). The Pareto front solutions have been highlighted to distinguish them from the near-Pareto solutions; however, there are no significant differences as all retrofit plans lie along the Pareto front. The retrofit savings target of 15.1 MW was not met by any retrofit plan, and the highest amount of energy savings was only 9.6 MW. Potentially, the retrofit savings target could be achieved if the constraints were relaxed, e.g., more retrofit stages and/or a longer payback period were allowed. The plan that results in the greatest TRP has been represented by a cross on the figures, and it can be seen that there are similar plans with similar energy savings; however, these tend to have a higher capital cost and a lower TRP.

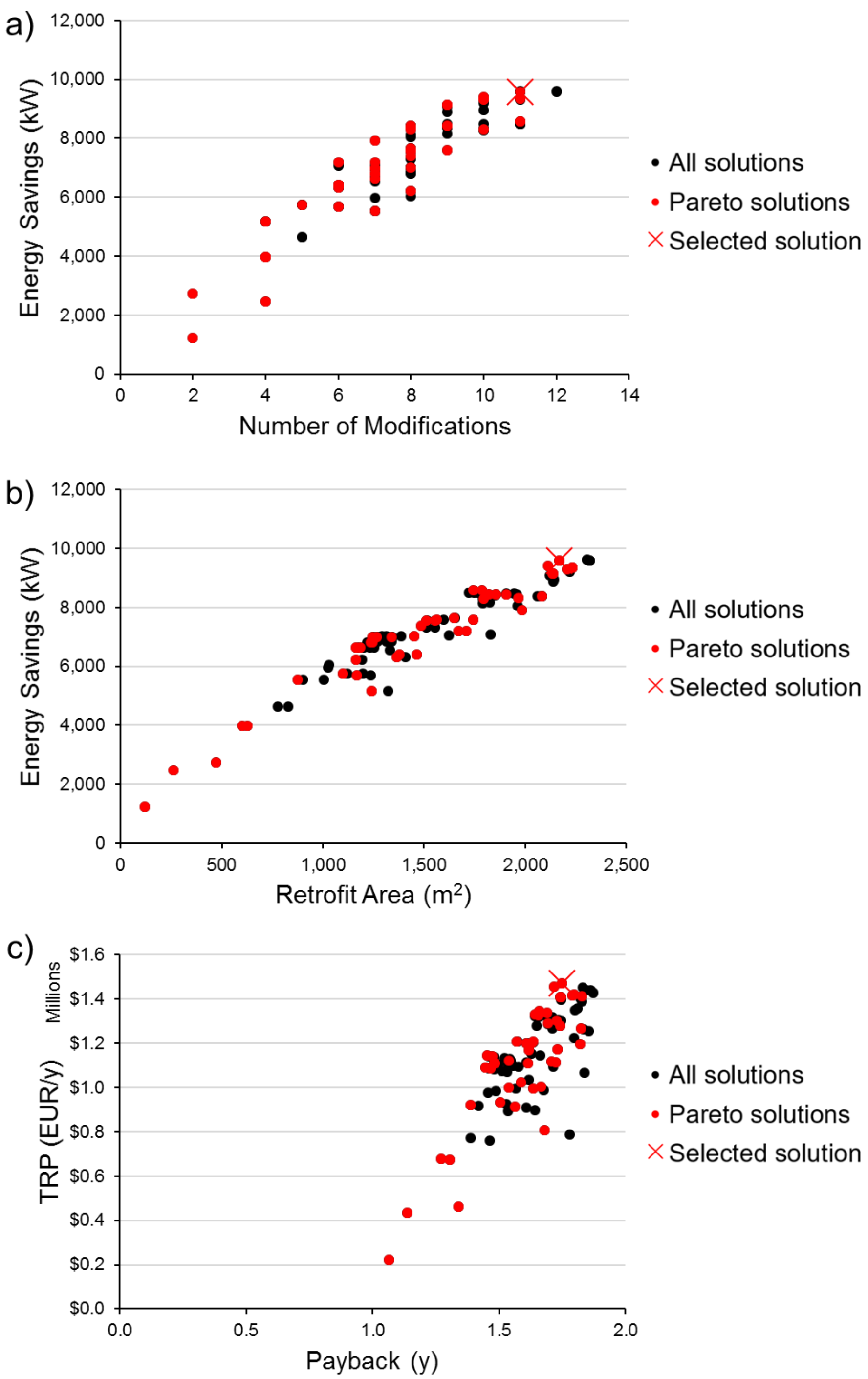


Figure 5.13: Analysis of retrofit plans for the petrochemical complex HEN: a) energy savings against the number of modifications, b) energy savings against the retrofit area, and c) total retrofit profit against payback.

The top-ranked retrofit plan is then compared against the other plans that originate from the same first retrofit stage. In Figure 5.14a, the energy savings are compared against the retrofit area and, predictably, there is a direct relationship between savings and area, showing the consequence of successive retrofit stages. In general, the PBs of the retrofit plans with multiple stages are similar to the design that results from the first stage, but with an increase in TRP (Figure 5.14b).

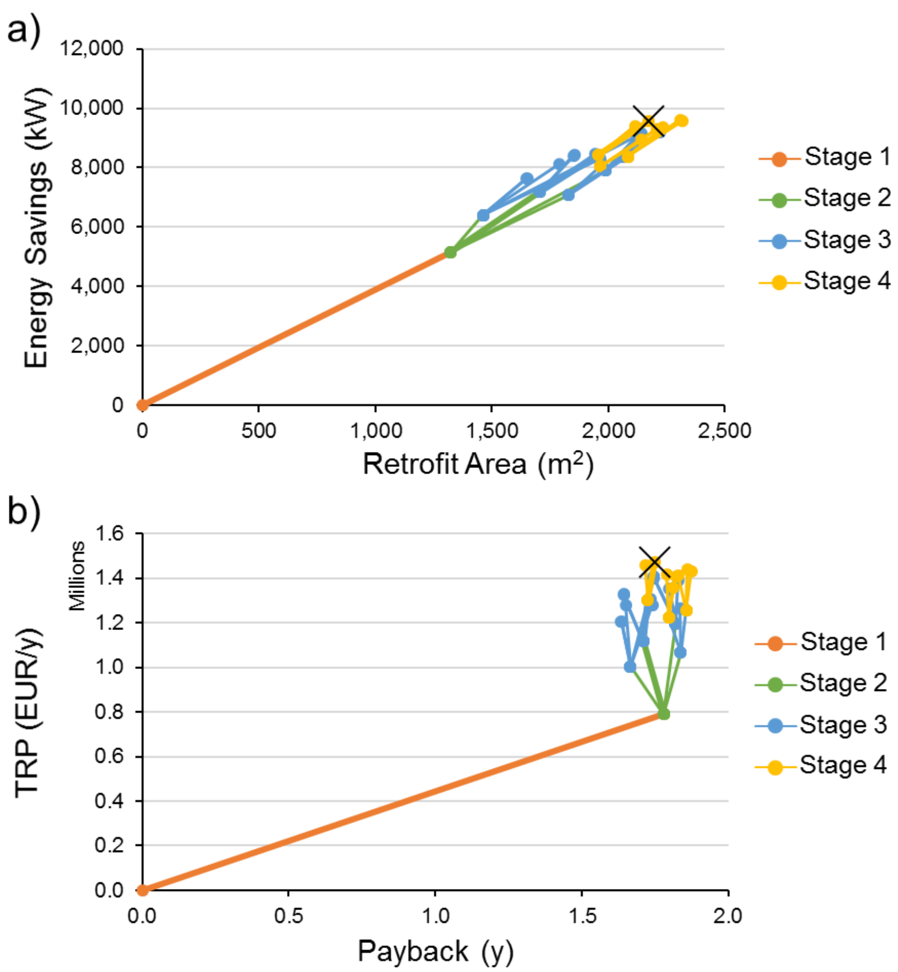


Figure 5.14: Analysis of the incremental effect of energy retrofit planning for the petrochemical complex: a) energy savings against retrofit area, and b) total retrofit profit against payback.

The individual stages and resulting economic evaluations are presented in Table 5.2. Interestingly, there is a slight discrepancy between the capital cost required for implementing the retrofit stages one-by-one and for implementing all stages simultaneously; however, only approximately 5,000 EUR. The difference is due to exchanger E15, which is involved in a Retrofit Bridge twice within the top-ranked retrofit plan. In stage 2, due to changes to E15, the new area is calculated to be 381.25 m^2, an increase of 137.89 m^2. In stage 4, when E15 is again involved in a Retrofit Bridge, the new area is calculated to be 377.78 m^2, less than the area estimated in stage 2. The discrepancy highlights the difference between implementing modifications one-by-one compared to implementing them simultaneously, as further modifications reduced the necessary retrofit area on E15 but only when the stages were applied together. In this case, the effect was only a 5,000 EUR difference in annual profit, but in other cases, the difference may be more pronounced. Additionally, while the overall plan had a shorter PB than the first stage, the modifications in stages 3 and 4 have a longer PB than stage 1. The cumulative effect of multiple stages reduces the overall PB for the retrofit project.

Table 5.2: Summary of the retrofit stages in the chosen retrofit plan for the petrochemical complex.

Stage	Retrofit Bridge	Savings (kW)	Retrofit Area (m^2)	Capital Cost (EUR)	Payback (y)	Profit (EUR/y)
1	C24-E8-E18-H1	5,170	1,323	1,976,806	1.78	789,834
2	C22-E15-H1	2,026	384	667,575	1.53	327,074
3	C22-E12-H2	1,225	250	480,006	1.82	185,342
4	C16-E15-E6-H1	1,161	217	483,153	1.94	170,984
Overall	N/A	9,583	2,171	3,602,590	1.75	1,474,040

The top-ranked plan for the petrochemical complex results in a retrofit HEN design (Figure 5.15) with 11 retrofit modifications, a total retrofit area of 2,171 m^2, and no stream splitting. For clarity, temperatures have not been presented on the HEN and the only heat exchanger duties presented belong to existing exchangers that are modified or new exchangers. The heat transfer area required by new exchangers is also shown, as well as any additional heat transfer area that is needed by the existing exchangers. The retrofit plan heavily reduced the duty of H1 (three Retrofit Bridges targeted H1) with most of the increased heat recovery focusing on the streams S14, S15, S16, and S17. The sizes of the new exchangers range from 31 m^2 to 732 m^2. The capital cost was estimated to be 3.6 million Euros, but with an annual TRP of 1.47 million Euros and a PB of only 1.75 years, the investment is recommended, and the design could be carried forward to detailed analysis and business case development.

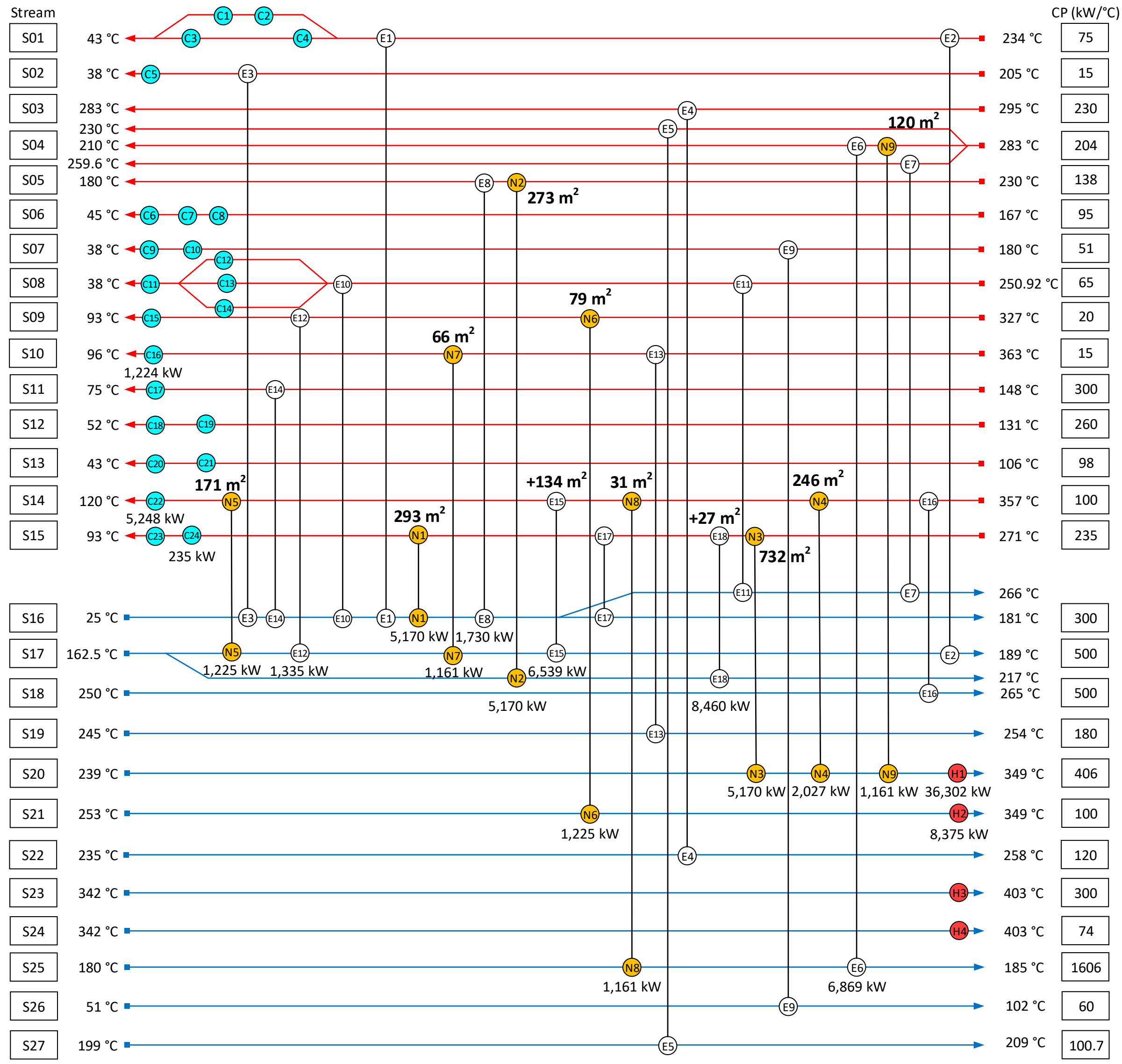


Figure 5.15: Retrofitted HEN for the petrochemical complex, based on the top-ranked retrofit plan.

The METD for the retrofitted HEN is presented in Figure 5.16. As the retrofit savings target has not been achieved, there are still savings opportunities – the minimum utility targets have not been met. There is still considerable cross-Pinch heat transfer in the HEN, leading to a new retrofit savings target of 5.53 MW. Future retrofit projects may reduce the demand for process heat further, but it is not always economical to do so, nor is it the absolute goal of a retrofit project. The retrofitted HEN presented above achieves a good level of energy savings with a high TRP and a relatively short PB (within the 2-year constraint) without achieving the Minimum Energy Network.

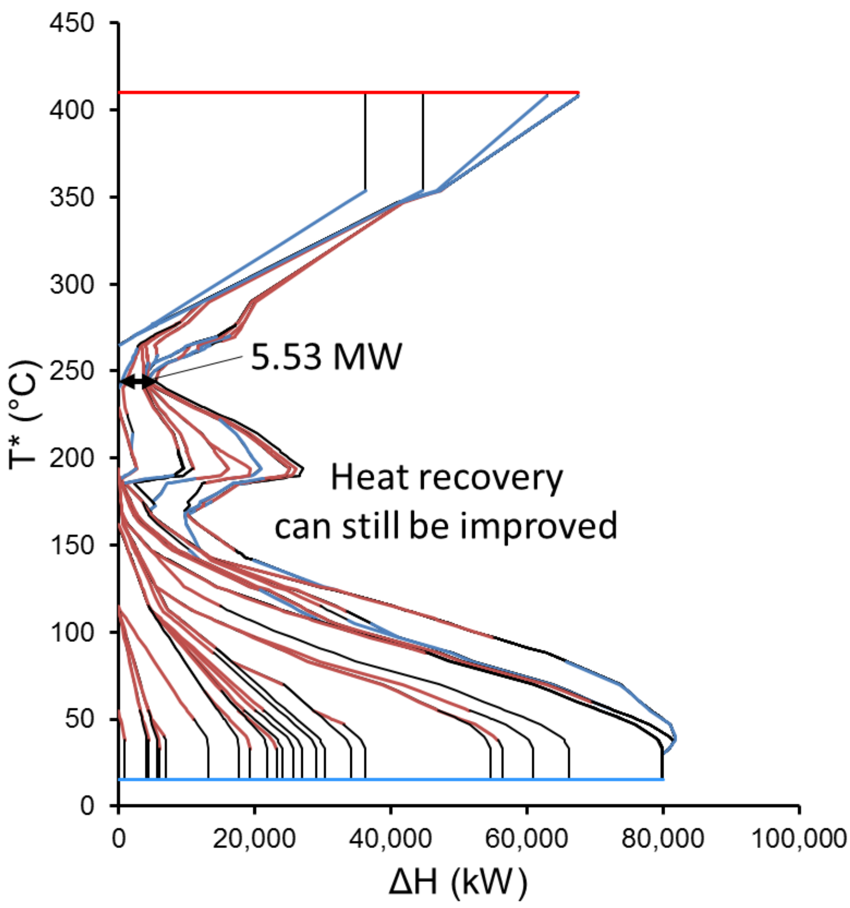


Figure 5.16: Final METD for the retrofitted petrochemical complex HEN.

5.5 Constraint Validation

Chapter 4 presented the Automated Retrofit Targeting (ART) algorithm that handles the Retrofit Bridge search but did not discuss the economics of the retrofit design options that the identified Retrofit Bridges created. The use of constraints can now be validated again based on the profitability of a retrofit design (Constraint 4 does not need to be validated as this can be a specification of the retrofit project). A brief study has been conducted to illustrate how constraints can be validated for a case study. For each industrial case study, different constraints are placed on the Retrofit Bridge search and the highest TRP of all identified retrofit plans is recorded. Therefore, it can be shown when a constraint would cause a more profitable plan to be excluded from the set of possible solutions. A curve is produced for each constraint, showing how increasing the restriction (e.g., decreasing Constraint 1, N_m, or increasing Constraint 2, Q/N_m) of that constraint affects the search for the most profitable retrofit solution. When one constraint is varied (by ±25 percentage increments), the other constraints are kept at the values used in the case studies. The Pareto front analysis is used normally. It is expected that weaker constraints (lower thresholds) will result in the identification of a greater number of retrofit plans, and therefore, allow help to identify more profitable solutions. Stronger constraints (higher thresholds) are more likely to result in the identification of a less profitable plan. Validation of the chosen constraints requires that the constraints can identify the most profitable solution without necessarily identifying all possible solutions – there is a trade-off between the confidence in a result and the computational effort required.

For the paper mill case study, Constraint 1 is varied from 10-1, Constraint 2 is varied from 0-1,100 kW/modification, and Constraint 3 is varied from 0-1.25 kW/m^2. Each constraint is not varied between the same ranges, as some constraints can quickly return zero solutions. Evidently, the chosen constraints are valid for finding the retrofit plan with the highest TRP (778,943 NZD/y) as the chosen constraints obtain the same highest TRP that the search with weaker constraints finds (Figure 5.17a). If the constraints are almost doubled (or halved, for Constraint 1), the highest TRP quickly drops; however, if the constraints become less restrictive, the same TRP is found. A similar result is seen in Figure 5.17b. In Figure 5.17b, the constraints used in the petrochemical complex case study are analysed, and it is shown that the chosen constraints do not result in a lower TRP than what can be found with less restrictive constraints. Here, Constraint 1 was varied from 12-2, Constraint 2 was varied from 87.5-700 kW/modification, and Constraint 3 was varied from 0.75-10.5 kW/m^2.

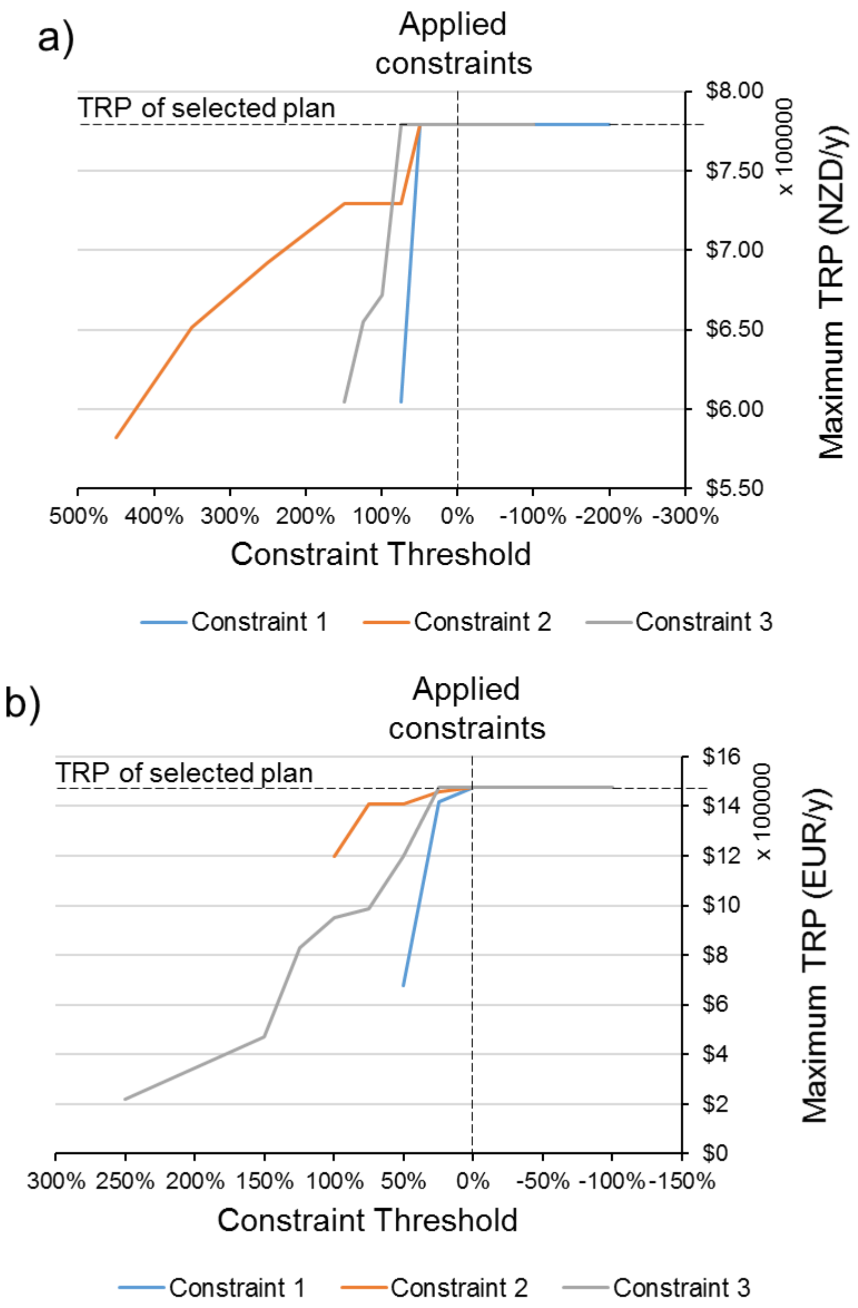


Figure 5.17: Validation of chosen constraints for a) the paper mill case study and b) the petrochemical complex case study.

5.6 Performance Analysis

To analyse the performance of the developed methods and algorithms (in the Excel spreadsheet tool), a brief study has been included to show how the number of Retrofit Bridges changes depending on the number of retrofit stages, the magnitude of the constraints, the use of a Pareto front analysis. The key results from the analysis are the retrofit plan with the highest TRP, the number of Retrofit Bridges identified in each retrofit stage and the number of Retrofit Bridges remaining after the Pareto front analysis (including duplicates).

The results of the performance analysis of the paper mill case study are presented in Table 5.3. The results show that increasing the magnitude of Constraint 2 (Q/N_m) would greatly reduce the computational time but increase the risk of excluding a potentially highly economic retrofit design (due to the successive retrofit stages that only become available through slightly less effect retrofit modifications in previous stages). This is highlighted in the trial with a constraint of 400 kW/modification, which has the shortest computational time of the recorded trials but also has a lower maximum TRP. This is a clear representation of the trade-off between computational time and retrofit analysis effectiveness. Using 200kW/modification as the constraint resulted in the highest maximum TRP (verified by the trial with no constraint) with a significant decrease in computational time.

Table 5.3: Retrofit Bridge search metrics for the paper mill case study.

Stage	Number of Retrofit Bridges							
	Q/N_m: 0		Q/N_m: 100		Q/N_m: 200		Q/N_m: 400	
	Identified	Returned	Identified	Returned	Identified	Returned	Identified	Returned
1	461	4	222	5	168	3	32	3
2	2,384	17	1,107	23	374	9	59	9
3	11,570	72	4,531	95	697	33	64	22
4	46,732	285	14,217	358	214	58	13	3
Total	-	378	-	481	-	103	-	37
Max. TRP (NZD/y)	-	778,943	-	778,943	-	778,943	-	729,222
Time (s)	-	204	-	160	-	43	-	23

The search metric results for the petrochemical complex case study are presented in Table 5.4. Similar observations can be made for the petrochemical complex as for the paper mill. As the search becomes more constrained, the number of Retrofit Bridges identified decreases as well as the time taken to compute the retrofit plans. The metrics show how thousands of Retrofit Bridges may be identified, but only a handful are likely to be economic enough for further analysis. Additionally, as Constraint 2 increases from 350 kW/modification to 450 kW/modification, the maximum TRP found decreases, validating the constraint from an economic perspective and again reflecting the trade-off with using constraints. Understanding this trade-off is vital for a retrofit analysis that considers multiple retrofit stages. Overall, using the constraints, together with the Pareto front analysis, allows for a retrofit analysis to be computed in a few minutes.

Table 5.4: Retrofit Bridge search metrics for the petrochemical complex case study.

Stage	Number of Retrofit Bridges					
	Q/N_m: 250		Q/N_m: 350		Q/N_m: 450	
	Identified	Returned	Identified	Returned	Identified	Returned
1	2764	4	1,635	4	678	4
2	7,737	19	3,765	19	1,330	19
3	22,490	67	9,443	68	3,364	57
4	26,483	23	10,805	17	3,050	9
Total	-	113	-	108	-	89
Max. TRP (€/y)	-	1,474,040	-	1,474,040	-	1,456,024
Time (s)	-	560	-	295	-	131

5.7 Advantages and Limitations

The advantage of multi-stage retrofitting is the increased number of retrofit opportunities that can be identified and formulated into a medium-term energy retrofit plan via a retrofit plan. With each successive retrofit stage and design, many more retrofit opportunities become clear. This allows the retrofit analysis to push towards a Minimum Energy Network while maintaining economic viability. If it is not possible for all retrofit modifications to be completed in one go, due to time constraints or capital constraints, the multi-stage retrofit analysis can also detail the step-by-step retrofit modifications that could be taken. Multi-stage retrofitting alongside the HSDT and METD also allows for a more comprehensive analysis of the HEN problem and the increased level of computation that is introduced in this paper allows for other areas of retrofit design to be considered in the future, such as pressure drop and spatial constraints. The software tool provides a good base for more detailed retrofit analysis in the future.

In each stage, many Retrofit Bridges are identified, quantified, and used to develop retrofit HEN designs. However, with constraints and the Pareto front analysis, this number can be quickly reduced to a few economic retrofit designs (more noticeable in the first stage as the results from successive stages are stacked). It is important to note the trade-off between constraints and computational time. A low constraint allows a greater number of Retrofit

Bridges to be analysed, but this will greatly increase the computational effort without necessarily increasing the likelihood of finding the optimal solution. Understanding this trade-off is vital for a retrofit analysis that considers multiple retrofit stages. Overall, using the constraints and Pareto front analysis allows for a complex and rigorous retrofit analysis to be computed in minutes.

The main limitation of the method is that there is no indication of how close the retrofit options come to the global optimum of the model. The current implementation of constraints (especially Q/N_m thresholds) and the Pareto front analysis cut out numerous unfavourable retrofit designs that may be an excellent base design for the next retrofit stage. Therefore, some profitable designs may be neglected, and only a locally optimal solution can be determined. Considering the many possibilities and variabilities, ensuring a global optimal is not easily achievable.

Despite the quick computational speed for a single stage, the amount of computation that would be required to compute every possible Retrofit Bridge and every Retrofit Bridge's subsequent possible Retrofit Bridges (after retrofit HEN design), and so on, would be immense. Realising this, the goal of the method has been to provide a user with a computational tool for quickly finding retrofit design options that are likely to be economical and then provide the user with the tools to make informed decisions about the retrofit project.

5.8 Conclusions

The improved method overcomes several limitations through the development of the Automated Retrofit Targeting (ART) method for Bridge Analysis. The primary output for the extended ART is a range of retrofit plans that form the basis for an industrial energy retrofit planning tool. The extended spreadsheet tool also now includes the automated design of retrofit HEN designs featuring the removal of redundant heat exchangers, merging of linked exchangers, and stream splitting, which enabled improved estimation of retrofit area and capital cost. The automatic HEN design also permitted for a multi-stage retrofit algorithm to be developed. The multi-stage analysis allows for the identification of retrofit opportunities that can only be realised once other stages have been established. This can help to reach a Minimum Energy Network, based on meeting retrofit targets determined by the Modified Energy Transfer Diagram. Retrofit Bridge search constraints have been used, along with a

Pareto front analysis, to reduce the exponentially large number of possible retrofit options to those that provide the greatest economic benefit. The retrofit tool and method can be used to quickly provide industries with retrofit plans that can improve the energy productivity of the HEN, reduce the use of process heat and related emissions, and assist with industrial energy retrofit planning.

Chapter 6

Monte Carlo Simulation of Retrofitted Heat Exchanger Networks

6.1 Introduction

In the previous chapters, the retrofit analysis (Bridge Analysis) used the Automated Retrofit Targeting (ART) algorithm to search for Retrofit Bridges and then evaluate them. This analysis relied on the design stream data (i.e., supply temperatures and flow rates). In reality, these variables are not necessarily constant – even when at steady state. The steady state supply temperatures and flow rates can vary. Variations can occur due to several factors, such as seasonal changes (i.e., ambient conditions during summer or winter), changes in feedstock that propagate through the processes and HEN, or operational changes. These variations can affect the performance of the HEN and cause deviations away from targets. Variations are often recorded in the historical measured process stream data, which can be utilised in a performance analysis. The effect of process stream variability on HEN performance should be considered, especially when implementing retrofit changes that could greatly alter the flexibility of the HEN. In this thesis, flexibility is defined as the ability of a HEN to remain feasible for a range of operating conditions. Variation in the steady state parameters can be characterised as a range of operating conditions. Many retrofit design methods do not consider the effect that retrofit modifications could have on the flexibility of the HEN.

One potential tool for this analysis is Monte Carlo Simulation. Monte Carlo Simulation (MCS) is a stochastic analysis method based around artificially recreating a chance process over many iterations and then observing the results (Barreto & Howland, 2005). The inputs to a calculation are randomly sampled from a probability distribution many times to allow the calculation of a range of possible and probable outputs. For the evaluation of a retrofitted HEN, the temperature and flow rate of a real process stream can be represented by a probability distribution (e.g., a Normal distribution) which the MCS can randomly sample from each iteration. This allows the variations to be propagated through a model and the effects on the outputs to be analysed, in this case, a HEN model. The dynamic effect of these variations and the dynamic response of the retrofitted HEN is not considered in this thesis; however, these are important parts of retrofit HEN performance and process control and should be considered in the retrofit design process. The focus of this chapter is on the steady state feasibility of the retrofitted HENs.

This chapter presents a novel method for evaluating the steady state feasibility of retrofit HEN designs using Monte Carlo Simulation. The primary goal of the analysis is to determine the inflexibility of the HEN – the probability of the retrofitted HEN to fail to meet its target temperatures at different possible steady state operating conditions. The term 'inflexibility' is used as it is determined by failure to be flexible and to avoid confusion or similarity with the established Flexibility Index (Swaney & Grossmann, 1985). The results from the MCS-based analysis can also be used as a comparative tool (between different exchangers in a HEN, or between different HENs), as well as provide economic estimates that are based on the probabilistic performance of the HEN rather than its design performance (i.e., as designed through Bridge Analysis). The novel method is demonstrated with the illustrative example and the industrial paper mill case study.

6.2 Method

The proposed method is created as an extension to the retrofit design method known as Bridge Analysis, although, the method is not limited to Bridge Analysis and can be used alongside most retrofit design methods. The proposed method does not affect the generation of retrofit HEN designs; rather it assists with the evaluation (and selection) of the final retrofit design to be continued in a business case development (retrofit designs created using other methods can also be analysed). Figure 6.1 provides an overview of the novel method.

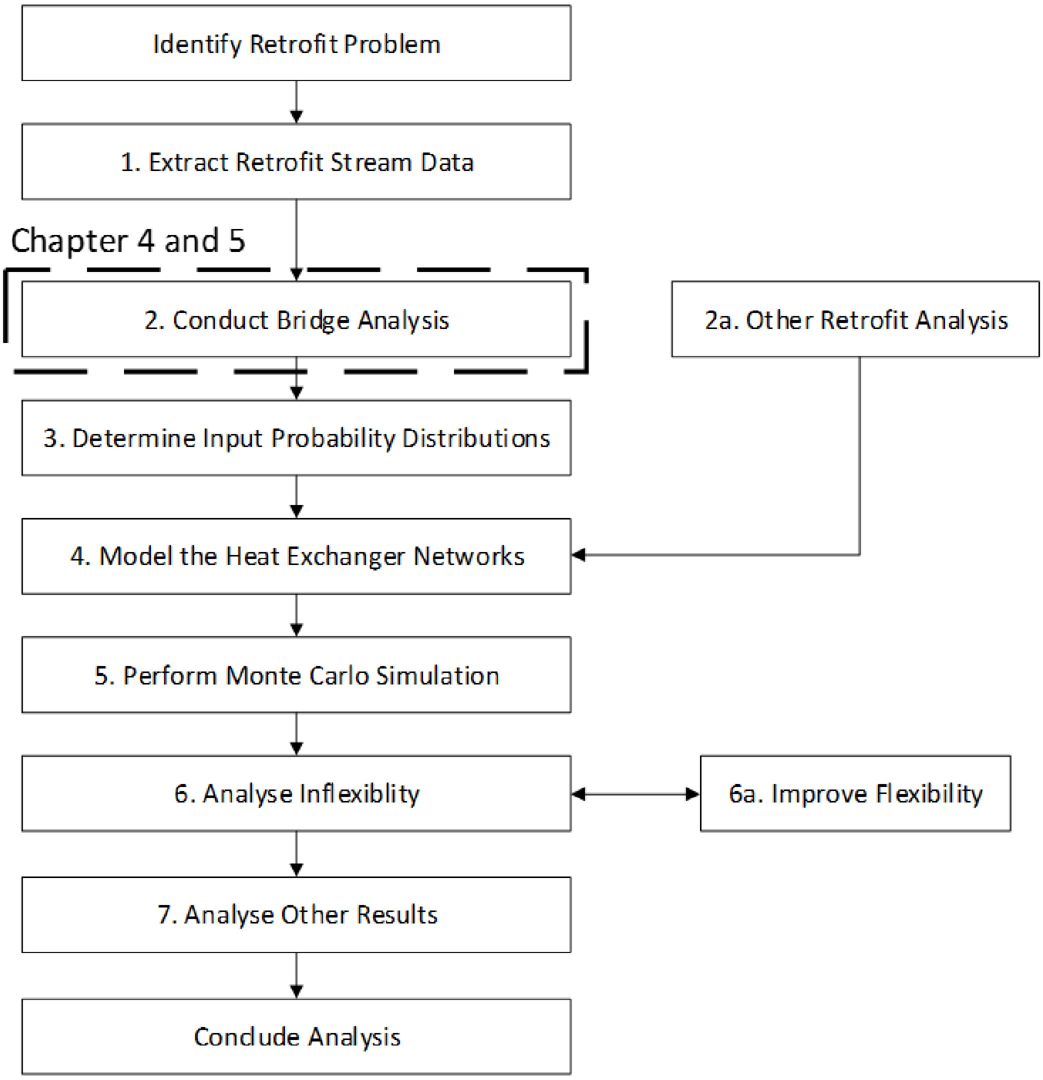


Figure 6.1: Overview of the novel method based around Monte Carlo Simulation.

6.2.1 Step 1: Extract Retrofit Stream Data

While the design of retrofitted HENs is conducted using a single set of design values, the retrofit stream data required for the MCS-based analysis is different. For MCS, a range of measured steady state data (supply temperatures and flow rates excluding during start-up and shutdown) over an extended period is needed to determine the variability in the stream data. The relevant data should be taken from a processing plant's historical data, if possible, at regular time steps. Measurements taken with higher frequency (for the same period) are likely to give a better representation of the process stream variation. Ideally, the data would represent one complete cycle, as to not show bias towards certain operating conditions; however, the duration of a cycle is dependent on the industry. Sometimes retrofit stream data, aside from the design or average values, may be difficult to extract, or completely unavailable. For these situations, guidance is given in Section 6.2.3.

6.2.2 Step 2: Conduct the Retrofit Analysis

The retrofit analysis is conducted to create retrofit HEN designs. For the retrofit analysis, Bridge Analysis is used (including the multi-stage retrofit analysis presented in Chapter 5); however, the method is not limited to Bridge Analysis as the evaluation of retrofitted HENs is independent to Retrofit Bridges and the techniques used to create the designs. However, in this case, the design values must be used to generate the Retrofit Bridges and corresponding retrofit HEN designs. The measured values and variability are accounted for in the MCS results.

6.2.3 Step 3: Determine Input Probability Distributions

To model the variability in the HEN inputs (supply temperatures and flow rates), MCS requires the model inputs to be represented by probability distributions that can be sampled from. A Microsoft Excel™-based software package named @Risk (Palisade, 2018) is used to create or fit distributions to data, in addition to conducting the simulation itself. While the method could be implemented using other platforms or software, such as MATLAB®, the use of @Risk is advantageous because it is Excel-based and can be more easily integrated with the Excel-based spreadsheet tool developed for Bridge Analysis and ART.

@Risk fits each set of stream data (temperature or flow rate) (e.g., Figure 6.2a) with a probability distribution, including Normal, Weibull, Pareto, Laplace distributions. The fit of the probability distributions is then compared using criteria such as the Akaike Information Criterion (AIC). The AIC is based on a distribution model's ability to predict future values (Mohammed et al., 2015) but also penalises for complexity, or over-parameterisation (Bozdogan, 1987). When comparing different distributions, the distribution with the lowest

AIC is considered to have the best fit (though, not necessarily a good fit). The better the fit, the more accurate the representation of the possible outcomes (compared with other distribution models). Figure 6.2b shows an example of fitting three different probability distributions to the temperature data presented in Figure 6.2a. The Kumaraswamy, Weibull, and Normal distributions have AIC values of 66440, 66551, and 66816. As the AIC is comparative and lower AIC values indicate a better fit, the Kumaraswamy distribution is selected as the best fit for the given data. In the following case studies, when a distribution can be fitted, the distribution with the lowest AIC has been used by default. If there is no retrofit stream data (over an extended period) available, the variability may be represented by a user-selected probability distribution based on estimates or experience.

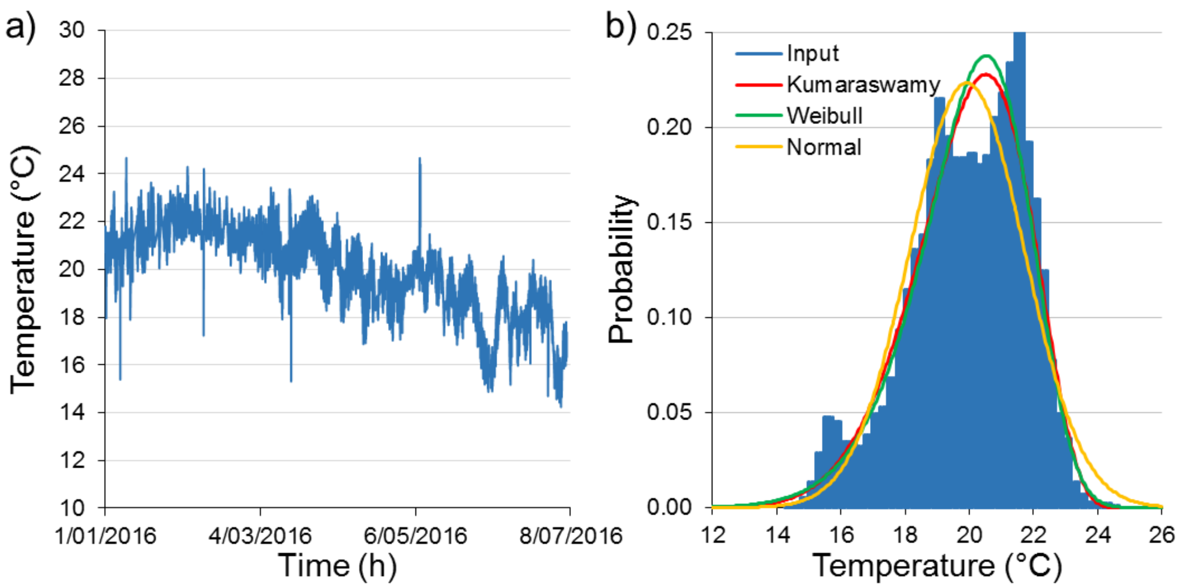


Figure 6.2: a) Raw process stream data for the supply temperature of a stream, and b) fitting several different distributions to the variable temperature.

Preparation of the input probability distributions also includes the identification of correlations between stream variables. In an industrial processing plant, some streams will inevitably interact with other streams, and the measured data can be linked. For example, a cold stream and a hot stream could be linked if it is physically the same stream but represented as two separate streams depending on the need for heating or cooling. Some properties of the streams may be considered correlated, although, correlation does not imply causation, merely an association. If a correlation is identified and defined, the MCS must maintain this correlation as it randomly samples from the input probability distributions. For example, if there is a positive correlation between the temperatures of two different streams, if a higher temperature value is sampled from one stream, a higher temperature value must also be sampled from the correlated stream. The effect of the correlation is defined by the correlation coefficient. A correlation coefficient close to zero is a weak correlation, while a correlation close to ±1 is a strong correlation (Taylor, 1990). The sign of the coefficient indicates the direction of the correlation (i.e., direct/positive or inverse/negative). @Risk maintains correlations using Spearman's rank-order correlations (a measure of the strength and direction of the relationship between two variables) (Palisade, 2018).

6.2.4 Step 4: Model the Heat Exchanger Networks

The model of a HEN represents the set of calculations that the MCS must perform in each iteration to provide probability distributions of the selected outputs, such as utility duty and target temperatures. A model is required for each HEN being analysed, such as the original HEN and the retrofitted HEN or HENs. Each heat exchanger is sized using the area estimation method used in Chapter 4 (Section 4.3.3) or according to the real areas of the existing heat exchangers at an industrial processing plant (if available). The heat exchanger duty is calculated using the ε-NTU method. As with the area estimation in Chapter 4, the ε-NTU method in this chapter assumes that the heat exchangers are double pipe counter-flow heat exchangers (other correlations can be easily used). As the heat transfer area is known, NTU is calculated using Equation 6.1:

$$NTU = \frac{UA}{CP_{\min}} \tag{6.1}$$

Where U is the overall heat transfer coefficient (kW/m^2°C), A is the heat exchanger area (m^2), and CP_{min} is the minimum heat capacity flow rate of the matched streams (kW/°C). The correlation in Equation 6.2 is used to calculate the effectiveness (ε) (Çengel, 2007):

$$\varepsilon = \frac{1 - \exp\left(-NTU(1-c)\right)}{1 - c\exp\left(-NTU(1-c)\right)}, \quad \text{where } c = \frac{CP_{\min}}{CP_{\max}} \tag{6.2}$$

As heat exchanger area is fixed, the varying temperatures and flow rates (heat capacity flow rate) will result in different heat exchanger duties in each iteration. The heat exchanger duty, Q, is calculated with Equation 6.3:

$$Q = \varepsilon Q_{\max} = \varepsilon CP_{\min}\left(T_{h,\text{in}} - T_{c,\text{in}}\right) \tag{6.3}$$

If the estimated area of an existing heat exchanger is lower than the area for the same exchanger in the original HEN, then the original area is maintained as it is important to utilise existing equipment. This can lead to slight changes in the operation of the HEN compared with the design, including ΔT_{min} violations. ΔT_{min} does not constrain the operation of heat exchangers in real-life, so the ΔT_{min} does not constrain the model of the HEN. Additionally, in some retrofit designs, utility exchangers are made redundant due to increases in heat recovery. In reality, these utility exchangers would remain for control purposes, mostly as trim utility exchangers to ensure that target temperatures are maintained.

The utility exchangers are modelled using Q = CP ΔT and are assumed to be over-sized – the heat transfer area is not determined. The target temperatures of the utility exchangers are fixed. In a more in-depth analysis, the utility exchangers could be sized, and the utility streams could be represented as inputs. Other calculations involve iterative calculations for heat exchanger loops and the calculation of the temperature after two streams are mixed after a stream split or bypass. When a stream split or bypass are used, the new temperature after the mixing (T_{mix}) of the split stream or bypass with the main stream is given by the following approximation (Equation 6.4):

$$T_{\text{mix}} \approx \frac{(CP_1T_1 + CP_2T_2)}{CP_2 + CP_2} \tag{6.4}$$

Where the indices 1 and 2 represent the split stream and the main stream. The approximation of T_{mix} assumes that the heat capacity flow rates are constant through each stream segment. Heat capacity flow rates are varied according to the probability distributions but are constant within an iteration and do not vary along the stream (other than when split).

Bypasses are controlled using Excel Solver (in each iteration) to ensure that the target temperatures are maintained. The dynamic behaviour of bypasses is not considered – only the static effect that different bypass fractions will have on the control variables is considered. Therefore, the bypass fractions are reset after every calculation.

6.2.5 Step 5: Perform the Monte Carlo Simulation

The Monte Carlo Simulation (using @Risk) computes many iterations worth of outputs based on the input probability distributions and the HEN models. In each iteration, a set of temperatures and flow rates is randomly sampled from their corresponding probability distributions to represent the variation present in process stream data. These temperatures and flow rates (heat capacity flow rates) are used to calculate the specified outputs of the model (through a series of calculations defined by the model). This is then repeated with a different set of randomly sampled inputs as many times as specified (e.g., 10,000 iterations). Several Excel-based macros are run before and after every iteration as needed (i.e., to adjust a bypass fraction).

Histograms representing the probability distribution of the outputs are generated using the collection of calculated outputs (in addition to other statistical calculations and results). The outputs are typically the target temperatures and duties of heat exchangers and utilities. The general outline for MCS (from input probability distributions to calculated output probability distributions) is presented in Figure 6.3.

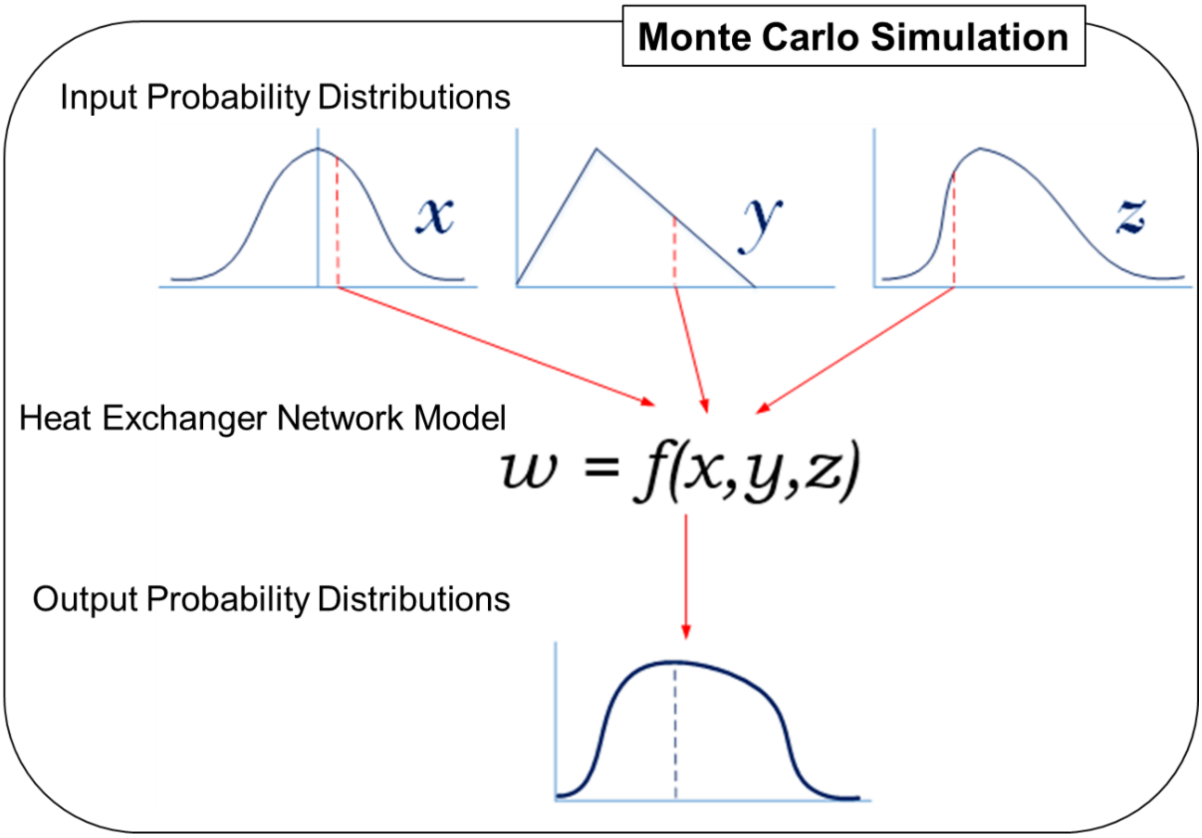


Figure 6.3: The Monte Carlo Simulation process.

Repeated random sampling is an important part of the MCS process. The random number generation (RNG), or rather pseudo-RNG (PRNG), used for the @Risk-based MCS is the Mersenne Twister algorithm developed in 1998 by Matsumoto and Nishimura (1998). The Mersenne Twister algorithm is a widely used PRNG that is known for its high quality and is the default PRNG for many programs, including Microsoft Excel, MATLAB, and Python.

6.2.6 Step 6: Analyse Inflexibility

The main result from the MCS is the generation of probability distributions for each specified output. As the results show the probability for certain values of outputs, such as utility duty or temperature, MCS can be used to determine the probability of an output reaching an extreme or unwanted value. The goal of a HEN is to ensure that process streams meet their target temperatures (which can have allowable tolerances or minimum/maximum limits), either through heating or cooling (including recovery); therefore, if a target temperature cannot be achieved then the HEN has 'failed' this goal. MCS can be used to determine the probability of a HEN failing to meet these temperature targets. These probabilities are indicative of the flexibility, or lack of flexibility, of the HEN. Flexibility is defined in this chapter as the ability of a HEN to operate feasibly at steady state despite variations (following the definition in Section 2.6.1 of Chapter 2). Considerations of flexibility in the early stages of retrofit HEN design are important because retrofit modifications could lead to an uncontrollable HEN (Westphalen et al., 2003), despite the retrofit analysis reporting a high profitability or significant reduction in hot utility consumption.

As this analysis is centred on the probability for failure, a simple estimate of 'inflexibility' is determined using the MCS results. HEN inflexibility (as a percentage) is calculated using Equation 6.5 and Equation 6.6, which have been developed for this analysis:

$$\forall\ i \in n, \qquad \begin{cases} t_{lower,j} \leq v_{j(i)} \leq t_{upper,j} \ \ \forall\ j:\ \ p_i = 0 \\ \text{Else:}\ \ p_i = 1 \end{cases} \tag{6.5}$$

$$\text{Inflexibility} = \frac{1}{n}\sum p_i \tag{6.6}$$

Where i is the iteration number within the simulation, v_j is the controlled variable (i.e., target temperature) (with j number of controlled variables), t is the target value (which can have an upper and a lower limit), n is the total number of iterations, and p_i is an integer that represents a pass (0) or a fail (1) for the target being met. In other words, if any controlled variables do not meet their target, p_i is equal to one for that iteration. In Equation 6.6, the total number of non-zero values of p_i is divided by the total number of iterations to find the inflexibility. The inflexibility of the HEN is different from the sum of the probabilities for failed targets as these failures are not necessarily dependent; although, they can be equal if the failure probabilities are independent to each other. If one target temperature is not met, then another may not be achieved for the same reason (e.g., a higher-than-normal supply temperature is upstream to both targets). Rather than double count these failures, inflexibility considers the ability of the HEN to meet all targets simultaneously. This is similar to the flexibility index proposed by Swaney and Grossmann (1985); however, the probability of failure is used to define flexibility (inflexibility) rather than the size of the deviation from the nominal operation.

The inflexibility is calculated for the starting HEN and any retrofit HEN designs. If a HEN design has a high inflexibility, it should be penalised as it cannot handle the steady state variations and continue to operate feasibly. Control strategies can be implemented in future development to improve flexibility (and controllability, safety, etc.), but there are several modifications that can be made to the HEN designs to help reduce the probability for failure, the inflexibility. Several modifications include the use of bypasses or changing (increasing or decreasing) the heat exchanger area on certain exchangers – not decreasing the area of existing exchangers. There is a trade-off with these modifications, in addition to capital costs, as larger bypass fractions may also require larger heat exchanger areas (Luyben, 2011) and reducing the area of new heat exchangers may reduce the overall energy savings. Regardless, once the inflexibility has been calculated, several different approaches can be used to reduce the inflexibility of the HEN, at least based on the results from the MCS.

6.2.7 Step 7: Analyse Other MCS Results

Histograms

Histograms for the output variables are one of the key outputs of the method and MCS. The flexibility analysis in the previous section uses the histograms to visualise and help calculate the inflexibility. The histograms can also provide other insights and can be used to compare the performance (heat exchanger duty) of different heat exchangers. Depending on the project, comparisons can be made between heat exchanger units (including utilities) in the same or different retrofit HEN designs. The spread and shape of the histogram provide significant information about the performance of the exchangers, i.e., the probability of extreme values, or predictability.

Economic Evaluation

Certain economic metrics can also be recalculated using the MCS results rather than the steady state results. Because the MCS shows that the utility duty can vary depending on the inputs, it is reasonable to expect that the total cost of utility can also vary. Economic performance can be estimated with more weight given to the probable outcomes (e.g., if there is a high probability for the utility duty to exceed the steady state value then this will be accounted for). Capital cost is calculated the same way (details provided in Chapter 5); however, the method for estimating the utility cost savings (ΔS) is different when based on MCS results. In the MCS-based analysis, Equation 6.7 is used for utility cost savings instead of Equation 5.7 (for steady state):

$$\Delta S = \sum_{i=1}^{n} \left[\left(p_{hu,i} \Delta Q_{hu,i} + p_{cu,i} \Delta Q_{cu,i} \right) \cdot t_i \right] \tag{6.7}$$

Where ΔQ_{hu} is the reduction in total hot utility duty (kW), ΔQ_{cu} is the reduction in total cold utility duty (kW), p_{hu} is the price of hot utility (currency unit per kWh), p_{cu} is the price of cold utility (currency unit per kWh), t_i is the hours of operation per year for the given interval *i.* Each interval is defined by the bins of the histogram for the hot utility duty. The total capital cost is calculated using the case study specific cost equations, and then the total retrofit profit (TRP) is calculated using Equation 5.9. The percentage difference between the steady state TRP and the MCS-based TRP is calculated to show the effect of the input variability.

6.3 Illustrative Example

The four-stream illustrative example is used again to demonstrate the novel methods outlined in this chapter. Although, as this is a textbook problem, there is no real process stream data to use and input probability distributions are specified. In this example, the three utility exchangers (C1, C2, and H1) control the target temperatures on streams F2, F4, and F3. Stream F1 has no utility exchanger to control the temperature; however, the target temperature is a soft temperature target (flexible) with a lower and upper limit. The target temperature of F1 should not deviate from 180 °C by more than ±10 °C. The grid diagram is presented in Figure 6.4, featuring two bypasses on streams F4 and F1 for the control of the target temperatures on those streams (requirement confirmed in the flexibility analysis).

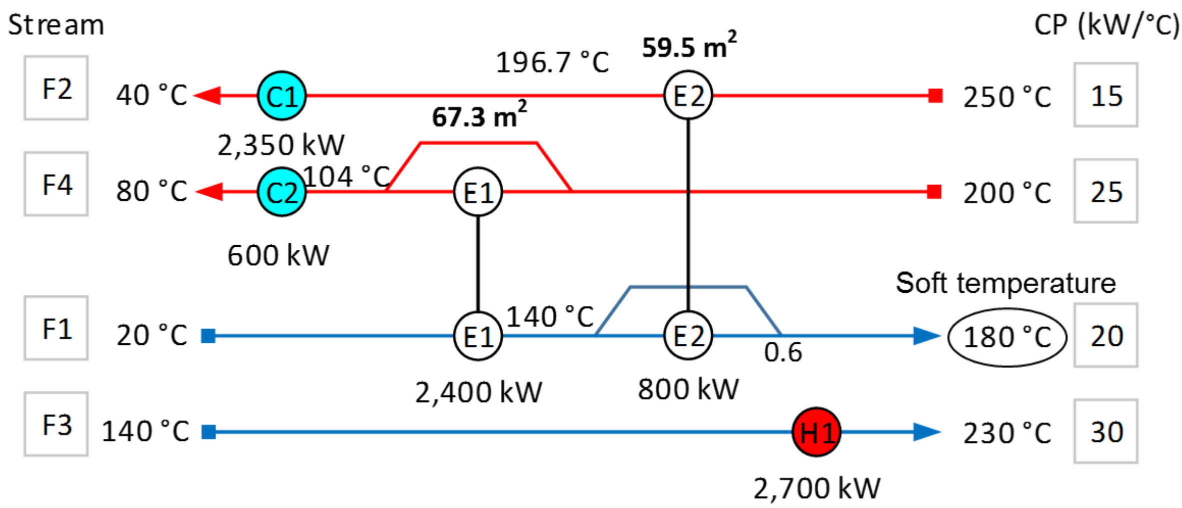


Figure 6.4: Grid diagram of the four-stream illustrative example.

6.3.1 Retrofit Analysis

From the retrofit analysis in Chapter 3, there are seven different Retrofit Bridges that could be applied to the HEN resulting in seven different retrofit HEN designs (multi-stage retrofitting is not used). These Retrofit Bridges and the resulting steady state economics of the designs are presented in Table 6.1. Total retrofit profit (TRP) has been calculated under the assumption that the utility consumption (hot utility only as the price of cold utility is negligible) is constant at the estimated steady state value. Heat exchanger area has also been estimated based on the design values and includes the additional area required for bypasses.

Table 6.1: Summary of the retrofit designs for the illustrative example, using the steady state values.

Retrofit Design	Retrofit Bridge	Savings (kW)	Retrofit Area (m^2)	Capital Cost (NZD)	TRP (NZD/y)	Figure
1	C1-E1-H1	1,250	291.8	458,999	292,800	Figure 6.5a
2	C1-H1	700	72.2	131,789	184,352	Figure 6.5b
3	C2-E1-E2-H1	600	86.4	172,172	148,380	Figure 6.5c
4	C1-E2-H1	700	61.0	140,602	182,918	Figure 6.5d
5	C1-E1-E2-H1	800	156.8	257,209	193,340	Figure 6.5e
6	C1-E2-E1-H1	700	108.4	259,042	163,642	Figure 6.5f
7	C2-E1-H1	600	66.5	161,717	150,081	Figure 6.5g

The grid diagram for each of the seven retrofit HEN designs is presented in Figure 6.5. The grid diagrams also show the placement of bypasses and the heat exchanger area in each recovery exchanger. In the previous retrofit analysis, the retrofit designs in Figure 6.5c and Figure 6.5g no longer require a cooler on stream F4 (cooler C2). In reality, these coolers would remain to ensure that the streams were cooled to target. In the following grid diagrams, these coolers are presented with zero duty, but this will vary during the MCS.

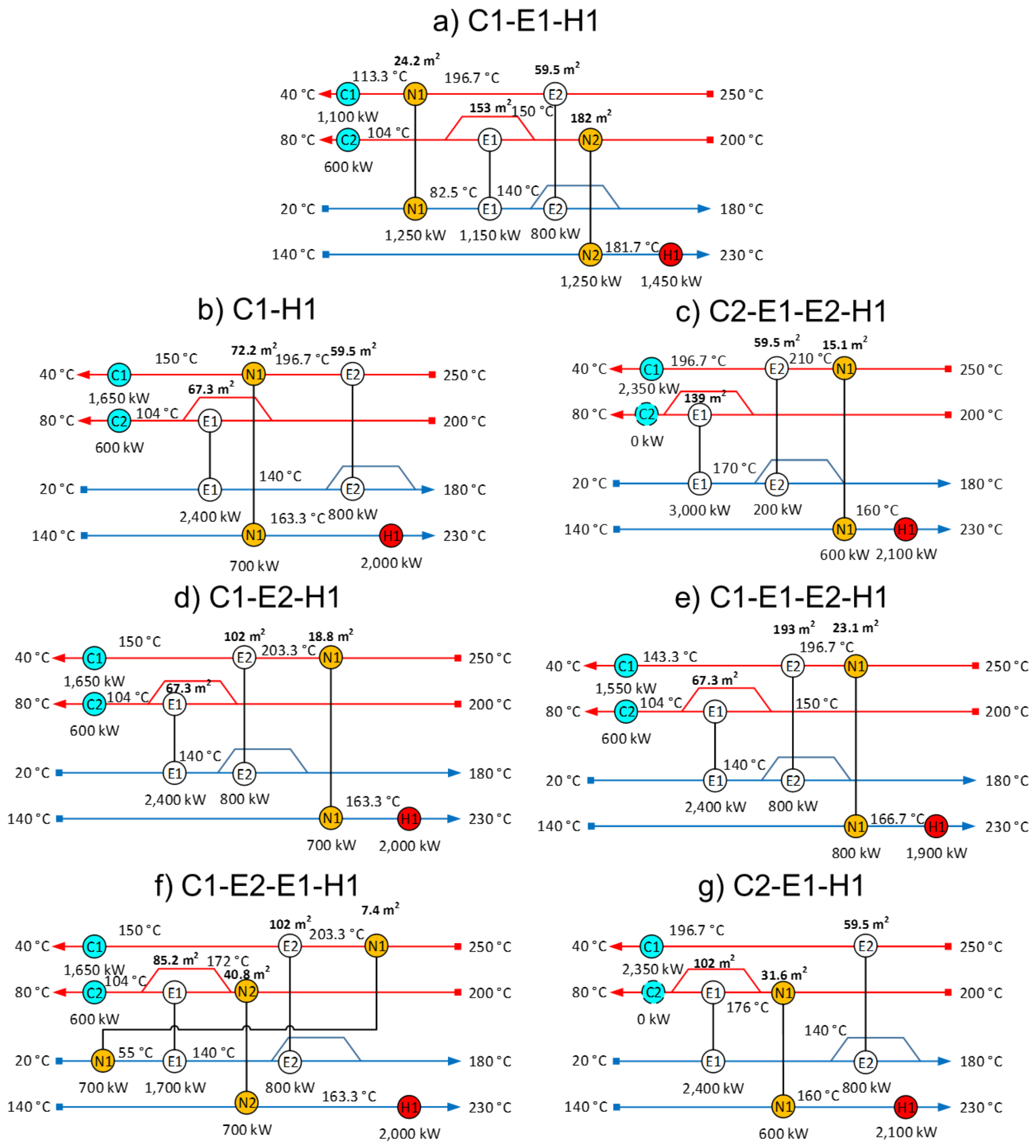


Figure 6.5: Grid diagrams for all seven retrofit HEN designs, including exchanger areas and bypasses (a-g). Temperatures and duties are design values.

6.3.2 Input Probability Distributions

In the absence of real stream data for the illustrative example, probability distributions have been assumed for each stream supply temperature and heat capacity flow rate (the variable inputs). These probability distributions are created using @Risk and are selected to provide a variety of distributions for the illustrative example. In a real case study, the AIC and @Risk would be used to select the best-fitting distribution for a real set of variable stream data – such as in the industrial case study later in the chapter. The selected probability distributions for each supply temperature and heat capacity flow rate are presented in Figure 6.6. Three different types of distributions have been used: PERT distributions, Normal distributions, and Beta General distributions. The distributions are distinct in shape, spread, and height. For example, the PERT distributions for both the supply temperature and heat capacity flow rate of stream F1 have a small spread and a high frequency of values close to the mean, representing little variation. On the other hand, the Normal distribution representing the flow rate of stream F4 has a large spread and will have significantly more variation. However, the small variation in stream F1 may have a larger impact on HEN performance than the variation in stream F4.

In this illustrative example, the heat capacity flow rate of stream F2 has been positively correlated with the temperature of stream F4. A correlation coefficient of 0.8 has been specified, indicating a strong positive correlation. When the MCS samples from the probability distribution of the heat capacity flow rate of stream F2, it will sample from the distribution of temperature of stream F4 such that the correlation (a Spearman rank-order coefficient) is maintained. In a real case study, the data can be analysed to determine if a correlation exists.

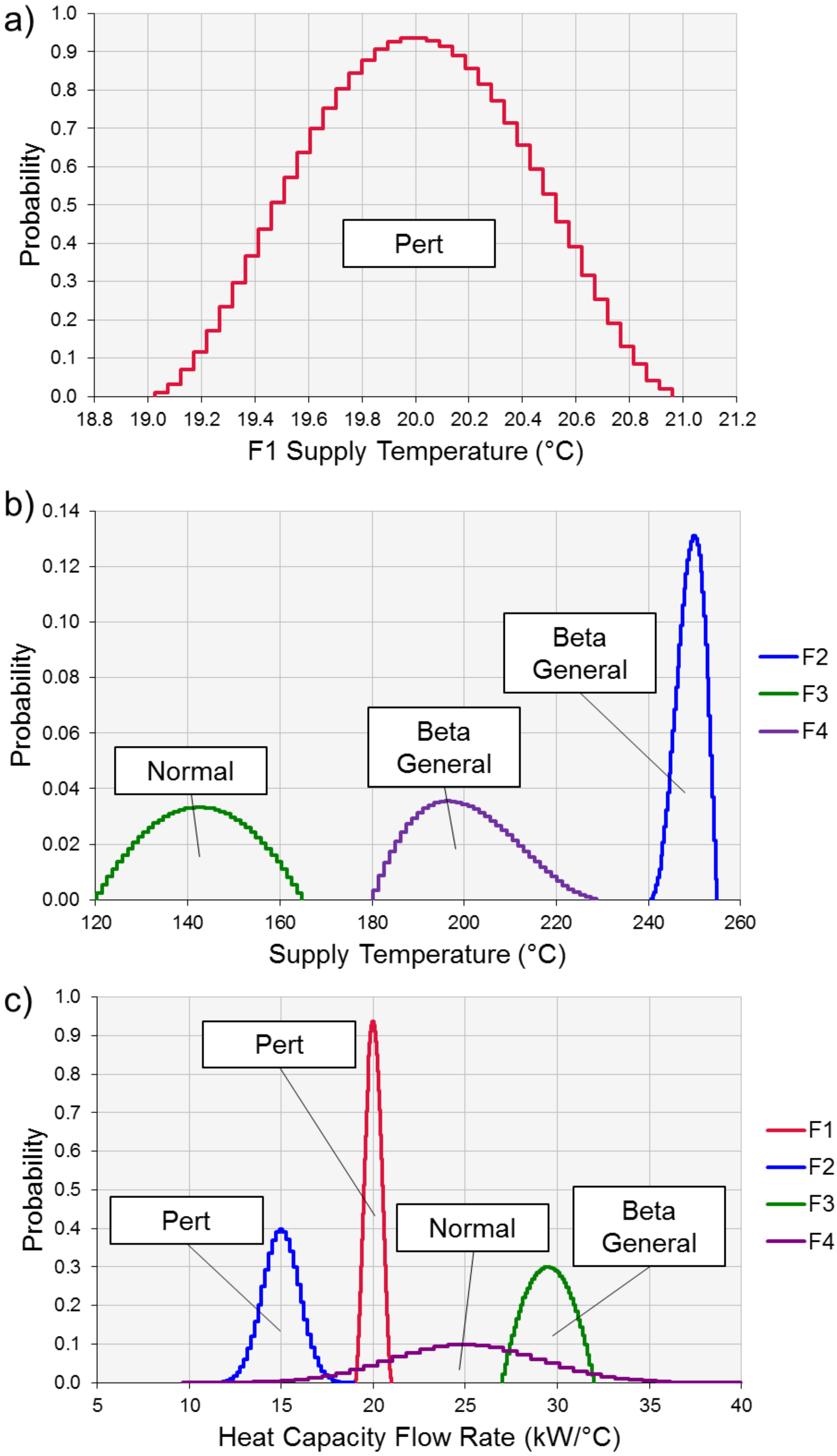


Figure 6.6: Probability distributions for the a) supply temperature of stream F1, b) supply temperatures of streams F2, F3 and F4, and c) heat capacity flow rates of all streams.

6.3.3 Heat Exchanger Network Models

Each of the seven retrofit designs from Bridge Analysis is modelled in Microsoft Excel, along with the initial (un-retrofitted) HEN. Each heat exchanger is modelled using the ε-NTU method, using the double pipe counter-flow correlation (as is used in previous chapters). The area has been previously calculated using the design or average values. Heat transfer coefficient is dependent on inlet conditions and varies with the heat capacity flow rate. Equation 6.8 (Timothy G. Walmsley, Walmsley, Atkins, et al., 2014) is used to determine the heat transfer coefficient (h) for a given heat capacity flow rate (CP):

$$h = h_{design}\left(\frac{CP}{CP_{design}}\right)^{n} \tag{6.8}$$

Where h_{design} is the design heat transfer coefficient of 1,000 W/m^2°C (all streams in the illustrative example have the same heat transfer coefficient), CP_{design} is the design heat capacity flow rate, and n is an exponent relating to the heat transfer coefficient correlation. In this example, n is 0.8.

In this original HEN, there are two bypasses: one on the hot-side of E1 and one on the cold-side of E2. These bypasses are modelled using an Excel macro to adjust the bypass fraction from its default setting when needed. The default bypass fraction for the E1 bypass is zero while the default bypass fraction for the E2 bypass is 0.6. Other bypasses may be added after the inflexibility analysis of the retrofit designs. Furthermore, due to the presence of a loop in retrofit design 1 (Retrofit Bridge C1-E1-H1) caused by exchangers N1 and E2, iterative calculations are required for the model.

6.3.4 Monte Carlo Simulation Results

The Monte Carlo Simulation is run for 10,000 iterations. The initial HEN (with and without bypasses) and all retrofit HEN designs are modelled simultaneously using the same set of inputs in each iteration. From the results of the MCS, the inflexibility of the HENs can be assessed and improved, and the HEN performance can be analysed.

Flexibility Analysis

Before considering the inflexibility of the retrofit HEN designs, the inflexibility of the initial HEN is determined, with and without bypasses. Without bypass control, the initial HEN has an inflexibility of 11.1%, which relates to approximately 930 hours of operation a year (total operation of 8,400 hours) that the HEN fails to meet all target temperatures. The target temperatures causing this inflexibility are the target temperature of streams F4 (controlled by C2) and F1. Figure 6.7a shows that there is a 1.5% probability for the duty of cooler C2 becoming negative (target temperature of F4 has been exceeded) while Figure 6.7b shows that there is a 10.7% probability of the outlet temperature of F1 falling outside of the allowable range (170-190 °C) – 6.8% below 170 °C and 3.9% over 190 °C. With bypasses, these probabilities are reduced to zero and the HEN can be considered flexible according to the inflexibility measure. The heat exchanger area of E2 must be increased to 59.5 m^2 to accommodate the bypass on stream F1 with a default bypass fraction of 0.6. With an inflexibility of zero, any adverse effects any retrofit modifications may have on the flexibility can be quantified and compared.

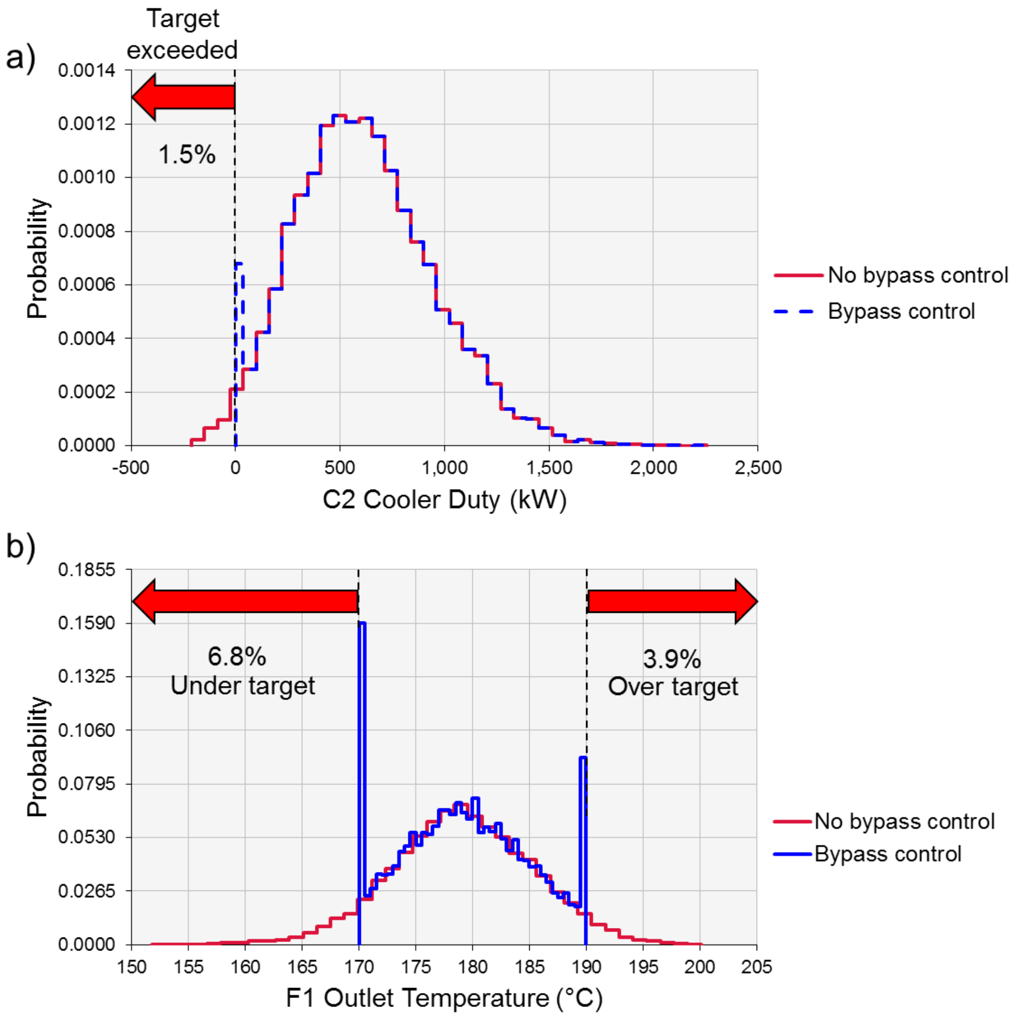


Figure 6.7: Flexibility analysis of a) the duty for cooler C2 with and without bypass control and b) the outlet temperature for stream F1 with and without bypass control.

As the target temperatures of streams F1 and F4 were identified as difficult to maintain, the flexibility analysis of the retrofit HEN designs is also focused on these targets (the other target temperatures remain unaffected). After the retrofit modifications have been applied to the initial HEN, only retrofit design 2 has an inflexibility of zero. In Figure 6.8a, the cooler C2 in retrofit design 1 has a low probability (0.1%) of becoming negative – all other retrofit designs maintain the F4 target temperature; however, retrofit designs 3-7 fail to maintain the F1 target temperature with a range of inflexibilities from 0.1 to 6.0% (Figure 6.8b). The existing bypasses help, such as in the case of retrofit design 2, but evidently, there is an issue with F1's outlet temperature being too cold. In the histograms of Figure 6.8a and Figure 6.8b, there are peaks in probability at zero duty point of cooler C2 and the upper and lower limits of the target temperature. This is due to the bypass action (using Excel Solver) to reach the target. The high probabilities indicate that the bypasses are heavily relied upon to maintain targets. In these situations, a logarithmic scale is used for the probability axis for clarity.

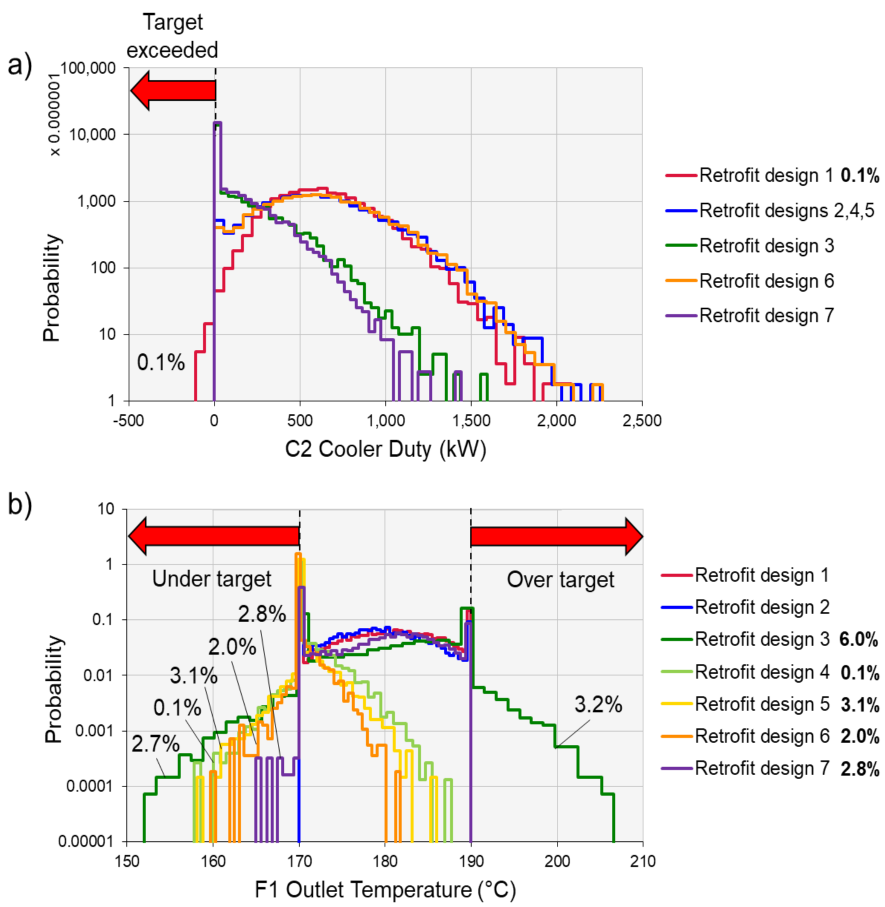


Figure 6.8: Flexibility analysis of a) the outlet temperature for stream F1 in each retrofit HEN design, and b) the duty for cooler C2 in each retrofit HEN design.

In the retrofit HEN designs with a failure probability for the F1 target temperature, a new heat recovery exchanger has been added upstream of exchanger E2, reducing the hot-side inlet temperature to E2, leading to a lower outlet temperature on the cold-side of E2 – lower than the lower limit of 170 °C. The large area on exchanger E1 leads to the outlet temperature becoming hotter than the upper limit. To decrease the inflexibility in these designs, there are several possible options: 1) introduce a heater (with a small load) to the stream as a control measure, 2) decrease the heat transfer area on the new heat exchanger (a bypass on the hot-side of the new heat exchanger could also work), or 3) increase the heat transfer area on heat exchanger E2. In the case of retrofit design 3, the retrofit area on exchanger E1 could also be decreased. The following figures have been prepared for retrofit design 3, which has the highest inflexibility (6.0%) of all retrofit designs, to illustrate the effect of these strategies (excluding option 1).

In Figure 6.9a, the area of the new heat exchanger is reduced by 2 m^2 increments (option 2), starting with the initial area of 15 m^2. Unfortunately, reducing area decreases the inflexibility but also increases the hot utility duty leading to a trade-off between flexibility and energy savings. Similarly, in Figure 6.9b, the area of exchanger E2 is increased in 20 m^2 increments from an original 59.5 m^2 (option 3), reducing the inflexibility. As exchanger E2 is not linked to a hot utility, there is no effect to the energy savings. In Figure 6.9a and Figure 6.9b, the modified area does not address the 3.2% probability of the temperature exceeding 190 °C and the inflexibility plateaus.

The retrofit area on exchanger E1 (which has been increased from 67.3 m^2 to 139 m^2) can be decreased to reduce the outlet temperature. Figure 6.9c shows that the area reduction initially causes the inflexibility to drop but after once the area has been reduced past 80 m^2, there is a significant increase in the inflexibility. This is because the temperature in F1 greatly drops and the temperature cannot be maintained within the allowable range. However, at 100 m^2, an inflexibility of 2.7% can be achieved with no energy savings penalties and no extra capital cost – in fact, less capital is needed for exchanger E1 as the retrofit area has been reduced. The remaining 2.7% can be lowered using options 1-3 but this will have an adverse effect on the probability. In general, if there is no simple modification for improving flexibility, the inflexibility of the retrofitted HEN can be used to penalise the design.

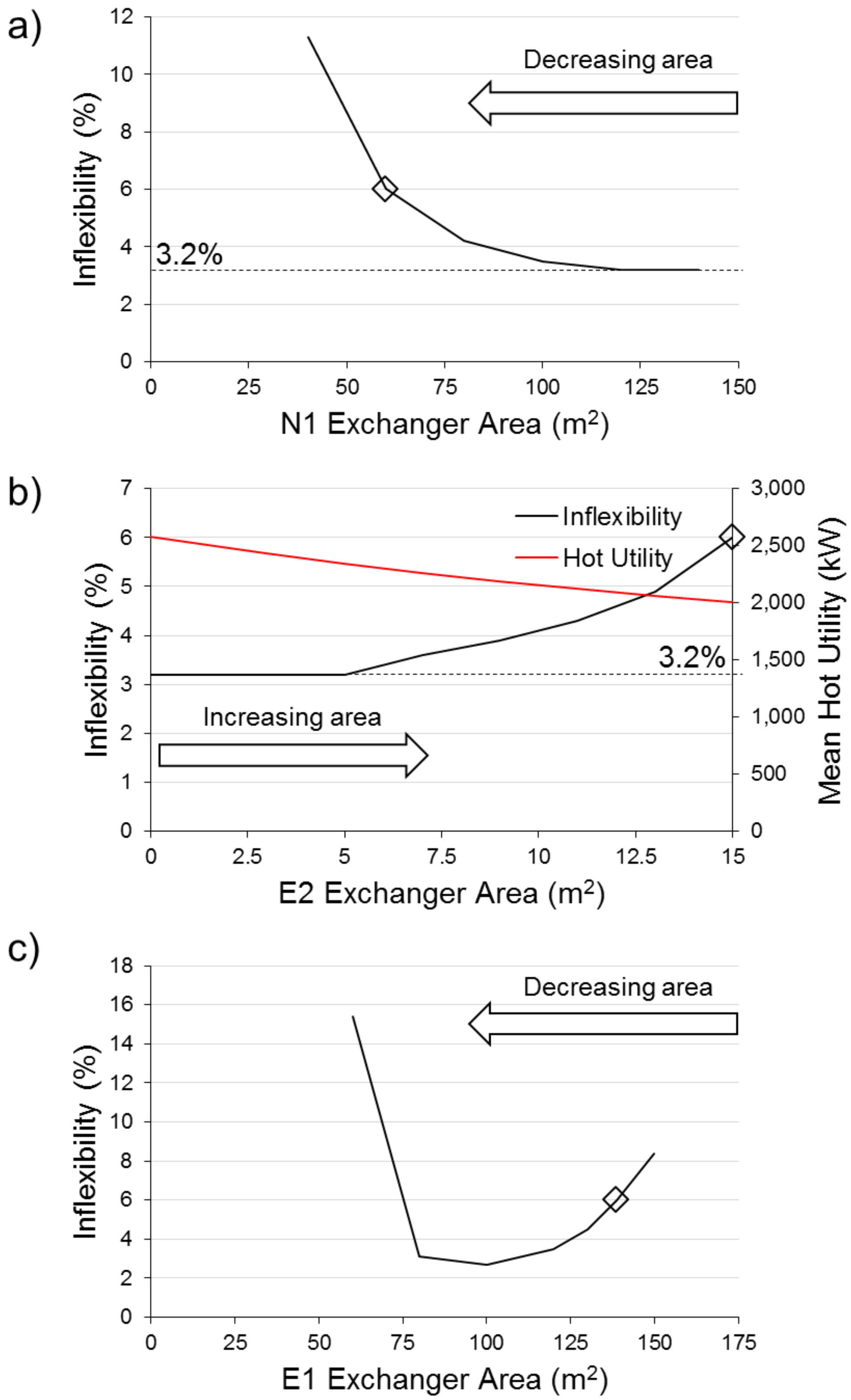


Figure 6.9: a) The effect of decreasing the heat exchanger area of the new exchanger on inflexibility and hot utility duty, b) the effect of increasing the heat exchanger area of exchanger E2 on inflexibility, and c) the effect of decreasing the heat exchanger area of exchanger E1 on inflexibility (without removing area).

Histograms

The Monte Carlo Simulation results can also be used to analyse the performance of additional heat exchangers and compare similar exchangers across different retrofit designs. For example, in retrofit designs 3 and 7, the duty of cooler C2 was effectively reduced to zero by the increase in heat recovery, in the steady state analysis. Despite being ‘removed’, this cooler is still required to ensure that the stream is cooled to the target temperature. To confirm this, Figure 6.10a presents the duty of cooler C2 for retrofit designs 3 and 7 showing that there is still a significant probability of a positive cooler duty (note that the bypass on E1 prevents the target temperature from going below the target of 80 °C). Control strategies may be implemented to control the target temperature using bypasses, but it is much simpler to keep the existing utility exchanger, especially due to the negligible cost of cooling water.

Figure 6.10b shows the histogram for the duty of heater H1 in each retrofit design. As the hot utility is the main factor for utility cost savings, the probability of utility usage is important. Figure 6.10b shows that the mean duty has decreased as expected, due to the retrofit modifications, but the peak loads can still be very high. During these instances, the cost of utility will greatly increase or could even exceed capacity (i.e., boiler capacity). Additionally, the spread of duty values for each retrofit design is less than the spread of the duty values for the starting HEN, indicating that the utility’s usage deviates less from steady state.

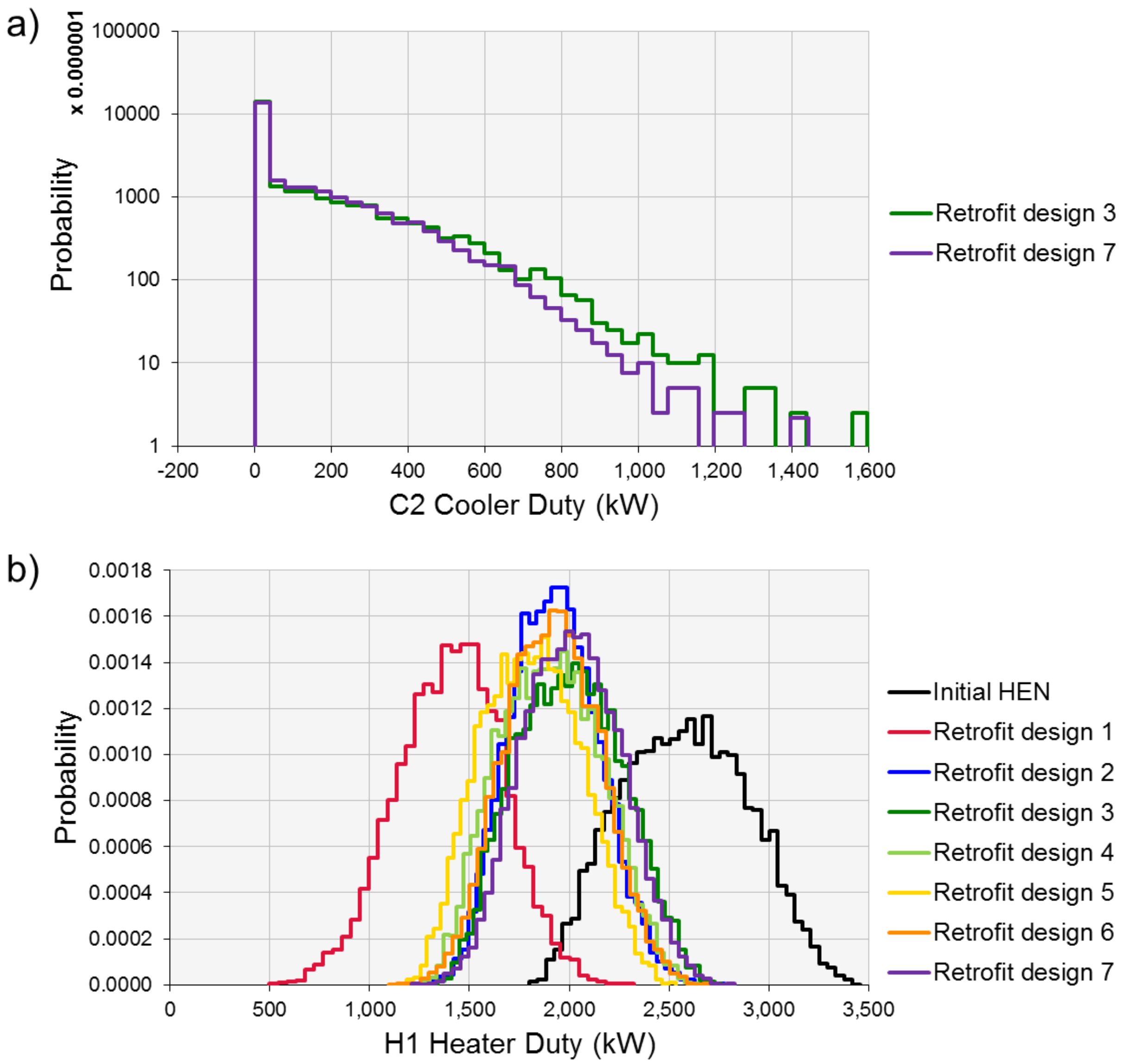


Figure 6.10: Histograms of a) the duty of cooler C2 in retrofit designs 3 and 7, and b) the duty of heater H1 in all retrofit designs.

The MCS results can also be used to highlight the differences between two similar HEN designs. For example, retrofit designs 2 and 4 are considerably similar as they both only require one new heat exchanger, reduce the hot utility consumption by 700 kW (steady state) and match between the same streams – but in a different sequence relative to existing exchanger E2. The amount of area required by the retrofit is also different. In one design, additional area is required on exchanger E2, and less area is required on exchanger N1. The analysis can show how these differences can affect the heat exchanger performance. The duties of exchanger E2 and the new exchangers are compared and presented in Figure 6.11. Figure 6.11a shows the heat exchanger duty probabilities for the existing exchanger E2 while Figure 6.11b shows the heat exchanger duty probabilities for the new exchangers (identified as N1 in both grid diagrams, Figure 6.5b and Figure 6.5d). In the cases where a large amount of heat transfer area was required (N1 in retrofit design 2 and E2 in retrofit design 4), the spread of possible duties becomes much wider. This is not indicative of the performance of the overall HEN, as it is the utility exchangers that affect cost and target temperatures, but the results do give an insight into how heat transfer area can affect individual recovery exchanger performance. Additional heat transfer area is a common retrofit modification and this comparative analysis could be useful when determining whether to add area to an existing exchanger or to add a new exchanger to the HEN.

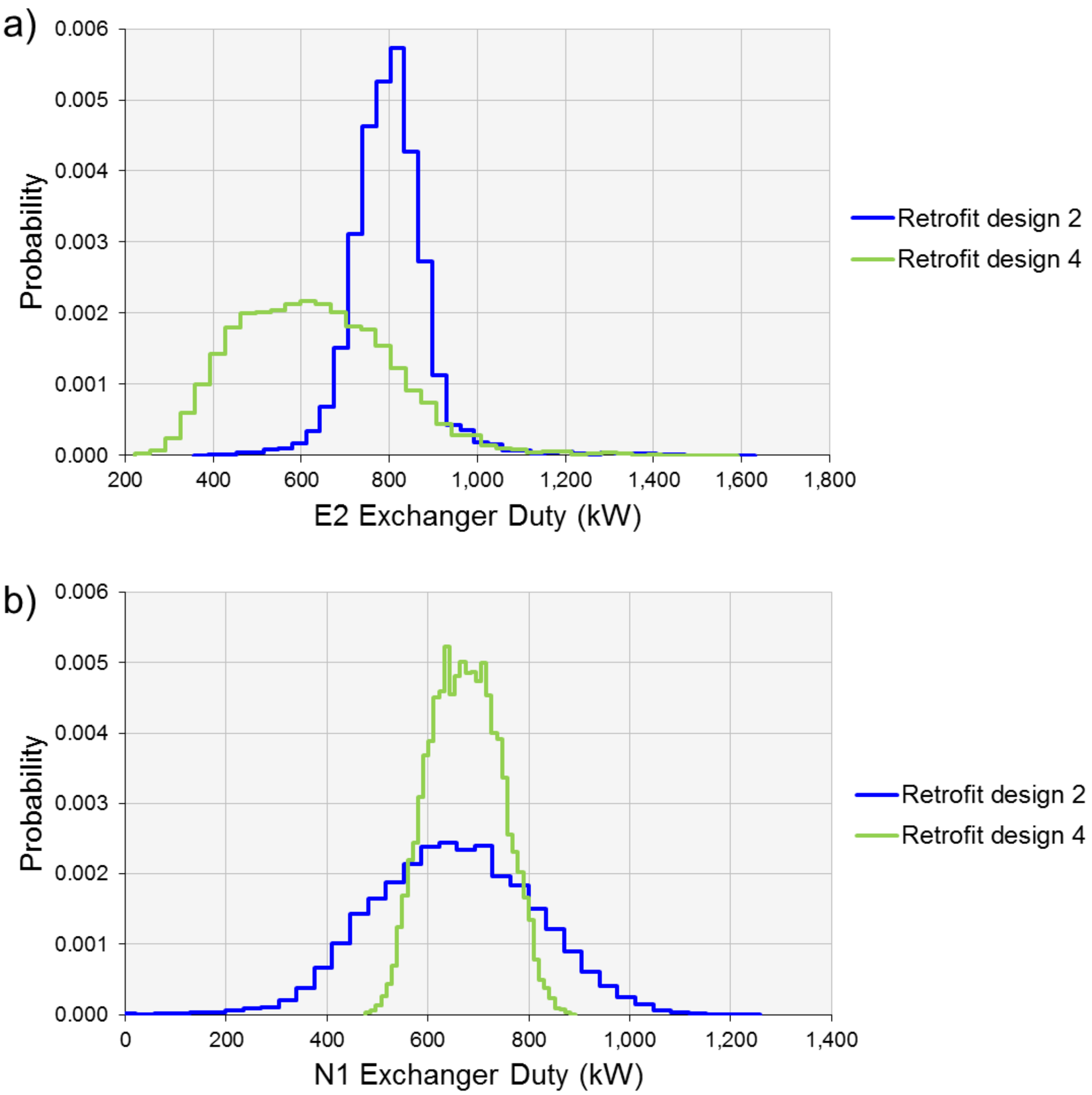


Figure 6.11: Histograms of a) the duty of existing exchanger E2 in retrofit designs 2 and 4, and b) the duty of new exchanger N1 in retrofit designs 2 and 4.

Economic Evaluation and Summary

The MCS results are also used to calculate economic metrics, primarily total retrofit profit (TRP), as an alternative to the economic metrics calculated using design values. These economic results are summarised in Table 6.2. In all retrofit designs, the TRP calculated using the MCS results was less than the steady state TRP by up to 7.7%, suggesting that the analysis with design values could have overestimated the profitability in this illustrative example. In both analyses, retrofit design 1 was most profitable, owing to the large reduction in hot utility consumption (1,250 kW at design). Of the seven retrofit designs examined, retrofit design 1 is likely to be recommended for further business case development – the same conclusion as in Chapter 3 – due to the low inflexibility and high profitability (both estimates). The inflexibility of the other retrofit designs could be reduced further, using the techniques previously discussed for retrofit design 3. As this illustrative example has been used to demonstrate the method and not solve a specific problem, the results for the original retrofit HEN designs are presented in Table 6.2, rather than the zero-inflexibility retrofit designs.

Table 6.2: Summary of economic estimates using non-MCS results and MCS results.

Retrofit Design	Total Retrofit Profit (NZD/y)		Difference (%)	Inflexibility (%)	Capital Cost (NZD)
	Non-MCS	MCS			
1	292,800	271,913	-7.7	0.1	458,999
2	184,352	172,574	-6.8	0	131,789
3	148,380	143,272	-3.6	6.0	172,173
4	182,918	176,951	-3.4	0.1	140,602
5	193,340	186,559	-3.6	3.1	257,209
6	163,642	155,134	-5.5	2.0	259,042
7	150,081	142,260	-5.5	2.8	161,718

In summary, using the MCS-based method has allowed the flexibility of each retrofit HEN design to be assessed. In the cases where there is a non-zero inflexibility, several example strategies are applied to a single case to demonstrate how flexibility can be improved. However, these improvements can come at a cost, i.e., decreased energy savings or additional capital cost. The probable performance of specific heat exchangers can also be analysed, including utility exchangers, which can be used to identify potential problem areas or case-specific insights. The novel method provides tools that can be used to evaluate the different retrofit HEN designs so that the decision-making process is better informed.

6.4 Case Study: Paper Mill

In the application of the novel methods presented in this chapter, the paper mill case study is revisited (Figure 6.12a), using real process stream data to simulate the HEN performance. The goal of this analysis is not to compare several designs against each other, like in the illustrative example. Instead, the retrofit HEN design selected in the previous chapter (Figure 6.12b) is analysed using MCS to analyse how the HEN performance will be affected by this specific retrofit design. The analysis will help to validate the selected retrofit design plan and improve the retrofit design. Different retrofit HEN designs could be investigated, but this is not the goal for this case study.

In this case study, there are two coolers that are not actually used in the real HEN – coolers C3 and C4. These coolers cool the exhaust air streams (EX 1 and EX 2) to 40 °C but, in practice, these exhaust air streams are not cooled to any target temperature and are exhausted to the environment. These coolers represent the surplus of heat that can be recovered from these exhaust air streams, hence their inclusion in the retrofit analysis. In the MCS analysis, the coolers are modelled, but the outlet temperatures of the exhaust air streams are not targeted. Similarly, the outlet temperature of the wastewater stream (WW) needs to be less than or equal to 30 °C but does not need to be cooled to exactly 30 °C. If the cooler duty of C1 would become negative in the MCS, it means that the inlet temperature of the cooler (the outlet of exchanger E3) is less than 30 °C (as the model needs to 'heat' the stream back to 30 °C). This is acceptable for this stream and target temperature. All other streams with a utility exchanger must be cooled or heated to that specific target temperature (as seen on the grid diagrams below). Two streams do not have any utility exchangers present on the stream to maintain the temperature. For stream OI (other inputs), the target temperature can be within ± 10 °C of the steady state temperature of 50 °C. For the repulper stream (RP), the temperature is not controlled, and it does not have a target temperature.

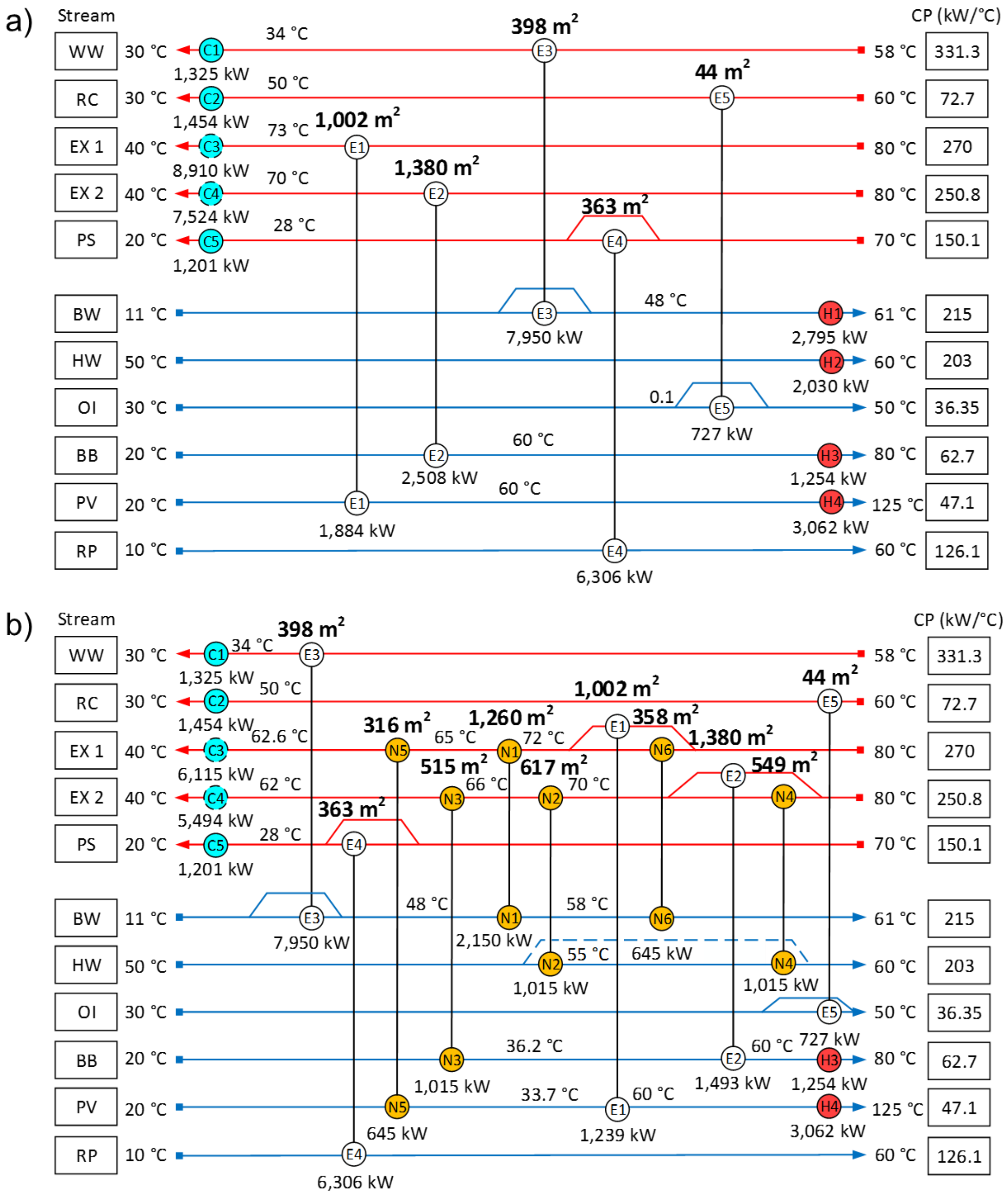


Figure 6.12: a) Grid diagram for the paper mill case study and b) a selected retrofit design (retrofit analysis in Chapter 5) showing the design temperatures and duties.

6.4.1 Input Probability Distributions

Process stream data was extracted for the supply temperature or flow rate of several streams in the paper mill HEN every 15 minutes from over a period of two months. When process stream data was unavailable, a Normal distribution has been used to represent steady state variability in the stream properties. No correlations were identified in the data using @Risk.

@Risk fits several distributions to the available stream data and uses the AIC as a comparative tool to find the best fit. Table 6.3 presents each process stream variable and the probability distribution used to represent the variation for the Monte Carlo Simulation. All Normal distributions have been defined in the same way the probability distributions were defined for the process stream data in the illustrative example.

Table 6.3: Summary of process stream data and the distributions used to represent the variation.

Stream	Probability Distribution	
	Heat Capacity Flow Rate (kW/°C)	Supply Temperature (°C)
WW	Normal	Weibull
RC	Beta General	Laplace
EX 1	Normal	Weibull
EX 2	Normal	Gamma
PS	Weibull	Kumaraswamy
BW	Normal	Normal
HW	Normal	Laplace
OI	Normal	Normal
BB	Normal	Kumaraswamy
PV	Normal	Normal
RP	Kumaraswamy	Normal

Figure 6.13 presents sets of stream data to show how the data collected over time relates to the probability distribution found using @Risk. In Figure 6.13a, three different distributions were applied to the data presented in Figure 6.13a (the supply temperature for stream EX 1). Of these, the Weibull distribution was selected based on the AIC values. Similarly, a Weibull distribution was selected for the stream data in Figure 6.13c (the heat capacity flow rate for stream PS), as seen in Figure 6.13d. Other distributions, such as the Beta General distribution, could also be used; however, the Weibull distribution was deemed to be a better fit.

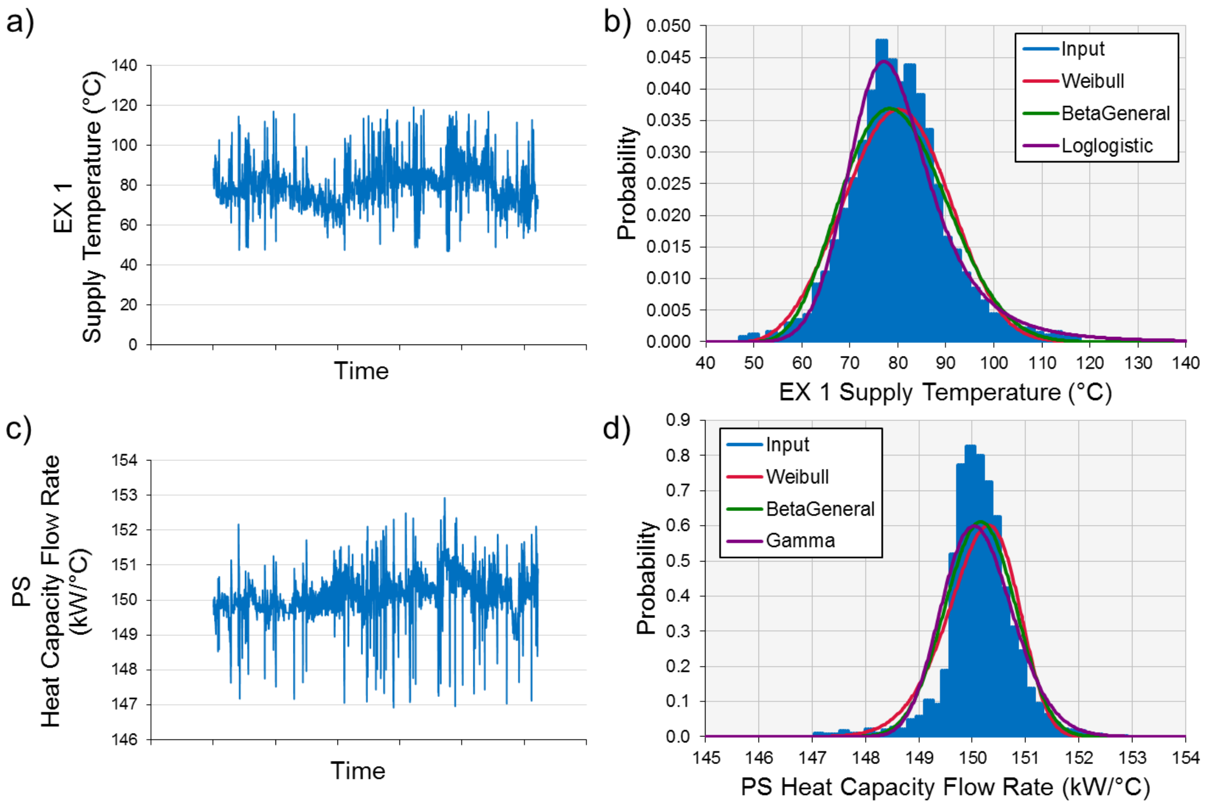


Figure 6.13: Stream data (a, c) and corresponding probability distributions (b, d) for two different process stream variables.

6.4.2 Heat Exchanger Network Models

The actual design information for the heat exchangers in the existing HEN was unavailable. Therefore, as with the illustrative example, recovery exchangers are modelled with the ε-NTU method using the double pipe counter-flow heat exchanger correlations (following Section 4.3.3 for the initial area estimation and then Section 6.3.3 for the model when the area is fixed), and heat transfer coefficients are modelled using Equation 6.8, using the steady state heat transfer coefficients as the design values. Utility exchangers are modelled simply using $Q = CP\Delta T$. Iterative calculations are used to model the four loops in the retrofitted HEN.

While the original HEN features no stream splits, the retrofitted HEN features several stream splits. For the model, the stream split ratios are calculated based on the design values and are kept constant. In both HEN models, there are three bypasses. The first bypass is on the hot-side of exchanger E4 for the control of the target temperature of stream RC (so it does not go below 30 °C. The second bypass is on the cold-side of exchanger E3 for the control of the target temperature of stream BW. The third bypass is on the cold-side of exchanger E5 so that the temperature of stream OI can be controlled. This bypass has a default bypass fraction of 0.1, while the other bypasses default at zero – bypass closed.

6.4.3 Monte Carlo Simulation Results

The Monte Carlo Simulation is conducted with 10,000 iterations of calculations. As with the illustrative example, all HENs (i.e., initial and retrofit, with and without bypasses) are modelled simultaneously using the same inputs for each iteration.

Flexibility Analysis

The target temperatures (including soft temperature targets) are outlined in the introduction of the case study – several target temperatures are controlled, including a soft temperature target with tolerances of ±10 °C. Considering the initial HEN, without bypasses, the following figures present the failure probabilities for the target temperatures controlled by coolers C2 and C5 (Figure 6.14a) and the heaters (Figure 6.14b). Two utility exchangers (cooler C5 and heater H1) have a non-zero probability of failing to meet target temperatures (on streams PS and BW), as well as the non-utility-controlled target temperature of stream OI (Figure 6.14c). These failure probabilities result in an inflexibility of 6.2% for the initial HEN without bypasses.

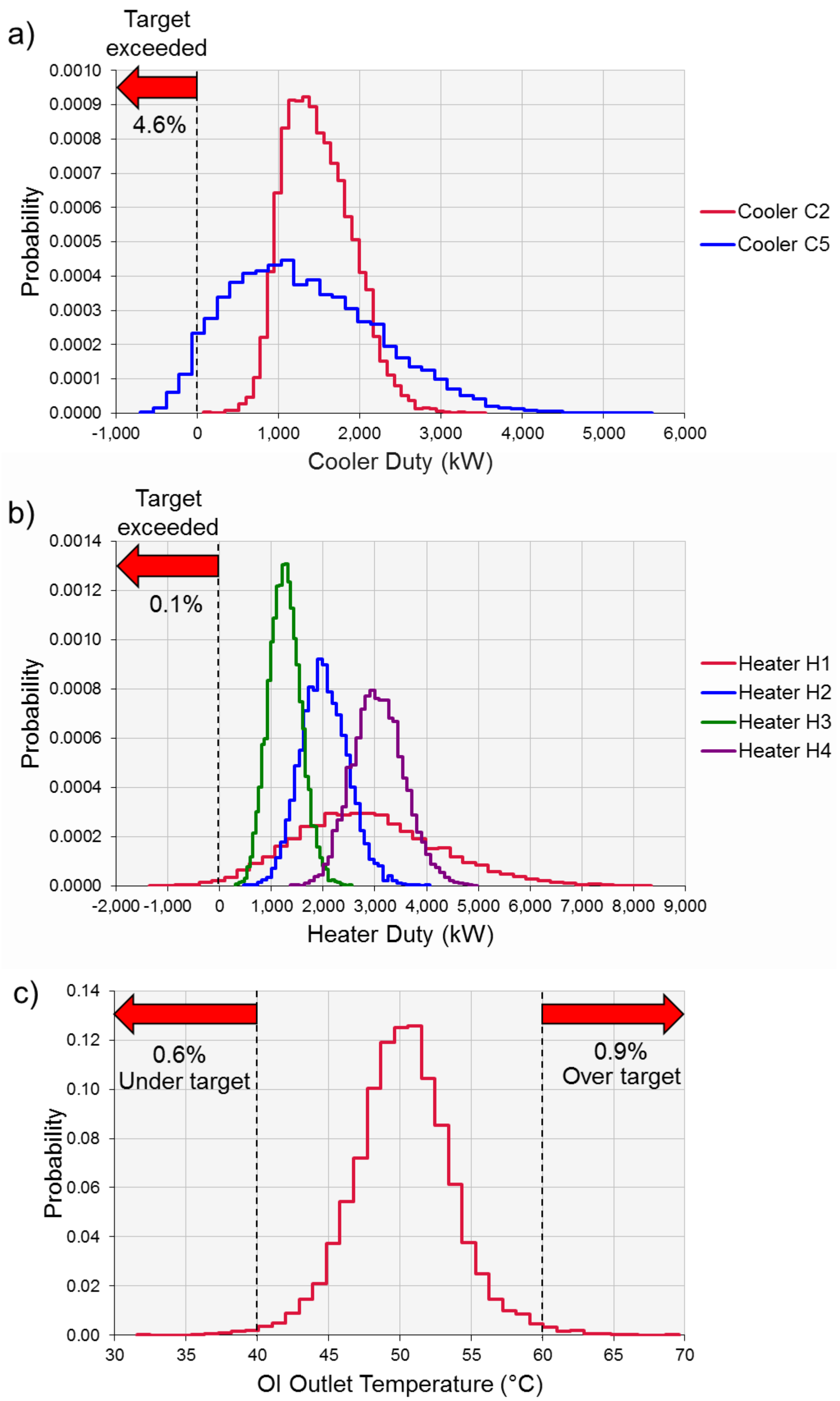


Figure 6.14: Flexibility analysis of a) the duty for the coolers C2 and C5, b) the duty for each of the four heaters, and c) the outlet temperature for the stream OI in the initial paper mill HEN (without bypasses).

With bypasses, the failure probability for cooler C5 and heater H1 is reduced to zero (Figure 6.15a), and the target temperature of stream OI does not exceed the upper limit of 60 °C; however, there is still a 0.4% probability of a final temperature less than the lower limit of 40 °C (Figure 6.15b). This means that the inflexibility of the initial HEN with bypasses is 0.4%, although, as the target temperature is already a soft target, the 0.4% chance of temperature outside of 40-60 °C is unlikely to have significant adverse effects. The bypass on the cold-side of E5 has a default bypass fraction of 0.1 resulting in a minor increase in heat exchanger area for the exchanger E5 (as seen in Figure 6.12a). The use of bypasses does not affect any other target temperatures.

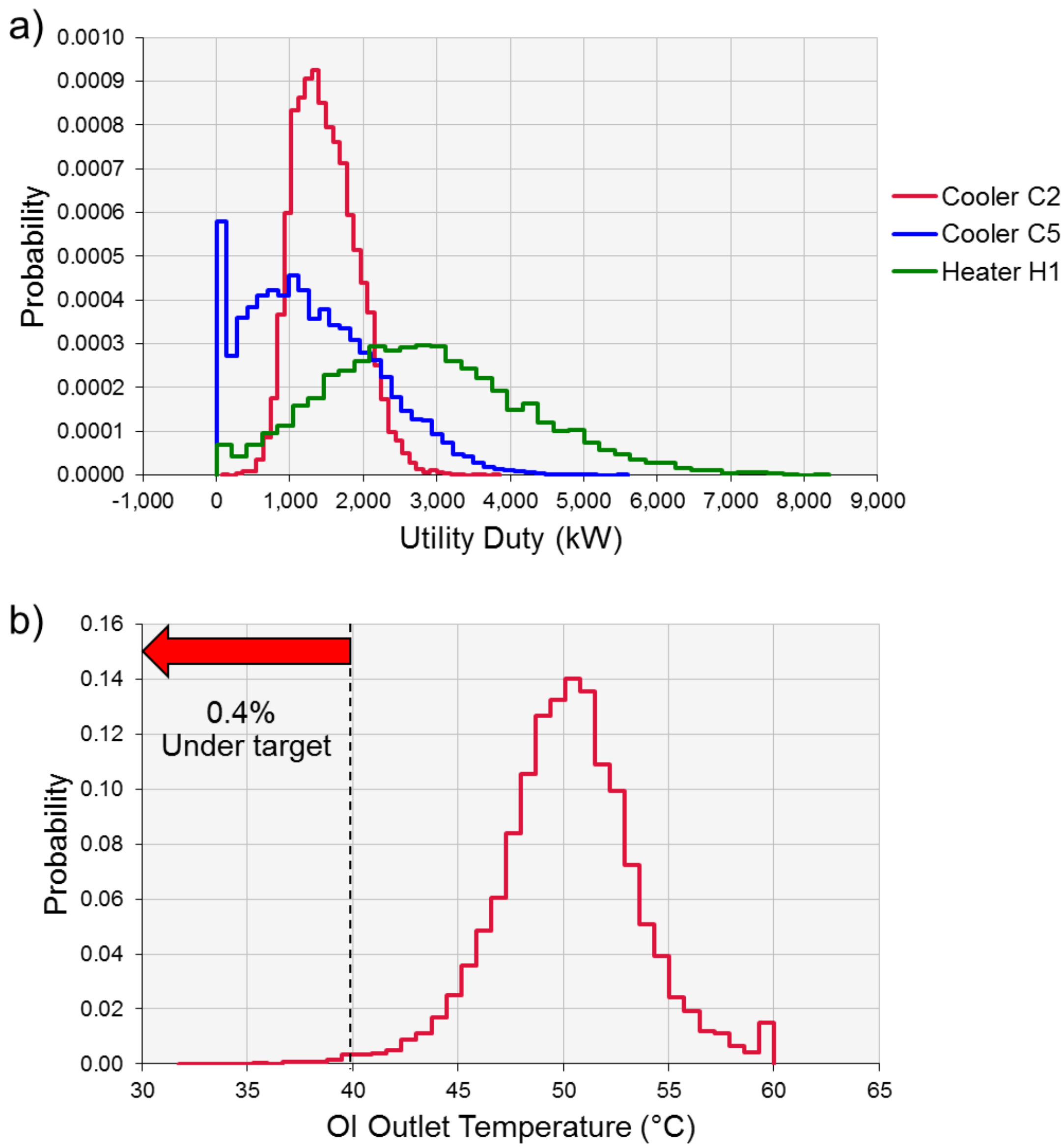


Figure 6.15: Flexibility analysis of a) the duty for the cooler C5 and heater H1, and b) the outlet temperature for the stream OI in the initial paper mill HEN (with bypasses).

The modifications to the retrofit HEN design lead to a high inflexibility (51.3%) mostly owing to the stream HW target temperature. The combination of improved heat recovery and process stream variability lead to the temperature exceeding the target 50.8% of the time (Figure 6.16a). As a solution, the new exchangers N2 and N4 can be bypassed to allow the stream's cold supply temperature to cool the heater inlet through mixing. Using this bypass, the failure probability for the stream HW target temperature is reduced from 50.8% to 3.6%; however, the actual temperature deviation that this 3.6% failure probably represents is less than 0.0025 °C and is within a reasonable margin (Figure 6.16b). For comparison, with the additional bypass, the deviation can reach over 1 °C.

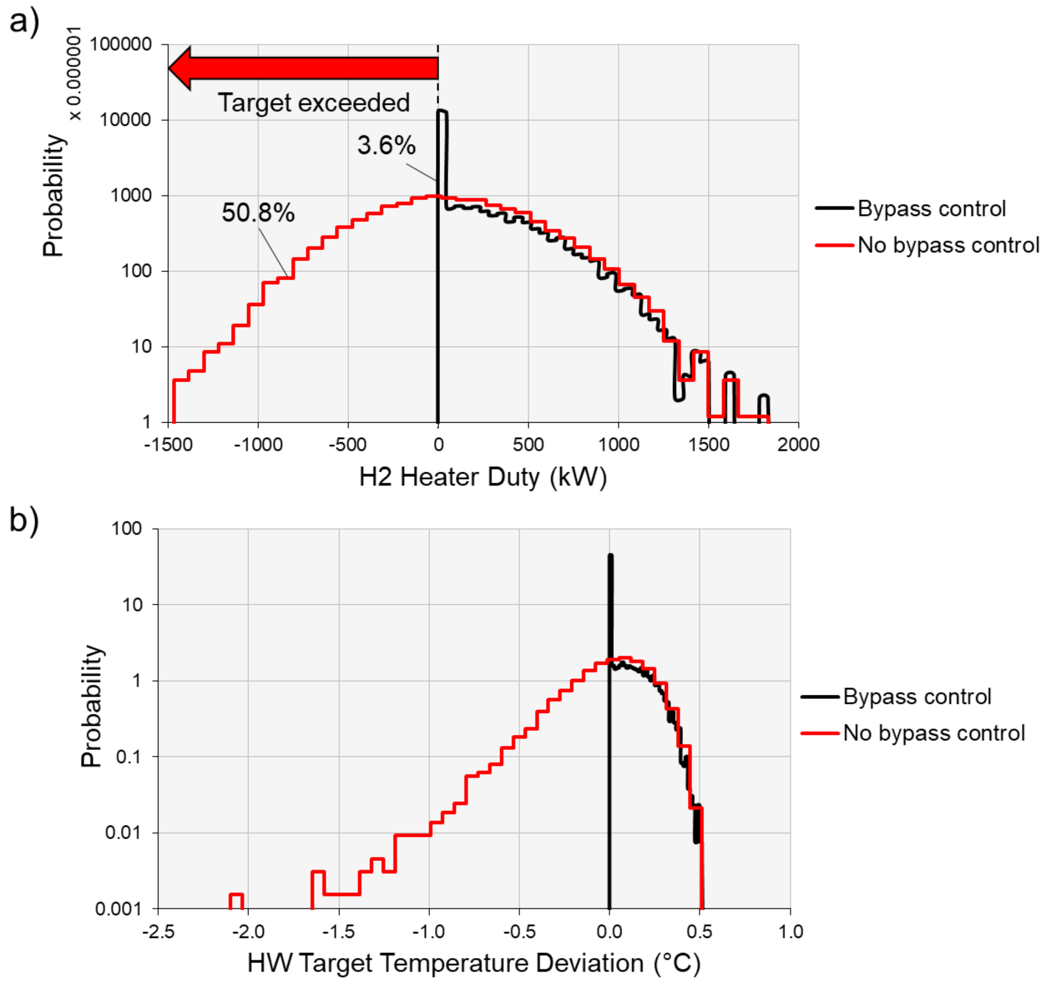


Figure 6.16: a) Histograms of the duty of heater H2 in the retrofitted HEN with and without bypass control over exchangers N2 and N4 and b) histograms of the temperature deviation (from the target) for the target temperature of stream HW, with and without bypass control.

A similar result would have likely been observed for stream BW (heater H1), but the existing bypass helps to maintain the target (with a 0.1% failure probability and a maximum negative deviation of 0.005 °C). The failure probability of the OI temperature target remains unchanged as the retrofit modifications did not affect that stream.

The final retrofit HEN has an inflexibility of 4.1%, but the temperature deviations indicate that this is acceptable. The summary of the flexibility analysis is presented in Table 6.4. When the failure probabilities are independent of each other (such as in this case), the inflexibility is equal to the sum of the failure probabilities. In other situations, there may be a variation in a stream that propagates effects to several target temperatures, causing them to 'fail' to be met. The inflexibility would be less than the sum because inflexibility is a measure of the likelihood of the overall HEN to fail to meet targets.

Table 6.4: Summary of the flexibility analysis for the paper mill case study.

Scenario		Target Temperature Failure (%)				Inflexibility (%)
		PS	BW	HW	OI	
Initial HEN	No bypass	4.6	0.1	0	1.5	6.2
	With bypass	0	0	0	0.4	0.4
Retrofit HEN	No new bypass	0	0.1	50.8	0.4	51.3
	With new bypass	0	0.1	3.6	0.4	4.1

Histograms

The histograms in this section will examine the retrofit HEN design with the additional bypass. Figure 6.17a shows the histograms for each cooler in the retrofitted HEN, including coolers C3 and C4, which are merely representative of the amount of heat surplus available, and cooler C1, which is only required to cool the temperature of stream WW to at least 30 °C. The probability distributions for coolers C3 and C4 show that there is still a significant amount of heat that is being rejected to the environment through the exhaust air, despite the retrofit modifications that have recovered heat from these streams. Cooler C5 has a high probability of duty close to zero, showing that the heat recovery has the potential to over-cool the stream. Additionally, cooler C2 has a small spread of possible duties while cooler C1 has a very large spread. In the case of cooler C1, it is fortunate that the cost of cooling water is not high as the duty has a high probability of exceeding 10,000 kW.

The steady state variability of the heaters is much less than the coolers, as seen in Figure 6.17b. These heaters do not have massive peak duties either and stay within a few 1,000 kW of the steady state or mean duty. Both heaters H1 and H2 have a high probability of zero duty, owing to the bypass control and improved heat recovery in the HEN.

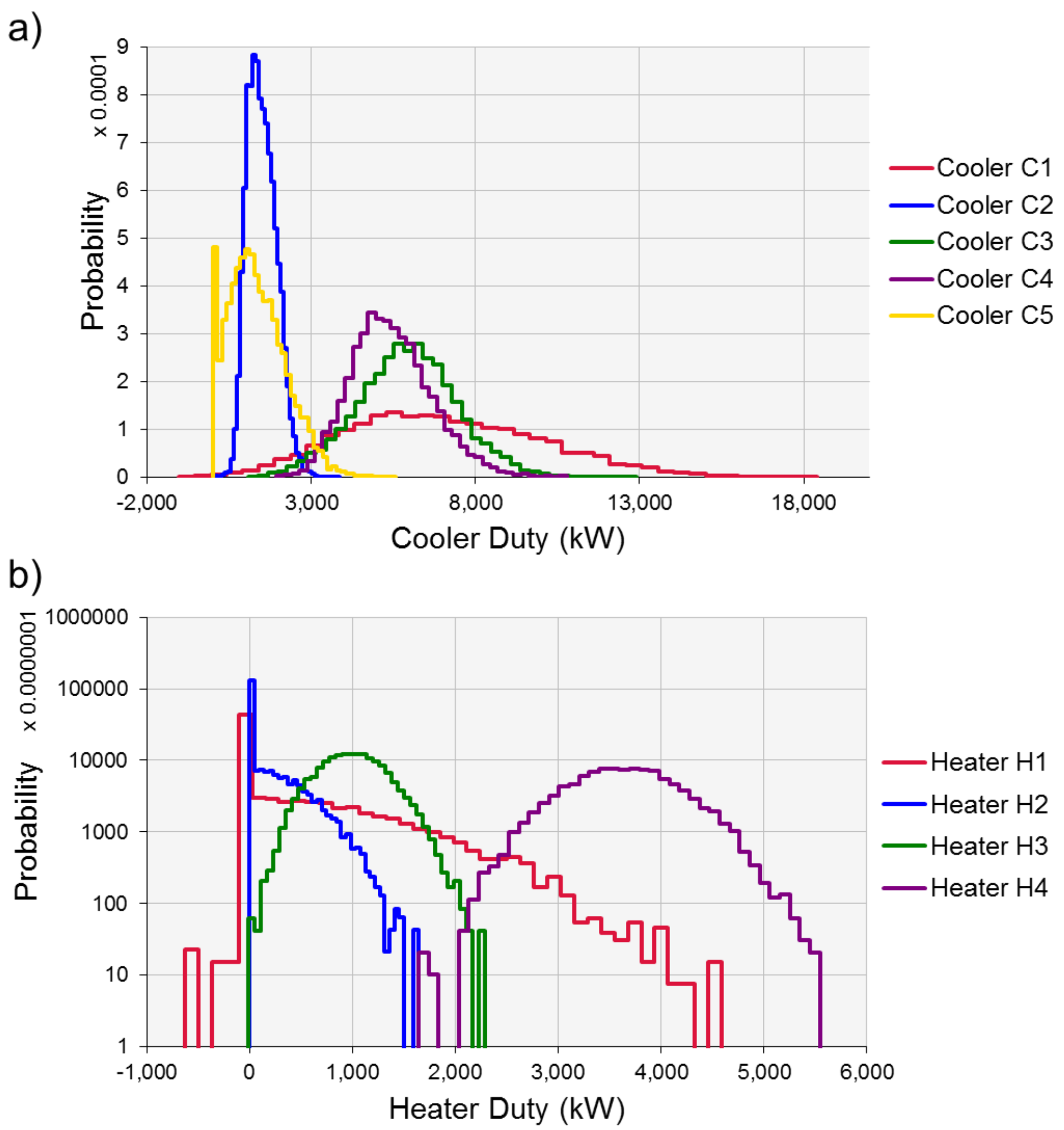


Figure 6.17: Histograms for a) the duty of each cooler in the retrofitted HEN, and b) the duty of each heater in the retrofitted HEN.

The MCS analysis also shows that one of the heaters (H4) increases its utility consumption as a response to the retrofit modifications and subsequent modifications for flexibility. Figure 6.18 compares the histograms for the heater duty in both the original HEN and the retrofitted HEN and shows even the mean duty has increased by almost 600 kW. As this heater was not targeted by any of the Retrofit Bridges, the cause of this increase is the effect of the retrofit on exchanger E1 (the cold stream in the match is controlled by heater H4). These downstream effects are found using MCS. The increase in utility consumption may substantially decrease the profitability of the retrofit design, in addition to the extra utility in heaters H1 and H2 (compared to the original retrofit design).

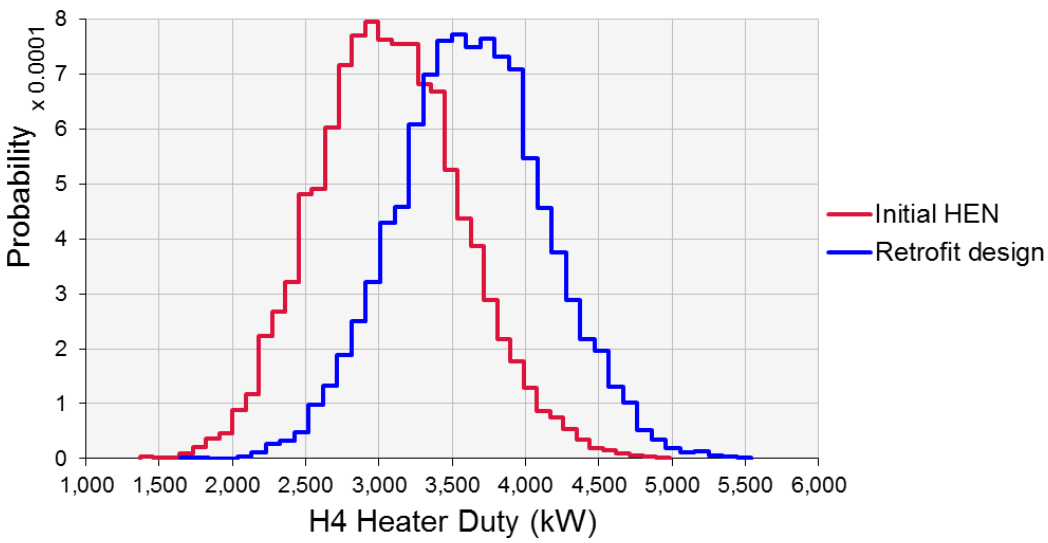


Figure 6.18: Comparison of the histograms of H4 heater duty in the original HEN design and the retrofitted HEN design.

Economic Evaluation and Summary

The economic evaluation for the paper mill case study involves the comparison of the total retrofit profit estimated using the steady state results and the MCS results. Only one retrofit design is considered in this analysis, but others could be analysed using the same process. From Chapter 5, the steady state TRP is 778,943 NZD/y. When accounting for the steady state variability in process stream data, and the use of heaters H1 and H2 and the increase in H4 duty, the TRP based on MCS results is 644,934 NZD/y. This is a decrease of 17.2%. The analysis with the design values (non-MCS) treats the duty of heaters H1 and H2 as zero; however, these utilities are still used (as demonstrated above) and will still contribute to the total utility cost. With the MCS results and analysis, greater confidence can be found in the TRP estimate and the overall performance of the retrofitted HEN.

6.5 Limitations

While Monte Carlo Simulation is a useful tool for using variable process stream data to compute variable outputs, there are several limitations. The major limitation is the need to obtain enough data from an extended period to characterise the variability meaningfully. Getting this data from industrial processing plants can be difficult for several reasons, including a lack of measurement instrumentation at the plant itself. The flow rates and temperatures can be represented by a distribution selected by an expert, but the results are less meaningful than if the real measured data was used. Other limitations include the lack of considerations towards actual process control systems, the dynamic nature of the HEN, and heat exchanger fouling. Dynamic behaviour is especially important when considering the deadtime and the time taken for variations to take effect in heat exchangers and then propagate throughout the HEN or be resolved via process control. The analysis presented in this chapter does not cover these aspects, instead focusing on the ability of the HEN to be flexible for different steady state conditions. Dynamic analysis is the next required step for this type of work surrounding flexibility and controllability.

The flexibility analysis in this chapter is an indicative tool and is not meant to replace a detailed analysis, but rather give a simple estimate of flexibility in the early stages of retrofit design, where it is often neglected. If the data is readily available, then the method can be applied to a real-life HEN retrofit project to provide an extra level of analysis, despite these limitations.

The MCS also relies on an accurate model of the HEN, which is not always so easy to develop, especially for larger problems with complexities such as stream splits and heat exchanger loops. The time taken to prepare the models is a barrier to this analysis. With increased digitalisation of plant information, this limitation (and others) may be alleviated in the future.

6.6 Conclusions

The novel method has been demonstrated with two examples. The first example was the illustrative example, presenting a final analysis for the four-stream HEN that has been used throughout this thesis. The illustrative example was used to demonstrate how different types of data could be represented as probability distributions and how those variable inputs (steady state variations) could affect HEN performance. Using the MCS-based analysis, the seven retrofit designs could be compared and evaluated based on their estimated inflexibility (an indicator). The second example was the paper mill industrial case study, using historical process stream data as the basis for steady state stream variability. In both cases, the usefulness of the method was demonstrated, especially in determining the inflexibility of the HENs (which could then be improved through further retrofit modifications). The histograms show how the variation in process stream data can affect the network (including downstream effects that were not considered by the original analysis), as well as how existing exchangers or utilities can behave in different configurations. This information is then used in the decision-making process, helping to identify the optimal retrofit design that can be carried forward into a more detailed design. Detailed analysis is still required before a project can be realised, as well as an in-depth analysis of the dynamic behaviour of the HEN and how it dynamically responds to variations and disturbances, but the novel method provides the tools for a simple analysis that can help to distinguish designs and prevent the selection of designs that would be uncontrollable or inflexible.

Chapter 7

Conclusions and Recommendations for Future Work

7.1 Conclusions

The developed method for the automated retrofit design and analysis of heat exchanger networks features several contributions that can assist in unlocking significant and cost-effective energy and emission savings. Two new diagrammatical retrofit tools have been introduced. The first was the Modified Energy Transfer Diagram (METD), which improved the representation of the Energy Transfer Diagram and emphasised the heat surpluses and deficits in the total cascade of process heat in a heat exchanger network. The METD also strengthened the links to Pinch Analysis concepts (within the tool rather than in a comparative discussion) such as the Pinch temperature, the Grand Composite Curve, and Pinch violations. These developments strongly improve the identification of viable retrofit modifications for a given HEN, also known as Retrofit Bridges, as well as enable the calculation of energy savings. While the Energy Transfer Diagram is a capable tool, the METD is a better tool for performing retrofit analysis on a HEN.

The second diagrammatical retrofit tool was the Heat Surplus-Deficit Table (HSDT); however, the HSDT is primarily a numerical tool adapted from the Problem Table Algorithm from conventional Pinch Analysis. Like the Problem Table Algorithm, the HSDT provides significant information about the net enthalpy (i.e., net surplus or deficit) in each temperature interval. These enthalpies facilitate the identification and quantification of Retrofit Bridges – i.e., a sequence of modifications that reduces demand for hot and cold utility. The METD and HSDT have individual strengths that combine for an improved retrofit analysis: the METD establishes the retrofit savings target and highlights Pinch violations, while the HSDT is a simple way to quantify the amount of heat transfer that is feasible in each Retrofit Bridge.

The tabular format of the HSDT also allowed the search for Retrofit Bridges to be automated using the Automated Retrofit Targeting (ART) algorithm. ART addresses a major limitation in graphical retrofit analysis methods in that large problems become difficult to solve by visual inspection alone. Using ART, feasible and economical Retrofit Bridges could be quickly identified using computation. For the industrial case studies, such as the petrochemical complex, with a large number of process streams and heat exchanger units, there can be numerous potential Retrofit Bridges. ART allows the search for Retrofit Bridges to be automated without removing the usefulness of the METD or HSDT and without requiring computational expense. ART has also enabled each Retrofit Bridge to be used to create a retrofit HEN design automatically, improving the ability to evaluate and compare retrofit designs based on capital investment and profitability. To reduce the computational burden, as well as the number of ineffective Retrofit Bridges, several performance-based constraints were applied to the search showing that great reductions in search space could be achieved without excluding the economic results. These performance constraints represented the trade-off between energy savings and capital cost and were vital to the development of ART.

The final significant contribution was the implementation of multi-stage retrofit analysis for energy retrofit planning. Multi-stage retrofit analysis refers to the application of multiple retrofit stages to a single HEN for greater energy savings. It was shown that applying additional retrofit stages could reduce the payback time while significantly increasing the total retrofit profit. The only limitation is the initial capital investment. Multi-stage retrofit analysis is largely absent from the literature despite these benefits, but with ART and the developed spreadsheet, multi-stage retrofit analysis has been made possible – outside of the mathematical programming space in which the optimisation of superstructures may lead to the same retrofit HEN designs as those that consider multiple Retrofit Bridges.

Furthermore, as a tool for retrofit design evaluation, Monte Carlo Simulation was used for the first time to evaluate retrofitted heat exchanger networks. Monte Carlo Simulation proved valuable in understanding the steady state performance of retrofitted networks in variable conditions based on the historical variability in process streams. Several key insights can be obtained through this stochastic analysis, including information about the probable economic performance and HEN flexibility. This method for design evaluation is not limited to Bridge Analysis and is considered separate from Bridge Analysis, but nonetheless, can be used to evaluate and compare the retrofit designs that are produced from Retrofit Bridges.

All computation is implemented in Microsoft Excel™ with the aid of Visual Basic for Application, avoiding expensive and time-consuming solvers that are typically relied upon for mathematical programming-based retrofit design methods. The developed spreadsheet tool is capable of rigorously searching and solving for Retrofit Bridges. The spreadsheet tool is a critical output of this thesis and could provide industrial practitioners with an easy-to-use retrofit tool to identify energy saving opportunities. Through effective retrofit of heat exchanger networks, the demand for process heat in industrial processing plants can be economically reduced, helping to reduce the carbon emissions related to fossil fuel-generated process heat and create an easier path for fuel-switching and sustainability.

7.2 Recommendations for Future Work

Spatial Arrangement of the Heat Exchanger Network

The spatial arrangement of the HEN is an area that has not been researched sufficiently. One key paper has been published by Pouransari and Maréchal (2014), but there is room for a refinement of the method for retrofit analysis. When looking at HEN retrofit problems, there is no consideration for the real-life location of process streams and heat exchanger units. Piping costs and associated costs may show that certain matches are more favourable than others. Process safety may also be a factor. With ART and the spreadsheet tool, a coordinate system could be used to keep track of exchanger units and constrain the Retrofit Bridge search to exclude distant matches or matches that would require high piping costs, etc. In a brief exploration of this concept, Lal et al. (2018) published a conference paper that featured piping costs based on plant layout in the Retrofit Bridge analysis; however, future work could look into the development of a more robust methodology for considering spatial arrangement and piping costs using ART.

Heat Transfer Enhancement

Another major part of retrofit analysis for HENs is heat transfer enhancement (HTE), as identified in the literature review. Generally, HTE improves heat transfer (at the cost of pressure drop) by increasing the overall heat transfer coefficient, reducing the need for retrofit area. In a retrofit study, where existing exchangers can be modified and require additional heat transfer area, it has been shown that HTE can reduce the required amount of area – even to zero. The role of Bridge Analysis is to identify Retrofit Bridges and create pathways, but the only retrofit modifications considered are the addition of new heat exchangers to the HEN or the addition of heat transfer area to existing exchangers. Developing ART and the spreadsheet to check the viability of HTE as a retrofit modification as well is one of the next major stages for retrofit analysis (only applicable in some situations, including flexibility improvement). The consequence of HTE on pressure drop will also need to be considered, as well as the effect on multi-stage retrofitting.

There are many works in literature for determining how HTE should be used, such as the work by Akpomiemie and Smith (2015). These methods can provide guidance on how to integrate HTE into Bridge Analysis; however, the challenge will be to model the effect of HTE. It is possible that Monte Carlo Simulation may be able to predict the probable performance of a heat exchanger retrofitted with HTE.

Optimised Heat Exchanger Sizing

In the flexibility analysis in Chapter 6, it was shown how modifying the retrofit area of new and existing heat recovery exchangers could affect the inflexibility, as well as the utility consumption. This presents an area for future work, as Monte Carlo Simulation could be used to formally optimise the assignment of retrofit area for increased flexibility or increased profitability (total retrofit profit). The allocation of retrofit area could also be explored using a combination of the Cost Derivative Method (Timothy G. Walmsley, Walmsley, Morrison, et al., 2014) and Monte Carlo Simulation, utilising flow-on factors and process stream variability for improved analysis of retrofit HEN designs.

Dynamic Analysis

The Monte Carlo Simulation highlighted the importance of an analysis based around the flexibility of a HEN, especially when proposing retrofit modifications. The next step for this body of work is a detailed dynamic analysis. Currently, the MCS analysis is used to evaluate the effect of steady state variations without any consideration to the dynamic behaviour of heat exchangers and how the effect of variations can propagate throughout a retrofitted HEN. Dynamic analysis will provide a more thorough understanding of the behaviour of a retrofitted HEN and is necessary before implementation of a retrofit design. The MCS analysis should help to inform the subsequent dynamic analyses that are recommended for future.

Spreadsheet Tool Development

With algorithms such as ART in place, there is significant potential to allow for additional considerations or constraints in the developed spreadsheet tool. Presently, the considered constraints are based on energy savings, the number of modifications, retrofit area, and payback. Other constraints can include piping constraints (mentioned above), pressure drop constraints, profitability, and more. Economic metrics such as Net Present Value and Internal Rate of Return would also be useful constraints/metrics to incorporate into ART and the spreadsheet tool. The type of constraints needed will depend on the project's requirements and what is able to be input to the spreadsheet tool.

References

Abbas, H., Wiggins, G., Lakshmanan, R., & Morton, W. (1999). Heat exchanger network retrofit via constraint logic programming. *Computers & Chemical Engineering*, *23, Supplement*, S129–S132. https://doi.org/10.1016/S0098-1354(99)80033-7

Abbood, N. K., Manan, Z. A., & Wan Alwi, S. R. (2012). A combined numerical and visualization tool for utility targeting and heat exchanger network retrofitting. *Journal of Cleaner Production*, *23*(1), 1–7. https://doi.org/10.1016/j.jclepro.2011.10.020

Akpomiemie, M. O., & Smith, R. (2015). Retrofit of heat exchanger networks without topology modifications and additional heat transfer area. *Applied Energy*, *159*, 381–390. https://doi.org/10.1016/j.apenergy.2015.09.017

Akpomiemie, M. O., & Smith, R. (2016). Retrofit of heat exchanger networks with heat transfer enhancement based on an area ratio approach. *Applied Energy*, *165*, 22–35. https://doi.org/10.1016/j.apenergy.2015.11.056

Akpomiemie, M. O., & Smith, R. (2017). Pressure drop considerations with heat transfer enhancement in heat exchanger network retrofit. *Applied Thermal Engineering*, *116*, 695–708. https://doi.org/10.1016/j.applthermaleng.2017.01.075

Akpomiemie, M. O., & Smith, R. (2018). Cost-effective strategy for heat exchanger network retrofit. *Energy*, *146*, 82–97. https://doi.org/10.1016/j.energy.2017.09.005

Al-Riyami, B. A., Klemeš, J. J., & Perry, S. (2001). Heat integration retrofit analysis of a heat exchanger network of a fluid catalytic cracking plant. *Applied Thermal Engineering*, *21*(13), 1449–1487. https://doi.org/10.1016/S1359-4311(01)00028-X

Arnold, U., & Yildiz, Ö. (2015). Economic risk analysis of decentralized renewable energy infrastructures – A Monte Carlo Simulation approach. *Renewable Energy*, *77*, 227–239. https://doi.org/10.1016/j.renene.2014.11.059

Arya, D., & Bandyopadhyay, S. (2018). Stochastic Pinch Analysis for Resource Allocation Networks with Multiple Resources. *Chemical Engineering Transactions*, *70*, 1441–1446. https://doi.org/10.3303/CET1870241

Asante, N. D. K., & Zhu, X. X. (1997). An Automated and Interactive Approach for Heat Exchanger Network Retrofit. *Chemical Engineering Research and Design*, *75*(3), 349–360. https://doi.org/10.1205/026387697523660

Athier, G., Floquet, P., Pibouleau, L., & Domenech, S. (1998). A mixed method for retrofiting heat-exchanger networks. *Computers & Chemical Engineering*, *22*, S505–S511. https://doi.org/10.1016/S0098-1354(98)00094-5

Atkins, M. J., Morrison, A. S., Walmsley, M. R. W., & Riley, J. (2008). *Non-Continuous Pinch Analysis of a Paper Machine in an Integrated Kraft Pulp & Paper Mill*. CHISA 2008.

Ayotte-Sauvé, E., Ashrafi, O., Bédard, S., & Rohani, N. (2017). Optimal retrofit of heat exchanger networks: A stepwise approach. *Computers & Chemical Engineering*, *106*, 243–268. https://doi.org/10.1016/j.compchemeng.2017.06.008

Badar, M. A., Zubair, S. M., & Sheikh, A. K. (1993). Uncertainty analysis of heat-exchanger thermal designs using the Monte Carlo simulation technique. *Energy*, *18*(8), 859–866. https://doi.org/10.1016/0360-5442(93)90063-J

Bagajewicz, M., Valtinson, G., & Nguyen Thanh, D. (2013). Retrofit of Crude Units Preheating Trains: Mathematical Programming versus Pinch Technology. *Industrial & Engineering Chemistry Research*, *52*(42), 14913–14926. https://doi.org/10.1021/ie401675k

Bakar, S. H. A., Hamid, Mohd. K. Abd., Alwi, S. R. W., & Manan, Z. A. (2015). Effect of Delta Temperature Minimum Contribution in Obtaining an Operable and Flexible Heat Exchanger Network. *Energy Procedia*, *75*, 3142–3147. https://doi.org/10.1016/j.egypro.2015.07.648

Bakar, S. H. A., Hamid, Mohd. K. Abd., Alwi, S. R. W., & Manan, Z. A. (2016). Selection of minimum temperature difference (ΔTmin) for heat exchanger network synthesis based on trade-off plot. *Applied Energy*, *162*, 1259–1271. https://doi.org/10.1016/j.apenergy.2015.07.056

Bakhtiari, B., & Bedard, S. (2013). Retrofitting heat exchanger networks using a modified network pinch approach. *Applied Thermal Engineering*, *51*(1–2), 973–979. https://doi.org/10.1016/j.applthermaleng.2012.10.045

Barbaro, A., & Bagajewicz, M. J. (2005). New rigorous one-step MILP formulation for heat exchanger network synthesis. *Computers & Chemical Engineering*, *29*(9), 1945–1976. https://doi.org/10.1016/j.compchemeng.2005.04.006

Barreto, H., & Howland, F. (2005). *Introductory Econometrics: Using Monte Carlo Simulation with Microsoft Excel*. Cambridge University Press.

Benjamin, M. F. D., Tan, R. R., & Razon, L. F. (2017). Assessing the Sensitivity of Bioenergy Parks to Capacity Disruptions using Monte Carlo Simulation. *Chemical Engineering Transactions*, *56*, 475–480.

Biyanto, T. R., Gonawan, E. K., Nugroho, G., Hantoro, R., Cordova, H., & Indrawati, K. (2016). Heat exchanger network retrofit throughout overall heat transfer coefficient by using genetic algorithm. *Applied Thermal Engineering*, *94*, 274–281. https://doi.org/10.1016/j.applthermaleng.2015.10.146

Björk, K.-M., & Nordman, R. (2005). Solving large-scale retrofit heat exchanger network synthesis problems with mathematical optimization methods. *Chemical Engineering and Processing: Process Intensification*, *44*(8), 869–876. https://doi.org/10.1016/j.cep.2004.09.005

Bonhivers, J.-C., Alva-Argaez, A., Srinivasan, B., & Stuart, P. R. (2017). New analysis method to reduce the industrial energy requirements by heat-exchanger network retrofit: Part 2 – Stepwise and graphical approach. *Applied Thermal Engineering*, *119*, 670–686. https://doi.org/10.1016/j.applthermaleng.2015.05.085

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. https://doi.org/10.1016/j.applthermaleng.2013.10.046

Bonhivers, J.-C., Moussavi, A., Alva-Argaez, A., & Stuart, P. R. (2016). Linking pinch analysis and bridge analysis to save energy by heat-exchanger network retrofit. *Applied Thermal Engineering*, *106*, 443–472. https://doi.org/10.1016/j.applthermaleng.2016.05.174

Bonhivers, J.-C., Moussavi, A., Hackl, R., Sorin, M., & Stuart, P. R. (2019). Improving the network pinch approach for heat exchanger network retrofit with bridge analysis. *Canadian Journal of Chemical Engineering*, *97*(3), 687–696. Scopus. https://doi.org/10.1002/cjce.23422

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. https://doi.org/10.1016/j.applthermaleng.2014.04.078

Bonhivers, J.-C., Svensson, E., Berntsson, T., & Stuart, P. R. (2014). Comparison between pinch analysis and bridge analysis to retrofit the heat exchanger network of a kraft pulp mill. *Applied Thermal Engineering*, *70*(1), 369–379. https://doi.org/10.1016/j.applthermaleng.2014.04.052

Bonhivers, J.-C., Svensson, E., Sorin, M. V., Berntsson, T. S., & Stuart, P. R. (2015). Energy transfer diagram for site-wide analysis and application to a kraft pulp mill. *Applied Thermal Engineering*, *75*, 547–560. https://doi.org/10.1016/j.applthermaleng.2014.09.045

Bozdogan, H. (1987). Model selection and Akaike's Information Criterion (AIC): The general theory and its analytical extensions. *Psychometrika*, *52*(3), 345–370. https://doi.org/10.1007/BF02294361

Briones, V., & Kokossis, A. (1996). A new approach for the optimal retrofit of heat exchanger networks. *Computers & Chemical Engineering*, *20, Supplement 1*, S43–S48. https://doi.org/10.1016/0098-1354(96)00018-X

Briones, V., & Kokossis, A. C. (1999a). Hypertargets: A Conceptual Programming approach for the optimisation of industrial heat exchanger networks — II. Retrofit design. *Chemical Engineering Science*, *54*(4), 541–561. https://doi.org/10.1016/S0009-2509(98)00236-X

Briones, V., & Kokossis, A. C. (1999b). Hypertargets: A Conceptual Programming approach for the optimisation of industrial heat exchanger networks—I. Grassroots design and network complexity. *Chemical Engineering Science*, *54*(4), 519–539. https://doi.org/10.1016/S0009-2509(98)00235-8

Briones, V., & Kokossis, A. C. (1999c). Hypertargets: A Conceptual Programming approach for the optimisation of industrial heat exchanger networks—Part III. Industrial applications. *Chemical Engineering Science*, *54*(5), 685–706. https://doi.org/10.1016/S0009-2509(98)00237-1

Bulatov, I. (2005). Retrofit Optimization Framework for Compact Heat Exchangers. *Heat Transfer Engineering*, *26*(5), 4–14. https://doi.org/10.1080/01457630590927273

Çengel, Y. A. (2007). *Heat and Mass Transfer: A Practical Approach* (3rd ed.). McGraw-Hill Higher Education.

Chen, X., Wang, R. Z., & Du, S. (2017). Heat integration of ammonia-water absorption refrigeration system through heat-exchanger network analysis. *Energy*, *141*, 1585–1599. https://doi.org/10.1016/j.energy.2017.11.100

Ciric, A. R., & Floudas, C. A. (1990). A mixed integer nonlinear programming model for retrofitting heat-exchange networks. *Industrial & Engineering Chemistry Research*, *29*(2), 239–251.

Clarke, D. D., Vasquez, V. R., Whiting, W. B., & Greiner, M. (2001). Sensitivity and uncertainty analysis of heat-exchanger designs to physical properties estimation. *Applied Thermal Engineering*, *21*(10), 993–1017. https://doi.org/10.1016/S1359-4311(00)00101-0

Cui, C., & Sun, J. (2017). Coupling design of interunit heat integration in an industrial crude distillation plant using pinch analysis. *Applied Thermal Engineering*, *117*, 145–154. https://doi.org/10.1016/j.applthermaleng.2017.02.032

Escobar, M., Trierweiler, J. O., & Grossmann, I. E. (2013). Simultaneous synthesis of heat exchanger networks with operability considerations: Flexibility and controllability. *Computers & Chemical Engineering*, *55*, 158–180. https://doi.org/10.1016/j.compchemeng.2013.04.010

Floudas, C. A., Aggarwal, A., & Ciric, A. R. (1989). Global optimum search for nonconvex NLP and MINLP problems. *Computers & Chemical Engineering*, *13*(10), 1117–1132. https://doi.org/10.1016/0098-1354(89)87016-4

Furman, K. C., & Sahinidis, N. V. (2001). Computational complexity of heat exchanger network synthesis. *Computers & Chemical Engineering*, *25*(9), 1371–1390. https://doi.org/10.1016/S0098-1354(01)00681-0

Furman, K. C., & Sahinidis, N. V. (2002). A Critical Review and Annotated Bibliography for Heat Exchanger Network Synthesis in the 20th Century. *Industrial & Engineering Chemistry Research*, *41*(10), 2335–2370. https://doi.org/10.1021/ie010389e

Gadalla, M. A. (2015). A new graphical method for Pinch Analysis applications: Heat exchanger network retrofit and energy integration. *Energy*, *81*, 159–174. https://doi.org/10.1016/j.energy.2014.12.011

Gadalla, M. A., Abdelaziz, O. Y., & Ashour, F. H. (2016). Conceptual insights to debottleneck the Network Pinch in heat-integrated crude oil distillation systems without topology modifications. *Energy Conversion and Management*, *126*, 329–341. https://doi.org/10.1016/j.enconman.2016.08.011

Grossmann, I. E., & Guillén-Gosálbez, G. (2010). Scope for the application of mathematical programming techniques in the synthesis and planning of sustainable processes. *Computers & Chemical Engineering*, *34*(9), 1365–1376. https://doi.org/10.1016/j.compchemeng.2009.11.012

Grossmann, I. E., & Morari, M. (1983). Operability, Resiliency, and Flexiblity: Process design objectives for a changing world. *Proceedings of the 2nd International Conference on Foundations of Computer Aided Process and Design*, 931–1030.

Gu, S., Liu, L., Zhang, L., Bai, Y., Wang, S., & Du, J. (2018). Heat exchanger network synthesis integrated with flexibility and controllability. *Chinese Journal of Chemical Engineering*. https://doi.org/10.1016/j.cjche.2018.07.017

Gundersen, T. (2000). A process integration primer—Implementing agreement on process integration. *Trondhiem, Norway: International Energy Agency, SINTEF Energy Research*, 34–47.

Heggs, P. J., & Vizcaíno, F. (2002). A Rigorous Model for Evaluation of Disturbance Propagation Through Heat Exchanger Networks. *Chemical Engineering Research and Design*, *80*(3), 301–308. https://doi.org/10.1205/026387602753582097

Hohmann, E. C. (1971). *Optimum Networks for Heat Exchange*. University of Southern California.

Interim Climate Change Committee. (2019). *Accelerated electrification: Evidence, analysis and recommendations*. Interim Climate Change Committee.

Isafiade, A. J. (2018). Heat Exchanger Network Retrofit Using the Reduced Superstructure Synthesis Approach. *Process Integration and Optimization for Sustainability*, *2*(3), 205–219. https://doi.org/10.1007/s41660-018-0046-1

Jiang, N., Shelley, J. D., Doyle, S., & Smith, R. (2014). Heat exchanger network retrofit with a fixed network structure. *Applied Energy*, *127*, 25–33. https://doi.org/10.1016/j.apenergy.2014.04.028

Jiang, N., Shelley, J. D., & Smith, R. (2014). New models for conventional and heat exchangers enhanced with tube inserts for heat exchanger network retrofit. *Applied Thermal Engineering*, *70*(1), 944–956. https://doi.org/10.1016/j.applthermaleng.2014.06.015

Kamel, D. A., Gadalla, M. A., Abdelaziz, O. Y., Labib, M. A., & Ashour, F. H. (2017). Temperature driving force (TDF) curves for heat exchanger network retrofit – A case study and implications. *Energy*, *123*, 283–295. https://doi.org/10.1016/j.energy.2017.02.013

Kamel, D. A., Gadalla, M. A., & Ashour, F. H. (2017). Analysis and revamping of heat exchanger networks for crude oil refineries using temperature driving force graphical technique. *Clean Technologies and Environmental Policy*, 1–16. https://doi.org/10.1007/s10098-017-1403-4

Kang, L., & Liu, Y. (2015). Multi-objective optimization on a heat exchanger network retrofit with a heat pump and analysis of CO2 emissions control. *Applied Energy*, *154*, 696–708. https://doi.org/10.1016/j.apenergy.2015.05.050

KBC. (2019). *Industrial Energy Transition Manifesto* (p. 15). KBC Advanced Technologies. https://www.kbc.global/insights/whitepapers/industrial-energy-transition-manifesto/

Kemp, I. C. (2011). *Pinch analysis and process integration: A user guide on process integration for the efficient use of energy* (2nd ed.). Butterworth-Heinemann.

Klemeš, J. J., & Kravanja, Z. (2013). Forty years of Heat Integration: Pinch Analysis (PA) and Mathematical Programming (MP). *Current Opinion in Chemical Engineering*, *2*(4), 461–474. https://doi.org/10.1016/j.coche.2013.10.003

Klemeš, J. J., Varbanov, P. S., Alwi, S. R. W. W., & Manan, Z. A. (2014). *Process Integration and Intensification: Saving Energy, Water and Resources*. Walter de Gruyter GmbH & Co KG.

Klemeš, J. J., Wang, Q.-W., Varbanov, P. S., Zeng, M., Chin, H. H., Lal, N. S., Li, N.-Q., Wang, B., Wang, X.-C., & Walmsley, T. G. (2020). Heat transfer enhancement, intensification and optimisation in heat exchanger network retrofit and operation. *Renewable and Sustainable Energy Reviews*, *120*, 109644. https://doi.org/10.1016/j.rser.2019.109644

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. https://doi.org/0.3303/CET1761273

Lai, Y. Q., Manan, Z. A., & Wan Alwi, S. R. (2018). Simultaneous diagnosis and retrofit of heat exchanger network via individual process stream mapping. *Energy*, *155*, 1113–1128. https://doi.org/10.1016/j.energy.2018.05.021

Lai, Y. Q., Wan Alwi, S. R., & Manan, Z. A. (2019). Customised retrofit of heat exchanger network combining area distribution and targeted investment. *Energy*, *179*, 1054–1066. https://doi.org/10.1016/j.energy.2019.05.047

Lakshmanan, R., & Bañares-Alcántara, R. (1996). A Novel Visualization Tool for Heat Exchanger Network Retrofit. *Industrial & Engineering Chemistry Research*, *35*(12), 4507–4522. https://doi.org/10.1021/ie960372+

Lakshmanan, R., & Bañares-Alcántara, R. (1998). Retrofit by inspection using thermodynamic process visualisation. *Computers & Chemical Engineering*, *22*, S809–S812. https://doi.org/10.1016/S0098-1354(98)00154-9

Lal, N. S., Walmsley, T. G., Atkins, M. J., Walmsley, M. R. W., & Neale, J. R. (2018). Solving Complex Retrofit Problems using Constraints and Bridge Analysis. *Chemical Engineering Transactions*, *70*, 1951–1956. https://doi.org/10.3303/CET1870326

Linnhoff, B., & Flower, J. R. (1978a). Synthesis of heat exchanger networks: I. Systematic generation of energy optimal networks. *AIChE Journal*, *24*(4), 633–642. https://doi.org/10.1002/aic.690240411

Linnhoff, B., & Flower, J. R. (1978b). Synthesis of heat exchanger networks: II. Evolutionary generation of networks with various criteria of optimality. *AIChE Journal*, *24*(4), 642–654. https://doi.org/10.1002/aic.690240412

Linnhoff, B., & Hindmarsh, E. (1983). The pinch design method for heat exchanger networks. *Chemical Engineering Science*, *38*(5), 745–763. https://doi.org/10.1016/0009-2509(83)80185-7

Linnhoff, B., Townsend, D. W., Boland, D., Hewitt, G. F., Thomas, B. E. A., Guy, A. R., & Marsland, R. H. (1982). *A User Guide on Process Integration for the Efficient Use of Energy*. IChemE.

Liu, X., Luo, X., & Ma, H. (2014). Studies on the retrofit of heat exchanger network based on the hybrid genetic algorithm. *Applied Thermal Engineering*, *62*(2), 785–790. https://doi.org/10.1016/j.applthermaleng.2013.10.036

Luyben, W. L. (2011). Heat-Exchanger Bypass Control. *Industrial & Engineering Chemistry Research*, *50*(2), 965–973. https://doi.org/10.1021/ie1020574

Mathisen, K. W., Skogestad, S., & Wolff, E. A. (1992). Bypass selection for control of heat exchanger networks. *Computers & Chemical Engineering*, *16*, S263–S272. https://doi.org/10.1016/S0098-1354(09)80031-8

Matsumoto, M., & Nishimura, T. (1998). Mersenne Twister: A 623-dimensionally Equidistributed Uniform Pseudo-random Number Generator. *ACM Trans. Model. Comput. Simul.*, *8*(1), 3–30. https://doi.org/10.1145/272991.272995

MBIE. (2019). *Energy in New Zealand 2019*. Ministry of Business, Innovation & Employment.

MBIE, & EECA. (2019). *Process Heat in New Zealand: Opportunities and barriers to lowering emissions*. Ministry of Business, Innovation & Employment.

Mohammed, E. A., Naugler, C., & Far, B. H. (2015). Chapter 32—Emerging Business Intelligence Framework for a Clinical Laboratory Through Big Data Analytics. In Q. N. Tran & H. Arabnia (Eds.), *Emerging Trends in Computational Biology, Bioinformatics, and Systems Biology* (pp. 577–602). Morgan Kaufmann. https://doi.org/10.1016/B978-0-12-802508-6.00032-6

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. https://doi.org/10.1007/s11705-015-1520-8

Nguyen, D. Q., Barbaro, A., Vipanurat, N., & Bagajewicz, M. J. (2010). All-At-Once and Step-Wise Detailed Retrofit of Heat Exchanger Networks Using an MILP Model. *Industrial & Engineering Chemistry Research*, *49*(13), 6080–6103. https://doi.org/10.1021/ie901235c

Nie, X. R., & Zhu, X. X. (1999). Heat exchanger network retrofit considering pressure drop and heat-transfer enhancement. *AIChE Journal*, *45*(6), 1239–1254. https://doi.org/10.1002/aic.690450610

Nielsen, J. S., Weel Hansen, M., & bay Joergensen, S. (1996). Heat exchanger network modelling framework for optimal design and retrofitting. *Computers & Chemical Engineering*, *20*, S249–S254. https://doi.org/10.1016/0098-1354(96)00052-X

Nishida, N., Liu, Y. A., & Lapidus, L. (1977). Studies in chemical process design and synthesis: III. A Simple and practical approach to the optimal synthesis of heat exchanger networks. *AIChE Journal*, *23*(1), 77–93. https://doi.org/10.1002/aic.690230113

Nordman, R., & Berntsson, T. (2001). New pinch technology based hen analysis methodologies for cost-effective retrofitting. *The Canadian Journal of Chemical Engineering*, *79*(4), 655–662. https://doi.org/10.1002/cjce.5450790426

Nordman, R., & Berntsson, T. (2009a). Use of advanced composite curves for assessing cost-effective HEN retrofit I: Theory and concepts. *Applied Thermal Engineering*, *29*(2–3), 275–281. https://doi.org/10.1016/j.applthermaleng.2008.02.021

Nordman, R., & Berntsson, T. (2009b). Use of advanced composite curves for assessing cost-effective HEN retrofit II. Case studies. *Applied Thermal Engineering*, *29*(2–3), 282–289. https://doi.org/10.1016/j.applthermaleng.2008.02.022

Novak Pintarič, Z., & Kravanja, Z. (2004). A strategy for MINLP synthesis of flexible and operable processes. *Computers & Chemical Engineering*, *28*(6–7), 1105–1119. https://doi.org/10.1016/j.compchemeng.2003.09.010

Novak Pintarič, Z., & Kravanja, Z. (2015). A methodology for the synthesis of heat exchanger networks having large numbers of uncertain parameters. *Energy*, *92*, 373–382. https://doi.org/10.1016/j.energy.2015.02.106

Ochoa-Estopier, L. M., Jobson, M., & Chen, L. (2018). Area-based optimization approach for refinery heat exchanger networks. *Applied Thermal Engineering*, *129*, 606–617. https://doi.org/10.1016/j.applthermaleng.2017.10.049

Ochoa-Estopier, L. M., Jobson, M., Chen, L., Rodríguez-Forero, C. A., & Smith, R. (2015). Optimization of Heat-Integrated Crude Oil Distillation Systems. Part II: Heat Exchanger Network Retrofit Model. *Industrial & Engineering Chemistry Research*, *54*(18), 5001–5017. https://doi.org/10.1021/ie503804u

Oliveira, S. G., Liporace, F. S., Araújo, O. Q. F., & Queiroz, E. M. (2001). The importance of control considerations for heat exchanger network synthesis: A case study. *Brazilian Journal of Chemical Engineering*, *18*(2), 195–210. https://doi.org/10.1590/S0104-66322001000200007

Osman, A., Abdul Mutalib, M. I., Shuhaimi, M., & Amminudin, K. A. (2009). Paths combination for HENs retrofit. *Applied Thermal Engineering*, *29*(14–15), 3103–3109. https://doi.org/10.1016/j.applthermaleng.2009.04.006

Osman, A., Mutalib, M. I. A., & Shigidi, I. (2016). Heat recovery enhancement in HENs using a combinatorial approach of paths combination and process streams' temperature flexibility. *South African Journal of Chemical Engineering*, *21*, 37–48. https://doi.org/10.1016/j.sajce.2016.05.002

Palisade. (2018). *@RISK: Risk Analysis using Monte Carlo Simulation in Excel and Project*. Palisade. www.palisade.com/risk/

Pan, M., Bulatov, I., & Smith, R. (2013). New MILP-based iterative approach for retrofitting heat exchanger networks with conventional network structure modifications. *Chemical Engineering Science*, *104*, 498–524. https://doi.org/10.1016/j.ces.2013.09.049

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. https://doi.org/10.1016/j.apenergy.2015.09.073

Pan, M., Bulatov, I., & Smith, R. (2018). Heat transfer intensification for retrofitting heat exchanger networks with considering exchanger detailed performances. *AIChE Journal*, *64*(6), 2052–2077. https://doi.org/10.1002/aic.16075

Pan, M., Bulatov, I., Smith, R., & Kim, J.-K. (2013). Optimisation for the retrofit of large scale heat exchanger networks with different intensified heat transfer techniques. *Applied Thermal Engineering*, *53*(2), 373–386. https://doi.org/10.1016/j.applthermaleng.2012.04.038

Pan, M., Smith, R., & Bulatov, I. (2013). A novel optimization approach of improving energy recovery in retrofitting heat exchanger network with exchanger details. *Energy*, *57*, 188–200. https://doi.org/10.1016/j.energy.2012.10.056

Papalexandri, K. P., & Pistikopoulos, E. N. (1993). A multiperiod minlp model for improving the flexibility of heat exchanger networks. *Computers & Chemical Engineering*, *17*, S111–S116. https://doi.org/10.1016/0098-1354(93)80215-9

Papalexandri, K. P., & Pistikopoulos, E. N. (1994). Synthesis and Retrofit Design of Operable Heat Exchanger Networks. 1. Flexibility and Structural Controllability Aspects. *Industrial & Engineering Chemistry Research*, *33*(7), 1718–1737. https://doi.org/10.1021/ie00031a012

Payet, L., Thery Hétreux, R., Hétreux, G., Bourgeois, F., & Floquet, P. (2018). Flexibility Assessment of Heat Exchanger Networks: From a Thorough Data Extraction to Robustness Evaluation. *Chemical Engineering Research and Design*, *131*, 571–583. https://doi.org/10.1016/j.cherd.2017.11.036

Pettersson, F. (2005). Synthesis of large-scale heat exchanger networks using a sequential match reduction approach. *Computers & Chemical Engineering*, *29*(5), 993–1007. https://doi.org/10.1016/j.compchemeng.2004.11.001

Piacentino, A. (2011). Thermal analysis and new insights to support decision making in retrofit and relaxation of heat exchanger networks. *Applied Thermal Engineering*, *31*(16), 3479–3499. https://doi.org/10.1016/j.applthermaleng.2011.07.002

Ponton, J. W., & Donaldson, R. A. B. (1974). A fast method for the synthesis of optimal heat exchanger networks. *Chemical Engineering Science*, *29*(12), 2375–2377. https://doi.org/10.1016/0009-2509(74)80014-X

Pouransari, N., & Maréchal, F. (2014). Heat exchanger network design of large-scale industrial site with layout inspired constraints. *Computers & Chemical Engineering*, *71*, 426–445. https://doi.org/10.1016/j.compchemeng.2014.09.012

Rangaiah, G., Sharma, S., & Sreepathi, B. K. (2015). Multi-objective optimization for the design and operation of energy efficient chemical processes and power generation. *Current Opinion in Chemical Engineering*, *10*, 49–62. https://doi.org/10.1016/j.coche.2015.08.006

Rezaei, E., & Shafiei, S. (2009). Heat exchanger networks retrofit by coupling genetic algorithm with NLP and ILP methods. *Computers & Chemical Engineering*, *33*(9), 1451–1459. https://doi.org/10.1016/j.compchemeng.2009.03.009

Rohani, N., Ayotte-Sauvé, E., Ashrafi, O., & Bédard, S. (2016). Multiple modifications in stepwise retrofit of heat exchanger networks. *Chemical Engineering Transactions*, *52*, 313–318. https://doi.org/10.3303/CET1652053

Sadeghian Jahromi, F., & Beheshti, M. (2017). An extended energy saving method for modification of MTP process heat exchanger network. *Energy*, *140*, 1059–1073. https://doi.org/10.1016/j.energy.2017.09.032

Sieniutycz, S., & Jezowski, J. (2009). *Energy Optimization in Process Systems*. Elsevier.

Sieres, J., & Campo, A. (2018). Uncertainty analysis for the experimental estimation of heat transfer correlations combining the Wilson plot method and the Monte Carlo technique. *International Journal of Thermal Sciences*, *129*, 309–319. https://doi.org/10.1016/j.ijthermalsci.2018.03.019

Silva, A. P., Ravagnani, M. A. S. S., & Biscaia, E. C. (2009). Particle Swarm Optimisation Applied in Retrofit of Heat Exchanger Networks. In R. M. de Brito Alves, C. A. O. do Nascimento, & E. C. Biscaia (Eds.), *Computer Aided Chemical Engineering* (Vol. 27, pp. 1035–1040). Elsevier. https://doi.org/10.1016/S1570-7946(09)70393-1

Smith, R., Jobson, M., & Chen, L. (2010). Recent development in the retrofit of heat exchanger networks. *Applied Thermal Engineering*, *30*(16), 2281–2289. https://doi.org/10.1016/j.applthermaleng.2010.06.006

Soršak, A., & Kravanja, Z. (2004). MINLP retrofit of heat exchanger networks comprising different exchanger types. *Computers & Chemical Engineering*, *28*(1), 235–251. https://doi.org/10.1016/S0098-1354(03)00167-4

Sreepathi, B. K., & Rangaiah, G. P. (2014a). Improved heat exchanger network retrofitting using exchanger reassignment strategies and multi-objective optimization. *Energy*, *67*, 584–594. https://doi.org/10.1016/j.energy.2014.01.088

Sreepathi, B. K., & Rangaiah, G. P. (2014b). Review of Heat Exchanger Network Retrofitting Methodologies and Their Applications. *Industrial & Engineering Chemistry Research*, *53*(28), 11205–11220. https://doi.org/10.1021/ie403075c

Sreepathi, B. K., & Rangaiah, G. P. (2015). Retrofitting of heat exchanger networks involving streams with variable heat capacity: Application of single and multi-objective optimization. *Applied Thermal Engineering*, *75*, 677–684. https://doi.org/10.1016/j.applthermaleng.2014.09.067

Sun, L., Zha, X., & Luo, X. (2018). Coordination between bypass control and economic optimization for heat exchanger network. *Energy*, *160*, 318–329. https://doi.org/10.1016/j.energy.2018.07.021

Swaney, R. E., & Grossmann, I. E. (1985). An index for operational flexibility in chemical process design. Part I: Formulation and theory. *AIChE Journal*, *31*(4), 621–630. https://doi.org/10.1002/aic.690310412

Tan, R. R., Aviso, K. B., & Foo, D. C. Y. (2017). P-graph and Monte Carlo simulation approach to planning carbon management networks. *Computers & Chemical Engineering*, *106*, 872–882. https://doi.org/10.1016/j.compchemeng.2017.01.047

Tan, R. R., & Foo, D. C. Y. (2007). Pinch analysis approach to carbon-constrained energy sector planning. *Energy*, *32*(8), 1422–1429. https://doi.org/10.1016/j.energy.2006.09.018

Tan, R. R., Foo, D. C. Y., & Manan, Z. A. (2007). Assessing the sensitivity of water networks to noisy mass loads using Monte Carlo simulation. *Computers & Chemical Engineering*, *31*(10), 1355–1363. https://doi.org/10.1016/j.compchemeng.2006.11.005

Taylor, R. (1990). Interpretation of the Correlation Coefficient: A Basic Review. *Journal of Diagnostic Medical Sonography*, *6*(1), 35–39. https://doi.org/10.1177/875647939000600106

Tellez, R., Svrcek, W. Y., Ross, T. J., & Young, B. R. (2006). Heat exchanger network process modifications for controllability using design reliability theory. *Computers & Chemical Engineering*, *30*(4), 730–743. https://doi.org/10.1016/j.compchemeng.2005.12.002

Tjoe, T. N., & Linnhoff, B. (1986). Using pinch technology for process retrofit. *Chemical Engineering*, *93*(8), 47–60.

Towler, G. P., Mann, R., Serriere, A. J.-L., & Gabaude, C. M. D. (1996). Refinery hydrogen management: Cost analysis of chemically-integrated facilities. *Industrial and*

Engineering Chemistry Research, *35*(7), 2378–2388. Scopus. https://doi.org/10.1021/ie950359+

Townsend, D. W., & Linnhoff, B. (1983). Heat and power networks in process design. Part II: Design procedure for equipment selection and process matching. *AIChE Journal*, *29*(5), 748–771. https://doi.org/10.1002/aic.690290509

van Reisen, J. L. B., Grievink, J., Polley, G. T., & Verheijen, P. J. T. (1995). The placement of two-stream and multi-stream heat-exchangers in an existing network through path analysis. *Computers & Chemical Engineering*, *19*, 143–148. https://doi.org/10.1016/0098-1354(95)87029-6

van Reisen, J. L. B., Polley, G. T., & Verheijen, P. J. T. (1998). Structural targeting for heat integration retrofit. *Applied Thermal Engineering*, *18*(5), 283–294. https://doi.org/10.1016/S1359-4311(97)00067-7

Varbanov, P. S., & Klemeš, J. J. (2000). Rules for paths construction for HENs debottlenecking. *Applied Thermal Engineering*, *20*(15–16), 1409–1420. https://doi.org/10.1016/S1359-4311(00)00015-6

Verheyen, W., & Zhang, N. (2006). Design of flexible heat exchanger network for multi-period operation. *Chemical Engineering Science*, *61*(23), 7730–7753. https://doi.org/10.1016/j.ces.2006.08.043

Walmsley, Timothy G., Walmsley, M. R. W., Atkins, M. J., & Neale, J. R. (2014). Integration of industrial solar and gaseous waste heat into heat recovery loops using constant and variable temperature storage. *Energy*, *75*, 53–67. https://doi.org/10.1016/j.energy.2014.01.103

Walmsley, Timothy G., Walmsley, M. R. W., Morrison, A. S., Atkins, M. J., & Neale, J. R. (2014). A derivative based method for cost optimal area allocation in heat exchanger networks. *Applied Thermal Engineering*, *70*(2), 1084–1096. https://doi.org/10.1016/j.applthermaleng.2014.03.044

Walmsley, Timothy Gordon. (2014). *Heat Integrated Milk Powder Production* [Thesis, University of Waikato]. http://researchcommons.waikato.ac.nz/handle/10289/8767

Wan Alwi, S. R., & Manan, Z. A. (2010). STEP—A new graphical tool for simultaneous targeting and design of a heat exchanger network. *Chemical Engineering Journal*, *162*(1), 106–121. https://doi.org/10.1016/j.cej.2010.05.009

Wang, Y. P., & Smith, R. (1994). Wastewater minimisation. *Chemical Engineering Science*, *49*(7), 981–1006. https://doi.org/10.1016/0009-2509(94)80006-5

Wang, Y., Pan, M., Bulatov, I., Smith, R., & Kim, J.-K. (2012). Application of intensified heat transfer for the retrofit of heat exchanger network. *Applied Energy*, *89*(1), 45–59. https://doi.org/10.1016/j.apenergy.2011.03.019

Westphalen, D. L., Young, B. R., & Svrcek, W. Y. (2003). A Controllability Index for Heat Exchanger Networks. *Industrial & Engineering Chemistry Research*, *42*(20), 4659–4667. https://doi.org/10.1021/ie020893z

Yee, T., & Grossmann, I. (1986). Optimization model for structural modifications in the retrofit of heat exchanger networks. *Department of Civil and Environmental Engineering*. http://repository.cmu.edu/cee/36

Yee, T., & Grossmann, I. (1988). A screening and optimization approach for the retrofit of heat exchanger networks. *Department of Chemical Engineering*. http://repository.cmu.edu/cheme/133

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. https://doi.org/10.1016/j.applthermaleng.2015.04.025

Yoon, S.-G., Lee, J., & Park, S. (2007). Heat integration analysis for an industrial ethylbenzene plant using pinch analysis. *Applied Thermal Engineering*, *27*(5), 886–893. https://doi.org/10.1016/j.applthermaleng.2006.09.001

Young, B. R., Westphalen, D. L., & Svrcek, W. Y. (2006). Heat Exchanger Network Dynamic Analysis. *Developments in Chemical Engineering and Mineral Processing*, *14*(3–4), 505–514. https://doi.org/10.1002/apj.5500140317

Zhang, H., & Rangaiah, G. P. (2013). One-step approach for heat exchanger network retrofitting using integrated differential evolution. *Computers & Chemical Engineering*, *50*, 92–104. https://doi.org/10.1016/j.compchemeng.2012.10.018

Zhang, T., Zhu, T., An, W., Song, X., Liu, L., & Liu, H. (2016). Unsteady analysis of a bottoming Organic Rankine Cycle for exhaust heat recovery from an Internal Combustion Engine using Monte Carlo simulation. *Energy Conversion and Management*, *124*, 357–368. https://doi.org/10.1016/j.enconman.2016.07.039

Zhu, X. X., Zanfir, M., & Klemeš, J. J. (2000). Heat Transfer Enhancement for Heat Exchanger Network Retrofit. *Heat Transfer Engineering*, *21*(2), 7–18. https://doi.org/10.1080/014576300270988

Zore, Ž., Zirngast, K., Novak Pintarič, Z., & Kravanja, Z. (2017). Stochastic Multi-Objective Process Optimization by using the Composite Objective Function. In A. Espuña, M. Graells, & L. Puigjaner (Eds.), *Computer Aided Chemical Engineering* (Vol. 40, pp. 601–606). Elsevier. https://doi.org/10.1016/B978-0-444-63965-3.50102-1

Appendix A: Retrofit Stream Data

This Appendix presents the retrofit stream data for the three heat exchanger network problems analysed in the thesis: the illustrative example, paper mill, and petrochemical complex.

Illustrative Example Retrofit Stream Data

The original stream data for the illustrative example has been taken from Klemeš et al. (2014) and used to design a HEN that can be retrofitted. The stream data is presented in Table 0.1, including ΔT_{cont} and heat transfer coefficients (HTC).

Table 0.1: Retrofit stream data for the four-stream illustrative example.

Unit	Stream	T_s (°C)	T_t (°C)	ΔH (kW)	ΔT_{cont} (°C)	HTC (W/m^2°C)
C01	F2	196.7	40	2,350	5	1,000
C02	F4	104	80	600	5	1,000
E01	F1	20	140	2,400	5	1,000
E01	F4	200	104	2,400	5	1,000
E02	F1	140	180	800	5	1,000
E02	F2	250	196.7	800	5	1,000
H01	F3	140	230	2,700	5	1,000

Paper Mill Retrofit Stream Data

The retrofit stream data for the paper mill has been adapted from Atkins et al. (2008) and is presented in Table 0.2.

Table 0.2: Retrofit stream data for the paper mill.

Unit	Stream	T_s (°C)	T_t (°C)	ΔH (kW)	ΔT_{cont} (°C)	HTC (W/m^2°C)
C01	WW (Wastewater)	34	30	1,325	5	2,555
C02	RC (Recycle)	50	30	1,454	5	2,555
C03	EX1 (Exhaust air 1)	73	40	8,910	10	111
C04	EX2 (Exhaust air 2)	70	40	7,524	10	111
C05	PS (Press seal tank)	28	20	1,201	5	2,555
E01	EX1	80	73	1,884	10	111
E01	PV (Pocket ventilation air)	20	60	1,884	10	111
E02	EX2	80	70	2,508	10	111
E02	BB (Bore water)	20	60	2,508	10	111
E03	WW	58	34	7,950	5	2,555
E03	BW	11	48	7,950	5	2,555
E04	PS	70	28	6,306	5	2,555
E04	RP (Repulper)	10	60	6,306	5	2,555
E05	RC	60	50	727	5	2,555
E05	OI (Other inputs)	30	50	727	5	2,555
H01	BW	48	61	2,795	5	2,555
H02	HW (Hot water)	50	60	2,030	5	2,555
H03	BB (Blow back air)	60	80	1,254	10	111
H04	PV	60	125	3,062	10	111

Petrochemical Complex Retrofit Stream Data

Due to the large size of the retrofit stream data, the coolers, recovery exchangers, and heaters have been divided into three tables for clarity. The stream data for the 24 coolers is presented in Table 0.3. The stream data for the four heaters is presented in Table 0.4. Finally, the stream data for the 18 recovery exchangers is presented in Table 0.5.

Table 0.3: Retrofit stream data for the coolers in the petrochemical complex.

Unit	Stream	T_s (°C)	T_t (°C)	ΔH (kW)	ΔT_{cont} (°C)	HTC (W/m²°C)
C01	S01	60	43	935	5	1,000
C02	S01	118	60	3,190	5	1,000
C03	S01	60	43	340	5	1,000
C04	S01	118	60	1,160	5	1,000
C05	S02	65	38	405	5	1,000
C06	S06	55	45	950	5	1,000
C07	S06	120	55	6,175	5	1,000
C08	S06	167	120	4,465	5	1,000
C09	S07	71	38	1,683	5	1,000
C10	S07	120	71	2,499	5	1,000
C11	S08	60	38	1,430	5	1,000
C12	S08	117	60	798	5	1,000
C13	S08	117	60	1,710	5	1,000
C14	S08	117	60	1,197	5	1,000
C15	S09	199	93	2,120	5	1,000
C16	S10	255	96	2,385	5	1,000
C17	S11	88	75	3,900	5	1,000
C18	S12	60	52	2,080	5	1,000
C19	S12	131	60	18,460	5	1,000
C20	S13	60	43	1,666	5	1,000
C21	S13	106	60	4,508	5	1,000
C22	S14	205	120	8,500	5	1,000
C23	S15	151	93	13,630	5	1,000
C24	S15	174	151	5,405	5	1,000

Table 0.4: Retrofit stream data for the heaters in the petrochemical complex.

Unit	Stream	T_s (°C)	T_t (°C)	ΔH (kW)	$ΔT_{cont}$ (°C)	HTC (W/m^2°C)
H01	S20	239	349	44,660	5	1,000
H02	S21	253	349	9,600	5	1,000
H03	S23	342	403	18,300	5	1,000
H04	S24	342	403	4,514	5	1,000

Table 0.5: Retrofit stream data for the recovery exchangers in the petrochemical complex.

Unit	Stream	Ts (°C)	Tt (°C)	ΔH (kW)	$ΔT_{cont}$ (°C)	HTC (W/m^2°C)
E01	S01	194	118	5,700	5	1,000
E01	S16	100	119	5,700	5	1000
E02	S01	234	194	3,000	5	1000
E02	S17	183	189	3,000	5	1000
E03	S02	205	65	2,100	5	1000
E03	S16	25	32	2,100	5	1000
E04	S03	295	283	2,760	5	1000
E04	S22	235	258	2,760	5	1000
E05	S04	283	230	1,007	5	1000
E05	S27	199	209	1,007	5	1000
E06	S04	283	210	8,030	5	1000
E06	S25	180	185	8,030	5	1000
E07	S04	283	260	1,755	5	1000
E07	S16	239	266	1,755	5	1000
E08	S05	230	180	6,900	5	1000
E08	S16	119	142	6,900	5	1000
E09	S07	180	120	3,060	5	1000
E09	S26	51	102	3,060	5	1000
E10	S08	154	117	2,400	5	1000

E10	S16	92	100	2,400	5	1000
E11	S08	251	154	6,305	5	1000
E11	S16	142	239	6,305	5	1000
E12	S09	327	199	2,560	5	1000
E12	S17	162.48	167.6	2,560	5	1000
E13	S10	363	255	1,620	5	1000
E13	S19	245	254	1,620	5	1000
E14	S11	148	88	18,000	5	1000
E14	S16	32	92	18,000	5	1000
E15	S14	282	205	7,700	5	1000
E15	S17	167.6	183	7,700	5	1000
E16	S14	357	282	7,500	5	1000
E16	S18	250	265	7,500	5	1000
E17	S15	213	174	9,165	5	1000
E17	S16	142	181	9,165	5	1000
E18	S15	271	213	13,630	5	1000
E18	S17	162.48	217	13,630	5	1000

Appendix B: Spreadsheet Tool

This Appendix presents the spreadsheet tool, including screenshots of the program and the output results. The spreadsheet tool is developed in Microsoft Excel™ using Visual Basic for Applications. The retrofit stream data (Appendix A) is copied directly into the spreadsheet tool, as seen in Figure 0.1. From here, the retrofit analysis developed in the thesis can be executed.

RUN Exchanger	Stream	T_s (°C)	T_t (°C)	ΔH (kW)	ΔT_{cont} (°C)	HTC (W/m^2°C)
C01	WW	34	30	1325	5	2555
C02	RC	50	30	1454	5	2555
C03	EX1	73	40	8910	10	111
C04	EX2	70	40	7524	10	111
C05	PS	28	20	1201	5	2555
E01	EX1	80	73	1884	10	111
E01	PV	20	60	1884	10	111
E02	BB	20	60	2508	10	111
E02	EX2	80	70	2508	10	111
E03	BW	11	48	7950	5	2555
E03	WW	58	34	7950	5	2555
E04	PS	70	28	6306	5	2555
E04	RP	10	60	6306	5	2555
E05	OI	30	50	727	5	2555
E05	RC	60	50	727	5	2555
H01	BW	48	61	2795	5	2555
H02	HW	50	60	2030	5	2555
H03	BB	60	80	1254	10	111
H04	PV	60	125	3062	10	111

Stream Data | HSDT | RB Results | Retrofit HSDT

Figure 0.1: Example of retrofit stream data input to the spreadsheet tool.

The following forms (Figure 0.2) allow the user to control the retrofit analysis, including setting the number of allowable retrofit stages for the energy retrofit planning as well as the constraints used during the Retrofit Bridge search. Other options, such as whether to use Pareto front analysis or allow stream splits are also included. With these forms, the user can tailor the retrofit analysis to their needs.

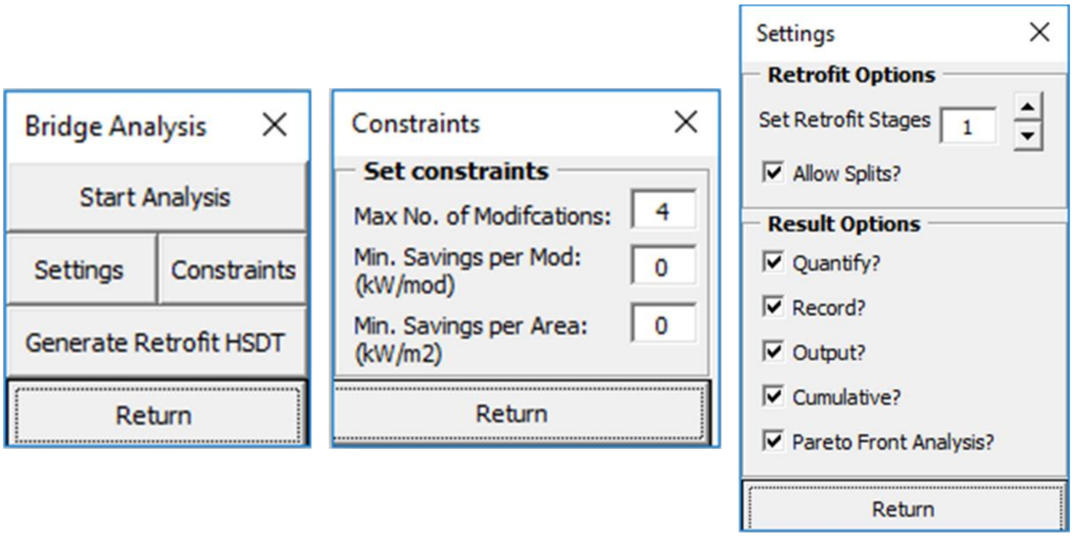


Figure 0.2: User forms for conducting Bridge Analysis using the spreadsheet tool, including settings and constraints.

Once the retrofit analysis is complete, the spreadsheet tool provides results in the form of a list of energy retrofit design plans, complete with economic metrics and other useful information. An example of results, for the petrochemical complex, is provided in Figure 0.3. Different colours are used to represent energy retrofit design plans with a different number of retrofit stages. These colours match several figures in Chapter 5: orange for stage 1, green for stage 2, blue for stage 3, and yellow for stage 4.

#	Retrofit Design Plan	Stage 1	Stage 2	Stage 3	Stage 4	Savings (kW)	No. Mod	Area (m2)	Q/n (kW/mod)	Q/A (kW/m2)	Capital (NZD)	Payback (y)	Profit (NZD/y)
1	58	C16-E12-H01				1237.80	2	117.61	618.90	10.52	$283,054.54	1.06	$220,061.18
2	58/22	C16-E12-H01	C22-E15-H01			3977.80	4	624.51	994.45	6.37	$1,116,452.57	1.31	$673,529.48
3	58/22//1	C16-E12-H01	C22-E15-H01	C08-E08-E06-H01		6640.07	7	1255.29	948.58	5.29	$2,189,163.48	1.53	$1,071,338.98
4	58/22//4	C16-E12-H01	C22-E15-H01	C22-E08-E06-H01		6640.07	7	1200.83	948.58	5.53	$2,113,392.34	1.48	$1,083,670.38
5	58/22//6	C16-E12-H01	C22-E15-H01	C24-E08-E18-H01		6845.38	8	1340.10	855.67	5.11	$2,320,463.90	1.58	$1,094,111.63
6	58/22//8	C16-E12-H01	C22-E15-H01	C24-E08-E06-H01		6640.07	7	1187.00	948.58	5.59	$2,093,462.76	1.47	$1,086,913.83
7	58/24	C16-E12-H01	C22-E15-E20-H01			2475.60	4	258.95	618.90	9.56	$604,505.04	1.14	$433,873.59
8	58/24//1	C16-E12-H01	C22-E15-E20-H01	C08-E08-E06-H01		5544.87	7	1004.03	792.12	5.52	$1,829,074.40	1.53	$894,473.82
9	58/24//6	C16-E12-H01	C22-E15-E20-H01	C22-E08-E18-H01		6212.68	8	1165.18	776.58	5.33	$2,054,240.59	1.54	$1,001,407.75
10	58/24//9	C16-E12-H01	C22-E15-E20-H01	C22-E08-E06-H01		5544.87	7	876.74	792.12	6.32	$1,654,729.59	1.39	$922,847.63
11	58/24//16	C16-E12-H01	C22-E15-E20-H01	C24-E08-E18-H01		6212.68	8	1191.46	776.58	5.21	$2,090,426.56	1.57	$995,518.65
12	58/24//19	C16-E12-H01	C22-E15-E20-H01	C24-E08-E06-H01		5544.87	7	901.45	792.12	6.15	$1,690,189.97	1.42	$917,076.62
13	58/40	C16-E12-H01	C22-E08-E18-H01			5691.34	6	1166.31	948.56	4.88	$1,910,728.27	1.56	$912,675.75
14	58/40//1	C16-E12-H01	C22-E08-E18-H01	C24-E21-E15-H01		7589.53	9	1561.87	843.28	4.86	$2,657,347.57	1.63	$1,199,278.23
15	58/47	C16-E12-H01	C22-E08-E06-H01			4642.44	5	774.89	928.49	5.99	$1,383,703.73	1.39	$772,932.22
16	58/47//1	C16-E12-H01	C22-E08-E06-H01	C15-E21-E15-H01		6042.44	8	1031.32	755.30	5.86	$1,932,887.21	1.49	$984,555.13
17	58/47//2	C16-E12-H01	C22-E08-E06-H01	C22-E21-E15-H01		6798.98	7	1243.08	971.28	5.47	$2,169,684.02	1.48	$1,108,674.29
18	58/47//3	C16-E12-H01	C22-E08-E06-H01	C22-E21-E15-E16-H02		6842.44	8	1270.48	855.30	5.39	$2,269,273.94	1.54	$1,101,809.74
19	58/47//4	C16-E12-H01	C22-E08-E06-H01	C22-E21-E15-E16-H01		6842.44	8	1264.33	855.30	5.41	$2,259,121.21	1.54	$1,103,462.05
20	58/47//5	C16-E12-H01	C22-E08-E06-H01	C24-E21-E15-H01		6798.98	8	1219.01	849.87	5.58	$2,190,768.51	1.50	$1,105,242.88
21	58/67	C16-E12-H01	C24-E08-E18-H01			5691.34	6	1238.30	948.56	4.60	$2,007,708.94	1.64	$896,892.59
22	58/67//2	C16-E12-H01	C24-E08-E18-H01	C22-E15-H02		7591.34	8	1742.35	948.92	4.36	$2,824,011.82	1.73	$1,172,543.05
23	58/67//3	C16-E12-H01	C24-E08-E18-H01	C22-E15-H01		7589.53	8	1597.85	948.69	4.75	$2,641,661.25	1.62	$1,201,831.11
24	58/67//11	C16-E12-H01	C24-E08-E18-H01	C22-E15-E04-H01		8431.34	9	1906.58	936.82	4.42	$3,135,174.65	1.73	$1,302,502.74
25	58/67//13	C16-E12-H01	C24-E08-E18-H01	C22-E12-E15-H01		7013.54	8	1451.43	876.69	4.83	$2,436,875.56	1.62	$1,111,320.70
26	58/73	C16-E12-H01	C24-E08-E06-H01			4642.44	5	828.03	928.49	5.61	$1,459,512.94	1.46	$760,594.62
27	58/73//3	C16-E12-H01	C24-E08-E06-H01	C22-E15-H02		6542.44	7	1332.09	934.63	4.91	$2,275,815.82	1.62	$1,036,245.08
28	58/73//4	C16-E12-H01	C24-E08-E06-H01	C22-E15-H01		6798.98	7	1237.61	971.28	5.49	$2,162,114.95	1.48	$1,109,906.12
29	58/73//11	C16-E12-H01	C24-E08-E06-H01	C22-E15-E04-H01		7382.44	8	1483.94	922.80	4.97	$2,569,810.11	1.62	$1,168,998.86
30	58/73//13	C16-E12-H01	C24-E08-E06-H01	C22-E12-E15-H01		5964.64	7	1026.28	852.09	5.81	$1,867,147.26	1.46	$978,527.01
31	113	C22-E15-H01				2740.00	2	472.52	1370.00	5.80	$788,449.93	1.34	$460,783.41
32	113/10	C22-E15-H01	C08-E08-E06-H01			5737.64	5	1196.23	1147.53	4.80	$1,984,945.58	1.61	$910,550.87
33	113/10//6	C22-E15-H01	C08-E08-E06-H01	C16-E12-H02		6975.44	7	1345.55	996.49	5.18	$2,318,472.58	1.55	$1,122,397.89
34	113/10//7	C22-E15-H01	C08-E08-E06-H01	C16-E12-H01		6975.44	7	1338.96	996.49	5.21	$2,308,283.96	1.54	$1,124,056.04
35	113/10//16	C22-E15-H01	C08-E08-E06-H01	C16-E08-E12-H02		7017.64	8	1385.77	877.20	5.06	$2,427,999.52	1.61	$1,113,645.88
36	113/31	C22-E15-H01	C16-E12-H01			3977.80	4	599.22	994.45	6.64	$1,086,380.51	1.27	$678,423.58
37	113/31//1	C22-E15-H01	C16-E12-H01	C08-E08-E06-H01		6640.07	7	1230.00	948.58	5.40	$2,159,091.41	1.51	$1,076,233.07
38	113/31//4	C22-E15-H01	C16-E12-H01	C22-E08-E06-H01		6640.07	7	1175.53	948.58	5.65	$2,083,320.27	1.46	$1,088,564.47
39	113/31//6	C22-E15-H01	C16-E12-H01	C24-E08-E18-H01		6845.38	8	1314.81	855.67	5.21	$2,290,391.83	1.56	$1,099,005.72
40	113/31//8	C22-E15-H01	C16-E12-H01	C24-E08-E06-H01		6640.07	7	1161.70	948.58	5.72	$2,063,390.69	1.45	$1,091,807.92
41	113/69	C22-E15-H01	C22-E08-E18-H01			6324.04	6	1408.24	1054.01	4.49	$2,281,250.35	1.68	$988,405.48
42	113/69//10	C22-E15-H01	C22-E08-E18-H01	C16-E12-H02		7561.84	8	1557.56	945.23	4.85	$2,614,777.35	1.61	$1,200,252.50
43	113/69//11	C22-E15-H01	C22-E08-E18-H01	C16-E12-H01		7561.84	8	1555.52	945.23	4.86	$2,611,627.25	1.61	$1,200,765.16

Figure 0.3: Example of results from the spreadsheet tool (petrochemical complex case study).

Appendix C: VBA Code

This Appendix presents the code used in the spreadsheet tool.

Main Module

```
'Settings
Public CUMULATIVE As Boolean, OUTPUT As Boolean
Public RECORD As Boolean, QUANTIFY As Boolean
Public ALLOW_SPLITS As Boolean
Public PARETO As Boolean, CONSTRAINTS As Boolean
Public case_study As String
Public CUMULATIVE_2 As Boolean

'Constraints
Public Q_MIN As Double, N_MAX As Integer
Public Q_A_MIN As Double, PB_MAX As Double

Public MAX_STEP As Integer
Public Const MAX_RB = 1000000
Public Const Counter_MAX = 100000
Public Const ZERO = 0.001

'Sheets
Public Const HSDT_Sheet = "HSDT"
Public Const Results_Sheet = "RB Results"
Public Const SearchMetrics_Sheet = "Metrics"

'Coordinates of the HSDT
Public Const R_Table = 16
Public Const C_Table = 1

Public MasterArray As Variant, countArray As Variant, HEN_data_Original As Variant

Public RB_step As Integer, RB_paths As Long

'Counters
Public Tot_C As Integer, Tot_R As Integer, Tot_H As Integer, Tot_RB As Long

'Split checkers
Public match_split As Boolean
Public network_split As Boolean
Public splitCnt As Integer

Sub run()
Application.ScreenUpdating = False

    'Settings
    OUTPUT = Settings_Form.Output_Check.Value       'Default = TRUE
    RECORD = Settings_Form.Record_Check.Value       'Default = TRUE
    QUANTIFY = Settings_Form.Quantify_Check.Value   'Default = TRUE
    CUMULATIVE = Settings_Form.Cumul_Check.Value     'Default = TRUE (Disable for step-by-step
investment planning)
```

```
    ALLOW_SPLITS = Settings_Form.Split_Check.Value  'Default = TRUE (Disable to disallow stream
splitting)
    MAX_STEP = Settings_Form.Step_Textbox.Value     'Default = 1    (Number of retrofit steps)
    PARETO = Settings_Form.Pareto_Check.Value       'Default = TRUE
    CONSTRAINTS = True
    CUMULATIVE_2 = False

    'Prepares the workbook
    Sheets(Results_Sheet).UsedRange.ClearContents
    Generate_Header

    'Screening constraints
    Q_MIN = Criteria_Form.Savings_Unit_Textbox.Value
    Q_A_MIN = Criteria_Form.Savings_Area_Textbox.Value
    N_MAX = Criteria_Form.Mod_Textbox.Value 'Default = 4
    PB_MAX = 0

    'Creating and sizing the HSDT and HEN_data arrays
    Sheets(HSDT_Sheet).Activate
    n_HX = Calc_Initial_HX()
    n_T = Calc_Initial_T()
    Dim HSDT() As Variant, HEN_data() As Variant
    ReDim HSDT(n_HX + 1, n_T), HEN_data(n_HX + 1, 18)

    case_study = Cells(1, 2)
    P_UtS = 215 'set the hot utility price

    ReDim countArray(MAX_STEP, 5)

    'Determining the HSDT and HEN_data arrays
    Read_Write_2D HSDT, R_Table, C_Table, True

    'Starts timing
    SecondsElapsed = 0
    StartTime = Timer

    Calc_Initial_HEN HEN_data, HSDT, R_Table

    'Retrofit Analysis
    Tot_RB = 1: RB_step = 1
    ReDim MasterArray(MAX_RB, 15 + MAX_STEP)
    HEN_data_Original = HEN_data

    RB_Solve HSDT, HEN_data

    'If PARETO Then Final_Paerato_Optimal MasterArray 'I sometimes use this

    SecondsElapsed = Timer - StartTime
    RemoveBridgeDuplicates MasterArray
    'Outputs the bridge options
    If OUTPUT Then
        Sheets(Results_Sheet).Activate
        i = 1: R = 4
        For i = 1 To UBound(MasterArray, 1) Step 1
            If IsEmpty(MasterArray(i, 1)) Then i = UBound(MasterArray, 1)
            For j = 1 To UBound(MasterArray, 2) Step 1
                Cells(R, j) = MasterArray(i, j)
```

```
            Next j
            R = R + 1
        Next i

        Sheets(SearchMetrics_Sheet).Activate
        Cells(1, 2) = SecondsElapsed

        r_start = 3
        c_start = 1
        For i = 1 To MAX_STEP Step 1
            For j = 1 To 5 Step 1
                Cells(r_start + i, c_start + j) = countArray(i, j)
            Next j
        Next i
    End If

ProgramPause True
Application.ScreenUpdating = True
End Sub

Sub RemoveBridgeDuplicates(ByRef input_array)

    i = 1
    While input_array(i, 1) <> vbNullString
        i = i + 1
    Wend
    array_length = i - 1

    Dim copy As Variant

    For i = 1 To array_length Step 1
        If input_array(i, 1) <> vbNullString Then
            For j = i + 1 To array_length Step 1
                If input_array(j, 1) <> vbNullString And i <> j Then
                    If Abs(input_array(j, MAX_STEP + 13) - input_array(i, MAX_STEP + 13)) < ZERO Then
                        If Abs(input_array(j, MAX_STEP + 7) - input_array(i, MAX_STEP + 7)) < ZERO Then
                            For k = 1 To UBound(input_array, 2) Step 1
                                input_array(j, k) = vbNullString
                            Next k
                            m = m + 1
                        End If
                    End If
                End If
            Next j
        End If
    Next i

    ReDim copy(array_length - m, UBound(input_array, 2))

    j = 1
    For i = 1 To array_length Step 1
        If input_array(i, 1) <> vbNullString Then
            For k = 1 To UBound(input_array, 2) Step 1
                copy(j, k) = input_array(i, k)
            Next k
            j = j + 1
        End If
```

```
   Next i

   input_array = copy

End Sub

Sub Read_Write_2D(ByRef input_array, r_start, Optional c_start = 1, Optional read = True, Optional j)
'Read or write arrays from/to current sheet
   i_max = UBound(input_array, 1)
   j_max = UBound(input_array, 2)
   If IsMissing(j) Then j = 1
   For j = j To j_max Step 1
      For i = 1 To i_max Step 1
         If read Then input_array(i, j) = Cells(r_start - 1 + j, i) Else Cells(r_start + j, c_start - 1 + i) = input_array(i, j)
      Next i
      ProgramPause , 100
   Next j
End Sub

Function Calc_Initial_HX() As Integer
'Calculates the number of HX based on input HSDT
   i = 0
   Do
      i = i + 1
   Loop While Not Cells(3, i + 2) = vbNullString
   Calc_Initial_HX = i
End Function

Function Calc_Initial_T() As Integer
'Calculates the number of T intervals based on input HSDT
   i = 0
   Do
      i = i + 1
   Loop While Not Cells(R_Table + i, C_Table) = vbNullString
   Calc_Initial_T = i
End Function

Sub ProgramPause(Optional force_doevents = False, Optional count_step = 1)
'Allow external events to occur and prevent crashes
   counter = counter + count_step
   If counter >= Counter_MAX Or force_doevents Then
'      Application.StatusBar = "Total Retrofit Bridges: " & Format(RB_paths, "#,###")
      temp = DoEvents
      counter = 0
   End If
End Sub

Private Sub Generate_Header()
'Generates the header for the results based on number of steps

   Sheets(Results_Sheet).Activate
   For i = 1 To MAX_STEP Step 1
      Cells(1, 2 + i) = "Step " & i
   Next i
   i = i + 1
```

```
    Cells(1, 1) = "RB #"
    Cells(1, 2) = "ID"

    Cells(1, i + 2) = "Duty"
    Cells(2, i + 2) = "kW"

    Cells(1, i + 3) = "No. Splits"

    Cells(1, i + 4) = "No. Mod"

    Cells(1, i + 5) = "Area"
    Cells(2, i + 5) = "m^2"

    Cells(1, i + 6) = "A^n"
    Cells(2, i + 6) = "m^2n"

    Cells(1, i + 7) = "Q/n"
    Cells(2, i + 7) = "kW/unit"

    Cells(1, i + 8) = "Q/A"
    Cells(2, i + 8) = "kW/m^2"

    Cells(1, i + 9) = "Capital"
    Cells(2, i + 9) = "EUR"

    Cells(1, i + 10) = "Payback"
    Cells(2, i + 10) = "y"

    Cells(1, i + 11) = "Profit"
    Cells(2, i + 11) = "EUR/y"

End Sub

Sub StartButton()

    Load BA_Form
    BA_Form.Show

End Sub

Sub TurnScreenUpdatingOn()

    Calculate
    Application.ScreenUpdating = True

End Sub
```

Initial Setup Module

```
Dim Tot_C As Integer, Tot_H As Integer, Tot_E As Integer
Const R_Table = 3
Const C_Table = 1
Public Const SD_Sheet = "Stream Data"  'the sheet with the stream data

Sub Generate_HSDT()
```

```
'Sub for running the program
Application.ScreenUpdating = False

   'Selects and sorts the stream data
   Sheets(SD_Sheet).Activate
   OrderProcessStreams

   'Reads the stream data from the sheet
   n_rows = Calc_Segs()
   Dim Stream_Data() As Variant
   ReDim Stream_Data(n_rows, 7)
   Read_Data Stream_Data, R_Table, C_Table

   'Creates the HEN_data array
   Tot_C = 0
   Tot_H = 0
   Tot_E = 0
   Calc_Totals Stream_Data, Tot_C, Tot_E, Tot_H
   Dim HEN_data() As Variant
   ReDim HEN_data(Tot_C + Tot_H + Tot_E, 12)
   Copy_HEN_Data HEN_data, Stream_Data


   'Calculates the HSDT
   Dim HSDT() As Variant
   Calc_HSDT HSDT, HEN_data

   'Prepares the output sheet
   With Sheets(HSDT_Sheet)
      .Activate
      .UsedRange.ClearContents
   End With

   'Prints the HSDT and header to the sheet
   HSDT_Header HEN_data
   For i = 1 To UBound(HSDT, 1) Step 1
      For j = 1 To UBound(HSDT, 2) Step 1
         Cells(16 - 1 + j, i) = HSDT(i, j)
      Next j
   Next i

Application.ScreenUpdating = True
End Sub

Function Max_Temp_Data(ByRef HEN_data) As Double
'Finds the maximum temperature

   Max_Temp_Data = -100000000000#

   For i = 2 To UBound(HEN_data, 1) Step 1
      If HEN_data(i, 8) - HEN_data(i, 2) > Max_Temp_Data Then Max_Temp_Data = HEN_data(i, 8)
- HEN_data(i, 2)
      If HEN_data(i, 11) + HEN_data(i, 4) > Max_Temp_Data Then Max_Temp_Data = HEN_data(i,
11) + HEN_data(i, 4)
   Next i

End Function
```

```
Function Min_Temp_Data(ByRef HEN_data) As Double
'Finds the minimum temperature

   Min_Temp_Data = 100000000000#

   For i = 2 To UBound(HEN_data, 1) Step 1
      If HEN_data(i, 10) + HEN_data(i, 4) < Min_Temp_Data Then Min_Temp_Data = HEN_data(i, 10)
+ HEN_data(i, 4)
      If HEN_data(i, 9) - HEN_data(i, 2) < Min_Temp_Data Then Min_Temp_Data = HEN_data(i, 9) -
HEN_data(i, 2)
   Next i

End Function

Sub Calc_Totals(ByRef Stream_Data, x, y, z)
'Calculates how many exchangers (and type) are present

   For i = 1 To UBound(Stream_Data, 1) Step 1
      If Stream_Data(i, 1) Like "*C*" Then
         x = x + 1
      ElseIf Stream_Data(i, 1) Like "*H*" Then
         z = z + 1
      ElseIf Stream_Data(i, 1) Like "*E*" Then
         If Stream_Data(i, 1) = Stream_Data(i + 1, 1) Then
            y = y + 1
            i = i + 1
         End If
      End If
   Next i

End Sub

Sub Calc_HSDT(ByRef HSDT, ByRef HEN_data)
'Calculates the HSDT after the HEN_data has been determined
'Retrofit purposes

   ReDim HSDT(UBound(HEN_data, 1) + 1, 2) 'The second dimension will be updated
   HSDT(1, 1) = Max_Temp_Data(HEN_data)
   HSDT(1, 2) = Min_Temp_Data(HEN_data)

   'Creates the first column of the HSDT with all inlet and outlet temperatures
   For i = 1 To UBound(HEN_data, 1) Step 1
      Insert_Temp HSDT, HEN_data(i, 8) - HEN_data(i, 2)  'T_hi
      Insert_Temp HSDT, HEN_data(i, 9) - HEN_data(i, 2)  'T_ho
      Insert_Temp HSDT, HEN_data(i, 10) + HEN_data(i, 4) 'T_ci
      Insert_Temp HSDT, HEN_data(i, 11) + HEN_data(i, 4) 'T_co
   Next i

   'Calculates the HSDT for each exchanger
   For i = 1 To UBound(HEN_data, 1) Step 1
      'Temperatures and CPs
      T_hi = HEN_data(i, 8) - HEN_data(i, 2)
      T_ho = HEN_data(i, 9) - HEN_data(i, 2)

      T_ci = HEN_data(i, 10) + HEN_data(i, 4)
      T_co = HEN_data(i, 11) + HEN_data(i, 4)
```

```
        If T_hi - T_ho = 0 Then CP_h = 0 Else CP_h = HEN_data(i, 12) / (T_hi - T_ho)
        If T_co - T_ci = 0 Then CP_c = 0 Else CP_c = HEN_data(i, 12) / (T_co - T_ci)

        'Calculates the HSDT
        For j = 1 To UBound(HSDT, 2) Step 1
            'Neither hot or cold are present
            If HSDT(1, j) + ZERO >= T_hi And HSDT(1, j) + ZERO >= T_co Then
                HSDT(i + 1, j) = vbNullString
            'When only hot is present
            ElseIf HSDT(1, j) + ZERO <= T_hi And HSDT(1, j) + ZERO > T_ho And HSDT(1, j) + ZERO > T_co
Then
                HSDT(i + 1, j) = (HSDT(1, j - 1) - HSDT(1, j)) * CP_h
            'When both streams are present
            ElseIf HSDT(1, j) + ZERO >= T_ho And HSDT(1, j) + ZERO < T_hi And HSDT(1, j) + ZERO < T_co
And HSDT(1, j) + ZERO >= T_ci Then
                HSDT(i + 1, j) = (HSDT(1, j - 1) - HSDT(1, j)) * (CP_h - CP_c)
            ElseIf (HSDT(1, j) + ZERO < T_ho And HSDT(1, j) + ZERO < T_co And HSDT(1, j) + ZERO >= T_ci
And T_ci <> 0) Or (T_ho = 0 And HSDT(1, j) + ZERO >= T_ci) Then
                HSDT(i + 1, j) = (HSDT(1, j - 1) - HSDT(1, j)) * -CP_c
            'Neither stream is present
            Else
                HSDT(i + 1, j) = vbNullString
            End If
        Next j
    Next i
End Sub

Sub Copy_HEN_Data(ByRef HEN_data, ByRef Stream_Data)
'Sub for moving data from the Stream Data array to the HEN data array

    'For all coolers
    For i = 1 To Tot_C Step 1
        HEN_data(i, 1) = Stream_Data(i, 1)
        HEN_data(i, 2) = Stream_Data(i, 6)
        HEN_data(i, 3) = Stream_Data(i, 7)
        HEN_data(i, 6) = Stream_Data(i, 2)
        HEN_data(i, 8) = Stream_Data(i, 3)
        HEN_data(i, 9) = Stream_Data(i, 4)
        HEN_data(i, 12) = Stream_Data(i, 5)
    Next i

    'For all exchangers
    j = i
    For i = i To Tot_E + Tot_C Step 1

        'Determines which stream is hot and which is cold
        If Stream_Data(j, 3) < 0 Then
            Debug.Print "HERE"
        End If
        If (Stream_Data(j, 3) + ZERO) > Stream_Data(j, 4) And Stream_Data(j + 1, 3) < (Stream_Data(j
+ 1, 4) + ZERO) Then
            h = j
            c = j + 1
        Else
            h = j + 1
            c = j
```

```
        End If

        HEN_data(i, 1) = Stream_Data(j, 1)
        HEN_data(i, 2) = Stream_Data(h, 6)
        HEN_data(i, 3) = Stream_Data(h, 7)
        HEN_data(i, 4) = Stream_Data(c, 6)
        HEN_data(i, 5) = Stream_Data(c, 7)
        HEN_data(i, 6) = Stream_Data(h, 2)
        HEN_data(i, 7) = Stream_Data(c, 2)
        HEN_data(i, 8) = Stream_Data(h, 3)
        HEN_data(i, 9) = Stream_Data(h, 4)
        HEN_data(i, 10) = Stream_Data(c, 3)
        HEN_data(i, 11) = Stream_Data(c, 4)
        HEN_data(i, 12) = Stream_Data(j, 5)

        j = j + 2

    Next i

    'For all heaters
    j = Tot_C + 2 * Tot_E + 1
    For i = i To Tot_E + Tot_C + Tot_H Step 1
        HEN_data(i, 1) = Stream_Data(j, 1)
        HEN_data(i, 4) = Stream_Data(j, 6)
        HEN_data(i, 5) = Stream_Data(j, 7)
        HEN_data(i, 7) = Stream_Data(j, 2)
        HEN_data(i, 10) = Stream_Data(j, 3)
        HEN_data(i, 11) = Stream_Data(j, 4)
        HEN_data(i, 12) = Stream_Data(j, 5)
        j = j + 1
    Next i

End Sub

Sub OrderProcessStreams()
'Order process streams in the Stream Data sheet.

MAX_STREAMS = 500

Sheets(SD_Sheet).Select
    Range(Cells(3, 1), Cells(MAX_STREAMS + 2, 9)).Select
    SELECTION.copy
    SELECTION.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:=False, Transpose:=False
    Application.CutCopyMode = False

    'Sorts based on the Exchanger first, Stream second, and then Ts
    ActiveWorkbook.Worksheets(SD_Sheet).Sort.SortFields.Clear
    ActiveWorkbook.Worksheets(SD_Sheet).Sort.SortFields.Add Key:=Range(Cells(3, 1), Cells(MAX_STREAMS + 2, 1)), SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:=xlSortNormal
    ActiveWorkbook.Worksheets(SD_Sheet).Sort.SortFields.Add Key:=Range(Cells(3, 2), Cells(MAX_STREAMS + 2, 2)), SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:=xlSortNormal
    ActiveWorkbook.Worksheets(SD_Sheet).Sort.SortFields.Add Key:=Range(Cells(3, 3), Cells(MAX_STREAMS + 2, 3)), SortOn:=xlSortOnValues, Order:=xlDescending, DataOption:=xlSortNormal
```

```
    With ActiveWorkbook.Worksheets(SD_Sheet).Sort
        .SetRange Range(Cells(3, 1), Cells(MAX_STREAMS + 2, 9))
        .Header = xlGuess
        .MatchCase = False
        .Orientation = xlTopToBottom
        .SortMethod = xlPinYin
        .Apply
    End With

    'Cells(3, 1).Select
End Sub

Sub Read_Data(ByRef input_array, r_start, Optional j)
'Read or write arrays from/to current sheet
    i_max = UBound(input_array, 1)
    j_max = UBound(input_array, 2)
    If IsMissing(j) Then j = 1
    For j = j To j_max Step 1
        For i = 1 To i_max Step 1
            input_array(i, j) = Cells(r_start - 1 + i, j)
        Next i
        ProgramPause , 100
    Next j
End Sub

Function Calc_Segs() As Integer
'Calculates the number of HX based on input HSDT
    i = 0
    Do
        i = i + 1
    Loop While Not Cells(3 + i, 1) = vbNullString
    Calc_Segs = i
End Function

Sub HSDT_Header(ByRef HEN_data)
'Sub for writing the HSDT header

    Cells(1, 1) = "Case:"
    Cells(3, 1) = "HX Name"
    Cells(4, 1) = "DTcont,h"
    Cells(5, 1) = "HTC,h"
    Cells(6, 1) = "DTcont,c"
    Cells(7, 1) = "HTC,c"
    Cells(8, 1) = "S,h"
    Cells(9, 1) = "S,c"
    Cells(10, 1) = "T,hi"
    Cells(11, 1) = "T,ho"
    Cells(12, 1) = "T,ci"
    Cells(13, 1) = "T,co"
    Cells(14, 1) = "Q"
    Cells(15, 1) = "Ti"

    For i = 1 To UBound(HEN_data, 1) Step 1
        For j = 1 To UBound(HEN_data, 2) Step 1
            Cells(R_Table - 1 + j, i + 1) = HEN_data(i, j)
        Next j
    Next i
```

End Sub

HSDT Functions Module

```
Sub Calculate_HSDT(ByRef HSDT, ByRef HEN_data)
'Calculates the HSDT after the HEN_data has been determined
'Retrofit purposes

    temp_n = 4 * (UBound(HEN_data, 1) - 1)

    Dim tempArray()
    ReDim tempArray(temp_n)

    'Creates the first column of the HSDT with all inlet and outlet temperatures
    Timer1 = Timer
    For i = 2 To UBound(HEN_data, 1) Step 1
        tempArray(k) = HEN_data(i, 10) - HEN_data(i, 8): k = k + 1
        tempArray(k) = HEN_data(i, 11) - HEN_data(i, 8): k = k + 1
        tempArray(k) = HEN_data(i, 16) + HEN_data(i, 14): k = k + 1
        tempArray(k) = HEN_data(i, 17) + HEN_data(i, 14): k = k + 1
    Next i

    QuickSort_1D tempArray
    RemoveDuplicates_1D tempArray
    ReverseArray_1D tempArray
    timer1_Total = timer1_Total + (Timer - Timer1)

    ReDim HSDT(UBound(HEN_data, 1), UBound(tempArray))  'The second dimension will be
updated

    For i = 1 To UBound(HSDT, 2) Step 1
        HSDT(1, i) = tempArray(i)
    Next i

    'Calculates the HSDT for each exchanger
    For i = 2 To UBound(HEN_data, 1) Step 1
        'Temperatures and CPs
        T_hi = HEN_data(i, 10) - HEN_data(i, 8)
        T_ho = HEN_data(i, 11) - HEN_data(i, 8)
        CP_h = HEN_data(i, 12)
        T_ci = HEN_data(i, 16) + HEN_data(i, 14)
        T_co = HEN_data(i, 17) + HEN_data(i, 14)
        CP_c = HEN_data(i, 18)

        'Calculates the HSDT
        For j = 1 To UBound(HSDT, 2) Step 1
            'Neither hot or cold are present
            If HSDT(1, j) + ZERO >= T_hi And HSDT(1, j) + ZERO >= T_co Then
                HSDT(i, j) = 0
            'When only hot is present
            ElseIf HSDT(1, j) + ZERO <= T_hi And HSDT(1, j) + ZERO > T_ho And HSDT(1, j) + ZERO > T_co
Then
                HSDT(i, j) = (HSDT(1, j - 1) - HSDT(1, j)) * CP_h
                If Abs(HSDT(i, j)) < ZERO Then HSDT(i, j) = 0
            'When both streams are present
```

```
        ElseIf HSDT(1, j) + ZERO >= T_ho And HSDT(1, j) + ZERO < T_hi And HSDT(1, j) + ZERO < T_co
And HSDT(1, j) + ZERO >= T_ci Then
          HSDT(i, j) = (HSDT(1, j - 1) - HSDT(1, j)) * (CP_h - CP_c)
          If Abs(HSDT(i, j)) < ZERO Then HSDT(i, j) = 0
        ElseIf (HSDT(1, j) + ZERO < T_ho And HSDT(1, j) + ZERO < T_co And HSDT(1, j) + ZERO >= T_ci
And T_ci <> 0) Or (T_ho = 0 And HSDT(1, j) + ZERO >= T_ci) Then
          HSDT(i, j) = (HSDT(1, j - 1) - HSDT(1, j)) * -CP_c
          If Abs(HSDT(i, j)) < ZERO Then HSDT(i, j) = 0
        'Neither stream is present
        Else
          HSDT(i, j) = 0
        End If
      Next j
    Next i
End Sub

Sub Insert_Temp(ByRef HSDT, T)

    Dim clone() As Variant
    ReDim clone(UBound(HSDT, 1), UBound(HSDT, 2))

    Timer3 = Timer
    For i = 1 To UBound(HSDT, 2) Step 1
      'Checks if the temperature already exists in the HSDT
      If T <= HSDT(1, i) + ZERO And T >= HSDT(1, i) - ZERO Then
        clone = HSDT
        GoTo 100
      End If

      Timer2 = Timer
      If T < HSDT(1, i) + ZERO Then
        clone(1, i) = HSDT(1, i)
      ElseIf T > HSDT(1, i) + ZERO And T < HSDT(1, i - 1) + ZERO Then

        ReDim Preserve clone(UBound(clone, 1), UBound(clone, 2) + 1)

        clone(1, i) = T
      Else
        clone(1, i) = HSDT(1, i - 1)
      End If
      timer2_total = timer2_total + (Timer - Timer2)
    Next i
    timer3_total = timer3_total + (Timer - Timer3)

    If UBound(clone, 2) = i Then clone(1, i) = HSDT(1, i - 1)
100
    Timer4 = Timer
    HSDT = clone
    timer4_total = timer4_total + (Timer - Timer4)

End Sub

Sub Draw_HSDT(ByRef HSDT, ByRef HEN_data)

    Sheets("Retrofit HSDT").Activate
    Sheets("Retrofit HSDT").UsedRange.ClearContents
    r_hsdt = 15
```

```
    For i = 1 To UBound(HSDT, 1) Step 1
        For j = 1 To UBound(HSDT, 2) Step 1
            Cells(r_hsdt + j, i) = HSDT(i, j)
        Next j
    Next i

    Cells(1, 1) = "Bridge: "
    Cells(15, 1) = "Ti"

    For i = 1 To UBound(HEN_data, 1) Step 1
        Cells(3, i) = HEN_data(i, 1)
        Cells(4, i) = HEN_data(i, 8)
        Cells(5, i) = HEN_data(i, 9)
        Cells(6, i) = HEN_data(i, 14)
        Cells(7, i) = HEN_data(i, 15)
        Cells(8, i) = HEN_data(i, 7)
        Cells(9, i) = HEN_data(i, 13)
        Cells(10, i) = HEN_data(i, 10)
        Cells(11, i) = HEN_data(i, 11)
        Cells(12, i) = HEN_data(i, 16)
        Cells(13, i) = HEN_data(i, 17)
        Cells(14, i) = HEN_data(i, 6)
    Next i
End Sub

Function Max_Temp(ByRef HEN_data) As Double
'Finds the maximum temperature

    Max_Temp = -100000000000#

    For i = 2 To UBound(HEN_data, 1) Step 1
        If HEN_data(i, 10) - HEN_data(i, 8) > Max_Temp Then Max_Temp = HEN_data(i, 10) - HEN_data(i, 8)
        If HEN_data(i, 17) + HEN_data(i, 14) > Max_Temp Then Max_Temp = HEN_data(i, 17) + HEN_data(i, 14)
    Next i

End Function

Function Min_Temp(ByRef HEN_data) As Double
'Finds the minimum temperature

    Min_Temp = 100000000000#

    For i = 2 To UBound(HEN_data, 1) Step 1
        If HEN_data(i, 16) + HEN_data(i, 14) < Min_Temp Then Min_Temp = HEN_data(i, 16) + HEN_data(i, 14)
        If HEN_data(i, 11) - HEN_data(i, 8) < Min_Temp Then Min_Temp = HEN_data(i, 11) - HEN_data(i, 8)
    Next i

End Function
```

HEN Functions Module

```
Sub RB_Solve(ByRef HSDT, ByRef HEN_data)
'Conducts the retrofit analysis for all RBs, before Pareto optimisation and

  Dim RB_data() As Variant, RB_record() As Variant
  ReDim RB_data(UBound(HSDT, 1)), RB_record(MAX_RB, MAX_STEP + 12)

  Count_Units HEN_data

  prev_RB = Tot_RB - 1

  Determine_RB_pathways RB_record, HEN_data, HSDT, RB_data, prev_RB

  If RB_paths = 0 Then Exit Sub

  If PARETO Then Paerato_Optimal RB_record, RB_paths

  For i = 1 To RB_paths Step 1

    Q_HR = RB_record(i, MAX_STEP + 3)
    If CUMULATIVE_2 Then Q_HR = RB_record(i, MAX_STEP + 3) - MasterArray(prev_RB, 
MAX_STEP + 4)

    network_split = False: splitCnt = 0
    Dim HSDT_2() As Variant, HEN_data_2() As Variant
    Bridge = Q_HR & "-" & RB_record(i, RB_step + 1)

    Retrofit HEN_data, HSDT, HEN_data_2, HSDT_2, Bridge, Q_HR

    'Recalculates metrics after network has been designed
    A_tot = 0: A_star_tot = 0: n_mod = 0
    Dim total_cost As Double
    total_cost = 0

    If CUMULATIVE Then
      Calc_Retrofit_Area HEN_data_Original, HEN_data_2, A_tot, A_star_tot, n_mod, total_cost
      Q_HR = Q_HR + MasterArray(prev_RB, 4 + MAX_STEP)
      splitCnt = splitCnt + MasterArray(prev_RB, 5 + MAX_STEP)
    Else
      Calc_Retrofit_Area HEN_data, HEN_data_2, A_tot, A_star_tot, n_mod, total_cost
    End If
    Calc_RB_Metrics RB_record, n_mod, A_tot, A_star_tot, Q_HR, i, splitCnt, total_cost

'    If RB_step = 4 Then
'      Draw_HSDT HSDT_2, HEN_data_2
'    End If

    'Records the retrofit design information
    MasterArray(Tot_RB, 1) = Tot_RB
    For j = 1 To UBound(RB_record, 2) Step 1
      MasterArray(Tot_RB, j + 1) = RB_record(i, j)
    Next j
    If CUMULATIVE_2 = False Then
      If RB_step > 1 Then
        MasterArray(Tot_RB, MAX_STEP + 14) = MasterArray(Tot_RB, MAX_STEP + 13) + 
MasterArray(prev_RB, MAX_STEP + 14)
      Else
        MasterArray(Tot_RB, MAX_STEP + 14) = MasterArray(Tot_RB, MAX_STEP + 13)
```

```
         End If
      End If
      Tot_RB = Tot_RB + 1

      'The next retrofit step
      If RB_step < MAX_STEP Then
         RB_step = RB_step + 1
         RB_Solve HSDT_2, HEN_data_2
         RB_step = RB_step - 1
      End If
   ProgramPause True
   Next i
End Sub

Sub Retrofit(ByRef HEN_data, ByRef HSDT, ByRef HEN_data_2, ByRef HSDT_2, Bridge, Q_HR)
'Conducts the retrofit

   rb_pathway = split(Bridge, "-")
   new_HX = UBound(rb_pathway, 1) - 1

   'Resizes and clones the HEN data array
   ReDim HEN_data_2(UBound(HEN_data, 1) + new_HX * 2, 18)
   For i = 1 To UBound(HEN_data, 1) Step 1
      For j = 1 To UBound(HEN_data, 2) Step 1
         HEN_data_2(i, j) = HEN_data(i, j)
      Next j
   Next i

   'Inserts new exchangers at every step of the bridge
   For i = 1 To new_HX Step 1
      Insert_HX HEN_data_2, Q_HR, rb_pathway(i), rb_pathway(i + 1)

      If network_split = True And ALLOW_SPLITS = False Then
         'Exits the retrofit design if splits are disallowed
         HEN_data_2 = HEN_data
         HSDT_2 = HSDT
         Exit Sub
      End If
   Next i

   Order_HEN HEN_data_2

   Calculate_HSDT HSDT_2, HEN_data_2

   For i = 2 To UBound(HEN_data_2, 1)
      HEN_Calculations HEN_data_2, HSDT_2, i
   Next i

End Sub

Sub HEN_Calculations(ByRef HEN_data, ByRef HSDT, i)
'Performs all necessary HEN calculations

   j = 2
   If HSDT(i, j) > ZERO Then
      HEN_data(i, 4) = j 'Max T row
      GoTo 100
```

```
    End If
    For j = j To UBound(HSDT, 2) Step 1
        If Abs(HSDT(i, j - 1)) < ZERO And HSDT(i, j) > ZERO And (HEN_data(i, 2) = "C" Or HEN_data(i, 2)
= "R") Then
            HEN_data(i, 4) = j  'Max T row
            GoTo 100
        End If
    Next j
100
    j = UBound(HSDT, 2)
    If HSDT(i, j) < -ZERO Then
        HEN_data(i, 5) = j 'Min T row
        GoTo 200
    End If
    For j = j - 1 To 1 Step -1
        If HSDT(i, j) < -ZERO And Abs(HSDT(i, j + 1)) < ZERO And (HEN_data(i, 2) = "H" Or HEN_data(i,
2) = "R") Then
            HEN_data(i, 5) = j 'Min T row
            GoTo 200
        End If
    Next j
200
End Sub

Sub Calc_HC(ByRef HSDT, ByRef HSC, ByRef HDC)
    i_max = UBound(HSDT, 1) 'based on number of HX
    j_max = UBound(HSDT, 2) 'based on temperatures
    ReDim HSC(i_max, j_max), HDC(i_max, j_max)
    For i = 2 To i_max Step 1
        HSC(i, 1) = 0
        HDC(i, 1) = 0
        For j = 2 To j_max Step 1
            Select Case HSDT(i, j)
            Case Is > ZERO ''surplus
                HSC(i, j) = HSC(i, j - 1) - HSDT(i, j) 'cumulative update
                HDC(i, j) = HDC(i, j - 1)
            Case Is < ZERO ''deficit
                HSC(i, j) = HSC(i, j - 1)
                HDC(i, j) = HDC(i, j - 1) + HSDT(i, j)
            Case Else 'when nothing is happening
                HSC(i, j) = HSC(i, j - 1) ''takes the previous result
                HDC(i, j) = HDC(i, j - 1)
            End Select
        Next j
    Next i
    For i = 2 To i_max Step 1
        H_shift = -HDC(i, j_max)
        If H_shift > ZERO Then
            For j = 1 To j_max Step 1
                HDC(i, j) = HDC(i, j) + H_shift
            Next j
        End If
    Next i
End Sub

Sub Order_HEN(ByRef HEN_data)
```

```
    For i = 2 To UBound(HEN_data, 1) Step 1
        If HEN_data(i, 1) <> vbNullString Then HX_count = HX_count + 1
    Next i

    For i = 2 To UBound(HEN_data, 1) Step 1
        Merge = False
        If (HEN_data(i, 6) = 0 And HEN_data(i, 6) <> vbNullString) Then
            HEN_data(i, 2) = vbNullString ': HX_count = HX_count - 1
        Else
            'Need to merge exchangers
            For j = 2 To UBound(HEN_data, 1) Step 1
                If (j = i Or HEN_data(j, 1) = vbNullString) And j <> UBound(HEN_data, 1) Then j = j + 1

                If i <> j And Abs(HEN_data(i, 18) - HEN_data(j, 18)) < ZERO And Abs(HEN_data(i, 12) - 
HEN_data(j, 12)) < ZERO And HEN_data(i, 2) = "R" Then
                    If HEN_data(i, 7) = HEN_data(j, 7) And HEN_data(i, 13) = HEN_data(j, 13) And 
HEN_data(i, 7) <> vbNullString Then
                        If (Abs(HEN_data(i, 17) - HEN_data(j, 16)) < ZERO And Abs(HEN_data(i, 10) - 
HEN_data(j, 11)) < ZERO) _
                        Or (Abs(HEN_data(j, 17) - HEN_data(i, 16)) < ZERO And Abs(HEN_data(j, 10) - 
HEN_data(i, 11)) < ZERO) Then
                            'Determines which is the existing exchanger which will remain
                            If HEN_data(i, 1) = "N" Then
                                ex_HX = j: new_HX = i
                            ElseIf HEN_data(j, 1) = "N" Then
                                ex_HX = i: new_HX = j
                            ElseIf InStr(HEN_data(i, 1), "E") = 1 And InStr(HEN_data(j, 1), "E") = 1 Then
                                ex_HX = i: new_HX = j
                            Else
                                GoTo 100
                            End If

                            HEN_data(ex_HX, 2) = "R"

                            HEN_data(ex_HX, 6) = HEN_data(ex_HX, 6) + HEN_data(new_HX, 6)   'Updates Q
                            'If the existing exchanger is upstream (hot)
                            If HEN_data(ex_HX, 10) < HEN_data(new_HX, 10) Then
                                HEN_data(ex_HX, 10) = HEN_data(new_HX, 10)
                                HEN_data(ex_HX, 17) = HEN_data(new_HX, 17)
                            Else
                                HEN_data(ex_HX, 11) = HEN_data(new_HX, 11)
                                HEN_data(ex_HX, 16) = HEN_data(new_HX, 16)
                            End If

                            HEN_data(new_HX, 2) = vbNullString ': HX_count = HX_count - 1
                            Merge = True
                        End If
                    End If
                End If
100
            Next j
            If Merge = True Then i = i - 1
        End If
    Next i

    For i = 2 To UBound(HEN_data, 1) Step 1
        If HEN_data(i, 2) = vbNullString And HEN_data(i, 1) <> vbNullString Then
```

```
        HX_count = HX_count - 1
      End If
    Next i

    Dim HEN_copy() As Variant
    ReDim HEN_copy(HX_count + 1, UBound(HEN_data, 2))

    k = 1: m = 0: n = 0
    For i = 1 To UBound(HEN_data, 1) Step 1
      'Sorts Exchangers and names New Exchangers
      If HEN_data(i, 2) = "C" Then
        n = n + 1
      ElseIf HEN_data(i, 2) = "R" Then
        If InStr(HEN_data(i, 1), "E") = 1 Then n_HX = i
        If HEN_data(i, 1) = "N" Then
          If m = 0 Then
            m = GetNumeric(CStr(HEN_data(n_HX, 1)))
          End If
          m = m + 1
          If m < 10 Then m = "0" & m
          HEN_data(i, 1) = "E" & m
        End If
      End If
      'Need to place coolers and recovery exchangers first
      If HEN_data(i, 2) <> vbNullString And HEN_data(i, 2) <> "H" Then
        For j = 1 To UBound(HEN_data, 2) Step 1
          HEN_copy(k, j) = HEN_data(i, j)
        Next j
        k = k + 1
      End If
    Next i
    For i = n + 1 To UBound(HEN_data, 1) Step 1 'Records all heaters
      If HEN_data(i, 2) = "H" Then
        For j = 1 To UBound(HEN_data, 2) Step 1
          HEN_copy(k, j) = HEN_data(i, j)
        Next j
        k = k + 1
      End If
    Next i

    HEN_data = HEN_copy

  End Sub

  Sub Calc_HTC(ByRef HEN_data)

    CP_h = HEN_data(i, 12)
    CP_c = HEN_data(i, 18)
    m_h = CP_h / 4.18
    m_c = CP_c / 4.18

    vis = 1 * 10 ^ (-3) 'Ns/m2
    Pr = 7
    k = 0.6     'W/mC
    rho = 1000  'kg/m3
    c = 0.023
    A_tube = 0.1 'm2
```

```
    d_o = 0.025 'm
    d_i = 0.022 'm

    v_h = m_h / (rho * A_tube)  'm/s
    v_c = m_c / (rho * A_tube)  'm/s

    K_c = c * (k / d_i) * Pr ^ (1 / 3) * (0.022 * rho / vis) ^ 0.8
    K_h = (0.24 * 0.8 * 0.8 * rho ^ 0.64 * (m_h / 4.18 / 1000) ^ (1 / 3) * k ^ (2 / 3)) / (vis ^ 0.307 *
d_o ^ 0.36)

    HEN_data(i, 15) = K_c * v_c ^ 0.8
    HEN_data(i, 9) = K_h * v_h ^ 0.64

End Sub

Sub Insert_HX(ByRef HEN_data, Q_HR, HX_1, HX_2)

    'Finds the next available space in HEN_data
    i = 2
    While HEN_data(i, 1) <> vbNullString
        If HEN_data(i, 1) = HX_1 Then HX_S = i
        If HEN_data(i, 1) = HX_2 Then HX_D = i
        i = i + 1
    Wend

    If HX_S = vbNullString Then HX_S = HX_1
    If HX_D = vbNullString Then HX_D = HX_2

    'Performs all hot stream calculations
    Q_h = HEN_data(HX_S, 6) - Q_HR
    If Abs(Q_h) < ZERO Then Q_h = 0
    CP_h = HEN_data(HX_S, 12)
    HEN_data(i, 10) = HEN_data(HX_S, 10)    'T_hi of new exchanger
    HEN_data(HX_S, 10) = HEN_data(HX_S, 11) + Q_h / CP_h    'New T_hi of old exchanger
    HEN_data(i, 11) = HEN_data(HX_S, 10)    'T_ho of new exchanger

    'Performs all cold stream calculations
    Q_c = HEN_data(HX_D, 6) - Q_HR
    If Abs(Q_c) < ZERO Then Q_c = 0
    CP_c = HEN_data(HX_D, 18)
    HEN_data(i, 16) = HEN_data(HX_D, 16)    'T_ci of new exchanger
    HEN_data(HX_D, 16) = HEN_data(HX_D, 17) - Q_c / CP_c    'New T_ci of old exchanger
    HEN_data(i, 17) = HEN_data(HX_D, 16)    'T_co of new exchanger

    HEN_data(i, 1) = "N"
    HEN_data(i, 2) = "R"
        '3-5, These calculations are performed later
    HEN_data(i, 6) = Q_HR
    HEN_data(i, 7) = HEN_data(HX_S, 7)
    HEN_data(i, 8) = HEN_data(HX_S, 8)
    HEN_data(i, 9) = HEN_data(HX_S, 9)
        '10-11, These calculations have already been performed
    HEN_data(i, 12) = CP_h
    HEN_data(i, 13) = HEN_data(HX_D, 13)
    HEN_data(i, 14) = HEN_data(HX_D, 14)
    HEN_data(i, 15) = HEN_data(HX_D, 15)
        '16-17, These calculations have already been performed
```

```
    HEN_data(i, 18) = CP_c

    'Check for stream splitting
    If ALLOW_SPLITS Then
        Check_Splits HEN_data, i, HX_S, HX_D, Q_HR
    Else
        If Check_DT(HEN_data, HX_S) Or Check_DT(HEN_data, HX_D) Then
            network_split = True
            Exit Sub
        End If
    End If

    'Updates the duties of the utilities
    If match_split = False Then
        HEN_data(HX_S, 6) = Q_h
    End If
    If HEN_data(HX_D, 2) <> "R" Then HEN_data(HX_D, 6) = Q_c
    match_split = False

End Sub

Sub Check_Splits(ByRef HEN_data, HX_new, HX_S, HX_D, Q_HR)
'Checks for splits and DT_min violations
    If Check_DT(HEN_data, HX_S) Then
    'Need to split the surplus

        T_limit = HEN_data(HX_D, 16) - Q_HR / HEN_data(HX_D, 18)    'Need the original T of HX_D

        If (HEN_data(HX_S, 11) - HEN_data(HX_S, 8)) + ZERO < (T_limit + HEN_data(HX_D, 14)) Then
        'Series split

            T1 = HEN_data(HX_S, 10) + Q_HR / HEN_data(HX_S, 12)
            T2 = T_limit + HEN_data(HX_S, 8) + HEN_data(HX_D, 14)
            'T2 = T1 - Q_HR / (HEN_data(HX_S, 12) - HEN_data(HX_S, 18))

            Q_split = (T1 - T2) * HEN_data(HX_S, 12)

            split_ratio = Q_HR / Q_split

            'New exchanger
            HEN_data(HX_new, 12) = HEN_data(HX_S, 12) * split_ratio
            HEN_data(HX_new, 11) = HEN_data(HX_new, 10) - Q_HR / HEN_data(HX_new, 12)
            HEN_data(HX_new, 7) = HEN_data(HX_S, 7) + " " + CStr(RB_step) + "/a" + "/TypeB"
            'Existing exchanger (surplus)
            HEN_data(HX_S, 10) = HEN_data(HX_new, 11)   'Inlet temp after split
            HEN_data(HX_S, 6) = HEN_data(HX_S, 6) - Q_split             'Duty after split
            HEN_data(HX_S, 17) = HEN_data(HX_S, 16) + HEN_data(HX_S, 6) / HEN_data(HX_S, 18)

            'Need to place another exchanger in the new split
            j = HX_new + 1
            HEN_data(j, 1) = "N"
            HEN_data(j, 2) = "R"
            HEN_data(j, 6) = Q_split - Q_HR
            'HOT
            HEN_data(j, 7) = HEN_data(HX_S, 7) + " " + CStr(RB_step) + "/b" + "/TypeB"
            'Existing exchanger (surplus) 'stream name
            HEN_data(j, 8) = HEN_data(HX_S, 8)  'DT_cont
```

```
            HEN_data(j, 9) = HEN_data(HX_S, 9)  'HTC
            HEN_data(j, 10) = HEN_data(HX_new, 10)  'T_in
            HEN_data(j, 11) = HEN_data(HX_new, 11)  'T_out
            HEN_data(j, 12) = HEN_data(HX_S, 12) * (1 - split_ratio)    'CP
            'COLD
            HEN_data(j, 13) = HEN_data(HX_S, 13)    'stream name
            HEN_data(j, 14) = HEN_data(HX_S, 14)    'DT_cont
            HEN_data(j, 15) = HEN_data(HX_S, 15)    'HTC
            HEN_data(j, 16) = HEN_data(HX_S, 17)    'T_in
            HEN_data(j, 18) = HEN_data(HX_S, 18)    'CP
            HEN_data(j, 17) = HEN_data(j, 16) + HEN_data(j, 6) / HEN_data(j, 18) 'T_out
        Else
        'Parallel split
            Q_split = Q_HR
            split_ratio = Q_HR / HEN_data(HX_S, 6)
            HEN_data(HX_new, 7) = HEN_data(HX_S, 7) + " " + CStr(RB_step) + "/a" + "/TypeA"
            HEN_data(HX_new, 12) = HEN_data(HX_S, 12) * split_ratio 'new CP
            HEN_data(HX_new, 11) = HEN_data(HX_new, 10) - Q_HR / HEN_data(HX_new, 12) 'new
T_out

            HEN_data(HX_S, 7) = HEN_data(HX_S, 7) + " " + CStr(RB_step) + "/b" + "/TypeA"
            HEN_data(HX_S, 10) = HEN_data(HX_new, 10)   'new T_in
            HEN_data(HX_S, 12) = HEN_data(HX_S, 12) * (1 - split_ratio) 'new CP
            HEN_data(HX_S, 11) = HEN_data(HX_S, 10) - (HEN_data(HX_S, 6) - Q_HR) / HEN_data(HX_S,
12)   'new T_out

            HEN_data(HX_S, 6) = HEN_data(HX_S, 6) - Q_HR

            parallel_split = True
        End If

        match_split = True    'match_split refers to the single exchanger match
        network_split = True  'network_split refers to the entire network
        splitCnt = splitCnt + 1
    End If

    If Check_DT(HEN_data, HX_D) Then
    'Need to split the deficit

        T_limit = HEN_data(HX_S, 10) + Q_HR / HEN_data(HX_S, 12)

        If match_split = True Then
            T_limit = HEN_data(HX_S, 10) + Q_split / HEN_data(HX_S, 12)
        End If

        If parallel_split = True Then
            T_limit = HEN_data(HX_S, 10)
            parallel_split = False
        End If

        If (HEN_data(HX_D, 17) + HEN_data(HX_D, 14)) - ZERO > (T_limit - HEN_data(HX_S, 8)) Then
        'Series split

            T2 = HEN_data(HX_D, 16) - Q_HR / HEN_data(HX_D, 18)
            T1 = T_limit - HEN_data(HX_D, 14) - HEN_data(HX_S, 8)

            Q_split = (T1 - T2) * HEN_data(HX_D, 18)
```

```
        split_ratio = Q_HR / Q_split

        'New exchanger
        HEN_data(HX_new, 18) = HEN_data(HX_D, 18) * split_ratio
        HEN_data(HX_new, 17) = HEN_data(HX_new, 16) + Q_HR / HEN_data(HX_new, 18)
        HEN_data(HX_new, 13) = HEN_data(HX_D, 13) + " " + CStr(RB_step) + "/a" + "/TypeB"
        'Existing exchanger (deficit)
        HEN_data(HX_D, 16) = HEN_data(HX_new, 17)
        HEN_data(HX_D, 6) = HEN_data(HX_D, 6) - Q_split + Q_HR
        tempT = HEN_data(HX_D, 10) - (HEN_data(HX_D, 6)) / HEN_data(HX_D, 12)
        HEN_data(HX_D, 11) = tempT

        'Need to place another exchanger in the new split
        j = HX_new + 1
        If match_split = True Then j = j + 1
        HEN_data(j, 1) = "N"
        HEN_data(j, 2) = "R"
        HEN_data(j, 6) = Q_split - Q_HR
        'HOT
        HEN_data(j, 7) = HEN_data(HX_D, 7) 'stream name
        HEN_data(j, 8) = HEN_data(HX_D, 8)  'DT_cont
        HEN_data(j, 9) = HEN_data(HX_D, 9)  'HTC
        HEN_data(j, 10) = HEN_data(HX_D, 11)  'T_in
        HEN_data(j, 12) = HEN_data(HX_D, 12)  'CP
        HEN_data(j, 11) = HEN_data(j, 10) - HEN_data(j, 6) / HEN_data(j, 12)    'T_out
        'COLD
        HEN_data(j, 13) = HEN_data(HX_D, 13) + " " + CStr(RB_step) + "/b" + "/TypeB"     'stream
name
        HEN_data(j, 14) = HEN_data(HX_D, 14)    'DT_cont
        HEN_data(j, 15) = HEN_data(HX_D, 15)    'HTC
        HEN_data(j, 16) = HEN_data(HX_new, 16)  'T_in
        HEN_data(j, 17) = HEN_data(HX_new, 17)  'T_out
        HEN_data(j, 18) = HEN_data(HX_D, 18) * (1 - split_ratio)     'CP

        If match_split = False Then HEN_data(HX_S, 6) = HEN_data(HX_S, 6) - Q_HR
      Else
      'Parallel split
        split_ratio = Q_HR / HEN_data(HX_D, 6)
        HEN_data(HX_new, 13) = HEN_data(HX_D, 13) + " " + CStr(RB_step) + "/a" + "/TypeA"
        HEN_data(HX_new, 18) = HEN_data(HX_D, 18) * split_ratio
        HEN_data(HX_new, 17) = HEN_data(HX_new, 16) + Q_HR / HEN_data(HX_new, 18)

        HEN_data(HX_D, 13) = HEN_data(HX_D, 13) + " " + CStr(RB_step) + "/b" + "/TypeA"
        HEN_data(HX_D, 16) = HEN_data(HX_new, 16)
        HEN_data(HX_D, 18) = HEN_data(HX_D, 18) * (1 - split_ratio)
        HEN_data(HX_D, 17) = HEN_data(HX_D, 16) + (HEN_data(HX_D, 6) - Q_HR) /
HEN_data(HX_D, 18)

        If match_split = False Then HEN_data(HX_S, 6) = HEN_data(HX_S, 6) - Q_HR
      End If

      match_split = True
      network_split = True
      splitCnt = splitCnt + 1
   End If
End Sub
```

```
Function Check_DT(ByRef HEN_data, pos) As Boolean
'Calculates the minimum approach temperature for the exchanger

   Check_DT = False
   i = pos

   'Ignores utilities
   If HEN_data(i, 2) = "R" Then
      'Assumes counterflow process-to-process
      DT_1 = HEN_data(i, 10) - HEN_data(i, 17)
      DT_2 = HEN_data(i, 11) - HEN_data(i, 16)

      'Based on DT_cont
      DT_limit = HEN_data(i, 8) + HEN_data(i, 14)

      If DT_1 + ZERO < DT_limit Or DT_2 < DT_limit - ZERO Then
         Check_DT = True
      End If
   End If

End Function

Sub Count_Units(ByRef HEN_data)
'Calculates the numbers of coolers, recovery exchangers, and heaters

   'Resets the counters
   Tot_C = 0
   Tot_R = 0
   Tot_H = 0
   'Increments appropriate counters while looping
   For i = 2 To UBound(HEN_data, 1) Step 1
      Select Case HEN_data(i, 2)
         Case "C": Tot_C = Tot_C + 1
         Case "R": Tot_R = Tot_R + 1
         Case "H": Tot_H = Tot_H + 1
      End Select
   Next i
End Sub

Sub Calc_Initial_HEN(ByRef HEN_data, ByRef HSDT, ByRef R_Table)
'Calculates the HEN in the first iteration

   'HEN_data headings
   HEN_data(1, 1) = "HX Name"
   HEN_data(1, 2) = "HX Type"
   HEN_data(1, 3) = "Max DH"
   HEN_data(1, 4) = "Max T row"
   HEN_data(1, 5) = "Min T row"
   HEN_data(1, 6) = "Q"
   'Hot stream
   HEN_data(1, 7) = "S,h"
   HEN_data(1, 8) = "DTcont,h"
   HEN_data(1, 9) = "HTC,h"
   HEN_data(1, 10) = "Th,i"
   HEN_data(1, 11) = "Th,o"
   HEN_data(1, 12) = "CP,h"
   'Cold stream
```

```
    HEN_data(1, 13) = "S,c"
    HEN_data(1, 14) = "DTcont,c"
    HEN_data(1, 15) = "HTC,c"
    HEN_data(1, 16) = "Tc,i"
    HEN_data(1, 17) = "Tc,o"
    HEN_data(1, 18) = "CP,c"

    For i = 2 To UBound(HSDT, 1) Step 1
        'Information from spreadsheet
        HEN_data(i, 1) = Cells(R_Table - 13, i)
        HEN_data(i, 6) = Cells(R_Table - 2, i) 'Q
        'Hot stream
        HEN_data(i, 7) = Cells(R_Table - 8, i)
        HEN_data(i, 8) = Cells(R_Table - 12, i)
        HEN_data(i, 9) = Cells(R_Table - 11, i)
        HEN_data(i, 10) = Cells(R_Table - 6, i)
        HEN_data(i, 11) = Cells(R_Table - 5, i)
        If HEN_data(i, 10) <> 0 And HEN_data(i, 10) <> vbNullString Then
            HEN_data(i, 12) = HEN_data(i, 6) / (HEN_data(i, 10) - HEN_data(i, 11))
        End If
        'Cold stream
        HEN_data(i, 13) = Cells(R_Table - 7, i)
        HEN_data(i, 14) = Cells(R_Table - 10, i)
        HEN_data(i, 15) = Cells(R_Table - 9, i)
        HEN_data(i, 16) = Cells(R_Table - 4, i)
        HEN_data(i, 17) = Cells(R_Table - 3, i)
        If HEN_data(i, 16) <> 0 And HEN_data(i, 16) <> vbNullString Then
            HEN_data(i, 18) = HEN_data(i, 6) / (HEN_data(i, 17) - HEN_data(i, 16))
        End If

        If HEN_data(i, 7) <> vbNullString Then
            If HEN_data(i, 13) <> vbNullString Then
                HEN_data(i, 2) = "R"
            Else
                HEN_data(i, 2) = "C"
            End If
        Else
            HEN_data(i, 2) = "H"
        End If

        HEN_Calculations HEN_data, HSDT, i
    Next i

End Sub

Function GetNumeric(CellRef As String)

    Dim StringLength As Integer
    StringLength = Len(CellRef)
    For i = 1 To StringLength
        If IsNumeric(Mid(CellRef, i, 1)) Then Result = Result & Mid(CellRef, i, 1)
    Next i
    GetNumeric = Result

End Function
```

Bridge Functions Module

```
Private S_num As Integer, rb() As Variant, R_1 As Long

'Refinery costing
Public P_UtS As Double
Private Const n_exp = 0.85
Private Const FC = 30000  'EUR
Private Const VC = 3500   'EUR/m^2
Private Const i_rate = 0.1 '0.07 'for Refinery '0.1 'for Kraft
Private Const n_life = 10 'y  15'for Refinery '10 for Kraft

Sub Determine_RB_pathways(ByRef RB_record, ByRef HEN_data, ByRef HSDT, ByRef RB_data, ByVal prev_RB)

  ReDim rb(N_MAX + 1)
  counter = 0: RB_paths = 0: R_1 = 1

  Dim HSC() As Double, HDC() As Double
  Calc_HC HSDT, HSC, HDC
100
    For C_pos = 2 To Tot_C + 1 Step 1
    S_num = 1: HX_surp = C_pos: rb(S_num) = HX_surp: RB_data(C_pos) = 1
    Solve_Retro_Bridge HSDT, HSC, HDC, HEN_data, RB_record, RB_data, HX_surp, UBound(HEN_data, 1), prev_RB
    RB_data(C_pos) = 0
  Next C_pos

  ProgramPause True
End Sub

Sub Solve_Retro_Bridge(ByRef HSDT, ByRef HSC, ByRef HDC, ByRef HEN_data, ByRef RB_record, ByRef RB_data, _
           ByVal HX_surp, ByVal i_start, ByVal prev_RB, Optional ByVal Q_RB_0 = 1E+15)
  n = i_start
100
  For i = i_start To Tot_C + 1 Step -1
    countArray(RB_step, 1) = countArray(RB_step, 1) + 1
    If RB_data(i) < ZERO Then
      countArray(RB_step, 2) = countArray(RB_step, 2) + 1
      If HEN_data(HX_surp, 4) <= HEN_data(i, 5) + ZERO Then 'Find the next heat deficit in a compatible interval
        If HEN_data(i, 2) = "H" Then HX_num = S_num Else HX_num = S_num + 1
        If HX_num <= N_MAX Then
          If QUANTIFY Then
           'Determine maximum feasible HX duty, return 0 if below Q_MIN * n_HX threshold
            hs = -HSC(HX_surp, HEN_data(i, 5))
            hd = HDC(i, HEN_data(HX_surp, 4) - 1)
            If hs > hd Then Q_RB_1 = hd Else Q_RB_1 = hs
            If Q_RB_0 > Q_RB_1 Then Q_HR = Q_RB_1 Else Q_HR = Q_RB_0
            If Q_HR >= Q_MIN * HX_num Or HX_num = 1 Then Exit For
          Else
            Q_RB_1 = 1
            Exit For
          End If
        End If
```

```
            End If
        End If
    Next i

    If i > Tot_C + 1 Then
    'Located feasible bridge
        HX_def = i
        S_num = S_num + 1
        RB_data(HX_def) = S_num
        rb(S_num) = HX_def

        If HEN_data(HX_def, 2) = "H" Then
        'Retrofit bridge complete from cooler to heater
            If Q_HR = 0 Then GoTo 200
            Record_Performance RB_record, HEN_data, Q_HR, RB_data, prev_RB
            ProgramPause
        Else
        'Retrofit bridge incomplete
            Solve_Retro_Bridge HSDT, HSC, HDC, HEN_data, RB_record, RB_data, HX_def, n, prev_RB,
Q_HR
        End If
200
        RB_data(HX_def) = 0
        rb(S_num) = 0
        S_num = S_num - 1
        i_start = HX_def - 1
        GoTo 100
    Else
    'All feasible bridges exhausted -> exit
        If S_num > 1 Then HX_def = HX_surp
    End If
End Sub

Sub Record_Performance(ByRef RB_record, ByRef HEN_data, ByVal Q_HR, ByRef RB_data,
prev_RB)

    HX_num = S_num - 1: RB_paths = RB_paths + 1

    countArray(RB_step, 3) = countArray(RB_step, 3) + 1

    If Q_HR <= 0 + ZERO Or Q_HR = vbNullString Then
        RB_paths = RB_paths - 1
        Exit Sub
    End If

    network_split = False: splitCnt = 0

    Dim HSDT_2() As Variant, HEN_data_2() As Variant

    ReDim HEN_data_2(UBound(HEN_data, 1) + HX_num * 2, 18)
    For i = 1 To UBound(HEN_data, 1) Step 1
        For j = 1 To UBound(HEN_data, 2) Step 1
            HEN_data_2(i, j) = HEN_data(i, j)
        Next j
    Next i

    For i = 1 To HX_num Step 1
```

```
   Insert_HX HEN_data_2, Q_HR, rb(i), rb(i + 1)
   If network_split = True And ALLOW_SPLITS = False Then
      RB_paths = RB_paths - 1
      Exit Sub
   End If
Next i

Order_HEN HEN_data_2
Calculate_HSDT HSDT_2, HEN_data_2

For i = 2 To UBound(HEN_data_2, 1)
   HEN_Calculations HEN_data_2, HSDT_2, i
Next i

A_tot = 0: A_star_tot = 0: n_mod = 0
Dim total_cost As Double
total_cost = 0

'RB_record(i, 5 + MAX_STEP) = Q_HR

If CUMULATIVE_2 Then
   Calc_Retrofit_Area HEN_data_Original, HEN_data_2, A_tot, A_star_tot, n_mod, total_cost
   Q_HR = Q_HR + MasterArray(prev_RB, 4 + MAX_STEP)
Else
   Calc_Retrofit_Area HEN_data, HEN_data_2, A_tot, A_star_tot, n_mod, total_cost
End If

If CONSTRAINTS = True Then
   'Constraints
   If n_mod > N_MAX Or Q_HR < Q_MIN * n_mod Or Q_HR < Q_A_MIN * A_tot Then
      RB_paths = RB_paths - 1
      Exit Sub
   End If
   PB = Calc_PB(n_mod, A_star_tot, Q_HR)
   If PB > PB_MAX Then
      RB_paths = RB_paths - 1
      Exit Sub
   End If
End If

Calc_RB_Metrics RB_record, n_mod, A_tot, A_star_tot, Q_HR, RB_paths, splitCnt, total_cost
countArray(RB_step, 4) = countArray(RB_step, 4) + 1

'Record the RB number
Dim stpCntID As String
If RB_step <> 1 Then
   For i = 2 To RB_step Step 1
      stpCntID = stpCntID & "/"
   Next i
End If
RB_record(R_1, 1) = MasterArray(prev_RB, 2) & stpCntID & RB_paths

'Records the retrofit bridge pathway
RB_name = vbNullString
H_pos_start = UBound(RB_data) - Tot_H + 1
For i = H_pos_start To UBound(RB_data) Step 1
   If RB_data(i) <> vbNullString And RB_data(i) <> 0 Then H_pos = i
```

```
    Next i
    For i = 1 To RB_data(H_pos) Step 1
       For j = 2 To H_pos Step 1
          If RB_data(j) = vbNullString Or RB_data(j) = 0 Then j = j + 1
          If i = RB_data(j) Then
             RB_name = RB_name & HEN_data(j, 1)
             If i <> RB_data(H_pos) Then RB_name = RB_name & "-"
             j = UBound(RB_data)
          End If
       Next j
    Next i
    For i = 1 To RB_step Step 1
       If i <> RB_step Then
          RB_record(R_1, i + 1) = MasterArray(prev_RB, i + 2)
       Else
          RB_record(R_1, i + 1) = RB_name
       End If
    Next i
    R_1 = R_1 + 1

End Sub

Sub Calc_Retrofit_Area(ByRef HEN_data, ByRef HEN_data_2, total_area, area_star_tot, n_mod,
Optional total_cost As Double = 0)
'Calculates the additional area required by the retrofit

    AF = Annual_Factor(i_rate, n_life)

    For i = 2 To UBound(HEN_data_2, 1) Step 1
       If HEN_data_2(i, 2) = "R" Then

          'Calculates the new area
          Area = Calc_Area(HEN_data_2, HEN_data_2(i, 6), i, i)
          old_area = 0
          'Checks to see if the area is being added to an existing exchanger
          For j = 2 To UBound(HEN_data, 1) Step 1
             If HEN_data(j, 1) = HEN_data_2(i, 1) Then
                old_area = Calc_Area(HEN_data, HEN_data(j, 6), j, j)
                If old_area >= Area Then
                   Area = 0
                ElseIf old_area < Area Then
                   Area = Area - old_area
                End If
             End If
          Next j

          If Area <> 0 Then
             n_mod = n_mod + 1 'Area added is considered a modification
             'If old_area = 0 Then n_mod = n_mod + 1    'Area added is not considered a modification

             If case_study = "Kraft" Then
                If InStr(HEN_data_2(i, 7), "EX 1") = 1 Or InStr(HEN_data_2(i, 7), "EX 2") = 1 _
                   Or InStr(HEN_data_2(i, 13), "PV") = 1 Or InStr(HEN_data_2(i, 13), "BB") = 1 Then
                   cost = 500 / AF * Area ^ 0.815
                Else
                   cost = 1800 / AF + 200 / AF * Area
                End If
```

```
            total_area = total_area + Area
            total_cost = total_cost + cost
        ElseIf case_study = "4stream" Then
            If old_area <> 0 Then
                total_cost = total_cost + (2000 + 500 * Area ^ 0.83) / AF
            Else
                total_cost = total_cost + (4000 + 500 * Area ^ 0.83) / AF
            End If
            total_area = total_area + Area
        Else
            total_area = total_area + Area
            area_star_tot = area_star_tot + Area ^ n_exp
        End If
      End If
    End If
  Next i
End Sub

Sub Calc_RB_Metrics(ByRef RB_record, n_mod, A_tot, A_star_tot, Q_HR, i, Optional splitCnt As
Integer = 0, Optional total_cost As Double = 0)
'Calculates the RB metrics that will be output

  RB_record(i, MAX_STEP + 3) = Q_HR
  RB_record(i, MAX_STEP + 4) = splitCnt
  RB_record(i, MAX_STEP + 5) = n_mod
  RB_record(i, MAX_STEP + 6) = A_tot
  RB_record(i, MAX_STEP + 7) = A_star_tot
  If n_mod <> 0 Then
    RB_record(i, MAX_STEP + 8) = Q_HR / n_mod
  Else
    RB_record(i, MAX_STEP + 8) = Q_HR
  End If
  RB_record(i, MAX_STEP + 9) = Q_HR / A_tot
  If case_study = "Kraft" Or case_study = "4stream" And total_cost <> 0 Then
    RB_record(i, MAX_STEP + 10) = total_cost
  Else
    RB_record(i, MAX_STEP + 10) = (CDbl(FC) * n_mod) + (VC * A_star_tot)
  End If
  RB_record(i, MAX_STEP + 11) = RB_record(i, MAX_STEP + 10) / (Q_HR * P_UtS)
  RB_record(i, MAX_STEP + 12) = (Q_HR * P_UtS) - RB_record(i, MAX_STEP + 10) *
Annual_Factor(i_rate, n_life)

End Sub

Function Calc_PB(n_mod, A_star_tot, Q_HR) As Double

  If case_study = "Kraft" Or case_study = "4stream" And total_cost <> 0 Then
    Calc_PB = total_cost / (Q_HR * P_UtS)
  Else
    Calc_PB = ((CDbl(FC) * n_mod) + (VC * A_star_tot)) / (Q_HR * P_UtS)
  End If

End Function

Function Calc_Area(ByRef HEN_data, ByVal HR_duty, ByVal HX_surp, ByVal HX_def)
'Estimate the area retrofitted heat exchanger
```

```
   'Determine exchanger inlet/outlet temperatures and heat capacity flow rates
   T_hi = HEN_data(HX_surp, 10)
   CP_h = HEN_data(HX_surp, 12)
   T_ci = HEN_data(HX_def, 16)
   CP_c = HEN_data(HX_def, 18)
   T_ho = T_hi - HR_duty / CP_h    'CODE: don't need to recalculate T_ho in the HEN design step, only during ART

   'Calculate inputs for e-Ntu area estimation
   Q = CP_h * (T_hi - T_ho)
   If CP_h > CP_c Then
      c_min = CP_c: cmax = CP_h
   Else
      c_min = CP_h: cmax = CP_c
   End If
   Q_max = c_min * (T_hi - T_ci)
   c = c_min / cmax
   eff = Q / Q_max
   If eff = 1 Then eff = 0.99
   If c + ZERO > 1 Then c = 1

   'Estimate Ntu and area including total retrofit area
   'Counterflow HX
   If Not (c = 1) Then
      NTU = 1 / (c - 1) * Log((eff - 1) / (eff * c - 1))
   Else
      NTU = eff / (1 - eff)
   End If

   u = 1 / (1 / HEN_data(HX_surp, 9) + 1 / HEN_data(HX_def, 15)) / 1000
   Calc_Area = c_min * NTU / u
End Function

Function Annual_Factor(ByVal i, ByVal n)
   Annual_Factor = i * (1 + i) ^ (n) / ((1 + i) ^ (n) - 1)
End Function

Sub Paerato_Optimal(ByRef RB_record, ByRef RB_paths) 'Updated
   RB_num = RB_paths: dk = 0.05: dj = 0.05
   n_min_best = 3       'Assumes the nth best objective value is sufficient to be included in the expanded Pareto front

   'Metrics
   col_var_1 = 3 + MAX_STEP: Var_1_max = RB_record(1, col_var_1)     'Q
   col_var_2 = 3 + MAX_STEP + 6: Var_2_max = RB_record(1, col_var_2) 'Q/A
   col_var_3 = 3 + MAX_STEP + 5: Var_3_max = RB_record(1, col_var_3) 'Q/n

   For i = 1 To RB_num Step 1
      If Var_1_max < RB_record(i, col_var_1) Then Var_1_max = RB_record(i, col_var_1)
      If Var_2_max < RB_record(i, col_var_2) Then Var_2_max = RB_record(i, col_var_2)
      If Var_3_max < RB_record(i, col_var_3) Then Var_3_max = RB_record(i, col_var_3)
      RB_record(i, 0) = 0
   Next i

   'Define arrays to store the Pareto optimal solutions
   Dim pareto_solutions(), kj_solutions(), n_top_obj()
   ReDim pareto_solutions(1000), kj_solutions(1000), n_top_obj(n_min_best)
```

```
    n_single = 0: n_pareto = 0

    'Cycle through all possible combinations of k and j
    'Find all bridge options that are >= the nth best objective value
    For k = 0 To 1 + ZERO Step dk
        If k = 0 Then k = 0.001
        If k + ZERO > 1 Then k = 0.999

        For j = 0 To 1 + ZERO Step dj
            If j = 0 Then j = 0.001
            If j + ZERO >= 1 Then j = 0.999
            If k + j > 1 + ZERO Then GoTo 100

            'Reset values
            obj_nth_max = 0: n_single = 0

            'Find the nth maximum value of the Pareto objective
            For i = 1 To RB_num Step 1
                obj_var_i = (k * (RB_record(i, col_var_1) / Var_1_max) + j * (RB_record(i, col_var_2) /
Var_2_max) + (1 - j - k) * (RB_record(i, col_var_3) / Var_3_max)) * 100

                If n_top_obj(1) + ZERO / 10 < obj_var_i Then
                    n_top_obj(1) = obj_var_i
                    QuickSort_1D n_top_obj
                End If
            Next i

            'Set minimum objective value to the nth maximum
            obj_nth_max = n_top_obj(1)

            'Find all bridge options with objective value >= nth maximum value
            For i = 1 To RB_num Step 1
                obj_var_i = (k * (RB_record(i, col_var_1) / Var_1_max) + j * (RB_record(i, col_var_2) /
Var_2_max) + (1 - j - k) * (RB_record(i, col_var_3) / Var_3_max)) * 100

                'Check if the bridge is >= the nth best
                If obj_var_i > obj_nth_max - ZERO / 10 Then
                    n_single = n_single + 1
                    If n_single > UBound(kj_solutions, 1) Then ReDim Preserve
kj_solutions(UBound(kj_solutions, 1) + 1000)
                    kj_solutions(n_single) = i
                End If
            Next i

            'Record the n-best solution(s) with nth max obj for the given k and j values into the set of
Pareto optimal solutions
            For i = 1 To n_single Step 1
                If n_pareto + i > UBound(pareto_solutions, 1) Then ReDim Preserve
pareto_solutions(UBound(pareto_solutions, 1) + 1000)
                pareto_solutions(n_pareto + i) = kj_solutions(i)
            Next i
            n_pareto = n_pareto + n_single
            If j = 0.001 Then j = 0
        Next j
100
        If k = 0.001 Then k = 0
    Next k
```

```
    ReDim Preserve pareto_solutions(n_pareto)
    QuickSort_1D pareto_solutions
    RemoveDuplicates_1D pareto_solutions
    n_pareto = UBound(pareto_solutions)

    Dim temp() As Variant
    temp = RB_record
    ReDim RB_record(n_pareto, UBound(RB_record, 2))

    For i = 1 To n_pareto Step 1
        row_i = pareto_solutions(i)
        For j = 1 To UBound(temp, 2) Step 1
            RB_record(i, j) = temp(row_i, j)
        Next j
        countArray(RB_step, 5) = countArray(RB_step, 5) + 1
    Next i
    RB_paths = n_pareto

End Sub

Sub Final_Paerato_Optimal(ByRef MasterArray) 'Unchanged

    RB_num = Tot_RB - 1: dk = 0.05: dj = 0.05
    n_min_best = 10 'Assumes the nth best objective is sufficient to be included

    'Metrics
    col_var_1 = MAX_STEP + 4: Var_1_max = MasterArray(1, col_var_1)
    col_var_2 = MAX_STEP + 10: Var_2_max = MasterArray(1, col_var_2)
    col_var_3 = MAX_STEP + 9: Var_3_max = MasterArray(1, col_var_3)

    For i = 1 To RB_num Step 1
        If Var_1_max < MasterArray(i, col_var_1) Then Var_1_max = MasterArray(i, col_var_1)
        If Var_2_max < MasterArray(i, col_var_2) Then Var_2_max = MasterArray(i, col_var_2)
        If Var_3_max < MasterArray(i, col_var_3) Then Var_3_max = MasterArray(i, col_var_3)
        MasterArray(i, 0) = 0
    Next i

    Dim pareto_solutions(), kj_solutions(), n_top_obj()
    ReDim pareto_solutions(UBound(MasterArray, 1)), kj_solutions(UBound(MasterArray, 1)),
n_top_obj(n_min_best)
    n_single = 0: n_pareto = 0

    'Cycle through all possible combinations of k and j
    For k = 0 To 1 Step dk
        If k = 0 Then k = 0.001
        If k + ZERO > 1 Then k = 0.999

        For j = 0 To 1 Step dj
            If j = 0 Then j = 0.001
            If j + ZERO > 1 Then j = 0.999
            If k + j > 1 + ZERO Then GoTo 100

            'Reset values
            obj_max = 0: n_single = 0

            'Find the nth maximum value of the Pareto objective
```

```
        For i = 1 To RB_num Step 1
            obj_var_i = (k * (MasterArray(i, col_var_1) / Var_1_max) + j * (MasterArray(i, col_var_2) / Var_2_max) + (1 - j - k) * (MasterArray(i, col_var_3) / Var_3_max)) * 100

            If n_top_obj(1) + ZERO / 10 < obj_var_i Then
                n_top_obj(1) = obj_var_i
                QuickSort_1D n_top_obj
            End If
        Next i

        'Set minimum objective value to the nth maximum
        obj_nth_max = n_top_obj(1)

        'Find all bridge options with objective value >= nth maximum value
        For i = 1 To RB_num Step 1
            obj_var_i = (k * (MasterArray(i, col_var_1) / Var_1_max) + j * (MasterArray(i, col_var_2) / Var_2_max) + (1 - j - k) * (MasterArray(i, col_var_3) / Var_3_max)) * 100

            'Check if the bridge is >= the nth best
            If obj_var_i > obj_nth_max - ZERO / 10 Then
                n_single = n_single + 1
                If n_single > UBound(kj_solutions, 1) Then ReDim Preserve kj_solutions(UBound(kj_solutions, 1) + 1000)
                kj_solutions(n_single) = i
            End If
        Next i

        'Record the n-best solution(s) with nth max obj for the given k and j values into the set of Pareto optimal solutions
        For i = 1 To n_single Step 1
            If n_pareto + i > UBound(pareto_solutions, 1) Then ReDim Preserve pareto_solutions(UBound(pareto_solutions, 1) + 1000)
            pareto_solutions(n_pareto + i) = kj_solutions(i)
        Next i
        n_pareto = n_pareto + n_single
        If j = 0.001 Then j = 0
    Next j
100
  Next k

  ReDim Preserve pareto_solutions(n_pareto)
  QuickSort_1D pareto_solutions
  RemoveDuplicates_1D pareto_solutions
  n_pareto = UBound(pareto_solutions)

  Dim temp() As Variant
  temp = MasterArray
  ReDim MasterArray(n_pareto, UBound(MasterArray, 2)) 'n_pareto

  For i = 1 To n_pareto Step 1
    row_i = pareto_solutions(i)
    For j = 1 To UBound(temp, 2) Step 1
      MasterArray(i, j) = temp(row_i, j)
    Next j
  Next i

End Sub
```

```
Sub QuickSort_1D(ByRef pvarArray As Variant, Optional ByVal plngLeft As Long, Optional ByVal plngRight As Long)
'Returns a sorted list
'MedianThreeQuickSort1
'Omit plngLeft & plngRight; they are used internally during recursion

    Dim lngFirst As Long
    Dim lngLast As Long
    Dim varMid As Variant
    Dim lngIndex As Long
    Dim varSwap As Variant
    Dim a As Long
    Dim b As Long
    Dim c As Long

    If plngRight = 0 Then
        plngLeft = LBound(pvarArray)
        plngRight = UBound(pvarArray)
    End If
    lngFirst = plngLeft
    lngLast = plngRight
    lngIndex = plngRight - plngLeft + 1
    a = Int(lngIndex * Rnd) + plngLeft
    b = Int(lngIndex * Rnd) + plngLeft
    c = Int(lngIndex * Rnd) + plngLeft
    If pvarArray(a) <= pvarArray(b) And pvarArray(b) <= pvarArray(c) Then
        lngIndex = b
    Else
        If pvarArray(b) <= pvarArray(a) And pvarArray(a) <= pvarArray(c) Then
            lngIndex = a
        Else
            lngIndex = c
        End If
    End If
    varMid = pvarArray(lngIndex)
    Do
        Do While pvarArray(lngFirst) < varMid And lngFirst < plngRight
            lngFirst = lngFirst + 1
        Loop
        Do While varMid < pvarArray(lngLast) And lngLast > plngLeft
            lngLast = lngLast - 1
        Loop
        If lngFirst <= lngLast Then
            varSwap = pvarArray(lngFirst)
            pvarArray(lngFirst) = pvarArray(lngLast)
            pvarArray(lngLast) = varSwap
            lngFirst = lngFirst + 1
            lngLast = lngLast - 1
        End If
    Loop Until lngFirst > lngLast
    If (lngLast - plngLeft) < (plngRight - lngFirst) Then
        If plngLeft < lngLast Then QuickSort_1D pvarArray, plngLeft, lngLast
        If lngFirst < plngRight Then QuickSort_1D pvarArray, lngFirst, plngRight
    Else
        If lngFirst < plngRight Then QuickSort_1D pvarArray, lngFirst, plngRight
        If plngLeft < lngLast Then QuickSort_1D pvarArray, plngLeft, lngLast
```

```
   End If
End Sub

Sub RemoveDuplicates_1D(ByRef InputArray)
   j = 1
   For i = 2 To UBound(InputArray) Step 1
      If Abs(InputArray(j) - InputArray(i)) > ZERO Then
         j = j + 1
         InputArray(j) = InputArray(i)
      End If
   Next i
   ReDim Preserve InputArray(j)
End Sub

Sub ReverseArray_1D(ByRef input_array As Variant)
   max_row = UBound(input_array) + 1
   For i = 1 To max_row / 2 Step 1
      temp = input_array(i)
      input_array(i) = input_array(max_row - i)
      input_array(max_row - i) = temp
   Next
End Sub
```