Cost Effective Retrofit Methods for Heat Exchanger Networks

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Nomenclature

Abbreviations:

CAT	Constant Approach Temperature, °C
ES	Energy Saving, kW
GA	Genetic Algorithm
HEN	Heat Exchanger Network
IDE	Integrated Differential Evolution
ILP	Integer Linear Programming
ILP	Integer Linear Programming
LMTD	Logarithmic Mean Temperature Difference
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
NLP	Non-Linear Programming
RP	Retrofit Profit, $
SA	Simulated Annealing

Symbols:

A	Area based on the geometry of the heat exchanger, m^2
A'	Area based on the overall heat transfer coefficient, m^2
a, b	Friction factor constants used in Equations 3.17, 3.18, 3.25 and 3.26
A_{CF}	Shell-side cross flow area, m^2
B	Baffle spacing, m
B_C	Baffle cut
B_{in}	Inlet baffle spacing, m
B_{out}	Outlet baffle spacing, m
C_{De}	Pitch configuration factor
c_{FS}	Shell-side friction factor
c_{FT}	Tube-side friction factor
C_{NS}	Constants used in Equations 3.36
C_{NT}	Constants used in Equations 3.55
C_P	Specific heat capacity, J kg^{-1} $°C^{-1}$

CP	Heat capacity flowrate, kW °C^{-1}
D_B	Outside diameter of the tube bundle, m
d_e	Shell-side equivalent diameter, m
D_i	Tube inner diameter, m
D_{NS}	Diameter of shell-side nozzle, m
D_{NT}	Diameter of tube-side nozzle, m
D_o	Tube outer diameter, m
D_S	Shell inside diameter, m
f1, f2	Friction factor constants used in Equation 3.16
F_C	Tube-side friction factor constant used in Equation 3.52
F_L	The leakage factor
F_P	The pitch factor
F_S	Shell-side geometry factor
F_{SC}	Correction factor for the shell construction
F_{TC}	Tube count constant
G	Function used in Equation 3.89
h	Heat transfer coefficient, W m^{-2} °C^{-1}
h_{SF}	Shell-side fouling coefficient, W m^{-2} °C^{-1}
h_{TF}	Tube-side fouling coefficient, W m^{-2} °C^{-1}
k	Fluid thermal conductivity, W m^{-1} °C^{-1}
K_{ps1-3}	Correlations used in Equations 3.26 and 3.41
L	Length, m
L_{eff}	Effective tube length, m
L_{SB}	Shell-side bundle clearance, m
m	Mass flowrate, kg s^{-1}
m_{fo}	Correction constant based on baffle cut used in Equation 3.12
m_f	Friction factor determination constant used in Equation 3.52
N_B	Number of baffles
N_P	Number of tube passes
N_{SHELLS}	Number of shells
N_T	Number of tubes
P	Correlation used in Equation 3.88
P_{1-2}	Correlation for 1-2 heat exchangers used in Equation 3.86

p_C	Pitch configuration factor
p_{CF}	Pitch correction factor for flow direction
p_T	Tube pitch, m
Q	Heat duty, kW
R	Ratio of heat capacity flow rates used in Equation 3.68
R_S	Correction factor for unequal baffle spacing
T_C	Temperature of the cold stream, °C
T_H	Temperature of the hot stream, °C
U	Overall heat transfer coefficient, W m^{-2} $°C^{-1}$
v	Mean fluid velocity, m s^{-1}
v_{NS}	Velocity in shell-side nozzle, m s^{-1}
v_{NT}	Velocity in tube-side nozzle, m s^{-1}
X	Function used in Equations 3.72 and 3.90
Y	Function used in Equation 3.79
ΔP	Total pressure drop, k Pa
ΔP_{NS}	Pressure drop in shell-side nozzles, k Pa
ΔP_{NT}	Pressure drop in tube-side nozzles, k Pa
ΔP_{SS}	Pressure drop in the straight section of the shell, k Pa
$\Delta P_{SS,20\%}$	Pressure drop in the straight section of shell with 20% baffle cut, k Pa
$\Delta P_{SB,20\%}$	Pressure drop in one central baffle spacing zone with 20% baffle cut, k Pa
ΔP_{TE}	Pressure drop in the tube entrances, exits and reversal, k Pa
ΔP_{TT}	Pressure drop in the straight tubes, k Pa
ΔT_{LM}	Log Mean Temperature Difference, °C
ΔT_{min}	Minimum approach temperature, °C

Greek Symbols:

μ	Viscosity, Pa s
π	Constant (22/7)
ρ	Fluid density, kg m^{-3}
α	Constant function used in Equation 3.54

Dimensionless Groups:

Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number

Subscripts:

C	Cold
CC	Counter current used in Equation 3.84
H	Hot
I	Inlet/Inner
NS	Shell-side nozzle
NT	Tube-side nozzles
O	Outlet/Outer
S	Shell
Se	Shell-side equivalent diameter
T	Tube

Abstract

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Cost Effective Retrofit Methods for Heat Exchanger Networks
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Improving the energy efficiency of process plants is central to minimising operating costs and increasing profitability. Growing concerns on climate change is also an issue due to the increasing level of carbon dioxide emissions. Process industries remain one of the largest consumers of energy. Maximising energy recovery in heat exchanger networks (HENs) reduce the total energy consumption in process industries. However, cost effective retrofit of HENs remains a great challenge. An ideal retrofit design is one that has the right balance between efficient use of existing equipment and limited amount of modifications and downtime, while maximising energy recovery. The key objective of this thesis is to present novel methodologies for cost effective retrofit of HENs, while ensuring industrial applicability.

The cost associated with the application of structural modifications and additional heat transfer area, has led to an increased interest into the use of heat transfer enhancement for retrofit. Heat transfer enhancement is beneficial, as it usually requires low capital investment for fixed network topology, and no additional heat transfer area in existing heat exchangers. However, the challenges of heat transfer enhancement for industrial applications are: (1) identifying the best heat exchanger to enhance; (2) dealing with downstream effects on the HEN after applying enhancement; and (3) dealing with its effect on pressure drop. This thesis presents sequential based methodologies consisting of a combination of heuristics and a profit based non-linear optimisation model for tackling these three issues. The robustness of the new approach lies in its ability to provide useful insights into the interaction of various units in a HEN whilst being pertinent for automation.

Notwithstanding the drawbacks of structural modifications in retrofit, the degree of energy savings that can be obtained cannot be ignored. A robust retrofit strategy for the application of structural modifications in retrofit is required. This thesis presents a methodology that provides new fundamental insights into the application of structural modifications that ultimately leads to a faster retrofit procedure, without compromising the performance and feasibility of the retrofitted HEN. The new approach: (1) identifies the best location to apply a series of modifications; and (2) presents an algorithm that can be automated for the identification of the best single and multiple modifications that provides maximum energy recovery for a given HEN. The robustness of the new approach is tested by a comparison with the well-established stochastic optimisation approach for structural modifications i.e. simulated annealing. To improve the retrofit result, this work also considers combining the use of structural modifications and heat transfer enhancement. The aim is to harnesses the benefits of both methods to obtain a cost effective retrofit design. The analysis carried out in this work is subject to minimising the energy consumption and maximising the retrofit profit. A decision on the best retrofit strategy to apply to a given HEN depends on the given retrofit objective. However, this work provides an adequate basis on which the decision can be made based on industrial applicability, profit and energy saving.

Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institution of learning.

Akpomiemie Mary Onome

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Chapter 1 Introduction

Improving the energy efficiency of existing plants in the process industries is vital due to increasing environmental concerns due to the level of carbon dioxide emissions and depleting energy resources. Grossmann et al. (1987) and Gundersen (1990) presented general reviews on retrofit. They identified motivations for retrofit of existing plants, such as to improve product quality, to increase throughput, to implement a new technology, to improve process safety and reduce environmental impact, to improve process operability, controllability, maintenance or flexibility, to accommodate for changes in feed and product specification, and to reduce the energy consumption in an existing plant.

Regardless of the motivation for retrofit, the underlining principle is to be able to present cost effective methods by maximising the use of existing equipment in the existing plants. The shortfall with the use of existing equipment is that it might not be suited to the new role that it will be put to (Smith, 2016). The focus of this research is to present cost effective retrofit methodologies with emphasis on reducing the energy consumption in existing plants by retrofitting heat exchanger networks (HENs). This not only helps to mitigate environmental concerns (i.e. global warming) but also to reduce the operating costs in existing plants.

1.1 Retrofit of Heat Exchanger Networks

The desire to increase energy efficiency (use of decreased energy consumption to provide the same service) in process plants has led to the rise in the interest into the retrofit of heat exchanger networks (HENs). In plant-scale retrofit, HENs are normally much easier to implement than reactors and separators (Wang, 2012a). Traditionally, retrofit of HENs for energy recovery is considered from the viewpoint of changing the use of utility, performing structural modifications and increasing the heat transfer area of existing heat exchangers (Ciric and Floudes, 1989, 1990, Briones and Kokossis; 1996, Athier et al., 1998, Bochenek and Jezowski, 2006, Nguyen et al., 2010). Structural modifications include adding a new heat exchanger / new match, resequencing heat exchangers, splitting process streams, and repiping. In practice, HEN retrofit with the aforementioned methods may be difficult to implement due to topology, safety and downtime constraints imposed by the existing network. These retrofit methods will also incur an increased capital cost due to the considerable civil and piping works required, and negative financial implication resulting from potential production losses during modification. Owing to these drawbacks, there have been increased interests into the study of the use of techniques for heat transfer enhancement in the retrofit of HENs. Polley et al. (1992) first addressed the concept that brought about the combination of heat transfer enhancement and process integration. The use of heat transfer enhancement can be a very attractive option in HEN retrofit because its application is relatively simple. This lends itself to be applied during normal maintenance periods thereby ensuring production losses associated with retrofit are eliminated. In addition, it is generally cheaper to implement heat transfer enhancement than additional heat transfer area because of the decrease in civil and piping works that might be required (Ponce-Ortega et al., 2008a). In enhanced heat exchangers, energy reduction is achieved as an enhanced heat exchanger has a higher heat transfer coefficient to exchange the same duty with smaller area requirements. Similarly, if the area of the enhanced heat exchanger is kept constant, an enhanced heat exchanger can exchange a higher duty. This improves the energy recovery even though no topology modification is considered (Polley et al., 1992, Ponce-Ortega et al., 2008a). The drawback of the use of heat transfer enhancement is the effect on pressure drop (Jiang et al., 2014a). However, pressure drop could be reduced as heat transfer enhancement may allow for exchanger modifications such as changing shell arrangements, reducing the number of tube passes, etc. to be applied to existing heat exchangers. This process still allows for higher overall heat transfer coefficients at low velocities and reduced frictional losses compared to the plain unmodified exchanger.

1.2 Research Motivation

The desire to present a cost effective method for the retrofit of HENs drives this research. A cost effective retrofit can be considered as one with the fewest number of modifications and disruption from the existing HEN topology. The application of too many structural modifications leads to a more complex and expensive retrofit process. If both structural modifications and additional heat transfer area are not considered in retrofit, the retrofit process can be relatively simple and cost effective. The concept of using heat transfer enhancement for retrofit to tackle this problem has been studied over the years (Polley et al., 1992, Nie and Zhu, 1999, Zhu et al., 2000, Pan et al., 2011, Pan et al., 2012, Wang et al., 2012a, b, c, Gough et al., 2013, Pan et al., 2013a, Jiang et al., 2014a). The ease by which heat transfer enhancement can be applied pose an advantage, as it requires little civil and piping work and can be implemented during a normal shutdown periods. Heat transfer enhancement has the potential to be a cost effective option for retrofit as there is no need for expensive modifications and implementation of additional heat transfer area. So far, a systematic methodology that makes use of heat transfer enhancement for retrofit without both topology modifications and the need for additional heat transfer area is not available. One key aspect with the application of heat transfer enhancement that still needs to be addressed is determining the best candidate heat exchanger to enhance. Due to the close interactions between various units in a HEN, a change in one unit will affect the performance of others. Therefore, another key aspect that still needs to be addressed is how to deal with the downstream effects in a HEN after the application of heat transfer enhancement. A major drawback with the application of heat transfer enhancement industrially, is its effect on pressure drop. It is important to consider pressure drop alongside heat transfer enhancement in retrofit.

In terms of performing structural modifications in a given HEN, methods such as pinch analysis, mathematical programming and the network pinch approach have been used. The pinch analysis method identifies cross-pinch matches, disconnects the cross-pinch matches, and reconnects matches to obey the pinch decomposition. This method is fundamentally not suited for retrofit as it often leads to complex and uneconomic retrofits. Nevertheless, it can be used to set target performance of an existing process. In terms of mathematical programming methods, they are mostly limited by the size and complexity of the retrofit problem. The network pinch approach identifies the network bottleneck and overcomes this restriction by performing structural modifications. This method is ideal for retrofit based on structural modifications. However, insights into why a certain modification is preferred over others are unknown. Better insights into the factors that govern structural modifications in the retrofit are required. This can aid in reducing the number of network modifications required to achieve maximum energy recovery by identifying the best modifications, and the best location within the existing HEN to apply the said modification, at each stage of the retrofit process.

In addition, the combination of the benefits of the conventional retrofit methods and heat transfer enhancement needs to be addressed. This is to ensure the maximum energy recovery in an existing HEN is attained, while minimising the capital investment associated with the retrofit process.

1.3 Research Objectives

The previous section highlights the need for additional research into the cost effective retrofit of HENs with focus placed on energy recovery. Based on this, the four main objectives defined for this thesis are:

Objective 1:

Develop a novel methodology for the use of heat transfer enhancement in heat exchanger network retrofit without the need for topology modifications and additional heat transfer area.

Heat transfer enhancement was mostly used for reducing the additional area required, thereby reducing the cost of retrofit. By doing this, the advantages of heat transfer enhancement were not fully exploited. Most of the methodologies presented have been optimisation-based approaches that are usually difficult to implement industrially as the degree of enhancement cannot be guaranteed based on exchanger geometry. Wang et al. (2012b) proposed a novel methodology based on heuristics using only heat transfer enhancement for the retrofit of heat exchanger networks without the need for topology modifications. The main issues with this research are; present a method for automatically identifying the best heat exchanger to enhance, the augmentation level of the enhancement, and lack of clarity on how to deal with downstream effects after applying enhancement. Jiang et al. (2014a) presented an extension of this methodology. The issue of determining the augmentation level is addressed by using correlations for modelling different enhancement techniques (Jiang et al. 2014b). The other issues with the application of enhancement are not addressed. Therefore, the research questions for this thesis based on the objective are:

Question a: How to identify the best heat exchanger in the existing HEN to enhance?

Question b: How to deal with downstream effects on the network after enhancement?

Objective 2:

Consider pressure drop in HEN retrofit with heat transfer enhancement.

A major drawback that restricts the application of heat transfer enhancement in process industries is the effect of enhancement devices on pressure drop. Consideration of pressure drop with heat transfer enhancement is vital as pressure drop constraints on a HEN can affect the level of augmentation after enhancement and as such affect the level of energy recovery. The research questions are:

Question a: Are there methods to mitigate these effects of enhancement on pressure drop?

Question b: Can these methods be incorporated into a robust retrofit methodology with heat transfer enhancement?

Objective 3:

Present novel guidelines and methodology for the application of structural modifications in HEN retrofit.

Structural modifications in HEN retrofit are not only difficult to implement but are also costly due to the cost of civil and piping works required. There is also capital cost required because of additional heat transfer area required to maintain the energy balance in the HEN. The determination of the structural changes required for energy recovery has been carried out mostly based on black-box optimisation based approaches. Factors that govern the selection of the best structural modification, and the location to apply said modification are unknown. Therefore, there is a need to develop robust guidelines to identify the best network modification that limits the number of structural modifications required in retrofit. The research questions are:

Question a: Are there guidelines for identifying the most suitable location in an existing network to apply a network modification?

Question b: Can these guidelines be used to develop and algorithm that represents the underlying principles for the identification and selection of the best structural modifications for a given HEN?

Question c: Does the proposed approach ultimately lead to an energy efficient retrofit design?

Objective 4:

Present a new method for the application of structural modifications with heat transfer enhancement.

A practical method that capitalises on the benefits of both the structural modifications and heat transfer enhancement is required. The goal is to be able to maintain the energy recovery of structural modifications but reduce the retrofit cost with the application of heat transfer enhancement. The reduced cost is down to it being generally cheaper to implement heat transfer enhancement than additional heat transfer area, which is one of the factors associated with the high capital cost when structural modifications are used. The research questions are:

Question a: How to systematically incorporate the methodologies derived in Objective 2, Question b and Objective 3, Question b into a practical retrofit method for HENs?

1.4 Thesis Outline

Figure 1.1 illustrates the outline of the thesis and the interaction between the various chapters that makes up this thesis. The "alternative thesis format" is employed in this thesis, which incorporates paper published and/or submitted according to the University of Manchester standard.

Chapter 2 presents a review on HEN retrofit. It includes a systematic compilation from literature of various retrofit methods, background of heat transfer enhancement, techniques for heat transfer enhancement, network structure analysis, and pressure drop. These are essential as it forms the backbone for the development of new retrofit methods in subsequent chapters. Further literature review is also provided in appended papers.

Chapter 3 introduces a model for the design of HENs based on heat exchanger geometry. This represents concise models that can adequately predict the performance of existing heat exchangers in a HEN.

Chapter 4 is the core of the thesis. It introduces the first and second publication that presents novel methodologies for the retrofit of HENs with heat transfer enhancement. The first publication is an extension of the research conducted by Wang et al. (2012b) and Jiang et al. (2014a) based on sensitivity analysis. Methods of dealing with the shortfalls of the aforementioned approaches are presented. The second publication presents a new method for the retrofit of HENs based on an area ratio approach. This tackles the drawbacks associated with the use of sensitivity analysis in HENs with multiple utilities. This chapter answers all the questions posed in Objective 1. It also forms part of the basis for dealing with objectives 2 and 4.

Chapter 5 presents methods for considering pressure drop with heat transfer enhancement. This makes up publication 3. Methods for mitigating pressure drop with heat transfer enhancement are presented. The effects of pressure drop consideration on the degree of energy saving compared with that obtained in Chapter 4 are presented. This chapter addresses the questions posed by Objective 2.

Chapter 6 describes the new guidelines for the retrofit of HENs based on structural modifications. The identification of the best network modification and location to apply such modification is analysed from a standpoint of energy savings, and makes up publication 4. The new method is based on the network pinch approach (Asante and Zhu, 1996, 1997, Smith et al., 2010). This chapter answers the questions posed in Objective 3.

Chapter 7 involves the combination of Chapters 4 and 6 to present a more robust method for the retrofit of HENs that can achieve the greatest decrease in energy consumption but at a considerably reduced retrofit cost. This makes up publication 5. The effect of Chapter 5 is also taken into account in this analysis. This answers the questions posed in Objective 4.

Chapter 8 finally, gives a summary of the main findings of this research, limitations and recommendations for future work.

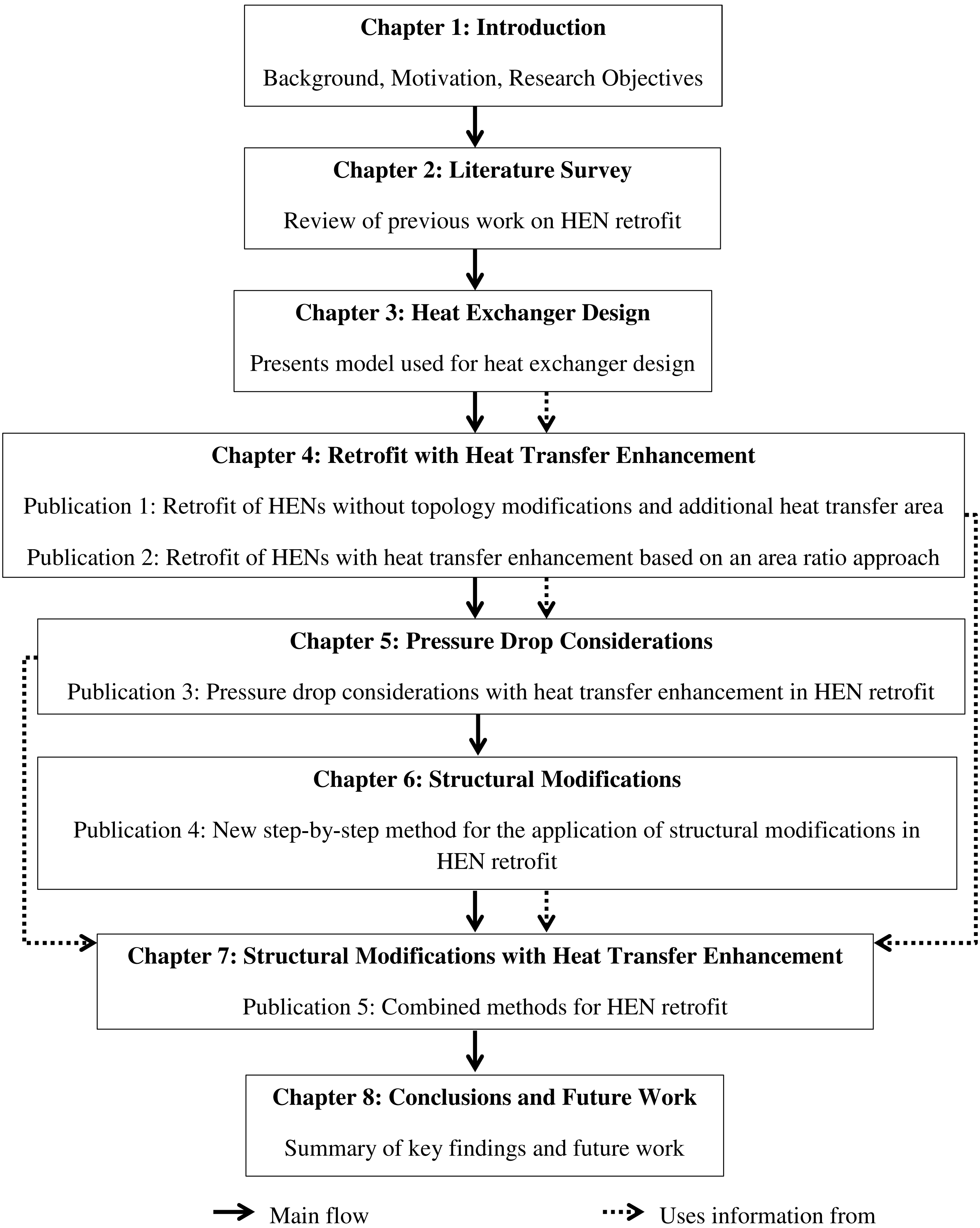

Figure 1.1: Thesis outline

Chapter 2 Literature Survey

The desire to increase the performance of heat exchanger networks (HENs) has made retrofit the subject of intensive research. Retrofit has the potential to reduce energy consumption, increase throughput and deal with changes in the process feed and product specifications. The difficulty in retrofit arises from the constraints imposed by the existing HEN, such as plant layout and congestion. Current methods used for HEN retrofit are centred on the use of Pinch Analysis, mathematical programming and a combination of both methods (hybrid methods). These methods all mostly depend on the application of structural modifications (i.e. resequencing, stream splitting or adding a new match/heat exchanger) and additional heat transfer area. The ideal retrofit option is one with the fewest modifications and lowest capital cost (Asante and Zhu, 1997). The drive to achieve the ideal retrofit design has led to an increased interest in the use of heat transfer enhancement for the retrofit of HEN, as structural modifications and the need for additional heat transfer area are capital intensive in retrofit. For industrial applications, there is no clear systematic methodology for the application of heat transfer enhancement. Another drawback is due to the increase in pressure drop that is obtained after the application of heat transfer enhancement. This literature survey examines the various methods found in the open research literature for HEN retrofit in detail, and reviews the application and techniques used for heat transfer enhancement in retrofit together with pressure drop considerations.

2.1 Pinch Analysis Methods

Pinch Analysis is a heuristic-based method used for grassroots design, heat recovery targeting, and reducing and/or eliminating heat transfer across the pinch. This method is based on the use of design tools such as composite curves, grand composite curves, and/or grid diagrams. The Pinch Analysis method is based on thermodynamic principles. Shenoy (1995), Kemp (2007) and Gundersen (2013) presented basic principles of pinch analysis such as: no cold and hot utility above and below the pinch respectively, and no process heat exchange across the pinch. The pinch analysis method generally consists of targeting and design stages. The targeting stage identifies the optimal targets for heat recovery, utility consumption and exchanger area required. The design stage makes use of a set of rules and design tools to achieve the specified retrofit target (Asante and Zhu, 1997).

Pinch Analysis is a well-established method for HEN design and retrofit. Tjoe and Linnhoff (1986) proposed a two-step systematic targeting and design methodology for HEN retrofit. The approach predicts the minimum temperature approach (ΔT_{min}) i.e. the minimum allowable temperature difference of a heat exchanger, prior to retrofit design. The targeting stage made use of the area targeting formula (Townsend and Linnhoff, 1984, Linnhoff and Ahmad, 1990) to calculate the area required at different values of ΔT_{min}. This target area corresponding to the utility consumption of the existing network is then compared to the actual area installed in the existing network, allowing for the scope of using the existing area to be explored. The ratio of the minimum area requirement for the existing ΔT_{min} and installed area is called the area efficiency. The assumption of constant area efficiency allowed for the trade-off between energy recovery and required heat transfer area to be optimised. The retrofit design is then initialised, since the optimal value of ΔT_{min} can be determined. The second step involves redesigning the existing network i.e. rearranging heat exchangers transferring heat across the pinch point (the temperature level at which ΔT_{min} occurs), and then designing the new network while retaining the existing structure even if new area would have to be installed.

Tjoe (1986) improved the synthesis procedure of the targeted network by identifying heat exchangers making poor use of the temperature driving force (ΔT_{min}) by means of the remaining area analysis. A slightly modified driving force plot is used as a guide for rearranging the poorly placed heat exchangers. New heat exchangers are then introduced where there are opportunities for energy recovery by investigating loops and utility paths. Rearranging poorly used heat exchangers and introducing new heat exchangers allowed for some of the existing heat exchangers in the network to be merged or removed from the design and the resulting ΔT_{min} slightly modified. In summary, the proposed method by Tjoe (1986) performed retrofit following the three basic rules of Pinch Analysis i.e. (1) no cold utility above the pinch, (2) no hot utility below the pinch, and (3) no process heat exchange across the pinch. The main drawback of the targeting method used based on area efficiency is that the area targets do not reflect the area distribution within the existing HEN.

Shokoya (1992) proposed an area matrix method using a linear model to determine the retrofit target. The area matrix represents the area distribution between each pair of hot and cold streams in the existing HEN. The first step involves generating a target matrix by assuming vertical heat transfer between the hot and cold composite curves. In the second step, the difference between the target area and the existing area matrices is defined as a deviation area matrix. The maximum compatibility of the target area matrix and the existing area matrix is found by minimising the sum of the squares of the elements in the deviation area matrix. Shokoya (1992) stated that the area matrix method provides a more realistic area target than that proposed by Tjoe and Linnhoff (1986) due to the consideration of area distribution. However, the methods proposed by Tjoe and Linnhoff (1986), Tjoe (1986) and Shokoya (1992) do not explicitly account for the cost of structural modifications in the retrofit design, which can lead to the representation of complex designs.

Carlsson et al. (1993) proposed the cost matrix method that tackles the limitation of the aforementioned studies for HEN retrofit. The objective is to find the cost-optimal solution taking into account various parameters such as the cost of heat transfer area, physical piping distance between pairs of streams, auxiliary equipment, and pumping and maintenance costs associated with each potential match. Unlike Pinch Analysis (Tjoe and Linnhoff, 1986), this method does not have a targeting stage, resulting in several networks requiring evaluation for different ΔT_{min}. The cost matrix and a set of rules are used in selecting matches until the level of heat recovery defined by ΔT_{min} is reached. The cost matrix method only considers networks with heat transfer across the pinch if there is equal amount of heat being transferred from below to above the pinch and vice versa, thereby allowing for criss-cross heat exchange (heat transfer from below to above the pinch and vice versa). However, the cost matrix method is not suitable for large-scale industrial applications due to its dependence on accurate piping and other cost data for each potential match making it impractical due to considerable amount of work required to generate the data.

To reduce the complexities of the retrofit process such as the time required to generate pinch designs, many researchers presented methods that can be applied to the HEN retrofit problems before solving. van Reisen et al. (1995) introduced path analysis to select and evaluate sub-networks of an existing HEN considered for retrofit. The proposed path analysis consists of four stages:

(1) Identification of sub-networks based on energy savings.
(2) Evaluation of the sub-networks together with the total network by using established targeting tools such as, composite curves.
(3) Generate the new sub-networks by using a rigorous algorithm or by the designer. This is subject to two criteria i.e. the sub-network must be heat balanced and a heater and cooler must be included.
(4) Design the new network using only the streams included in the sub-network in step (3) and then compare with the targets.

The path analysis method simplifies the retrofit problem significantly, as path analysis deals with sub-networks instead of the whole network (Sreepathi and Rangaiah, 2014). The difficulty identified with the application of this methodology is the quantification of the ranking of sub-networks i.e. having to evaluate alternative sub-networks, which can be considerable for large-scale HENs. The path analysis method was then extended to consider structural interconnections, while solving the retrofit problem. van Reisen et al. (1998) proposed a new targeting method based on dividing the existing process into zones. The division allowed for the identification of sections of the original network that has high saving potential and the associated section is addressed separately.

Nordman and Berntsson (2001) presented two methods based on Pinch Analysis. The first method presented an alternative to the grand composite curve used for Pinch Analysis. The new grand composite curve incorporates characteristics of the existing HEN to allow for feasible retrofit designs. The old grand composite curve was unable to highlight changes to the network to attain optimal levels of heat recovery. Nordman and Berntsson (2001) developed eight new temperature-enthalpy curves; four above the pinch and four below the pinch. Changes in heating and cooling can be identified and evaluated with the use of the new grand composite curve. The curves are used in identifying heat exchangers that violate pinch rules, and an area-energy trade-off is used to implement the retrofit design. The second method makes use of a matrix to design the network by identifying cost effective ways of improving the HEN. Other parameters such as the material requirements, heat exchanger types, maintenance costs, and auxiliary equipment are included together with the need to obtain energy savings. This study was later extended by Nordman and Berntsson (2009) to present useful insights into various scenarios such as criss-cross heat exchange, cooling above the pinch, and heating below the pinch as well as other retrofit alternatives. This leads to a crisscross network, in which the area-energy trade-off is applied to obtain the retrofit solution with the minimum total cost.

Li and Chang (2010) introduced a pinch-based retrofit method that determines the pinch temperatures, identifies cross-pinch matches and modifies these matches by decreasing their heat load until cross-pinch heat transfer is eliminated. Next, the unmatched split loads on each side of the pinch are combined and re-matched. One potential drawback of this method is that it attempts to mirror maximum energy recovery by eliminating all cross-pinch heat transfer. Although this may seem like a reasonable proposition in terms of energy savings, it might not always be practical as the associated capital costs with such a procedure might be prohibitive.

In summary, the Pinch Analysis method is a well-developed methodology capable of providing the designer with a retrofit target. It is a very useful tool when used in the correct way for the right problems (Smith, 2016). However, it is not fundamentally suited to retrofit, as a large number of modifications are required to the existing network, resulting in increased cost. It also ignores the constraints (such as: plant layout) associated with the existing network, reuses existing equipment in an ad hoc way, requires an expert user for its application. For some of the applications of Pinch Analysis, the retrofit problem is treated as a grassroots design, rather than accepting the features of the existing HEN (Wang, 2012).

2.2 Optimisation Methods

Optimisation methods convert the HEN problem into an optimisation task by formulating the retrofit problem as a mathematical model. The two important aspects in mathematical programming methods are finding an efficient way of representing the problem and providing an efficient optimisation technique for solving the problems. Optimisation methods can be divided into deterministic and stochastic methods. The optimisation methods are generally centred on the need to minimise either: retrofit cost, energy consumption and/or the number of modifications.

2.2.1 Deterministic Methods

Deterministic methods are based on the use of non-linear programming (NLP), mixed integer linear programming (MILP), or mixed integer non-linear programming (MINLP). Yee and Grossmann (1986) reported the first retrofit methodology for HENs based on mathematical programming. They developed an MILP assignment-transhipment model for predicting the smallest number of structural modifications in an existing network, based on the transhipment model proposed by Papoulias and Grossmann (1983). The objective of this model is to maximise the utilisation of existing heat exchanger units, minimise the number of new heat exchangers required and the reassignment of existing heat exchanger units to different matches. This approach leads to a final network structure that is as close as possible to the existing one.

Ciric and Floudas (1989) proposed a two-stage procedure for the retrofit of HENs. The first stage, a match selection stage, involves the formulation of an MILP model. This model is used in the identification of “ideal” structural modifications. The pairings of all possible matches and heat exchangers are evaluated and decisions regarding possible matches, reassigning heat exchangers, purchasing new heat exchangers and repiping streams are made. The objective of the MILP model was to minimise the sum of the cost of purchasing new heat exchangers, additional heat exchanger area, and the piping cost for a fixed heat recovery. The second stage consists of generating a superstructure containing all possible network configurations based on the result obtained from the first stage. This is then formulated and solved as a NLP problem. Ciric and Floudas (1990) extend this approach by presenting a single stage MINLP model. The network configuration is modelled by the generalised match-network hyper-structure (Ciric and Floudas, 1990). Compared to the first method, which is a sequential approach, the new method employs a simultaneous approach for optimisation. The objective function is extended to include structural modification costs.

Yee and Grossmann (1991) proposed an improved two-stage model for retrofit, a pre-screening stage and an optimisation stage. The purpose of the pre-screening stage is to determine the optimal heat recovery level and the economic feasibility of the retrofit design. This stage involved comparing the minimum annual cost of utilities, additional area requirement, and fixed cost of structural modifications estimated at different levels of heat recovery to the existing operating costs. The economic potential for retrofit can then be evaluated. The transhipment model proposed by Papoulias and Grossmann (1983) is used for calculating the utility requirements. The area targeting formula, proposed by Townsend and Linnhoff (1984), is used for determining the additional area required. The minimum structural modifications are then estimated by the method presented by Yee and Grossmann (1989). The optimisation stage takes into consideration only the number of new units required to achieve the optimum investment. It consists of the construction of a retrofit superstructure that includes all the possible retrofit designs embedded within. To determine the best retrofit design, an MINLP model is formulated and solved.

Briones and Kokossis (1999) proposed a two-stage approach for the retrofit of HENs. This consists of a screening and an optimisation stage. The screening involves the use of a conceptual MILP model based on the use of integer variables for structural modifications, and continuous variables for calculating heat loads and heat transfer area. The screening stage utilises targets for area and MILP model for existing HEN modification to determine the area and modifications required. The results from these models are then used in the second stage of the proposed approach, the optimisation stage. A retrofit hyper-target, similar to the targets provided by conventional methods, is developed. The model is capable of handling different objectives such as minimum heat transfer area and minimum investment cost.

Ma et al. (2000) proposed a two-step approach for HEN retrofit. The first step includes the development of a Constant Approach Temperature (CAT) model to optimise the HEN structure. With this, the area calculations are linearized by fixing the change in temperature to be constant for all heat exchangers. This allows the problem to be solved as an MILP problem as opposed to MINLP. The CAT model is developed based on the model proposed by Yee and Grossmann (1991). In the second step, an MINLP model is used, which includes additional variables for exchanger area and takes into account the actual approach temperatures of all heat exchangers. This model simultaneously takes into account network modifications, energy consumption and heat transfer area.

Sorsak and Kravanja (2004) extended the model of Yee and Grossmann (1990) by accounting for the different types of heat exchangers to solve retrofit problems using an MINLP model. The exchangers investigated are double pipe heat exchangers, shell-and-tube heat exchangers, and plate and frame heat exchangers. Analysis carried out show that the feasibility of heat transfer throughout the HEN is strongly dependent of the type of heat exchanger used.

Up to this point, most of the studies have assumed constant operating conditions. To overcome this drawback, Ponce-Ortega et al. (2008a) proposed a new MINLP model for solving HEN retrofit problems that considers HEN structure and process modifications simultaneously. In addition, this model assumes constant temperature streams (Ponce-Ortega et al., 2008b). The proposed model is based on the superstructure model proposed by Yee and Grossmann (1991).

Nguyen et al. (2010) proposed a rigorous MILP model to solve HEN retrofit problems. The proposed model is based on that originally developed by Barbaro and Bagajewicz (2005). In the proposed method, the difference between the supply and target temperatures of each stream considered for heat exchange between hot and cold streams, are divided into small temperature intervals. The network structure is then optimised simultaneously with the heat transfer area.

Pan et al. (2013b) proposed an MILP-based iterative approach for the retrofit of HENs. A superstructure of the retrofitted network is developed based on the concept of a pinching match. This superstructure is then solved in two optimisation stages using the developed MILP-based iteration method. In the first stage, the network topology is optimised by the elimination of redundant heat matches (i.e. matches with small duties or areas) for the retrofit from the network superstructure. In the second stage, the optimal retrofit structure obtained in the first stage is optimised so that the best modifications are selected to minimise the investment cost of the network structure. The major advantage of this methodology is the linearization of non-linear aspects of the models in both stages. This significantly decreases the computational difficulty of solving the models.

Automated design procedure using deterministic optimisation methods for HEN retrofit has benefits due to the ease of application and ability to be applied to variable retrofit problems. Drawbacks associated with using deterministic optimisation methods for retrofit include the lack of global optimality in solutions because of non-convexities in the objective function and its sensitivity to initial points.

2.2.2 Stochastic-based Approaches

Stochastic-based retrofit approaches make use of simulated annealing (SA), genetic algorithm (GA) or integrated differential evolution (IDE) for retrofit. Nielsen et al. (1996) presented a framework using SA as the optimisation tool for retrofit. The formulation is similar to that presented by Dolan et al. (1989). The framework presented for the design and retrofit of HENs includes detailed modelling of different types of heat exchangers, heat transfer coefficients and non-constant heat capacities. The work by Nielson et al. (1996) also considered pressure drop and flexibility.

Athier et al. (1998) proposed a retrofit methodology where the structural optimisation is carried out using a SA procedure. In this work, two loops are included; the SA procedure is used to select a HEN configuration in the outer loop, and the required additional area is optimised by an NLP procedure for a fixed HEN structure in the inner loop.

Rodriguez (2005) presented an approach making use of the SA algorithm for optimisation of both discrete variables, such as structural modifications (i.e. re-piping, resequencing of existing heat exchangers), and continuous variables, such as exchanger duties, heat transfer area and stream split fractions. However, simplification of objective functions and cost models in optimisation was not considered.

Bochenek and Jezowski (2006) proposed a two-level method based on GA for the retrofit of HENS. In this method, a structural optimisation problem is formulated as a multivariable problem using a structural matrix, which consists of all the structural features of the HEN in the first level. The features include the topology of heat exchangers and location of splitters. These are then optimised using GA. The structure developed in the first level is then used to find the heat exchanger area and split ratio in the second level. The drawback with this method is the prolonged computational time required even for small networks.

Rezaei and Shafiei (2009) mentioned that GA is not effective for dealing with continuous variables. To overcome these drawbacks, Rezaei and Shafiei (2009) presented a model that combines GA with NLP and integer linear programming (ILP) to solve the retrofit problem. In this proposed method, the GA is used to select structural modifications using node representation for location of exchangers in a HEN. The continuous variables i.e. heat loads, split fractions and temperatures are then optimised using the NLP. Finally, an ILP problem is formulated and solved with the objective of minimising the investment cost.

The IDE algorithm developed by Zhang and Rangaiah (2011), together with HEN structural representation based on matrices proposed by Jezowski et al. (2007) and Bochenek and Jezowski (2010) are used by Zhang and Rangaiah (2013) for solving HEN retrofit problems. The structural representation is made up of both discrete and continuous variables. In this work, both the discrete and continuous variables are solved simultaneously.

Liu et al. (2014) presented a hybrid GA for the solution of an MINLP formulation of the retrofit problem, based on the full utilisation of existing heat exchangers and network structures in the retrofitted network. The objective of the optimisation is to minimise the cost of modifications, and the utility cost of the retrofitted network. A superstructure model is used for the retrofit of the existing HEN in a six-step procedure. In the first step, the structure of the existing HEN is analysed, and the exchangers in the existing HEN are sequenced. The sequence of the existing heat exchangers is determined in the second step. The third step involves the representation of the location of each existing heat exchanger. In the fourth step, the areas of the existing heat exchangers are inputted to the hybrid genetic algorithm, and the location of each existing heat exchanger in the retrofitted network is determined. The fifth and sixth steps involve revising and running the genetic algorithm to obtain the final retrofitted network.

Stochastic optimisation methods have a greater chance of finding the global optimum compared with the deterministic method due to the random nature of the optimisation methods. However, stochastic methods require significantly more computational time compared to deterministic methods (Cavazzuti, 2013).

Mathematical programming methods for HEN retrofit have an advantage of being automated procedures. However, mathematical programming methods are not widely applied to large-scale processes due to the difficulty in formulating the retrofit problem, which hints that they might be difficult to implement in practice. The mathematical programming based methods reviewed can generally be divided into two classes i.e. simultaneous (one-step) and sequential (more than one step). In terms of obtaining an optimal solution, simultaneous approaches are recommended. However, this comes at a penalty of long computational times. If the optimality of the result is not a factor, sequential approaches can be employed, as less computational times are required.

2.3 Hybrid Methods

Methods combining aspects of the Pinch Analysis and mathematical programming methods are known as hybrid methods. These methods aim to take advantage of the automated characteristic of the mathematical programming methods, while also keeping the user interaction present as in Pinch Analysis methods in order to obtain faster and more efficient retrofit procedures.

Briones and Kokossis (1996) developed a three-stage hybrid procedure for retrofit. The first stage is the targeting stage. In this stage, potential solutions are screened based on pre-set targets on area and number of modifications. An MILP formulation is developed to identify feasible solutions with minimum area requirement and structural changes. The solution of the first stage is used to set up a model for the second stage where structural optimisation is performed. The heat transfer area and structural modifications to the existing HEN are optimised in this second stage. The solution of the second stage provides the network structure of the retrofitted HEN. This network structure is then represented as a superstructure and formulated as an NLP model that is optimised in the third stage to minimise the capital cost of the retrofitted network. However, maximum energy recovery is not guaranteed.

Asante and Zhu (1996, 1997) proposed a two-stage approach in which the hybrid method is used for the retrofit of HENs. Both works make use of both Pinch Analysis and mathematical programming for HEN retrofit. The goal is to minimise the number of structural modifications required to achieve an energy recovery target.

The term network pinch represents the energy recovery limit of a given HEN. To overcome the network pinch, structural modifications and additional heat transfer area must be applied. In the first stage, the diagnosis stage, the pinch method is used in identifying potential modifications to the existing configuration of the HEN. Then, each candidate modification is optimised for maximum heat recovery by varying heat loads of each heat exchanger. In the second stage, the optimisation stage, the "best" modification can be selected by the designer, and then further cost optimisation is carried out on the selected HEN with modified topology.

Varbanov and Klemes (2000) presented a systematic approach based on network pinch and simple heuristics. The proposed approach examined scenarios where the identification of network pinch is not possible, with the absence of a utility path despite poor heat recovery. They tried to improve the retrofit process by coming up with alternative means to perform retrofit. This was by providing a set of topology modifications to the existing network.

Smith et al. (2010) presented a methodology that combines the structural modifications and capital-energy optimisation into a single-step in order to obtain a cost-effective design. This method accounts for the temperature dependency of the stream thermal properties as this gives a true representation of the interaction in the network during retrofit.

Bakhtiari and Bedard (2013) extended the approach proposed by Asante and Zhu (1997). In their work, they modified the method to take into account some practical features. The proposed approach is capable of handling complex network configurations with stream segmentation and splitting. It involves a combination of the structural modification stage that gives the maximum heat recovery and the cost optimisation stage that optimises the use of additional heat exchanger area. The risks of missing cost-effective design solutions are reduced with this approach.

Although the hybrid method is sequential, structural modifications are explored systematically, while also providing insights to the design procedure. These characteristics make this method a promising retrofit method for large-scale problems. The hybrid method is able to obtain decrease in energy consumption by manipulating the degrees of freedom of the existing HEN. This comes at an area penalty, as additional heat transfer area is required to maintain a balanced network.

The main drawback is that the selection of the potential modifications is not based on costs but on energy demands, thus the design with minimum cost cannot be guaranteed. However, insights into the decision of structural modifications are not also provided.

2.4 Heat Transfer Enhancement

As mentioned earlier, the ideal retrofit design is one with the fewest modifications and lowest capital cost requirement. The desire to retrofit HENs without the need of additional heat transfer area and topology modifications has led to a rise in research for the use of heat transfer enhancement in HEN retrofit. Heat transfer enhancement can be used to avoid the implementation of additional heat transfer area, leading to significant cost savings. The reduction in cost is due to the considerable decrease in civil and piping works. Heat transfer enhancement is also beneficial as it can be implemented during normal maintenance periods, thereby avoiding production losses during retrofit.

Polley et al. (1992) proposed the idea of combining both heat transfer enhancement and HEN retrofit. Up until that point, both aspects have only been researched separately. Their research analysed the potential benefit of using heat transfer enhancement in retrofit, and the effect of pressure drop and fouling. It also contains a comparison between different enhancement devices. However, only a targeting methodology is proposed. This methodology is based on area efficiency. This study does not present a systematic way for applying heat transfer enhancement in retrofit.

Nie and Zhu (1999) proposed a retrofit methodology that considers heat transfer enhancement and pressure drop. In this work, heat transfer enhancement is only used in reducing capital investment and therefore not included in the methodology. The focus of this work is placed on pressure drop, and as such, does not highlight the benefits of only using heat transfer enhancement.

Zhu et al. (2000) proposed a methodology based on the network pinch approach for HEN retrofit including heat transfer enhancement based on a two-stage approach. The first stage, the targeting stage, is used to identify suitable heat exchangers in the existing HEN where heat transfer enhancement could be applied. The second stage, the selection stage, involved selecting the most suitable technique for heat transfer enhancement in each of the suitable candidates identified in the targeting stage using a pressure drop criterion. Enhancement is only considered when additional heat transfer area requirements are determined using the network pinch analysis. Again, similar to the previous study, the benefits of heat transfer enhancement are not fully explored.

Pan et al. (2011) proposed an MILP optimisation that considers tube-side enhancement. This work considers the exact value of the log mean temperature difference and correction factor as opposed to an approximate value commonly used in mathematical optimisation. Multiple tube passes are also considered in the optimisation process. The new method shows that the computational difficulties such as solving the non-linearity of the log mean temperature difference and correction factor can be effectively handled.

Pan et al. (2012) further improved the method by introducing an approach based on a simple MILP model and two-iteration loops to obtain a suitable retrofit result. In the first loop, the retrofit problem is solved to obtain optimal solutions based on either energy savings or retrofit profit (defined as the difference between profit from energy saving and total cost of retrofit). In the second loop, the maximum energy savings and retrofit profit for the given HEN is sought.

Wang et al. (2012b) proposed a systematic methodology for the retrofit of HENs based on simple heuristic rules. The heuristic rules are proposed to identify the most suitable heat exchangers in a network to apply heat transfer enhancement. The results obtained showed that the application of this approach allows for significant improvements in energy recovery, without fundamental structural modifications to the HEN. However, the augmentation level of the enhancement is assumed.

To overcome this drawback, Jiang et al. (2014a) proposed a new method for the application of heat transfer enhancement in retrofit. The level of enhancement for each candidate heat exchanger is determined using models developed for the chosen enhancement technique.

2.4.1 Heat Transfer Enhancement Techniques

Heat transfer enhancement can be divided into two categories: passive method (requires no direct stimulation from external power such as rough and extended surfaces or swirl flow devices) and active method (requires extra external power such as fluid vibration and suction). There are different enhancement techniques, all of which have different effects on pressure drop, fouling and heat transfer coefficients. For a shell-and-tube heat exchanger, which is by far the most commonly used exchanger in process industries, heat transfer enhancement can be applied on the shell-side, tube-side or on both the shell and tube sides.

2.4.1.1 Shell-Side Enhancement

In practice, the most commonly used shell-side enhancement is the segmental baffle. The conventional segmental baffle improves the shell-side heat transfer in an exchanger. Drawbacks of using the segmental baffle include high shell-side pressure drop, low shell-side mass flow velocity, fouling and vibration. Owing to the aforementioned drawbacks, helical baffles have been developed to reduce the number of dead spots created (Wang et al., 2010). Studies performed on the use of helical baffles for shell-side enhancement have highlighted its benefits (Stehlik et al., 1994, Gupta et al., 1995, Kral et al., 1996). These include, improved heat transfer coefficients, reduced pressure drops, low possibility of flow-induced vibration, and reduced fouling. There are two classes of helical baffles: continuous and non-continuous baffles (Wang et al., 2010). The non-continuous helical baffle supersedes the continuous helical baffle as it offers superior augmentation levels with an insignificant increase in pressure drop (Wang et al., 2010). Both classes of helical baffles offer high levels of augmentation at smaller helix angles and helical pitches.

External fins are also used for shell-side heat transfer enhancement. The use of external fins is beneficial as it increases the film coefficient with added turbulence and the heat transfer area. A study performed by Mukherjee (1998) shows that extended surface finned tubes provide two to four times as much heat transfer area on the outside compared to that of a bare tube. This in turn helps to offset a lower outside heat transfer coefficient. Other studies conducted to determine the performance of finned tubes show that they could enhance the heat transfer coefficient quite significantly but at an increased pressure drop penalty (Hashizume, 1981, Ganapathy, 1996, Lei et al., 2008).

2.4.1.2 Tube-Side Enhancement

García et al. (2005) classify tube-side enhancement into two categories. The first involves the addition of external devices in plain round tubes, e.g. the use of twisted tape and wire coil inserts. The second involves the modification of plain tubes, e.g. dimples tubes; or the manufacture of special tube geometries, e.g. use of internally fined tubes and twisted tube heat exchangers.

Twisted tape inserts consist of a thin strip of twisted metal. The thin strip of metal normally has the same width as that of the tube inner diameter. They are swirl-flow devices that create a spiral or secondary flow along the length of the tube to increase turbulence. Many studies (Date, 2000, Kazuhisa et al., 2004, Sarma et al., 2005) have been conducted to investigate the effect of the spiral flow on exchanger performance. The results obtained show that twisted tapes are able to provide, especially within the laminar region, high levels of enhancement. An important aspect that is also noticed is that the pressure drop penalty is very high and independent of Reynolds number, leading to the conclusion that if the pressure drop is of no concern, then twisted tapes should be preferred in both laminar and turbulent regions. In practice, this is not ideal, as pressure drop is an important factor in the design of HENs hence the reason why twisted tape inserts are not readily used in process industries.

Wire coil inserts consist of a helical coiled spring, which acts as a non-integral roughness. They are commonly used in pre-heaters or oil cooling devices. Wire coil inserts function by inducing a swirl effect and speeds the flow transition from laminar to turbulent. García et al. (2005) highlighted the advantages of using wire coil inserts. These include the ease of installation and removal (including in an existing heat exchanger), low cost and they do not disrupt the mechanical strength of the tube. Empirical correlations were developed by early research conducted concerning the performance of wire coil inserts in turbulent flow (Kumar and Judd, 1970, Sethumadhavan and Raja Rao, 1983). Following this, Uttawar and Rao (1985), Inaba et al. (1994) and Shoji et al. (2003) performed studies to predict the performance of wire coil inserts. The studies show that wire coil inserts provide greater enhancement under laminar flow conditions with only a small pressure drop penalty as a drawback. On the other hand, as the flow progressed from laminar to turbulent, the increase in pressure drop is relatively high. Jiang et al. (2014b) provided reliable correlations for predicting the performance of both wire coil and twisted tape inserts. The new correlations cover all flow regions for both wire coil and twisted tape inserts.

Internally finned tubes are one of the most widely used methods for heat transfer enhancement that requires no direct stimulation from external power (Bergles, 1983). Carnovos (1980) proposed correlations to predict the heat transfer coefficient and pressure drop for internally finned tubes in turbulent flow. Ravigururajan and Bergles (1996) proposed a more accurate and general method for predicting the heat transfer coefficient and pressure drop inside internally finned tubes. Jensen and Vlakancic (1999) performed experimental research to develop correlations to describe the heat transfer coefficient and pressure drop performance of internally finned tubes in turbulent flow. Based on the analysis carried out for internally finned tubes, it is concluded that internally finned tubes are not beneficial when used under laminar flow. In turbulent flow on the other hand, they are able to provide a medium-to-high level of enhancement on the overall heat transfer of a heat exchanger. This affects not only the tube-side heat transfer coefficient but also the overall heat transfer area.

Another enhancement device that can bring about improvement in both the shell and tube sides is the use of twisted tube heat exchangers. This involves replacing plain tubes with twisted tubes. This device can be used to tackle the drawbacks associated with the use of conventional shell and tube heat exchangers in retrofit. Twisted tubes are passive enhancement device, generally classified in a swirl-flow device category. This device increases the performance of existing heat exchangers because of fluid agitation and mixing induced by swirl flow. An attractive feature of twisted tubes is that the swirl is not produced by a device attached to the tube as in other enhancement techniques. As such, they do not require an extra attention during assembly, maintenance, inspection or cleaning. Dzyubenko et al. (2000) presented correlations for modelling and design of twisted tube heat exchangers. Butterworth et al. (1996) and Ljubicic (1999) presented advantages of the use of twisted tube heat exchangers in retrofit. The first advantage is their ability to increase the heat transfer coefficient due to shell and tube side turbulence as a result of the swirl flow and uniform flow distribution, which provide more effective length and surface area. Twisted tubes have no vibration because they are baffle free, instead are supported at multiple contact points along the entire length of the exchanger. Therefore, tube fretting and failure due to vibration is eliminated. They also have reduced pressure drop compared to the segmental baffle in the shell-side. The shorter length of twisted tube heat exchangers with decreased number of tube passes helps in reducing the pressure drop of the tube side.

In summary, the studies outlined above show that the use of heat transfer enhancement could be beneficial for HEN retrofit. They are particularly beneficial as structural modifications and additional heat transfer area could be avoided in retrofit, thus drastically reducing the cost of retrofit. The drawback is the effect on pressure drop, as the existing pumps might not be able to cope with the increase in pressure drop. Therefore, installation of new pumps or retrofitting existing pumps might be needed, which is capital intensive and might not be justified in retrofit. Other ways of mitigating the pressure drop effect with heat transfer enhancement need to be addressed.

2.5 Pressure Drop Considerations

Pressure drop is a major drawback with the application of heat transfer enhancement in HEN retrofit. Most enhancement techniques used in retrofit have a negative impact on the pressure drop of existing heat exchangers. Therefore, it is vital that pressure drop is considered alongside heat transfer enhancement in retrofit.

Polley et al. (1990) considered pressure drop by developing a correlation between the pressure drop, heat transfer coefficients and heat transfer area in retrofit based on the pinch approach presented by Tjoe and Linnhoff (1986a). This allowed for the maximum pressure drop of each stream in the HEN to be specified rather than the heat transfer coefficients. The approach utilised the allowable pressure drop as an objective to optimise the heat exchange area. The total area is minimised by calculating the heat transfer coefficients iteratively. The pinch-based methodology in this work is a drawback when it comes to its application in large-scale problems.

Nie and Zhu (1999) considered pressure drop with heat transfer enhancement in HEN retrofit. The research conducted showed that the application of heat transfer enhancement has a significant impact on pressure drop. They proposed a two-step methodology for considering pressure drop with heat transfer enhancement. In the first step, heat exchangers that require additional area are identified using a unit-based optimisation model. Then, a combined optimisation model is used in the second step to evaluate the duty of heat exchangers, the degree of enhancement and the shell arrangement simultaneously. The pressure drop is determined using the correlation presented by Polley et al. (1990). A constraint is imposed on the network during retrofit based on allowable pressure drop. This is not ideal for large-scale problems as good retrofit options might be missed in terms of maximum energy recovery.

Silva et al. (2000) proposed a method that combines area matrix with pressure drop considerations in HEN retrofit. The two-stage methodology includes a targeting stage and an optimisation stage. In the targeting stage, the area distribution and pressure drop are considered simultaneously. The optimisation stage is used in minimising the additional area requirement in retrofit. Similar to the study conducted by Nie and Zhu (1999), allowable pressure drop is used as a constraint in the optimisation stage as such is plagued by the same drawback listed previously associated with this constraint.

Panjeshahi and Tahouni (2008) presented a new methodology that tackles the issue with pressure drop by considering pump and/or compressor replacement. This is done while simultaneously optimising the additional area and operating cost of the HEN. Unlike the two previously listed retrofit approaches, the constraint of allowable pressure drop is not fixed. This allows for the drawback associated with the constraint of fixed allowable pressure drop in optimisation to be overcome.

Solatani and Shafiei (2011) presented a new method based on coupling a genetic algorithm (GA) with linear programming (LP) and integer linear programming (ILP) methods. GA is used in developing feasible HEN structures, which are then evaluated using LP to find the pressure drop costs. Finally, ILP is used in minimising the cost of modifications. By doing this, the cost associated with an increase in pressure drop is considered simultaneously as modifications are made ensuring the best savings in utilities as opposed to previous studies.

To conclude, most of the research conducted considers topology modification and additional heat transfer area in retrofit. Therefore, there is still a gap in research in identifying a method for reducing the pressure drop requirement with heat transfer enhancement without the need for additional heat transfer area. This is vital as a true representation of the influence of heat transfer enhancement on energy savings in an existing HEN can be presented.

2.6 Network Structure Analysis

Network structure analysis provides a degree of freedom in an existing HEN. The network structure analysis identifies key structural features in a HEN, which aids in the application of heat transfer enhancement, increasing heat transfer area of existing exchangers and structural modifications. Loops and utility paths are examples of structural features in HENs. Being able to identify these features is important as this can help to overcome the restriction imposed by the network pinch, thereby resulting in the design of flexible networks and identifying where in a HEN to apply enhancement.

The identification of structural features by inspection is not a reliable method, as key structural features might be missed when applied to large-scale networks. Linnhoff and Flower (1978a,b) proposed the stream grid representation of HEN. The drawback of this representation is that it cannot be used to locate heat load loops and utility paths in a HEN, but only the location of existing heat exchangers in the network.

The incidence matrix approach (Pethe et al., 1989) is a mathematical representation used for the identification of loops, but it fails to identify the link between two utilities through a process heat exchanger i.e. utility path. The incidence matrix approach is later extended to solve this drawback (Shenoy, 1995) by including a column vector to signify the connection between two utilities. The utility path could then be identified by performing linear combination of the independent columns in the incidence matrix.

Zhu et al. (1996) proposed a methodology that combines the node adjacency matrix and the stream table for the identification of both independent and dependent loops as well as utility paths.

Although these methods exist for the identification of utility paths and loops in a HEN, they have not been combined as part of a retrofit methodology with heat transfer enhancement for HENs.

2.7 Summary

The Pinch Analysis method can be used to set target performance in retrofit, but it is not always an economic target. Its dependency on an expert user for its application is also a drawback. Mathematical programming approaches cannot readily be applied to large-scale problems, as it requires long computational times and can be difficult to formulate. Hybrid methods are beneficial as they can identify the network bottleneck (limit for energy recovery) and the key structural modifications that can be applied in an existing HEN. They also encourage good user interaction.

Structural modifications can provide a high decrease in energy consumption. However, the number of modifications required and the time needed to apply these modifications are drawbacks. There is still a gap in research for the identification of the best network modifications to achieve maximum degree of energy saving with reduced complexity and minimum number of modifications.

Heat transfer enhancement has the potential to improve energy recovery without the need for additional heat transfer area and structural modifications. All the aforementioned techniques for shell-side and tube-side heat transfer enhancement provide an increase in heat transfer coefficients and pressure drops with the exception of helical baffles used for shell-side enhancement that have shown varied performances in various publications. However, it is impossible to say outright that one technology is superior to another, but there are technologies that for particular applications are better. Therefore, the focus of this Thesis is placed on developing methodologies for the application of heat transfer enhancement in retrofit. The decision of what form of enhancement device to use can be left to the user.

Pressure drop is an important constraint that should be imposed on a HEN during retrofit, especially with heat transfer enhancement. Without the consideration of pressure drop, the proposed retrofit design might not be feasible, thus not industrially applicable.

Given a shell and tube heat exchanger, it is vital to be able to model existing heat exchangers in a given HEN. This involves calculating the heat transfer coefficients in the shell and tube sides, the pressure drop of both sides, the heat transfer area, the overall heat transfer coefficients, the logarithmic-mean-temperature-difference and the correction factor. This is tackled in the next section of this thesis.

Chapter 3 Heat Exchanger Model

This section of the thesis presents the model developed by Jiang et al. (2014b) for the design of shell and tube heat exchangers. The model is used in this work to design heat exchangers presented in this work. A detailed problem statement is provided to highlight the assumptions with which this model was developed. The model is then validated with the use of a simple example and comparison with other established models.

3.1 Problem Statement

It is assumed in this report that energy recovery is based on heat transfer through shell and tube heat exchangers. This is because shell and tube heat exchangers are by far the most widely used heat exchangers in process industries. It is assumed that the following data are available:

- Stream data such as flowrates, start temperature, target temperature, density, specific heat capacity, viscosity, thermal conductivity and fouling coefficients;
- Tube-side geometry such as tube length, tube inner diameter, number of tubes, number of tube passes, tube wall conductivity and nozzle inner diameters;
- Shell-side geometry such as tube outer diameter, tube pitch, tube layout angle, shell inner diameter, number of shell passes, baffle spacing, baffle cut, shell bundle clearance and nozzle inner diameters.

3.2 Shell and Tube Heat Exchanger Model

For predicting the performance of a heat exchanger, it is important to be able to calculate the overall heat transfer coefficient and pressure drop in both the shell and tube sides. Figure 3.1 describes the geometric details of shell and tube heat exchangers that define various parameters and specifications required in the calculation of heat transfer coefficients and pressure drop.

In this section, equations used in calculating the shell and tube side heat transfer coefficients, their respective pressure drops, the overall heat transfer coefficient (U), logarithmic-mean-temperature-difference (LMTD), LMTD correction factor (F_T), and overall heat transfer area (A) are presented in sequence.

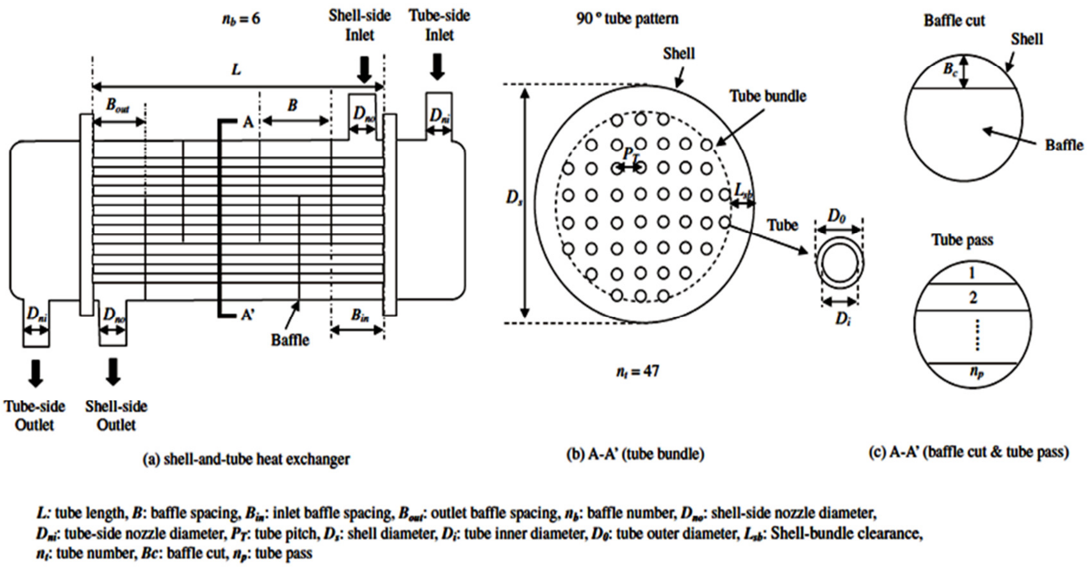

Figure 3.1: Geometry specifics of shell-and-tube heat exchanger (Frausto-Hernandez et al., 2003)

3.2.1 Shell-Side Heat Transfer Coefficient

Equation 3.1 (Ayub, 2005, Wang et al., 2012a) is used in calculating the shell-side heat transfer coefficient (h_S). Parameters such as the tube outer diameter (D_o); shell-side fluid thermal conductivity (k_S); shell-side fluid specific heat capacity (C_{PS}); and shell-side fluid viscosity (μ_S) are known.

$$h_S = \frac{0.06207 F_S F_P F_L k_S^{2/3} (C_{PS}\mu_S)^{1/3}}{D_o} \qquad \text{Equation 3.1}$$

F_S is the shell-side geometry factor to allow for baffle cut (B_C), baffle arrangement and flow regime i.e. based on Reynolds number (Re) (Wang et al., 2012b):

$$F_S = -5.9969\times10^{-4} Re_S^2 + 0.6191 Re_S + 17.793 \qquad Re_S \le 250 \qquad \text{Equation 3.2}$$

$$F_S = 1.40915 Re_S^{0.6633} B_C^{-0.5053} \qquad 250 \le Re_S \le 125{,}000 \qquad \text{Equation 3.3}$$

F_P is the pitch factor, which depends on the tube layout of the bundle (1 for triangular and diagonal square pitch, and 0.85 for in-line square pitch).

F_L is the leakage factor to allow for all the stream leakage, which is a function of bundle configuration (0.9 for straight tube bundle, 0.85 for U-tube bundle, and 0.8 for floating head bundle).

To calculate the Reynolds number (Equation 3.4), the shell-side velocity (v_S) must be determined (Equation 3.11). We assume the values for the fluid density (ρ_S), tube outer diameter (D_o), and shell-side fluid viscosity (μ_S) are known.

$$Re_S = \frac{\rho_S v_S D_o}{\mu_S} \qquad \text{Equation 3.4}$$

The definition of the shell-side fluid velocity needs careful consideration. The velocity in cross flow will vary as the fluid flows from one baffle window (or the inlet nozzle) to the next window (or to the exit nozzle). The shell-side velocity is normally defined by reference to the velocity at the widest point, which is on the shell diameter (D_S) and the slowest velocity across the shell. The velocity will depend on the area through which the fluid flows (A_{CF}) shown in Equation 3.5.

A_{CF} = Baffle spacing x [Area between the outside of the bundle and inside of the shell + Number of tubes across the widest point x Space between tubes] Equation 3.5

For a 90º layout, the number of tubes across the cross sectional area is dependent on the outside diameter of the tube bundle (D_B), the tube outside diameter (D_o) and the tube pitch (p_T). The gap between the tubes is dependent on tube pitch and tube outside diameter. Thus for a 90º layout:

$$A_{CF} = B[D_S - D_B] + \frac{(D_B - D_o)}{p_T}\left(p_T - D_o\right) \qquad \text{Equation 3.6}$$

For the flow across a rotated triangular (60º) layout, the minimum flow area is the minimum of $\sqrt{3}p_T$ and $2\left(p_T - D_o\right)$. The minimum again is used in practice, which is $2\left(p_T - D_o\right)$. Thus, for a 60º layout:

$$A_{CF} = B[D_S - D_B] + \frac{(D_B - D_o)}{\sqrt{3}p_T} 2(p_T - D_o)$$ Equation 3.7

For flow across a rotated square (45º) layout, the minimum flow area is the minimum of $\sqrt{2}p_T$ and $2(p_T - D_o)$. For the tube pitches used in practice (say: $p_T = 1.25D_o$), the minimum is $2(p_T - D_o)$. Thus, for a 45º layout:

$$A_{CF} = B[D_S - D_B] + \frac{(D_B - D_o)}{\sqrt{2}p_T} 2(p_T - D_o)$$ Equation 3.8

Finally, for a 30° layout, the flow area is taken to be the minimum flow area, which is the minimum of $(p_T - D_o)$ and $2(p_T - D_o)$, which is $(p_T - D_o)$. Thus, the flow area for a 30° layout is the same as that of a 90° given in Equation 3.6.

A pitch correction factor (p_{CF}) can be used in deriving a general equation for the flow area by combining Equations 3.6, 3.7 and 3.8. The values of p_{CF} shown in Equation 3.9 are 1 for 90º and 30º layouts; $\sqrt{3}/2$ for 60º layouts; and $\sqrt{2}/2$ for 45º layouts.

$$A_{CF} = B[D_S - D_B] + \frac{(D_B - D_o)}{p_{CF}p_T} (p_T - D_o)$$ Equation 3.9

Equation 3.10 shows the shell-side velocity as a function of the shell-side mass flowrate, density and the flow area. Combining this equation with Equation 3.9 gives the final equation for determining the velocity of the shell-side (Equation 3.11).

$$v_S = \frac{m_S}{\rho_S A_{CF}}$$ Equation 3.10

$$v_S = \frac{m_S}{\rho_S B[D_S - D_B] + \frac{(D_B - D_o)}{p_{CF}p_T} (p_T - D_o)}$$ Equation 3.11

3.2.2 Shell-Side Pressure Drop

The simplified Delaware method (Kern and Kraus, 1972) is used for the calculation of the shell-side pressure drop. This is because it is a relatively simple method and it makes use of less empirical equations, but provides accurate results (Serth, 2007) when compared to other methods for a wide operating range of shell-side diameter and flow velocity. The total pressure drop ΔP_S for the shell-side in one shell includes the pressure drop in the straight section of shell (ΔP_{SS}) and pressure drop in nozzles (ΔP_{NS}) (Kern and Kraus, 1972).

1. Pressure drop in the straight section of the shell ΔP_{SS} per shell (Kern and Kraus, 1972, Wang et al., 2012b):

This is dependent on the pressure drop in the straight section of the shell with 20% baffle cut ($\Delta P_{SS,\ 20\%}$), the baffle cut (in %), and the correction constant based on the baffle cut used (m_{fo}) as shown in Equation 3.12. The pressure drop in one central baffle spacing zone with 20% baffle cut ($\Delta P_{SB,20\%}$); the number of baffles (N_B); the correction factor for unequal baffle spacing (R_S) can be used in evaluating $\Delta P_{SS,\ 20\%}$ as shown in Equation 3.13. The shell-side friction factor; shell diameter, density, velocity and the shell-side equivalent diameter (d_e) can be used in calculating $\Delta P_{SB,\ 20\%}$ (Equation 3.14). The correction factor is dependent on the central (B), inlet (B_{in}) and outlet (B_{out}) baffle spacing as shown in Equation 3.15.

$$\Delta P_{SS} = \Delta P_{SS,20\%}\left(\frac{B_C}{0.2}\right)^{m_{fo}} \quad \text{Equation 3.12}$$

$$\Delta P_{SS,20\%} = (N_B - 1)\Delta P_{SB,20\%} + R_S \Delta P_{SB,20\%} \quad \text{Equation 3.13}$$

$$\Delta P_{SB,20\%} = \frac{c_{fs}\, D_S \rho_S v_S}{2d_e} \quad \text{Equation 3.14}$$

$$R_S = \left(\frac{B}{B_{in}}\right)^{1.8} + \left(\frac{B}{B_{out}}\right)^{1.8} \quad \text{Equation 3.15}$$

The values of the constant shown in Equation 3.12 are as follows:

m_{fo} = -0.26765 for $20\% \le B_C < 30\%$

m_{fo} = -0.36106 for 30% ≤ B_C < 40%

m_{fo} = -0.58171 for 40% ≤ B_C ≤ 50%

The shell-side friction factor can be determined using Equation 3.16 below. The corresponding friction factors (f_1 and f_2) are presented in Equations 3.17 and 3.18.

$$c_{fS} = 144\left[f_1 - 1.25\left(1 - \frac{B}{D_S}\right)(f_1 - f_2)\right]$$ Equation 3.16

$$f_1 = aRe_{Se}^{-0.125}$$ Equation 3.17

$$f_2 = bRe_{Se}^{-0.157}$$ Equation 3.18

The values of the constant shown in Equations 3.17 and 3.18 are as follows:

a = 0.008190 for $D_S \leq 0.9$m

a = 0.01166 for $D_S > 0.9$m

b = 0.004049 for $D_S \leq 0.9$m

b = 0.002935 for $D_S > 0.9$m

The Reynolds number based on the shell-side equivalent diameter (Re_{Se}) shown in Equations 3.17 and 3.18 is shown in Equation 3.19.

$$Re_{Se} = \frac{\rho_S v_S d_e}{\mu_S}$$ Equation 3.19

The equivalent diameter (d_e) is used to calculate the flow in non-circular channels in the same way as a circular tube. Equivalent diameter is defined as:

$$d_e = \frac{4 \times \text{Flow Area}}{\text{Wetted Perimeter}}$$ Equation 3.20

The equations used in calculating the equivalent diameter for both square and triangular pitches are shown in Equations 3.21 and 3.22.

$$d_e = \frac{4 \times \left(p_T^2 - \frac{\pi D_o^2}{4}\right)}{\pi d_o} = \frac{4p_T^2}{\pi d_o} - D_o$$ Equation 3.21

$$d_e = \frac{4 \times \left(\frac{1}{2} p_T^2 \frac{\sqrt{3}}{2} - \frac{1}{2}\frac{\pi D_o^2}{4}\right)}{\frac{\pi D_o}{2}} = \frac{2\sqrt{3}p_T^2}{\pi d_o} - D_o$$ Equation 3.22

Equations 3.21 and 3.22 can be expressed using a pitch configuration factor (C_{De}) as shown in Equation 3.23. The corresponding values or square and triangular pitches are $4/\pi$ and $2\sqrt{3}/\pi$ respectively.

$$d_e = \frac{C_{De} p_T^2}{D_o} - D_o$$ Equation 3.23

Thus, Equation 3.12 can be written as:

$$\Delta P_{SS} = K_{PS1} v_S^{1.875} + K_{PS2} v_S^{1.843}$$ Equation 3.24

Where:

$$K_{PS1} = 18\left(5\frac{B}{D_S} - 1\right)(N_B - 1 + R_S)\frac{aD_S\rho_S}{d_e}\left(\frac{B_C}{0.2}\right)^{m_{fo}}\left(\frac{\rho_S d_e}{\mu_S}\right)^{-0.125}$$ Equation 3.25

$$K_{PS2} = 90\left(1 - \frac{B}{D_S}\right)(N_B - 1 + R_S)\frac{bD_S\rho_S}{d_e}\left(\frac{B_C}{0.2}\right)^{m_{fo}}\left(\frac{\rho_S d_e}{\mu_S}\right)^{-0.157}$$ Equation 3.26

The equations developed so far allows for unequal baffle spacing in which the baffle spacing in the entrance and exit zones is different from the rest of the shell-side. In many designs, the baffle spacing is equal throughout the shell-side. In addition, assuming the baffle spacing is the same throughout the shell-side allows simplification for conceptual design. In order to eliminate N_B and R_S from the above expressions, an assumption that:

$$N_B - 1 + R_S \approx N_B + 1 \approx \frac{L}{B}$$ Equation 3.27

The tube length is given by:

$$L = \frac{A}{N_T \pi D_o}$$ Equation 3.28

The number of tubes (N_T) can be approximated using Equation 3.29. The pitch configuration factor (p_C) used for square pitch and triangular pitches are 1 and $\sqrt{3}/2$ respectively.

$$N_T = \frac{\pi \frac{D_S^2}{4}}{F_{TC} F_{SC} p_C p_T^2}$$ Equation 3.29

The tube count constant (F_{TC}) given in Table 3.1 accounts for the incomplete coverage of the shell diameter by the tubes, due to necessary clearances between the shell and the tube bundle and tube omissions due to the location of pass partition plates for multiple pass designs.

Table 3.1: F_{TC} for various passes (for D_S > 337mm)

Tube Passes	F_{TC}
$N_P = 1$	1.08
$N_P = 2$	1.11
$N_P = 4, 6$	1.45 for $D_S \leq$ 635mm; 1.18 for D_S > 635mm

The correction factor for the shell construction (F_{SC}) is given in Table 3.2.

Table 3.2: F_{SC} for various tube bundle geometries (for D_S > 337mm)

Head Type	F_{SC}
Fixed Head	1.0
Floating Head	1.15
U-Tube	1.05; 1.09 for 25mm outside diameter tubes on 1.25D_o

Rearranging Equation 3.9 gives the baffle spacing B:

$$B = \frac{A_{CF}}{[D_S - D_B] + \frac{(D_B - D_o)(p_T - D_o)}{p_{CF} p_T}} \qquad \text{Equation 3.30}$$

Combining Equation 3.10 and Equation 3.30 gives:

$$B = \frac{m_S}{\rho_S v_S [D_S - D_B] + \frac{(D_B - D_o)(p_T - D_o)}{p_{CF} p_T}} \qquad \text{Equation 3.31}$$

Thus,

$$(N_B - 1 + R_S) D_S \approx \frac{L}{B} D_S$$

$$= \frac{A}{N_T \pi D_o} \times \frac{\rho_S v_S}{m_S} \left[[D_S - D_B] + \frac{(D_B - D_o)(p_T - D_o)}{p_{CF} p_T} \right] \times D_S$$

$$= \frac{A}{\frac{\pi \frac{D_S^2}{4}}{F_{TC} F_{SC} p_C p_T^2} \pi D_o} \times \frac{\rho_S v_S}{m_S} \left[[D_S - D_B] + \frac{(D_B - D_o)(p_T - D_o)}{p_{CF} p_T} \right] \times D_S \qquad \text{Equation 3.32}$$

$$= \frac{F_{TC} F_{SC} p_C p_T^2 A \rho_S v_S}{\pi D_S \pi D_o m_S} \left[[D_S - D_B] + \frac{(D_B - D_o)(p_T - D_o)}{p_{CF} p_T} \right]$$

Substituting Equation 3.32 into Equation 3.24:

$$\Delta P_{SS} = K_{PS1} A v_S^{2.875} + K_{PS2} A v_S^{2.843} \qquad \text{Equation 3.33}$$

Where:

$$K_{PS1} = \frac{72}{\pi^2}\left(5\frac{B}{D_S} - 1\right) \times \frac{aF_{TC}F_{SC}p_C p_T^2 \rho_S^{1.875} \mu_S^{0.125}}{\pi^2 D_S D_o m_S d_e^{1.125}} \times$$

$$\left[[D_S - D_B] + \frac{(D_B - D_o)(p_T - D_o)}{p_{CF} p_T}\right]\left(\frac{B_C}{0.2}\right)^{m_{fo}}$$

Equation 3.34

$$K_{PS2} = \frac{360}{\pi^2}\left(1 - \frac{B}{D_S}\right) \times \frac{bF_{TC}F_{SC}p_C p_T^2 \rho_S^{1.843} \mu_S^{0.157}}{\pi^2 D_S D_o m_S d_e^{1.157}} \times$$

$$\left[[D_S - D_B] + \frac{(D_B - D_o)(p_T - D_o)}{p_{CF} p_T}\right]\left(\frac{B_C}{0.2}\right)^{m_{fo}}$$

Equation 3.35

The shell-side pressure drop is a strong function of the baffle spacing (B), since the shell-side fluid velocity (v_S) is inversely proportional to B (see Equation 3.31).

2. Pressure loss in the inlet and outlet nozzles ΔP_{NS} per shell is given by (Serth, 2007)

$$\Delta P_{NS} = \Delta P_{NS,inlet} + \Delta P_{NS,outlet} =$$

Equation 3.36

$$C_{NS,inlet}\rho_S v_{NS,inlet}^2 + C_{NS,outlet}\rho_S v_{NS,outlet}^2$$

Where:

$C_{NS, inlet} = 0.375$ for $Re_{NS, inlet} > 2100$; and $C_{NS, inlet} = 0.75$ for $100 \leq Re_{NS, inlet} \leq 2100$

$C_{NS, outlet} = 0.375$ for $Re_{NS, outlet} > 2100$; and $C_{NS,outlet} = 0.75$ for $100 \leq Re_{NS, outlett} \leq 2100$

The Reynolds number and velocity for the inlet and outlet nozzle are given in Equations 3.37 – 3.40. Both equations are a function of the inner diameter of the inlet and outlet nozzle for the shell-side fluid ($D_{NS, inlet}$ and $D_{NS, outlet}$ respectively).

$$Re_{NS, inlet} = \frac{\rho_S v_{NS, inlet} D_{NS, inlet}}{\mu_S}$$

Equation 3.37

$$v_{NS, inlet} = \frac{m_S}{\rho_S\left(\frac{\pi D_{NS, inlet}^2}{4}\right)}$$

Equation 3.38

$$Re_{NS,\ outlet} = \frac{\rho_S v_{NS,\ outlet} D_{NS,\ outlet}}{\mu_S}$$ Equation 3.39

$$v_{NS,\ outlet} = \frac{m_S}{\rho_S \left(\frac{\pi D_{NS,outlet}^2}{4}\right)}$$ Equation 3.40

Thus, the total pressure drop for the shell-side per shell is:

$$\Delta P_S = \Delta P_{SS} + \Delta P_{NS}$$ Equation 3.41

$$= K_{PS1} A v_S^{2.875} + K_{PS2} A v_S^{2.843} + C_{NS,\ inlet} \rho_S v_{NS,\ inlet}^2 + C_{NS,\ outlet} \rho_S v_{NS,\ outlet}^2$$

$$= K_{PS1} A v_S^{2.875} + K_{PS2} A v_S^{2.843} + K_{PS3}$$

Where:

$$K_{PS3} = C_{NS,\ inlet} \rho_S v_{NS,\ inlet}^2 + C_{NS,\ outlet} \rho_S v_{NS,\ outlet}^2$$

$$= \frac{16\ m_S^2}{\rho_S \pi^2} \left(\frac{C_{NS,\ inlet}}{D_{NS,\ inlet}^4} + \frac{C_{NS,\ outlet}}{D_{NS,\ outlet}^4}\right)$$ Equation 3.42

For heat exchangers with multiple shells connected in series, the total pressure drop on the shell-side fluid is estimated by the product of the pressure drop per shell and shell number in series as shown in Equation 3.43.

$$\Delta P_{S,\ N_{SHELLS}} = N_{SHELLS}\ \Delta P_S$$ Equation 3.43

For heat exchangers with multiple parallel shells, the total pressure drop on the shell-side fluid is equal to the pressure drop in a single shell ΔP_S.

3.2.3 Tube-Side Heat Transfer Coefficient

The equation used in calculating the tube-side heat transfer coefficient depends on the flow regime. The understanding of the fluid behaviour in the tube-side is relatively straightforward. Well-known Dittus-Boelter correlation (Equation 3.44) is used for the turbulent region (Bhatti and Shah, 1987).

$$Nu = \begin{cases} 0.024Re^{0.8}Pr^{0.4} & \text{for heating} \\ 0.023Re^{0.8}Pr^{0.4} & \text{for cooling} \end{cases} \quad \text{for } Re \geq 10^4$$ Equation 3.44

The relationship between the tube-side heat transfer coefficient (h_T) and the Nusselt number (Nu) is given in Equation 3.45 where, the inner diameter of the tube (D_i) and the tube-side thermal conductivity (k_T) are known. The dimensionless properties (Re_T: Tube-side Reynolds number and Pr_T: Tube-side Prandtl number) can be determined using Equations 3.46 and 3.47 respectively. To determine the mean fluid velocity inside the tube (v_T) required to calculate the Reynolds number, Equation 3.48 is used. This is dependent on the number of tube passes (N_P); number of tubes (N_T); mass flowrate on the tube-side (m_T); the tube inner diameter and tube-side fluid density (ρ_T). Properties such as the tube-side heat capacity (C_{PT}) and viscosity (μ_T) are known.

$$Nu = \frac{h_T D_i}{k_T}$$ Equation 3.45

$$Re_T = \frac{\rho_T v_T D_i}{\mu_T}$$ Equation 3.46

$$Pr_T = \frac{C_{PT}\mu_T}{k_T}$$ Equation 3.47

$$v_T = \frac{m_T\left(\frac{N_P}{N_T}\right)}{\rho_T\left(\frac{\pi D_i^2}{4}\right)}$$ Equation 3.48

For the transition region, the Hausen correlation (Equation 3.49) is used and the Seider-Tate correlation (Equation 3.50) used for the laminar region (Serth, 2007, Kraus et al., 2011).

$$Nu = 0.116\left(Re^{\frac{2}{3}} - 125\right)Pr^{\frac{1}{3}}\left[1+\left(\frac{D_i}{L}\right)^{\frac{2}{3}}\right] \quad \text{for } 2100 < Re < 10^4$$ Equation 3.49

$$Nu = 1.86\left[Re\ Pr\left(\frac{D_i}{L}\right)\right]^{\frac{1}{3}} \quad \text{for } Re \leq 2100 \text{ and } L \leq 0.05Re.Pr.D_i$$ Equation 3.50

3.2.4 Tube-Side Pressure Drop

There are three major contributing factors to determining the total tube-side pressure drop ΔP_T for a single shell. These are; the pressure drop in the straight tubes (ΔP_{TT}), pressure drop in the tube entrances, exits and reversals (ΔP_{TE}), and pressure drop in nozzles (ΔP_{NT}) (Serth, 2007).

1. Pressure drop in straight tubes ΔP_{TT} (Serth, 2007) given in Equation 3.51 is dependent on the tube-side friction factor (c_{FT}).

$$\Delta P_{TT} = \frac{2N_P c_{FT} L \rho_T v_T^2}{D_i}$$ Equation 3.51

The Fanning friction factor is given by:

$$c_{FT} = F_C Re^{m_f}$$ Equation 3.52

Where:

$F_C = 0.1034$, $m_f = -0.2585$ for $Re \geq 3000$

$F_C = 16$, $m_f = -1$ for $Re \leq 2100$

Substituting Equation 3.52 and 3.46 into Equation 3.51 yields:

$$\Delta P_{TT} = \frac{2N_P F_C \left(\frac{\rho_T D_i}{\mu_T}\right)^{m_f} L \rho_T v_T^{2+m_f}}{D_i}$$ Equation 3.53

2. Pressure drop in the tube entrances, exits and reversals ΔP_{TE} (Serth, 2007)

$$\Delta P_{TE} = 0.5 \alpha_R \rho_T v_T^2$$ Equation 3.54

Where:

$\alpha_R = 2N_P - 1.5$ for $Re > 2100$

$\alpha_R = 3.25N_P - 1.5$ for $500 \leq Re \leq 2100$

3. Pressure loss in the inlet and outlet nozzles ΔP_{NT} per shell (Serth, 2007)

$$\Delta P_{NT} = \Delta P_{NT,inlet} + \Delta P_{NT,outlet}$$ Equation 3.55

$$= C_{NT,inlet}\rho_T v_{NT,inlet}^2 + C_{NT,outlet}\rho_T v_{NT,outlet}^2$$

Where:

$C_{NT,\ inlet} = 0.375$ for $Re_{NT,\ inlet} > 2100$; and $C_{NT,\ inlet} = 0.75$ for $100 \leq Re_{NT,\ inlet} \leq 2100$

$C_{NT,\ outlet} = 0.375$ for $Re_{NT,\ outlet} > 2100$; and $C_{NT,outlet} = 0.75$ for $100 \leq Re_{NT,\ outlett} \leq 2100$

The Reynolds number and velocity for the inlet and outlet nozzle are given in Equations 3.56 – 3.59. Both equations are a function of the inner diameter of the inlet and outlet nozzle for the tube-side fluid ($D_{NT,\ inlet}$ and $D_{NT,\ outlet}$ respectively).

$$Re_{NT,\ inlet} = \frac{\rho_T v_{NT,\ inlet} D_{NT,\ inlet}}{\mu_T}$$ Equation 3.56

$$v_{NT,\ inlet} = \frac{m_T}{\rho_T \left(\frac{\pi D_{NT,\ inlet}^2}{4}\right)}$$ Equation 3.57

$$Re_{NT,\ outlet} = \frac{\rho_T v_{NT,\ outlet} D_{NT,\ outlet}}{\mu_T}$$ Equation 3.58

$$v_{NT,\ outlet} = \frac{m_T}{\rho_T \left(\frac{\pi D_{NT,outlet}^2}{4}\right)}$$ Equation 3.59

Thus, the total pressure drop for the tube side per shell is:

$$\Delta P_T = \Delta P_{TT} + \Delta P_{TE} + \Delta P_{NT}$$ Equation 3.60

For heat exchangers with multiple shells connected in series, the total pressure drop on the tube-side fluid is estimated by the product of the pressure drop per shell and shell number in series:

$$\Delta P_{T,\ N_{SHELLS}} = N_{SHELLS}\ \Delta P_T$$ Equation 3.61

For heat exchangers with multiple parallel shells, the total pressure drop on the tube-side fluid is equal to the pressure drop in a single shell.

3.2.5 Exchanger Design

1. Overall heat transfer coefficient (U):

Equation 3.62 can be used in calculating the overall heat transfer coefficient (U), where k_{tube} is the tube conductivity; h_{SF} and h_{TF} are fouling resistances of the shell and tube side respectively.

$$U = \left(\frac{1}{h_S} + \frac{1}{h_{SF}} + \frac{D_o \ln(D_o/D_i)}{2k_T} + \frac{D_o}{D_i h_{TF}} + \frac{1}{h_T}\right)^{-1}$$ Equation 3.62

2. Heat transfer area (A or A'):

The overall heat transfer area can be determined in two ways. One is based on the geometry of the heat exchanger (A), and the other is based on the overall heat transfer coefficient (A'). They are presented in equations 3.63 and 3.64 respectively.

$$A = N_T \pi D_o L_{eff}$$ Equation 3.63

Where, L_{eff} is the effective tube length.

$$A' = \frac{CP_H(T_{Hi} - T_{Ho})}{U \times F_T \times \Delta T_{LM}} = \frac{CP_C(T_{Co} - T_{Ci})}{U \times F_T \times \Delta T_{LM}}$$ Equation 3.64

3. Log-mean-temperature-difference (LMTD):

The outlet temperatures of the hot and cold side (T_{Ho} and T_{Co} respectively) of the heat exchanger have to be determined before the log mean temperature difference (ΔT_{LM}) can be found. Considering a counter-current heat exchanger, the equations described by (Kotjabasakis and Linnhoff, 1986) can be used in determining the LMTD of the heat exchanger as shown in Equations 3.65 – 3.67.

$$Q_H = CP_H(T_{Hi} - T_{Ho})$$ Equation 3.65

$$Q_C = CP_C(T_{Co} - T_{Ci})$$ Equation 3.66

$$Q_H = Q_C = UA\Delta T_{LM} = UA\frac{(T_{Hi} - T_{Co}) - (T_{Ho} - T_{Ci})}{\ln\left(\frac{T_{Hi} - T_{Co}}{T_{Ho} - T_{Ci}}\right)}$$ Equation 3.67

It is typically assumed that the physical properties of the streams, heat transfer area, exchanger geometry, inlet temperatures (hot side: T_{Hi} and cold side: T_{Ci}), and heat capacity flowrates of both hot and cold side (CP_H and CP_C) are known. With this, the outlet temperatures and heat duties on both the hot and cold side (Q_H and Q_C) can be calculated.

If the heat capacity flowrate of both the hot and cold sides are constant, we can derive an expression as shown in Equation 3.68 that relates the temperatures to the heat capacity flowrates, where R is a constant.

$$R = \frac{CP_C}{CP_H} = \frac{T_{Hi} - T_{Ho}}{T_{Co} - T_{Ci}} \qquad \text{Equation 3.68}$$

Combining Equation 3.66 and 3.67 gives:

$$\frac{T_{Hi} - T_{Co}}{T_{Ho} - T_{Ci}} = \exp\left[\frac{UA}{CP_C} \times \frac{(T_{Hi} - T_{Ho}) - (T_{Co} - T_{Ci})}{T_{Co} - T_{Ci}}\right] \qquad \text{Equation 3.69}$$

Combining Equations 3.68 and 3.69 gives:

$$\frac{T_{Hi} - T_{Co}}{T_{Ho} - T_{Ci}} = \exp\left[\frac{UA(R-1)}{CP_C}\right] \qquad \text{Equation 3.70}$$

Eliminating T_{Co} between Equations 3.68 and 3.70 gives (Kotjabaskis and Linnhoff, 1986):

$$(R-1)T_{Hi} + R(X-1)T_{Ci} + (1-RX)T_{Ho} = 0 \qquad R \neq 1 \qquad \text{Equation 3.71}$$

Where:

$$X = \exp\left[\frac{UA(R-1)}{CP_C}\right] \qquad \text{Equation 3.72}$$

Eliminating T_{Ho} between Equations 3.68 and 3.70 gives (Kotjabaskis and Linnhoff, 1986):

$$R(X-1)T_{Hi} + X(R-1)T_{Ci} + (1-RX)T_{Co} = 0 \qquad R \neq 1 \qquad \text{Equation 3.73}$$

If the inlet temperatures T_{Hi} and T_{Ci} are known, along with U, A, CP_H and CP_C, then Equations 3.71 and 3.73 constitute two equations with two unknowns (the outlet temperatures T_{Ho} and T_{Co}). Rearranging both equations to solve for the unknowns yields:

$$T_{Ho} = \frac{(R-1)T_{Hi} + R(X-1)T_{Ci}}{(RX-1)} \qquad R \neq 1 \qquad \text{Equation 3.74}$$

$$T_{Co} = \frac{R(X-1)T_{Hi} + X(R-1)T_{Ci}}{(RX-1)} \qquad R \neq 1 \qquad \text{Equation 3.75}$$

For the special case where R = 1:

$$Q_C = CP_C(T_{Co} - T_{Ci}) = UA(T_{Ho} - T_{Ci}) \qquad \text{Equation 3.76}$$

$$T_{Hi} - T_{Ho} = T_{Co} - T_{Ci} \qquad \text{Equation 3.77}$$

Eliminating T_{Co} between Equations 3.76 and 3.77 gives:

$$T_{Hi} + YT_{Ci} - (Y+1) = 0 \qquad R = 1 \qquad \text{Equation 3.78}$$

Where:

$$Y = \frac{UA}{CP_C} \qquad \text{Equation 3.79}$$

Rearranging Equation 3.76 and 3.77 and substituting in 3.79 to eliminate T_{Ho} gives:

$$YT_{Hi} + T_{Ci} - (Y+1)T_{Co} = 0 \qquad R = 1 \qquad \text{Equation 3.80}$$

Thus, for the special case of R=1, Equations 3.78 and 3.80 replace Equations 3.71 and 3.73. Therefore, for a single heat exchanger where R=1:

$$T_{Ho} = \frac{T_{Hi} + YT_{Ci}}{(Y+1)} \qquad R = 1 \qquad \text{Equation 3.81}$$

$$T_{Co} = \frac{YT_{Hi} + T_{Ci}}{(Y+1)} \qquad R = 1 \qquad \text{Equation 3.82}$$

4. Correction factor

The equation used in describing a non-counter-current heat exchanger has an added function, the log mean temperature difference correction factor (F_T), as shown in Equation 3.83. This creates a potential problem for rating heat exchangers, as the outlet temperatures of the heat exchanger are unknown. Herkenhoff (1981) proposed a methodology, which involves the manipulation of the equations for F_T to avoid iteration. The basic definition of F_T is given in Equation 3.84.

$$Q_H = Q_C = UA\Delta T_{LM}F_T \qquad \text{Equation 3.83}$$

$$F_T = \frac{\left(\frac{UA}{CP_C}\right)_{CC}}{\left(\frac{UA}{CP_C}\right)} = \frac{\sqrt{R^2+1}\,\ln\left[\frac{1-P_{1\text{-}2}}{1-RP_{1\text{-}2}}\right]}{(R-1)\ln\left[\frac{2-P_{1\text{-}2}\left(R+1-\sqrt{R^2+1}\right)}{2-P_{1\text{-}2}\left(R+1+\sqrt{R^2+1}\right)}\right]} \qquad \text{Equation 3.84}$$

The numerator of Equation 3.84 is the counter-current heat duty and the denominator the actual non-counter-current duty. Rearranging Equations 3.67 for a non-counter-current heat exchanger gives:

$$\left(\frac{UA}{CP_C}\right)_{CC} = \frac{\ln\left[\frac{T_{Hi}-T_{Co}}{T_{Ho}-T_{Ci}}\right]}{\left[\frac{T_{Hi}-T_{Ho}}{T_{Co}-T_{Ci}}\right]-1} = \frac{\ln\left[\frac{1-P}{1-RP}\right]}{R-1} \qquad \text{Equation 3.85}$$

For a series of N_{SHELLS} of 1-2 heat exchangers Equations 3.84, 3.85 can be combined to give:

$$\frac{\ln\left[\frac{1-P}{1-RP}\right]}{(R-1)\left(\frac{UA}{CP_C}\right)} = \frac{\sqrt{R^2+1}\,\ln\left[\frac{1-P_{1\text{-}2}}{1-RP_{1\text{-}2}}\right]}{(R-1)\ln\left[\frac{2-P_{1\text{-}2}\left(R+1-\sqrt{R^2+1}\right)}{2-P_{1\text{-}2}\left(R+1+\sqrt{R^2+1}\right)}\right]} \qquad \text{Equation 3.86}$$

Where:

$$\ln\left[\frac{1-P}{1-RP}\right] = N_{SHELLS}\ln\left[\frac{1-P_{1\text{-}2}}{1-RP_{1\text{-}2}}\right] \qquad \text{Equation 3.87}$$

Combining Equations 3.86 and 3.87 and rearranging gives:

$$P_{1\text{-}2} = \frac{2G - 2}{G\left(R + 1 + \sqrt{R^2+1}\right) - \left(R + 1 - \sqrt{R^2+1}\right)}$$ Equation 3.88

Where:

$$G = \exp\left[\frac{UA\sqrt{R^2+1}}{CP_C N_{SHELLS}}\right]$$ Equation 3.89

$P_{1\text{-}2}$ can be calculated using Equation 3.88; this value can then be substituted back into Equation 3.84 to calculate the value of F_T. For non-counter-current heat exchangers Equation 3.72 and 3.79 becomes:

$$X = \exp\left[\frac{UA(R - 1)F_T}{CP_C}\right]$$ Equation 3.90

$$Y = \frac{UAF_T}{CP_C}$$ Equation 3.91

3.3 Model Validation

The proposed model is compared with three models i.e. Wills-Johnston (Wills and Johnston, 1984), Bell-Delaware (Taborek, 1988) and Modified Simple Delaware (Wang et al., 2012b). The model was also compared with two commercial software; i.e. HEXTRAN® and HTRI®. The example heat exchanger used is that of Example 5 in Wang et al. (2012b) and its stream properties and geometric details are shown in Table 3.3.

Table 3.3: Stream data and geometry of heat exchanger

<table>
<tr><th colspan="2">Fluids</th><th>Shell-side</th><th>Tube-Side</th></tr>
<tr><td colspan="2">Specific Heat C_p (J/kg C)</td><td>2273</td><td>2303</td></tr>
<tr><td colspan="2">Thermal Conductivity k (W/m C)</td><td>0.08</td><td>0.0899</td></tr>
<tr><td colspan="2">Viscosity μ (Pa s)</td><td>1.89E-02</td><td>9.35E-04</td></tr>
<tr><td colspan="2">Density ρ (kg/m^3)</td><td>966</td><td>791</td></tr>
<tr><td colspan="2">Mass Flow rate m (kg/s)</td><td>46.25</td><td>202.54</td></tr>
<tr><td colspan="2">Inlet Temperature T_{in} (℃)</td><td>227</td><td>131</td></tr>
<tr><td colspan="2">Fouling Resistance (m^2 C/W)</td><td>0.00176</td><td>0.00053</td></tr>
<tr><th colspan="4">Heat exchanger geometry</th></tr>
<tr><td>Tube Pitch P_T (m)</td><td>0.03125</td><td>Shell Inner Diameter D_s (m)</td><td>0.965</td></tr>
<tr><td>Number of Tubes N_T</td><td>612</td><td>Number of Baffles N_B</td><td>25</td></tr>
<tr><td>Number of Passes N_P</td><td>2</td><td>Baffle Spacing B (m)</td><td>20%</td></tr>
<tr><td>Tube Length L (m)</td><td>6</td><td>Inlet Baffle Spacing B_{in} (m)</td><td>0.3117</td></tr>
<tr><td>Tube Effective Length L_{eff} (m)</td><td>5.903</td><td>Outlet Baffle Spacing B_{out} (m)</td><td>0.3117</td></tr>
<tr><td>Tube Conductivity k_{tube} (W/m℃)</td><td>51.91</td><td>Inner Diameter of Tube-side Inlet Nozzle $D_{NT,inlet}$ (m)</td><td>0.336</td></tr>
<tr><td>Tube Layout Angle</td><td>90</td><td>Inner Diameter of Tube-side Outlet Nozzle $D_{NT,outlet}$ (m)</td><td>0.336</td></tr>
<tr><td>Bundle Configuration</td><td>Straight Tube Bundle</td><td>Inner Diameter of Shell-side Inlet Nozzle $D_{NS,inlet}$ (m)</td><td>0.154</td></tr>
<tr><td>Tube Inner Diameter D_i (m)</td><td>0.02</td><td>Inner Diameter of Shell-side Outlet Nozzle $D_{NS,outlet}$ (m)</td><td>0.154</td></tr>
<tr><td>Tube Outer Diameter D_o (m)</td><td>0.025</td><td>Shell-Bundle Diametric Clearance L_{SB} (m)</td><td>0.069</td></tr>
</table>

Table 3.4: Modelling Result

Models	T_{Co} (°C)	ΔP_T (kPa)	h_T (W/m^2 C)	T_{Ho} (°C)	ΔP_S (kPa)	h_S (W/m^2 C)	U (W/m^2 C)
Bell-Delaware	≈195	55.6	1574.9	138	47.3	313.6	154.8
Wills-Johnston	≈188	55.6	2030.9	140	26.9	572.5	206.7
Modified Simple Delaware	≈191	55.6	2030.9	139	65.8	433.3	185.2
HTRI®	≈193	59.2	2060.6	139	76.4	371.7	173.3
HEXTRAN®	≈189	56.3	1574.8	140	52.4	570.9	199.1
New Model	≈192	55.6	1575.1	139	64.8	419.1	176.8

From Table 3.4, the tube-side heat transfer coefficient obtained using the new model is similar to HEXTRAN® and the Bell-Delaware models but it is lower than that of the modified simple Delaware and HTRI® because the former two makes use of the Colburn correlation as shown in Equation 3.44. Compared with the Dittus-Boelter correlation, the Colburn correlation uses a smaller factor to calculate the Nusselt number. There is a good agreement between almost all models for the calculation of the tube-side pressure drop. In terms of the shell-side calculations, the developed model falls in between the HEXTRAN® and HTRI® models and also very similar to that obtained by the Modified Simple Delaware model.

In conclusion, it has been demonstrated that this new model can be used for predicting the performance of heat exchangers in design and process engineering practices. As such, the new model is used for predicting the performance of all existing process heat exchangers in the networks examined in this thesis.

Chapter 4 Retrofit with Heat Transfer Enhancement

4.1 Introduction to Publications 1 and 2

This section tackles the first research objective given in Section 1.3 of this thesis. This section is made up of two peer-reviewed publications that have been published in the Applied Energy Journal. Section 4.1 provides a background of both publications. Section 4.4 presents a comparison of the non-linear optimisation model used in both publications and a Mixed-Integer Linear Programming (MILP) model used for heat exchanger network (HEN) retrofit with heat transfer enhancement (Pan et al. 2012).

The drive for exploring heat transfer enhancement is born from the desire to present low cost retrofit for HENs. This is because with heat transfer enhancement, no topology modifications are required and the heat transfer area of existing heat exchangers can be maintained. This considerably reduces the downtime for the retrofit process. Other benefits of heat transfer enhancement include low capital cost when used for grass root projects, low retrofit cost, and it improves the performance of heat exchangers in terms of operability, mitigation of fouling and improved flow distribution within existing heat exchangers in a network. Therefore, it is vital to present methodologies for successfully applying heat transfer enhancement in HEN retrofit.

4.1.1 Best Exchanger for Enhancement

This section answers the question posed in “Objective 1, Question a” of this thesis. Both publications present a two-step approach for the identification of the best heat exchanger to enhance. The first step is the identification of heat exchangers on a utility path. By definition, a utility path is a connection between two utilities through process heat exchangers. In order to improve energy recovery while maintaining the network topology, only heat exchangers on a utility path should be considered. This allows the duties of enhanced heat exchangers to be increased and consequently a reduction in the respective utilities is obtained while maintaining the energy balance of the network. For simple HENs, utility paths can be identified by inspection. However, in complex networks, a systematic method has to be used. This work proposes the use of the incidence matrix approach for the identification of exchangers on a utility path. The methodology used is presented in Publication 1. This methodology has been automated as part of the software developed in the University of Manchester used for HEN design (SPRINT, 2016). Having identified candidate heat exchangers for enhancement i.e. exchangers on a utility path, the next step is to identify the best heat exchanger and as such the best enhancement sequence in a given HEN. Publication 1 makes use of sensitivity analysis for the identification of the best heat exchanger to enhance. With sensitivity analysis, decision on the best heat exchanger to enhance is related to a key utility exchanger. For small-scale heat exchanger networks, this procedure is robust for the identification of the enhancement sequence. In large-scale HENs with multiple utilities, the use of sensitivity analysis has the potential of being a tedious task. This is because, with sensitivity analysis, only heat exchangers on a direct utility path with the most expensive utility are considered first. Then the next expensive utility exchanger is considered, and so on. To tackle the computational difficulty posed by sensitivity analysis in large-scale networks, a novel method, the area ratio approach is presented in Publication 2. The area ratio approach is based on existing heat exchanger geometry and their ability to accommodate for additional heat transfer area. The benefit of the area ratio approach over sensitivity analysis is highlighted in Publication 2.

Considering a shell and tube heat exchanger, the best location to apply heat transfer enhancement is on the side with higher resistance. This represents the side with lower heat transfer coefficient. Maximising energy recovery in heat exchanger networks (HENs) can bring down the total energy consumption. In crude unit HENs, the side with high resistance is usually the tube side. As such, this work focuses on tube-side enhancement techniques. Tube inserts were chosen as the enhancement device for both publications due to their ease of implementation that can be done during exchanger cleaning. Wire coil inserts and twisted tape inserts are explored in both publications. Correlations used in modelling both types of tube inserts are provided in the second publication. This allows for the actual augmentation level of enhanced heat exchangers to be determined based on exchanger geometry.

4.1.2 Downstream Effects

This section tackles the question posed in "Objective 1, Question b". The change in one unit in an existing HEN has effects of other units due to the close interaction within a HEN. Target temperature and heat transfer area violations are considered in both publications. To resolve the downstream effects on the HEN, a non-linear optimisation model is proposed in this work. The model used is presented in both publications. The model involves a systematic trade-off between energy recovery and the need for additional heat transfer area.

4.2 Publication 1:

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

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Retrofit of heat exchanger networks without topology modifications and additional heat transfer area

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HIGHLIGHTS

- Cost-effective retrofit based on sensitivity analysis is proposed.
- Energy performance is improved by the use of heat transfer enhancement.
- Network structure is maintained without the need for additional heat transfer area.

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ABSTRACT

Numerous design methods for the retrofit of heat exchanger networks have been proposed over the years, with most depending greatly on topology modification and additional heat transfer area. However, topology modifications and the installation of additional heat transfer area can lead to uneconomic retrofit in many cases, largely as a result of the expense of civil engineering work and pipework modifications. Retrofit of a heat exchanger network can be achieved without the need for topology modifications and additional heat transfer area by the use of heat transfer enhancement. This paper presents a methodology for heat exchanger network retrofit around a fixed network and without the need for additional heat transfer area and topology modifications. Heat transfer enhancement techniques are used to improve the energy performance of an existing heat exchanger network. A dominance ratio is explored to identify the best location to apply enhancement. Sensitivity analysis is used in finding the sequence of the most effective heat exchangers to enhance in order to improve the performance of the network. Sensitivity analysis introduced to study network flexibility is adapted to study heat transfer enhancement. Heat exchanger networks are complex systems with interactions between various components. A change in one component can have an effect on other downstream heat exchangers. Therefore, the proposed methodology presents a way of eliminating the need for additional heat transfer area after enhancement, while ensuring the stream target temperatures are met. This is based on a key optimisation strategy which depends on a trade-off between utility consumption and the need for additional heat transfer area.
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1. Introduction

Heat exchanger network (HEN) retrofit is an important way of improving the energy efficiency or accommodating an increase in throughput of an existing plant in the process industries. Generally, the fewer modifications employed in retrofit, the more attractive the retrofit is likely to be. This is because a small number of modifications will tend to lead to a lower capital cost. Conventional methods used in retrofit are, the use of additional heat transfer area and topology modifications (resequencing, repiping and stream splitting). In practice, HEN retrofit through the use of the aforementioned methods may be difficult to implement as a result of layout, safety and downtime constraints. These conventional retrofit methods will also incur an increased capital cost due to the considerable civil engineering and pipework required and potential production losses during modification. Owing to the aforementioned drawbacks in HEN retrofit, there have been increased interests into the use of heat transfer enhancement techniques for the retrofit of HENs. The use of heat transfer enhancement can be a very attractive option in HEN retrofit because the implementation of enhancement devices is a relatively simple task therefore, can be applied during normal maintenance period ensuring production losses are at a minimum. It is also generally cheaper to implement heat transfer enhancement than additional heat transfer area and, the civil engineering

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Nomenclature

P	column vector (–)
D_I	tube inner diameter (m)
L	length (m)
h_t	tube-side heat transfer coefficient (kW m^{-2} C^{-1})
C_P	heat capacity (J kg^{-1} C^{-1})
m	mass flow rate (kg s^{-1})
k	fluid thermal conductivity (W m^{-1} C^{-1})
N_P	number of tube passes (–)
N_T	number of tubes (–)
$d_{TN,inlet}$	inner diameter of the inlet nozzle for the tube-side fluid (m)
$d_{TN,outlet}$	inner diameter of the outlet nozzle for the tube-side fluid (m)
N_S	number of shells (–)
h_s	shell-side heat transfer coefficient (kW m^{-2} C^{-1})
D_o	tube outer diameter (m)
B_C	baffle cut (–)
B	baffle spacing (m)
D_S	shell inside diameter (m)
D_B	outside diameter of the tube bundle (m)
p_T	tube pitch (m)
n_b	number of baffles (–)
B_{in}	inlet baffle spacing (m)
B_{out}	outlet baffle spacing (m)
A	heat transfer area (m^2)
A_E	heat transfer area after enhancement (m^2)
$D_{TN,inlet}$	inner diameter of the inlet nozzle for the shell-side fluid (m)
$D_{TN,outlet}$	inner diameter of the outlet nozzle for the shell-side fluid (m)
L_{eff}	effective tube length (m)
Q	heat duty (kW)
Q_E	heat duty after enhancement (kW)
CP_H	heat capacity flowrate for the hot stream (kW C^{-1})
CP_C	heat capacity flowrate for the cold stream (kW C^{-1})
T_{in}	inlet temperature (°C)
T_{out}	outlet temperature (°C)
T_T	stream target temperature (°C)
$T_{T,E}$	stream target temperature after enhancement (°C)
U	overall heat transfer coefficient (kW m^{-2} °C^{-1})
U_E	enhanced overall heat transfer coefficient (kW m^{-2} °C^{-1})
F_T	correction factor (–)
ΔT_{LM}	log mean temperature difference (°C)
N_S	number of streams (–)
N_E	number of heat exchanger (–)
ΔT_{min}	minimum temperature approach (°C)
CP_{min}	minimum heat capacity flowrate (kW C^{-1})
ΔQ_{max}	maximum heat duty (kW)
TC_B	total cost for base case ($)
TC_E	total cost after enhancement ($)
$TC_{,HU,B}$	total hot utility cost for base case ($)
$TC_{,HU,E}$	total hot utility cost after enhancement ($)
$TC_{,CU,B}$	total cold utility cost for base case ($)
$TC_{,HU,E}$	total hot utility cost after enhancement ($)
$TC_{,R}$	total cost of retrofit ($)
$TC_{,E}$	total cost of enhancement ($)
$TC_{,A}$	total cost of additional area ($)
$TC_{,BP}$	total cost of bypass ($)
$RP_{,i}$	initial retrofit profit ($)
$RP_{,f}$	final retrofit profit ($)

Greek letters

μ	viscosity (Pa s)
ρ	fluid density (kg m^{-3})

and pipework are also reduced when compared with applying topology modifications in retrofit.

The methods widely used in the retrofit of HEN are either based on pinch analysis, mathematical programming methods, or a combination of these two methods. Tjoe and Linnhoff [1] first proposed the pinch retrofit method. The proposed concept is used to set targets for additional heat transfer area and utility consumption. The drawback associated with this method is, the area target obtained does not reflect the area distribution within the HEN. The limitations posed by the pinch retrofit method were overcome by the technique proposed by Shokoya and Kotjabasakis [2]. This technique incorporates the area distribution of the existing HEN into the targeting mechanism. This method provides a more realistic area target and retrofit design than that proposed by Tjoe and Linnhoff [1]. Although the pinch analysis promotes good user interaction and provides physical insights into the HEN retrofit problem, choosing the best retrofit design is left to the user and is based on their experience. In addition, the design process is time consuming due to the heuristic nature of the design.

With mathematical programming, HEN retrofit is converted into an optimisation task, by formulating the retrofit problem as a mathematical model. The two important aspects in mathematical programming methods are: finding an efficient way of representing the problem and providing an efficient optimisation technique for solving the problems. The objective when performing optimisation is to identify the most cost effective design from many possible solutions embedded in a superstructure. Yee and Grossmann [3] were the first to report retrofit of HENs that was based on a mathematical method. They developed a mixed integer linear programming (MILP) assignment–transhipment model for predicting the smallest number of structural modifications in an existing network. This was based on the transhipment model proposed by Papoulias and Grossmann [4]. The objective of the model was to maximise the utilisation of existing heat exchanger units, minimise the number of new heat exchangers required and the reassignment of existing heat exchanger units to different matches. This led to a final network structure that was as close as possible to the existing one. Ciric and Floudas [5] proposed a two-stage procedure for retrofitting HEN. The first stage, a match selection stage, involved the formulation of a MILP model. This model is used in the identification of ideal structural modifications. The pairings of all possible matches and heat exchangers are evaluated and decisions regarding selecting matches, reassigning heat exchangers, adding new heat exchangers and repiping streams are made. In the second stage, the optimisation stage, a superstructure is generated containing all possible network configurations based on the result obtained from the first stage. This is then formulated and solved as a non-linear programming (NLP) problem. They then went on to present a single stage mixed-integer non-linear programming (MINLP) model [6] that simultaneously optimised the HEN retrofit. Yee and Grossmann [7] proposed an improved two-stage model for retrofitting HENs: a pre-screening stage and an optimisation stage. The purpose of the pre-screening stage is to determine the optimal heat recovery level and the economic feasibility of the retrofit design. The optimisation stage takes into consideration only the number of new units required to achieve the optimum investment. It consists of the construction of a retrofit superstructure that includes all the possible retrofit designs embedded within it. To determine the best retrofit design, a MILP model is formulated and solved. As clearly outlined above, it can be noted that most work using mathematical modelling relies greatly on a screening and optimisation step. Even though the mathematical programming method allows for the HEN retrofit procedure to be automated, its weakness lies in the fact that it lacks user interaction, it is very sensitive to the initial guess and it requires expensive computational time.

To overcome the problems posed by the pinch analysis method and the mathematical programming method, the benefits of the aforementioned methods are combined. This gave rise to the birth of stochastic algorithms, such as simulated annealing algorithms [8] and genetic algorithms [9,10] to solve the HEN retrofit MINLP problems. Asante and Zhu [11] developed a new method for HEN retrofit and introduced the concept of the network pinch that identifies the bottleneck of the existing network that limits energy recovery and the most effective change. The retrofit MINLP problem was then decomposed into a MILP problem and a NLP problem. Modifications to this methodology were made to account for temperature-dependent thermal properties of streams, combined structural modifications and cost optimisation in a single step to avoid missing cost-effective solutions [12].

The desire to retrofit HENs without the need of additional heat transfer area and topology modification has led to a rise in the investigation into using heat transfer enhancement for retrofit. Heat transfer enhancement can be used to avoid the implementation of additional heat transfer area, which can lead to significant cost savings. The cost savings are due to the fact that with heat transfer enhancement there is no need for piping or civil works. Heat transfer enhancement is also beneficial as it can be implemented during normal maintenance periods, thereby, avoiding production losses during retrofit. However, the application of existing methods for HEN retrofit is limited when it comes to its application with heat transfer enhancement. Polley et al. [13] first proposed the idea of combining both heat transfer enhancement and HEN retrofit. Up until that point, both aspects have only been researched separately. The research conducted by Polley et al. [13] analysed the potential benefit of using heat transfer enhancement in retrofit, and the effect of pressure drop and fouling. The research also contained comparison between different enhancement devices. However, only a targeting methodology was proposed. This methodology was based on area efficiency in which area efficiency is the ratio between the target area and existing area installed for the level of heat recovery reached in the existing HEN. Finally, their study didn't present a systematic way for applying heat transfer enhancement in retrofit. Nie and Zhu [14] proposed a methodology considering heat transfer enhancement and pressure drop. In this work, heat transfer enhancement was only used in reducing retrofit investment, therefore, was not included in the methodology. The main focus of their work was placed on pressure drop. The methodology proposed is not robust enough, and hence, will be difficult to implement on large-scale problems. Zhu et al. [15] proposed a two-stage approach methodology based on the network pinch with heat transfer enhancement. The first stage, the targeting stage, makes use of the network pinch approach for the determination of the best heat exchanger candidates to be enhanced and also the augmentation level of enhancement. The second stage, the selection stage, involves selecting the most suitable heat transfer enhancement technique for each of the suitable candidates identified in the targeting stage using a pressure drop criterion. The drawback of this methodology is that enhancement is only considered when additional heat transfer area requirements are determined using the network pinch analysis. An MILP optimisation methodology was proposed to address the systematic implementation of heat transfer enhancement in retrofit without topology modifications [16]. This work considered the exact value of the log mean temperature difference and correlation factor F_T and multiple tube passes are also considered in the optimisation process. This allows for the optimisation of heat transfer enhancement and presents a simple implementation nature of heat transfer enhancement. However, this study is limited to small-scale design problems. Pan et al. [17] proposed an MILP based iterative method for the retrofit of HENs with heat transfer enhancement. This method was able to overcome drawbacks of existing design methods. However, the level of enhancement proposed cannot be guaranteed based on the geometry of existing heat exchangers in the network. Moreover, the applicability of the mathematical programming solution is quite challenging in industrial processes. Wang et al. [18] proposed a set a heuristic rules to retrofit HENs that overcomes the drawbacks posed by mathematical programming in terms of industrial application. Their work was able to provide the amount of energy saving and position of the required heat transfer enhancement. However, the work was based on the assumption of pure counter current heat exchangers, which is unrealistic in terms of industrial practice. The research also was unable to guarantee the feasibility of the required heat transfer enhancement. To overcome the drawback of this work, Jiang et al. [19] presented a methodology for retrofit without topology modifications that made use of the detailed design of heat exchangers in the network without assuming pure counter current heat exchangers. However, this method did not account for the effect of applying heat transfer enhancement on other heat exchangers in the network such as the need for additional heat transfer area in downstream heat exchangers after enhancement due to the decrease in driving force. This limits the level of energy saving that can be attained and also increases the capital cost associated with the use enhancement. Therefore, this work presents a retrofit methodology that makes use of heat transfer enhancement without the need for topology modifications and additional heat transfer area based on the detailed design of heat exchangers in the network. This is an extension to the methodology presented by Jiang et al. [19] by, (1) identifying the best location to apply enhancement; (2) presenting a methodology that can be used to automatically identify candidate heat exchangers for enhancement i.e. heat exchangers on a utility path and; (3) tackling the issue of downstream effects after enhancement with the aid of a cost based optimisation strategy. This allows for more exchangers to be enhanced and hence, provides a greater energy saving in retrofit at a low retrofit investment. The proposed methodology capitalises on the benefit of user interaction and a cost based optimisation model to guarantee an optimal retrofitted HEN that meets the retrofit objective. The validity and robustness of the proposed method will be tested with a case study.

2. Identification of utility paths

A utility path is a connection between two utilities through process streams and heat exchangers. This work aims to develop a cost effective methodology for retrofit of HENs without topology modifications and additional heat transfer area. To achieve the retrofit objective, exchangers to be modified must be on a utility path to allow for heat loads to be shifted. This is based by the concept proposed by Linnhoff and Hindmarsh [20]. HENs are complex system with interactions between various components. A change in one component, affects the performance of other components and the heat balance in the HEN. Utility paths can be used in tackling the effects of the change in exchanger performance and stream balance in HEN after enhancement.

Patel [21] proposed a method based on the incidence matrix approach for the identification of utility paths in HENs. The methodology is based on that proposed by Pethe et al. [22] for the identification of loops in HENs. The difference between both methods is the addition of a column vector to the incidence matrix to signify the pseudo link between two utilities. Outlined below is the methodology used in the identification of utility paths based on the incidence matrix approach.

1. Let N_S and N_E represent the number of streams and heat exchangers in the network respectively. The incidence matrix is a $N_S \times N_E$ matrix. The rows in the incidence matrix represent the process and utility streams. The columns represent the process and utility heat exchangers.
2. If a heat exchanger removes heat from a stream and supplies heat to another, a value of +1 is added column-wise in the row from which heat is removed and a value of −1 is added column-wise in the row to which heat is added.
3. The column vector added to the incidence matrix has all zero entries with the exception of entries of +1 and −1 for the hot and cold utility respectively.

A vital point to note when constructing the incidence matrix is that all hot utilities are assumed to have one stream and same for cold utilities. The example from Li and Chang [23] is used to demonstrate the incidence matrix approach for the identification of utility paths. From Fig. 1, both cold utilities C1 and C2 are assumed to be on the same stream and the hot utility H has its own stream. Therefore, the HEN has 7 streams and 7 heat exchangers. Applying the aforementioned procedure, the incidence matrix generated is given in Table 1. The utility path is dependent on the column vector P in the incidence matrix. This is represented as a linear combination of independent columns in the incidence matrix. If the column sums in the incidence matrix adds up to a row of zero, the matrix is said to be linearly dependent. This is because at least one of these rows can be represented as a linear combination of other rows. Based on the initial incidence matrix shown in Table 1, it can be noted that the column sum produces a row of zero therefore, the initial incidence matrix is said to be linearly dependent.

Converting the matrix from linear dependency to independency involves the following steps:

1. Scan through each row in the incidence matrix and find the first non-zero entry.
2. Ensure all other entries below this entry are zero. This can be achieved by making row operations.
3. Repeat for all rows in the incidence matrix.

The row operations performed based on data from Table 1 are outlined below. Table 2 shows the linearly independent incidence matrix obtained after row operations. From this table, it can be noted that the column sums no longer adds up to a row of zeros.

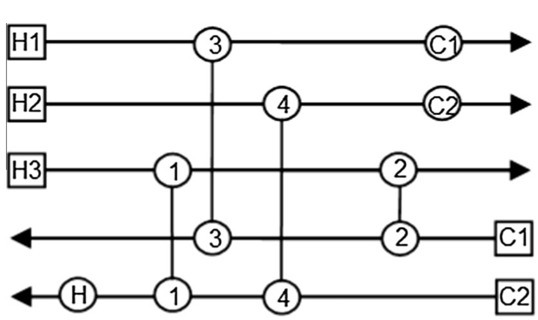

Fig. 1. An example HEN.

Table 1
Initial incidence matrix.

S/E	1	2	3	4	C1	C2	H	P
H1	0	0	+1	0	+1	0	0	0
H2	0	0	0	+1	0	+1	0	0
H3	+1	+1	0	0	0	0	0	0
C1	0	−1	−1	0	0	0	0	0
C2	−1	0	0	−1	0	0	−1	0
HU	0	0	0	0	0	0	+1	+1
CU	0	0	0	0	−1	−1	0	−1
Total	0	0	0	0	0	0	0	0

Table 2
Independent incidence matrix.

S/E	1	2	3	4	C1	C2	H	P
H1	0	0	+1	0	+1	0	0	0
H2	0	0	0	+1	0	+1	0	0
H3	+1	+1	0	0	0	0	0	0
C1	0	−1	0	0	+1	0	0	0
C2	0	0	0	0	+1	+1	−1	0
HU	0	0	0	0	0	0	+1	+1
CU	0	0	0	0	0	0	0	0
Total	+1	0	+1	+1	+3	+2	0	+1

- First row: Row H1 + Row C1
- Second row: Row H2 + Row C2
- Third row: Row H3 + Row C2
- Fourth row: Row C1 + Row C2
- Fifth row: Row C2 + Row CU
- Sixth row: Row HU + Row CU

The column vector P represents the utility path, which is a link between two utilities through process heat exchangers. Therefore, after finding a linearly independent matrix, the column vector P is then equated to a linear combination of columns in the incidence matrix, as shown in Table 3.

The linear combination follows the law of path analysis, which states that if a certain amount of heat load is added to a heater, that same amount must be subtracted from a process heat exchanger, added to the next process heat exchanger and so on, until it is finally added to a cooler. Graphical representations of the utility paths obtained are shown in Fig. 2.

The use of the incidence matrix approach for the identification of utility paths has advantages that include computational efficiency, ease of implementation, rigor even for large scale problems and the potential to be automated as part of a retrofit methodology for HENs.

3. Determination of enhancement location

Considering a shell and tube heat exchanger, a decision has to be made on the location to apply heat transfer enhancement (shell side, tube side or both). The overall heat transfer coefficient U of candidate heat exchangers is dependent on the tube side and shell side heat transfer coefficients (h_t and h_s respectively). The shell

Table 3
Path identification by incidence matrix approach.

Other columns (as linear combination of other columns)	Utility paths
Column P = Column H − Column 4 + Column C2	H–4–C2
Column P = Column H − Column 1 + Column 2 − Column 3 + Column C1	H–1–2–3–C1

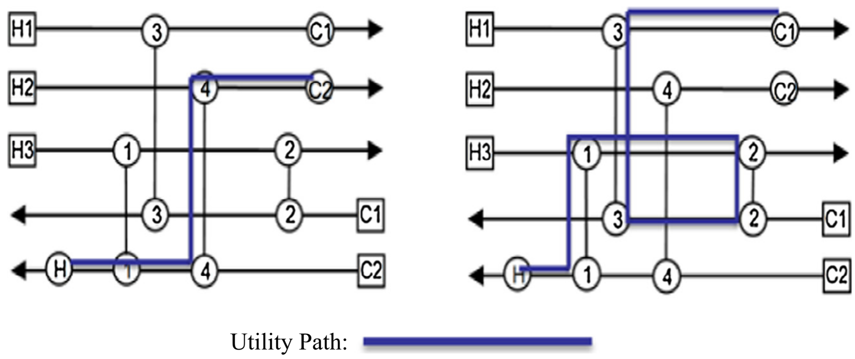

Fig. 2. Utility paths.

side and tube side heat transfer coefficients are determined using established design equations for shell and tube heat exchangers, which are fundamentally based on their geometries [24]. The value of U tends towards the value of the smaller heat transfer coefficient. The dominance ratio in shell and tube heat exchangers can be defined as the ratio between the shell side to tube side heat transfer coefficient, h_s/h_t. When $h_s/h_t < 1$ the shell side has a greater heat transfer resistance. In this case, enhancement should be applied to the shell side to harness the benefits of enhancement. On the other hand, when $h_s/h_t > 1$ enhancement should be applied to the tube side. Finally, if the dominance ratio is close to unity, enhancing both sides should be considered. It is important to point out that greater benefits of using enhancement will be attained the more the value of the dominance ratio deviates from unity. Fig. 3 represents the relationship between dominance ratio and determination of the best location to apply enhancement.

4. Sensitivity analysis

Sensitivity analysis was first proposed by Kotjabasakis and Linnhoff [25] for the purpose of enhancing the flexibility of HENs. It can identify the passive response in a HEN when design changes are made. Sensitivity analysis is based on the well-known heat transfer equation (shown in Eq. (1)). In order to perform sensitivity analysis, the only information needed is the base case stream data and the HEN structure.

$$Q = UA\Delta T_{LM}F_T \quad (1)$$

Sensitivity analysis is conducted by varying UAF_T of each candidate heat exchanger against the inlet temperature of the chosen utility heat exchanger that can bring about energy savings at reduced cost. Sensitivity analysis provides a simple approach to identify the best heat exchanger to apply enhancement in retrofit. Wang [26] highlighted some physical insights into the heat exchangers that exhibit high sensitivity. It was stated that for a heat exchanger to exhibit high sensitivity, the location of the heat exchanger is important. This is because, when a design change is made on a particular heat exchanger, there will be an effect on all other heat exchangers located downstream from the changed heat exchanger. Therefore, the closer the exchanger is to the key utility exchanger, the greater its impact in terms of energy saving. Another reason for high sensitivity is based on the maximum saving potential of candidate heat exchangers. The equation for the maximum energy recovery after enhancement (ΔQ_{max}) is depicted in Eq. (2). From the equation, it can be noted that ΔQ_{max} is directly proportional to both the minimum temperature difference (ΔT_{min}) and the minimum stream heat capacity flow rate of candidate exchanger (CP_{min}). Therefore, if ΔT_{min} and CP_{min} of a candidate heat exchanger are high, the heat exchanger will exhibit high sensitivity. The research also highlighted the importance of ΔT_{min} in respect to effectiveness of the application of heat transfer enhancement. It was pointed out that if ΔT_{min} of a heat exchanger is close to zero, the heat transfer area of that heat exchanger tends to be infinite. Alternatively, if ΔT_{min} is close to zero for a given heat transfer area, the heat transfer coefficient of that heat exchanger tends to infinity. Therefore, at very low ΔT_{min}, the application of heat transfer enhancement will not be effective.

$$\Delta Q_{max} = \Delta T_{min}\Delta CP_{min} \quad (2)$$

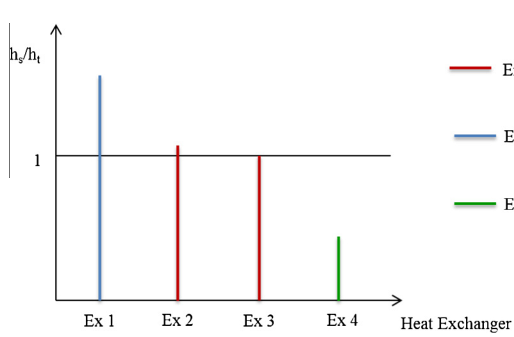

Fig. 3. Dominance ratio to determine enhancement location.

5. Optimisation

HENs are complex systems with interactions between various components. A change in one component affects the performance of other components in the HEN. When performing retrofit of HENs with heat transfer enhancement, without the need for topology modifications and additional area, two key violations that can occur after enhancement are target temperature and heat transfer area violations. Target temperature violation arises from the disturbance in the network after enhancement. Given the example HEN shown in Fig. 4, if exchanger 4 is enhanced, an increase and decrease in the target temperature of stream C2 and H2 will be observed respectively at constant duty of all other exchangers in the network. Heat transfer area violation on the other hand is as a result of a decrease in the driving force of heat exchangers located downstream from an enhanced heat exchanger. Similar to the target temperature violation, if exchanger 4 is enhanced, a decrease in the driving force of exchangers located downstream (in this case exchanger 1) will be observed. Therefore, at constant duty of exchanger 1, additional heat transfer area will be required in exchanger 1 as shown in Fig. 5.

An important feature of a utility path is that heat loads can be shifted from one utility to another utility through process heat

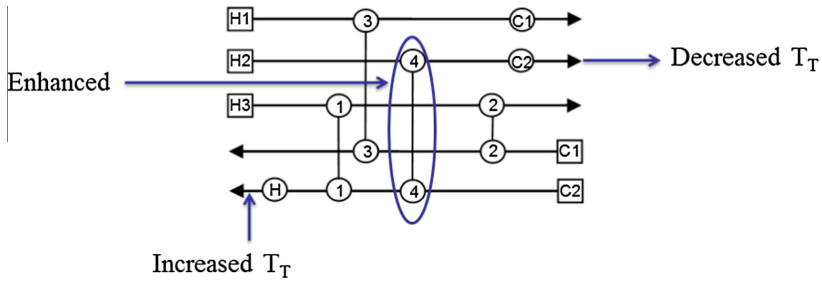

Fig. 4. Target temperature violation.

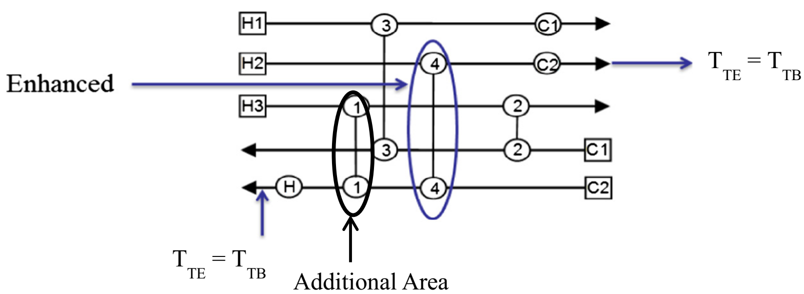

Fig. 5. Heat transfer area violation.

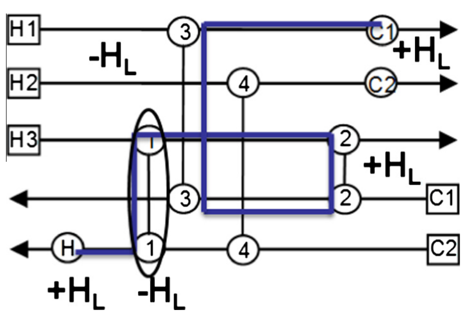

Fig. 6. Utility path analysis.

exchangers, as shown in Fig. 6. With this, the target temperatures of all streams are maintained and only the exchangers' operating conditions (heat load and driving force) are changed. In retrofit, if the heat transfer area of each heat exchanger is fixed when shifting heat loads along a utility path, heat exchangers with a higher duty will require increased heat transfer driving force and heat exchangers with a decreased duty will require a bypass.

Performing optimisation of the heat exchanger network after enhancement is vital to ensure the retrofit objective is met, while producing a feasible retrofitted HEN. The optimisation is based on utility path analysis. The amount of heat load (H_L) that needs to be shifted to correct additional heat transfer area and target temperature violations can be determined using an optimisation model. This model is based on a trade-off between utility savings and capital cost (additional heat transfer area). This trade-off can be seen in Fig. 6, which shows that a certain amount of heat load needs to be added to both utilities and subtracted from the exchanger requiring additional area. This in turn reduces the initial utility savings obtained when exchanger 4 was enhanced.

5.1. Model

Given that this is a retrofit problem, an assumption is made that the stream properties, heat exchanger data and stream matches are known. Detailed design of exchangers can be performed using models presented in [22]. The design and energy balance equations for all heat exchangers and streams are:

$$Q = UA\Delta T_{LM}F_T \quad \forall_{\text{exchangers}} \tag{3}$$

$$Q = CP_H(T_{in} - T_{out}) \quad \forall_{\text{hotstreams}} \tag{4}$$

$$Q = CP_C(T_{out} - T_{in}) \quad \forall_{\text{coldstreams}} \tag{5}$$

First the base case total cost of the utilities is calculated. The initial installation costs of all heat exchangers are not included.

$$TC_B = TC_{,HU,B} + TC_{,CU,B} \tag{6}$$

At constant heat transfer area, the enhanced duty of the enhanced heat exchanger can be calculated using:

$$Q_E = U_E A \Delta T_{LM} F_T \tag{7}$$

As a result of the downstream effect of the enhanced heat exchanger, the new heat transfer area for all process heat exchangers needs to be calculated. At constant duty, the new area after enhancement is given by:

$$A_E = \frac{Q}{U\Delta T_{LM}F_T} \tag{8}$$

The total cost after enhancement, which is given, by the new total cost of both utilities and the cost of retrofit as shown in Eq. (9).

$$TC_E = TC_{,HU,E} + TC_{,CU,E} + TC_{,R} \tag{9}$$

The cost of retrofit is dependent on the cost of applying enhancement, the cost of additional heat transfer area to existing heat exchangers and the cost of applying a bypass, as shown in Eq. (10).

$$TC_{,R} = TC_{,E} + TC_{,A} + TC_{,BP} \tag{10}$$

The goal is to perform retrofit with heat transfer enhancement without the need for topology modifications and additional heat transfer area, while maintaining a balanced network. Therefore, if the heat transfer area of existing heat exchangers after enhancement are greater than that before, and there are target temperature violations, optimisation is performed.

The objective when performing optimisation is to maximise the retrofit profit i.e. the difference between the total cost before enhancement and the total cost after enhancement as shown in Eq. (11). This is subject to maintaining the existing heat transfer area of all heat exchangers and maintaining the target temperatures of all streams by varying the duties of all heat exchangers where there are heat transfer area violations and, the utility heat exchangers on the same utility path.

$$\text{Objective function}: \quad \text{Maximise RP} = TC_B - TC_E \tag{11}$$

6. New retrofit methodology

Considering the robustness of sensitivity analysis for the identification of the best heat exchangers in the network to enhance, and the understanding of the interactions between various components in the network, an approach to cost-effective retrofit can be proposed. Fig. 7 shows the proposed flowchart for the retrofit of heat exchanger networks with heat transfer enhancement without topology modifications and additional heat transfer area. This includes:

Step 1: Given that this is a retrofit problem, we can assume that the heat exchanger and stream data are known. Considering a shell and tube heat exchanger, the first step involves the identification of the best location to apply enhancement (shell-side, tube-side or both sides).
Step 2: This involves the identification of candidate heat exchangers that can improve energy recovery in the existing HEN. The incidence matrix approach is employed as a result of its ability to efficiently identify all utility paths in a HEN.
Step 3: Sensitivity analysis is used to identify the best candidate heat exchangers from those identified in the previous step. This is based on the influence of candidate heat exchangers on the inlet temperature of the chosen utility heat exchanger under investigation.
Step 4: The best heat exchanger identified in step 3 can then be enhanced. After enhancement on the best heat exchanger is performed, the retrofit process could become infeasible as a result of either violations in stream target temperature, minimum temperature approach or additional heat transfer area requirement. Therefore, a feasibility check must be performed.
Step 5: The violations are then corrected by finding the optimal heat load that should be shifted through utility paths subject to maximising retrofit profit. If a situation exists where the minimum temperature approach is still limiting, modifications may be made to another heat exchanger.
Step 6: If the maximum retrofit profit after enhancement is less than the initial retrofit profit, the retrofit procedure should be aborted. If not, continue to step 7.
Step 7: After obtaining a feasible retrofitted HEN, further improvement can be sort by reinitialising the retrofit approach outlined in steps 1–6 based on the newly formulated base case. This procedure is repeated until the stopping criterion is violated.

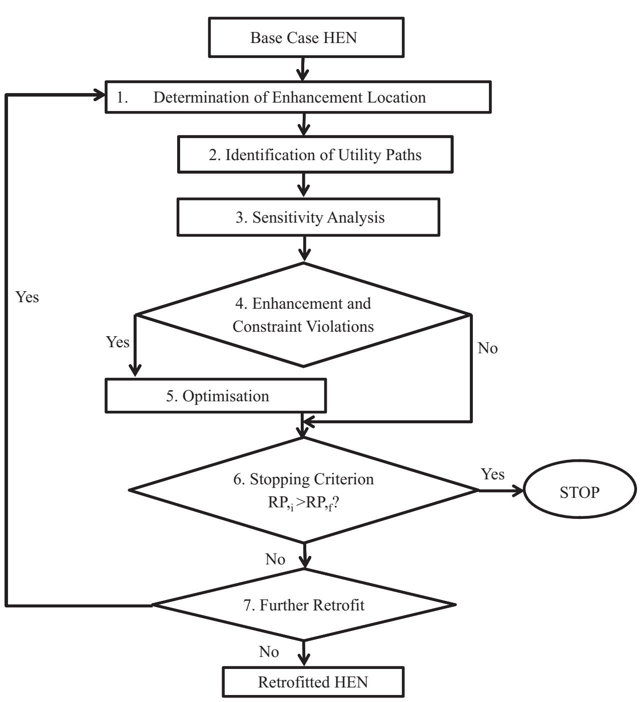

Fig. 7. Proposed HEN retrofit flowchart.

7. Case study

The case study is a simplified preheat train. As shown in Fig. 8, the base case HEN has twelve heat exchangers and six process streams (five hot streams and one cold stream). The details of the base case HEN are shown in Table 4. The hot utility (12) is supplied by a fired heater, while the cold utilities (8, 9, 10 and 11) are cooling water coolers. The retrofit objective is to maximise retrofit

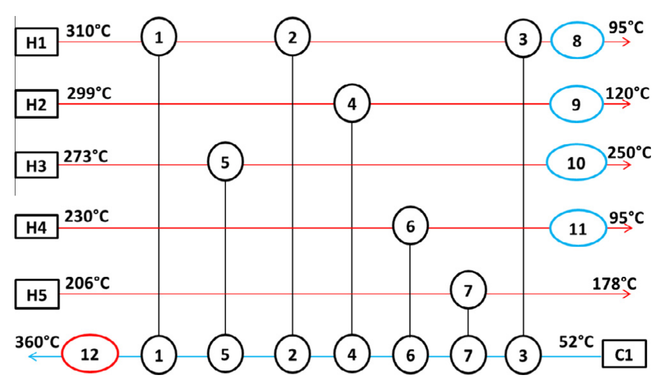

Fig. 8. Base case heat exchanger network.

Table 4
Heat exchanger details.

Exchanger	A (m^2)	h_s (kW/m^2 °C)	h_t (kW/m^2 °C)	U (kW/m^2 °C)	Q (kW)	N_S	F_T
1	396.72	2.07	1.33	0.52	6141.33	2	0.88
2	545.45	2.31	1.40	0.48	6134.83	2	0.82
3	633.85	4.54	0.78	0.16	5556.61	1	0.88
4	354.64	1.27	0.62	0.10	2688.79	1	0.94
5	183.85	2.56	0.78	0.32	3431.16	1	0.98
6	843.73	0.96	0.49	0.06	2291.88	1	0.97
7	114.28	3.38	0.98	0.36	3623.20	1	0.98
8	–	–	–	–	657.23	–	–
9	–	–	–	–	1141.81	–	–
10	–	–	–	–	816.94	–	–
11	–	–	–	–	880.62	–	–
12	–	–	–	–	14455.41	–	–

Table 5
Cost data.

Utility cost data	Retrofit cost data
Hot utility cost: 400 ($/kW y) Cold utility cost: 5.5 ($/kW y)	Cost of inserts: 500 + 10 ∗ A ($) Implementing by-pass: 500 ($) Cost of increasing heat exchanger area: 4000 + 200 ∗ A ($)

profit, without the need for topology modifications and additional heat transfer area in any process heat exchanger in the network.

The proposed retrofit methodology is applied to this case study with the following assumptions:

1. It is assumed that the cold utilities have only one stream and the hot utility has its own stream for the identification of utility path based on the incidence matrix approach.
2. Implementing a bypass can be used to reduce the duty of all heat exchangers.
3. The cost parameters used in this case study are outlined in Table 5.
4. The operating time is assumed to be one year for the purpose of calculating the total profit.

8. Results and discussion

Based on the retrofit methodology, the first step is the determination of enhancement location. It is found that all process heat exchangers are suitable for tube-side enhancement since the thermal resistances are all higher in the tubes, as shown in Table 6.

The next step is the identification of utility paths in the HEN. Tables 7 and 8 show the final incidence matrix and the utility paths in the HEN. From Table 8, it is clear that exchanger 7 is the only heat exchanger not on a utility path and as such, has been eliminated from the next step of the retrofit methodology.

For sensitivity analysis the hot utility is chosen as the key utility due to the fact that the hot utility is more expensive than the cold utility. As such, a greater retrofit profit will be attained if the hot utility consumption is reduced. Sensitivity analysis identifies the most influential heat exchangers that can have an effect on the consumption of the hot utility. The inlet temperature of the hot utility (12) has been used as the objective temperature for sensitivity analysis. A decrease in the inlet temperature directly correlates to a reduction in the usage of hot utility. From Fig. 9, it is clear that exchanger 5 exerts the greatest influence on the inlet temperature of the hot utility exchanger for the required range of UAF_T variation.

Exchanger 5 is then enhanced. Based on the dominance ratio of exchanger 5, tube side enhancement technique is used. Tube inserts are commonly used because inserts are relatively cheap and can be easily installed in existing heat exchangers. Heat transfer enhancement models for twisted tape and coiled wires [24] are used to calculate the enhanced performance of exchanger 5. Tables 9 and 10 show the details of exchanger 5 and its performance for the two enhancement techniques used respectively. From Table 10, twisted tape tube insert with a twist ratio of 2.66 and thickness 2.15 mm showed a better performance than coiled wire tube inserts with a pitch of 42.5 mm and thickness of 2.15 mm.

It is important to point out that the consequence of an increase in heat transfer coefficient is an increase in pressure drop. This might introduce constraints in practical applications. Whether such constraints apply depends on the design of the pumps in the system. If there is a limit in the capacity of the pumps, then this will restrict the number of heat exchangers that can be enhanced. In this work it will be assumed that the pumps have spare capacity to cope with the corresponding increase in pressure drop.

Twisted tape inserts have been chosen as the enhancement technique for this case study as it provides a greater degree of enhancement than coiled wire.

Feasibility check on the network after enhancing exchanger 5 found that exchanger 1 requires additional heat transfer area and the target temperatures of streams 3 and 6 are not met. Therefore, optimisation is conducted. Optimisation was conducted using global solver on LINDO Systems What's Best! [27]. Table 11 shows the results obtained after enhancement and after optimisation. Given an initial utility cost of $5,801,396, the maximum retrofit profit obtained after enhancing exchanger 5 is shown in Table 12.

The breakdown of load shift during optimisation is as follows:

1. Enhancing exchanger 5 correlated to the addition of 810.60 kW to its initial duty. Based on path analysis, to balance the target temperature, this same heat load had to be subtracted from utility exchanger on the same path as exchanger 5 (12 and 10).

Table 6
Determination of dominant side.

Exchanger	Dominance ratio (h_s/h_t)
1	1.56
2	1.65
3	5.82
4	2.04
5	3.28
6	1.96
7	3.45

Table 7
Final incidence matrix.

	1	2	3	4	5	6	7	8	9	10	11	12	P
H1	1	1	1	0	0	0	0	1	0	0	0	0	0
H2	0	0	0	1	0	0	0	0	1	0	0	0	0
H3	0	0	0	0	1	0	0	0	0	1	0	0	0
H4	0	0	0	0	0	1	0	0	0	0	1	0	0
H5	0	0	0	0	0	0	1	0	0	0	0	0	0
C1	0	0	0	0	0	0	0	1	1	1	1	−1	0
HEAT	0	0	0	0	0	0	0	0	0	0	0	1	1
CW	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum	1	1	1	1	1	1	1	2	2	2	2	0	1

Table 8
Utility paths present in the case study HEN.

Other columns (as linear combination of other columns)	Utility paths
Column P = Column 12 − Column 1 + Column 8	12–1–8
Column P = Column 12 − Column 2 + Column 8	12–2–8
Column P = Column 12 − Column 3 + Column 8	12–3–8
Column P = Column 12 − Column 4 + Column 9	12–4–9
Column P = Column 12 − Column 5 + Column 10	12–5–10
Column P = Column 12 − Column 6 + Column 11	12–6–11

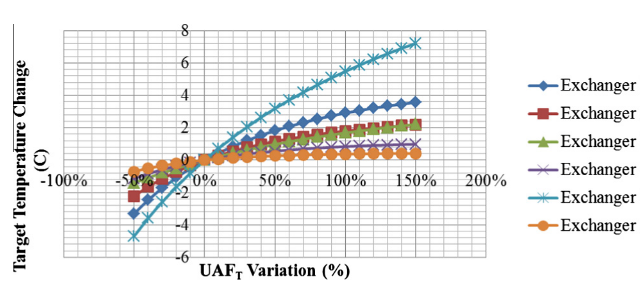

Fig. 9. Sensitivity analysis.

Table 9
Exchanger 5 data.

Streams	Shell-side	Tube-side
Heat capacity flowrate C_p (J/kg K)	2718.5	2325
Thermal conductivity k (W/m K)	0.104	0.0905
Viscosity μ (Pa s)	9.86E−05	1.14E−03
Density ρ (kg/m^3)	776	544.5
Mass flow rate m (kg/s)	67.94	61.90
Inlet temperature T_{in} (°C)	273	193.03
Outlet temperature T_{in} (°C)	254.42	216.87
Fouling resistance (m^2 K/W)	0.0007	0.00028
Heat exchanger geometry		
Tube pitch P_T (m)		0.025
Number of tubes n_t		665
Number of passes n_p		2
Tube length L (m)		4.5
Tube effective length L_{eff} (m)		4.4
Tube conductivity k_{tube} (W/m K)		51.91
Tube layout angle		90
Tube inner diameter D_i (m)		0.016
Tube outer diameter D_o (m)		0.020
Shell inner diameter D_s (m)		0.82
Number of baffles n_b		41
Baffle spacing B (m)		0.488
Inlet baffle spacing B_{in} (m)		0.488
Outlet baffle spacing B_{out} (m)		0.488
Baffle cut B_c		25%
Inner diameter of tube-side inlet nozzle $D_{i,inlet}$ (m)		0.3048
Inner diameter of tube-side outlet nozzle $D_{i,outlet}$ (m)		0.3048
Inner diameter of shell-side inlet nozzle $D_{o,inlet}$ (m)		0.3048
Inner diameter of tube-side outlet nozzle $D_{o,outlet}$ (m)		0.3048
Shell-bundle diametric clearance L_{sb} (m)		0.041

Table 10
Enhancement techniques result for exchanger 5.

Options	h_s (kW/m^2 °C)	h_t (kW/m^2 °C)	U (kW/m^2 °C)	Q (kW)
Twisted tape	2.56	1.67	0.448	4241.75
Coiled wires	2.56	1.66	0.447	4237.45

Table 11
Exchanger details after enhancement and optimisation.

Exchanger	$Q_{after\ enhancement}$ (kW)	ΔA (m^2)	$Q_{after\ optimisation}$ (kW)	ΔA (m^2)
1	6141.33	85.60	5769.86	0
2	6134.83	0	6134.83	0
3	5556.61	0	5556.61	0
4	2688.79	0	2688.79	0
5	4241.75	0	4241.75	0
6	2291.88	0	2291.88	0
7	3623.20	0	3623.20	0
8	657.23	–	1028.70	–
9	1141.81	–	1141.81	–
10	816.94	–	6.35	–
11	880.62	–	880.62	–
12	14455.41	–	14016.28	–

Table 12
Retrofit profit after enhancing exchanger 5.

Retrofit cost	Enhancement	$2338
	Increasing area	$0
	Implementing by-pass	$500
	Total cost	$2838
Retrofit profit	Utilities savings	$178,076
	Net saving (utility savings – total cost)	$175,238 (~3% of initial utility cost)

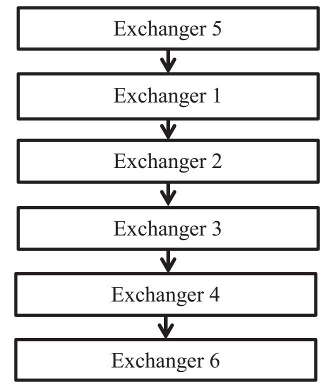

Fig. 10. Enhancement sequence.

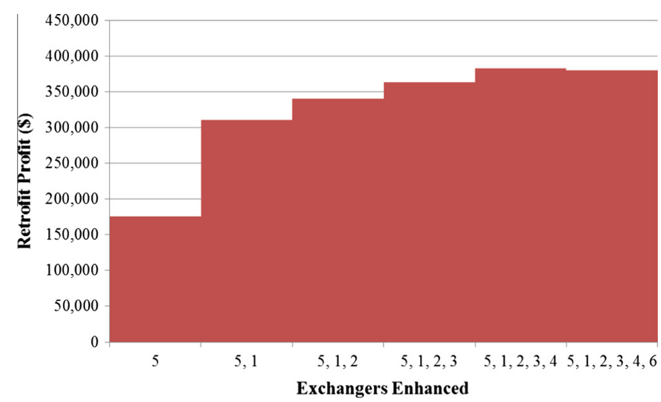

Fig. 11. Retrofit profit.

2. As a result of the decrease in driving force of exchanger 1, additional heat transfer area of 85.60 m^2 was required. To eliminate this additional area, 371.47 kW had to be subtracted from exchanger 1. Given that exchanger 1 is on a utility path with exchanger 12 and 8, this amount of heat load had to be added to the utility exchangers 12 and 8 to balance the network.
3. Therefore, the total heat load subtracted from the hot utility heat exchanger 12, is the difference between the maximum heat load subtracted based on enhancing exchanger 5 and that added to the utility exchanger 12 based on the elimination of additional heat transfer area in exchanger 1. This corresponds to a total of 439.13 kW.

Further retrofit, is carried out by repeating the retrofit methodology with the next most influential heat exchanger. Fig. 10 shows the enhancement sequence based on the case study. The retrofit profit after each enhancement is shown in Fig. 11. Given that the retrofit objective is to maximise retrofit profit, enhancement is stopped after enhancing the fifth most influential heat exchanger (exchanger 4). This is because, after enhancing the sixth exchanger (exchanger 6), there is a decrease in the retrofit profit obtained, which violates the specified stopping criterion. The resulting final cumulative retrofit profit is $382,866, which is approximately 6.6% of the initial total cost.

9. Conclusions

A retrofit methodology based on a combination of heuristic rules and an optimisation strategy is proposed for heat exchanger networks without topology modifications and additional heat transfer area. This method addresses ways of dealing with issues associated with the use of heat transfer enhancement in HEN retrofit. These issues include, identifying enhancement location, identifying the best heat exchanger to enhance and, dealing with downstream effects after enhancement. Dominance ratio is used in identifying the best location to apply enhancement. From the simple case study, all heat exchangers under investigation are suitable for tube-side enhancement as the thermal resistances in the tubes are dominant. Two enhancement techniques are considered in this study i.e. twisted tape inserts and coiled-wire inserts. Twisted tape inserts are used as the enhancement device in this study as they provided a greater increase in heat transfer coefficient than coiled-wire inserts. The identification of the best candidate heat exchanger is broken down into two parts; identifying candidate heat exchangers i.e. exchangers on a utility path and performing sensitivity analysis to efficiently identify the hierarchy in which candidate heat exchanger in the network should be enhanced. In terms of dealing with downstream effects, a cost based optimisation strategy is used. This ensures the feasibility of the retrofit procedure, while meeting set constraints such as heat transfer area and target temperature constraints. The retrofit procedure is repeated until the stopping criterion is violated. The proposed methodology applied to a simple case study resulted in a retrofit profit of approximately 6.6% of the initial cost before retrofit. This can be considered as a comparatively cost effective retrofit due to the fact that topology modifications and additional heat transfer area are not considered. However, sensitivity analysis is solely based on a single temperature, that of the inlet temperature to a hot utility exchanger, which might be a problem in systems with multiple utilities. Also, the analysis has to be repeated after each modification is made as a result of change in temperatures of the network. Therefore, a more comprehensive method of identifying the hierarchy for enhancing candidate heat exchangers that can deal with multiple utilities and independent of temperature change in a HEN should be explored. It has also been assumed that the pumps can completely accommodate for the increase in pressure drop associated with the use of heat transfer enhancement. In practice, pressure drop might constrain the introduction of heat transfer enhancement in some places in the network, depending on pump capacity. This will be the subject of future work.

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Retrofit of heat exchanger networks with heat transfer enhancement based on an area ratio approach

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HIGHLIGHTS

- Cost-effective retrofit based on area ratio approach is proposed.
- Energy performance is improved by the use of heat transfer enhancement.
- Fixed network topology and no need for additional heat transfer area in retrofit.
- Analysis is dependent on heat exchanger geometry.

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ABSTRACT

The goal for performing heat exchanger network (HEN) retrofit is not only to reduce utility consumption but to ensure that the retrofit is economically viable. The problem of using heat transfer enhancement for retrofit lies with the uncertainty of the best location in which to apply enhancement, the augmentation level and dealing with downstream effects after enhancement is conducted.

To solve these problems, a systematic methodology is proposed. The first step in this methodology is the identification of candidate heat exchangers. In the second step, two methods, sensitivity analysis and an area ratio approach are compared for the identification of the best candidate heat exchangers to enhance. Heat transfer enhancement is then performed on the best candidate heat exchanger and, a non-linear optimisation based model is used to deal with the downstream effects after enhancement, subject to meeting set constraints on the HEN, such as the stream target temperatures and heat transfer area. Following this approach, the problems posed by the use of enhancement for retrofit can be addressed in a simple and computationally inexpensive manner.

Heat transfer enhancement is an attractive option for HEN retrofit as it can provide energy saving without the need for topology modifications and additional heat transfer area with an added benefit of reduced implementation time, as modifications can be carried out during normal shutdown periods.

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1. Introduction

The desire to improve the energy efficiency in process industries has resulted in a rise of interest into the retrofit of heat exchanger networks (HENs). This is based on the heat integration strategies proposed to recover and utilise more of the heat available in the processes and reduce dependence on external utilities in satisfying process heating and cooling demands. The success or failure of these heat integration strategies depends on the design of HENs. The retrofit of heat exchanger networks (HENs) is commonly centred on the use of pinch analysis, mathematical programming or a combination of both methods (hybrid methods). The pinch analysis method was first proposed by Tjoe and Linnhoff [1]. This work provided retrofit targets (for additional heat transfer area and utility consumption), network analysis tools, and a modification strategy for energy saving retrofits. The drawback associated with this work was that the area targets obtained did not reflect a complete area distribution within the HEN. Polley and Panjeshahi [2] extended this work to take into account pressure drop constraints. Shokoya and Kotjabasakis [3] proposed a new technique that tackled the limitations of the pinch design method. The technique proposed takes into account the area distribution of the existing HEN into the retrofit target. This method provides a more realistic area target than that proposed by Tjoe and Linnoff [1] due to the consideration of area distribution. Carlsson et al. [4] introduced the cost matrix method for HEN retrofit. They considered the cost of heat transfer area, physical piping distance

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Nomenclature

Q	heat duty, kW
U	overall heat transfer coefficient, kW m^{-2} °C^{-1}
A	heat transfer area, m^2
ΔT_{LM}	log mean temperature difference, °C
F_T	correction factor, –
$A_{existing}$	existing heat transfer area, m^2
$Q_{utility}$	heat duty of utility heat exchangers, kW
h_S	shell-side heat transfer coefficient, kW m^{-2} °C^{-1}
h_{SF}	shell-side fouling resistance, kW m^{-2} °C^{-1}
D_o	tube outer diameter, m
D_i	tube inner diameter, m
k_{tube}	tube thermal conductivity, kW m^{-1} °C^{-1}
h_{TF}	tube-side fouling resistance, kW m^{-2} °C^{-1}
h_T	tube-side heat transfer coefficient, kW m^{-2} °C^{-1}
A_R	area ratio, –
y	twist ratio, –
H	twist pitch, m
u	fluid velocity, m s^{-1}
p	axial roughness pitch, m
e	wire diameter, m
C_P	heat capacity, J kg^{-1} °C^{-1}
k	fluid thermal conductivity, kW m^{-1} °C^{-1}
m	mass flowrate, kg s^{-1}
T_{in}	inlet temperature, °C
T_{out}	outlet temperature, °C
N_P	number of tube passes, –
N_T	number of tubes, –
N_S	number of shells, –
p_T	tube pitch, m
L_{eff}	effective tube length, m
D_S	shell inside diameter, m
B	baffle spacing, m
n_b	number of baffles, –
B_{in}	inlet baffle spacing, m
B_{out}	outlet baffle spacing, m
B_C	baffle cut, %
$D_{TN,inlet}$	inner diameter of the inlet nozzle for the shell-side fluid, m
$D_{TN,outlet}$	inner diameter of the outlet nozzle for the shell-side fluid, m
TT	target temperature, °C
TS	supply temperature, °C
THI	hot inlet temperature, °C
THO	hot outlet temperature, °C
TCI	cold inlet temperature, °C
TCO	cold outlet temperature, °C
THIS	hot inlet temperature of stream, °C
THOS	hot outlet temperature of stream, °C
TCIS	cold inlet temperature of stream, °C
TCOS	cold outlet temperature of stream, °C
RP	retrofit profit, $
RC	retrofit cost, $
UC	utility cost, $
EC	enhancement cost, $
AC	area cost, $
BC	bypass cost, $
CCU	cost parameter for cold utility, $/y
CHU	cost parameter for hot utility, $/y
OT	operating time, y
EF	enhancement factor, –

Greek letters

μ	viscosity, Pa s
ρ	fluid density, kg m^{-3}
δ	tape thickness, m
φ	physical correction factor, –

Dimensionless groups

Nu	Nusselt number $= \frac{hD_i}{k}$
Pr	Prandtl number $= \frac{C_p\mu}{k}$
Re	Reynolds number $= \frac{\rho u D_i}{\mu}$
Sw	Swirl number $= \frac{Re}{\sqrt{y}} \frac{\pi}{\pi - 4(\delta/D_i)} \left[1 + \left(\frac{\pi}{2y}\right)^2\right]^{\frac{1}{2}}$

Subscripts

B	base
E	enhanced
T	tube
S	shell
UWT	uniform wall temperature
b	bulk
w	wall
ex	exchanger
HS	hot stream
CS	cold stream
CU	cold utility
HU	hot utility
i	initial
f	final
E, O	enhanced and optimised

between pair of streams, auxiliary equipment and, pumping cost. The pinch analysis method although promoting good user interaction, can be very time consuming due to its heuristic nature. The heuristic nature of the decision process could make it difficult to apply pinch analysis to larger problems due to the increased number of design alternatives.

Mathematical programming methods can be further subdivided into deterministic and probabilistic (stochastic) optimisation methods. In both cases, the retrofit problem is converted into an optimisation task by formulating the problem as a mathematical model. Ciric and Floudas [5] proposed a systematic two-stage approach for retrofit of HENs. In the first stage, a minimum temperature approach for the HEN is selected and calculations for the minimum utility cost are made. All possible pairings of streams and heat exchangers are then considered, so that all possible structural modifications are included in the mixed integer linear programming (MILP) model. This model is then solved to obtain the minimum modification cost. The second stage consists of producing a superstructure containing all the alternative network structures and then solving this superstructure as a non-linear programming (NLP) problem. The solution of this superstructure is the retrofitted network with the minimum cost of investment. A major limitation of this methodology is the large and complex superstructure in the mathematical formulation. The complexity of the superstructure could make the application of the methodology to large systems prohibitive, as very long computational times (and cost) could be required to obtain a feasible solution. To relieve this problem, they then went on to present a single stage mixed integer non-linear programming (MINLP) model [6] that simultaneously optimised the HEN retrofit. To better account for trade-offs between energy and capital costs, Yee and Grossmann [7] presented a two-stage procedure consisting of a pre-screening and a superstructure optimisation stage. The economic feasibility of the retrofit of an existing heat exchanger network is investigated in the pre-screening stage. This involved comparing the minimum annual cost of utilities, additional area requirement, and fixed cost of structural modifications estimated at different levels of heat recovery to the existing operating costs. The optimisation stage takes into consideration only the number of new units required to achieve the optimum investment. To determine the best retrofit design, a MILP model is formulated and solved. Mathematical programming methods have the advantage of being able to be automated, but are not ideal for large industrial problems due to the black box nature of its analysis. It can also require extensive computation time and provides little scope for user interaction.

Asante and Zhu [8] introduced a novel two-stage hybrid methodology for the retrofit of HEN. The methodology is based on identifying structural limitations to the heat recovery of the existing network, and making modifications to ease those limitations. Points in the network where these limitations occur are labelled network pinch points. The first stage of the retrofit procedure, the diagnosis stage, involves sequential selection of topology modifications to the existing HEN. Only one modification is selected at a time during the procedure. After identification of a topology modification in the diagnosis stage, the HEN including the selected topology modification is then optimised in the optimisation stage (second stage). A superstructure optimisation is used to minimise the heat transfer area, and also optimise the branch flow rates of potential stream splits introduced to the HEN. The procedure can then be repeated for additional topology modifications until a satisfactory retrofitted HEN is obtained. Capital costs are not considered in the first stage of this optimisation procedure, and this may lead to cost effective solutions being dismissed solely because they offer slightly lower savings in terms of utility consumption. Smith et al. [9] presented a modified network pinch approach which can handle streams with temperature dependent thermal properties. The modified network pinch approach also combines both stages of the original network pinch approach into a single step. The stages are merged to prevent the possibility of missing cost effective modification options in the diagnosis stage. The methodology is formulated as a non-linear programming (NLP) problem and is solved using a simulated annealing algorithm with a feasibility solver.

The conventional retrofit methods usually rely greatly on topology modifications and additional heat transfer area. However, these methods are not ideal as they require high capital investment for retrofit, are difficult to implement as a result of the constraints posed by the existing HEN and they bring about high production losses from the prolonged shut down periods required during retrofit. As a result of the aforementioned drawbacks, there has been a rise in recent years into the use of heat transfer enhancement for retrofit. Heat transfer enhancement has the potential to improve energy recovery in existing HENs with fixed network structures and no additional heat transfer area. At constant heat load, reduced heat transfer area is required due to an increase in the heat transfer coefficient of enhanced heat exchangers. Also, higher thermodynamic efficiency can be attained as smaller driving forces can be used to transfer the same amount of heat load. Alternatively, a greater heat load can be exchanged for the same heat transfer area and driving force. In retrofit, the implementation of heat transfer enhancement is a relatively simple task with no production losses as modifications can be carried out during normal shutdown periods. The use of heat transfer enhancement in retrofit requires considerably reduced modifications to the existing HEN. It is also generally cheaper to implement than additional heat transfer area, thereby reducing retrofit cost.

The methods used for heat transfer enhancement can be divided into two categories: passive methods (require no direct stimulation from external power such as rough and extended surfaces or swirl flow devices) and, active methods (require extra external power such as fluid vibration and suction). There are different enhancement techniques, all of which have different effects on pressure drop, fouling and heat transfer coefficients. Shell and tube heat exchangers are by far the most commonly used heat exchangers in industry. As such, this paper focuses on the retrofit of this type of heat exchanger. The heat transfer enhancement techniques used can also be divided into two additional categories: shell-side and tube-side enhancement techniques.

The most commonly used shell-side enhancement is the segmental baffle. The conventional segmental baffle improves the shell-side heat transfer in the exchanger. Drawbacks of using the segmental baffle include: high shell-side pressure drop, low shell-side mass flow velocity, fouling and vibration. As a result of these drawbacks, helical baffles were developed to reduce the number of dead spots created by the segmental baffle design. A comparative analysis [10] made between segmental baffles and helical baffles for shell-side enhancement highlighted the benefits of the use of helical baffles. The result from the study was backed up that conducted by Kral et al. [11]. The benefits of helical baffles include: improved heat transfer coefficient, low pressure drop, low possibility of flow-induced vibration, and reduced fouling with an insignificant increase in pumping. There are two classes of helical baffles: continuous and non-continuous baffles. The non-continuous helical baffle is more effective than the continuous helical baffle as it offers superior augmentation levels with an insignificant increase in pressure drop. It is also important to point out that both classes of helical baffle offer high levels of augmentation at smaller helix angles and helical pitches. External fins are also used for shell-side heat transfer enhancement. The use of external fins is beneficial as it increases the heat transfer coefficient with added turbulence and also increases the heat transfer area. A study performed by Mukherjee [12] showed that extended surface finned tubes provide two to four times as much heat transfer area on the outside compared with a bare tube. This in turn helps to offset a lower outside heat transfer coefficient. Hashizume [13] performed a study which analysed the effects of externally finned tubes in terms of heat transfer and pressure drop. It was found that finned tubes are able to provide a high increase in heat transfer but at a high pressure drop penalty. Design models for finned tubes were presented by Ganapathy [14]. Two commonly used tube-side enhancement devices are twisted-tape inserts and coiled-wire inserts. Twisted-tape inserts consist of a thin strip of twisted metal with normally the same width as that of the tube inner diameter. They are swirl-flow devices that create a spiral or secondary flow along the length of the tube to increase turbulence. Studies [15,16] conducted showed that twisted-tapes are able to provide, especially within the laminar region, high levels of enhancement. An important fact that was also noticed was that the pressure drop penalty is very high and independent of Reynolds number. A conclusion was drawn that if the pressure drop is of no concern, then twisted-tapes should be preferred in both laminar and turbulent regions. In practice this is not ideal, as pressure drop is an important factor in the design of HENs, hence the reason why twisted-tape inserts are not widely used in the process industries. Coiled-wire inserts consist of a helical coiled spring, which acts as a non-integral roughness. They are commonly used in pre-heaters or oil cooling devices. Coiled-wire inserts function by inducing a swirl effect and speeds the flow transition from laminar to turbulent. Garcia et al. [17] presented the advantages of using coiled-wire inserts. These include: the ease of installation and removal (including in an existing heat exchanger), low cost and they do not disrupt the mechanical strength of the tube. Empirical correlations were developed by early research [18,19] regarding the performance of coiled-wire inserts in turbulent flow.

Following this, other studies [20–22] were performed to predict the performance of coiled-wire inserts. The studies showed that they provide greater enhancement under laminar flow conditions with only a small pressure drop increase as a drawback. On the other hand, as the flow progressed from laminar to turbulent, the increase in pressure drop was relatively high.

Pan et al. [23] presented an MILP optimisation methodology to address the systematic implementation of heat transfer enhancement in retrofit without topology modifications. This study took into account the exact value of the log mean temperature difference, correction factor and multiple tube passes [24] in the optimisation process. Another study [25] proposed an MILP based iterative method for HEN retrofit. However, the level of enhancement obtained in this study cannot be guaranteed based on the existing exchanger geometry in the network. In addition, the application of mathematical programming is difficult in industrial processes. A heuristic based method to overcome the drawbacks of mathematical programming was proposed by Wang et al. [26]. This work presented a method based on sensitivity analysis was able to identify heat exchangers that can bring about energy savings in HEN retrofit. However, the assumption of pure counter current heat exchangers, and the inability to guarantee the proposed level of enhancement were drawbacks in this research. Jiang et al. [27] presented a methodology for the retrofit of HEN with heat transfer enhancement that accounted for exchanger geometry when calculating the degree of enhancement. However, this method did consider the effect of applying heat transfer enhancement on other heat exchangers in the network. To solve this problem Akpomiemie and Smith [28] presented a new method for the retrofit of heat exchanger networks with heat transfer enhancement without the need for topology modifications and additional heat transfer area. This study made use of the methodology proposed by Wang et al. [26] for the identification of the best heat exchanger to enhance i.e. sensitivity analysis, and an optimisation model to deal with the downstream effects on the HEN after applying enhancement. A key drawback of the use of sensitivity analysis includes its dependence on a key utility heat exchanger. Therefore, in complex HENs with multiple utilities, finding the enhancement sequence can be computationally expensive. This is because; the analysis has to be repeated after each modification is made as a result of change in temperatures of the network. Therefore, exchangers that were considered good candidates for enhancement might no longer be, as a result of the changes in temperature after enhancement. Therefore, this paper focuses on presenting a methodology that identifies the hierarchy for enhancing candidate heat exchangers in a HEN. Comparison with the well-established sensitivity analysis will be made. The methodology also tackles the issue of downstream effects after enhancement. The validity of the proposed methodology will be tested with the aid of an illustrative example and an industrial case study.

2. Problem statement

It is assumed that heat recovery is based on heat transfer through shell-and-tube heat exchangers. This is because shell-and-tube heat exchangers are most widely used in the process industries. It is assumed that the following information is given:

1. Stream data: flowrates, inlet temperature, outlet temperature, density, specific heat transfer coefficient, viscosity, thermal conductivity and fouling coefficients.
2. Tube-side geometry of the heat exchanger: tube length, tube inner diameter, number of tubes, number of tube passes, tube wall conductivity and nozzle inner diameters.
3. Shell-side geometry of heat exchanger: tube outer diameter, tube pitch, tube layout angle, shell diameter, number of shell passes, baffle spacing, baffle cut, shell bundle clearance and nozzle diameters.
4. Matches between hot and cold streams (network structure).
5. Geometry of enhancement techniques.
6. The current use of utilities for heating and cooling in the existing HEN.
7. Cost for implementing heat transfer enhancement and utility costs.

3. New retrofit methodology

This paper focuses on the use of heat transfer enhancement for the retrofit of heat exchanger networks without additional heat transfer area and topology modifications. However, there are various problems with the effective implementation of heat transfer enhancement. These problems include, identifying candidate heat exchangers that can improve energy recovery, selection of the best heat exchanger for enhancement, dealing with downstream effects after enhancement and finally, specifying a suitable criterion that lends its self to identifying the number of heat exchangers that should be enhanced.

The proposed methodology shown in Fig. 1 is based on a combination of a set of heuristic rules and an optimisation model. The retrofit problem in this paper is considered from the view point of maximising retrofit profit. Detailed explanation of each heuristic rule and the optimisation model will be presented. The link between each rule and their respective importance will also be highlighted.

3.1. Heuristic 1: Network structure analysis

Being able to automatically analyse a network structure is vital during retrofit of HENs. Network structure analysis can be used in the identification of candidate heat exchangers that can improve energy recovery in an existing HEN. The objective in this paper is to maximise retrofit profit. This can be achieved by reducing the utility consumption through the process of shifting heat load through a utility path. Therefore, candidate heat exchangers for enhancement should be on a utility path. A utility path is a connection between two utilities through process streams and heat exchangers [29]. A detailed methodology for the identification of utility paths in HEN can be found in [30].

From Fig. 2, if Exchanger 3 is enhanced and a certain amount of heat load (Q) is added, based on the path concept [31,32], that same amount of heat load must be subtracted from the heater (HU) and the cooler (CU). This ensures that the enthalpy balance and stream target temperatures are maintained. However, in retrofit, this is not a straight forward task as the operating conditions are changed as a result of load shifting. In a situation where other heat exchangers are located downstream from the enhanced heat exchanger, a change in driving force may be observed. This may result in constraints imposed on the network to be violated. The proposed retrofit methodology considers ways by which the constraints are met by making use of path analysis through load shifting.

3.2. Heuristic 2: Identification of the best candidate for enhancement

This step is vital as the energy saving potential of each candidate exchanger (exchangers on a utility path) is analysed by identifying promising design changes. The commonly used method for the identification of the best candidate is sensitivity analysis [28]. A new numerical method for the identification of the best

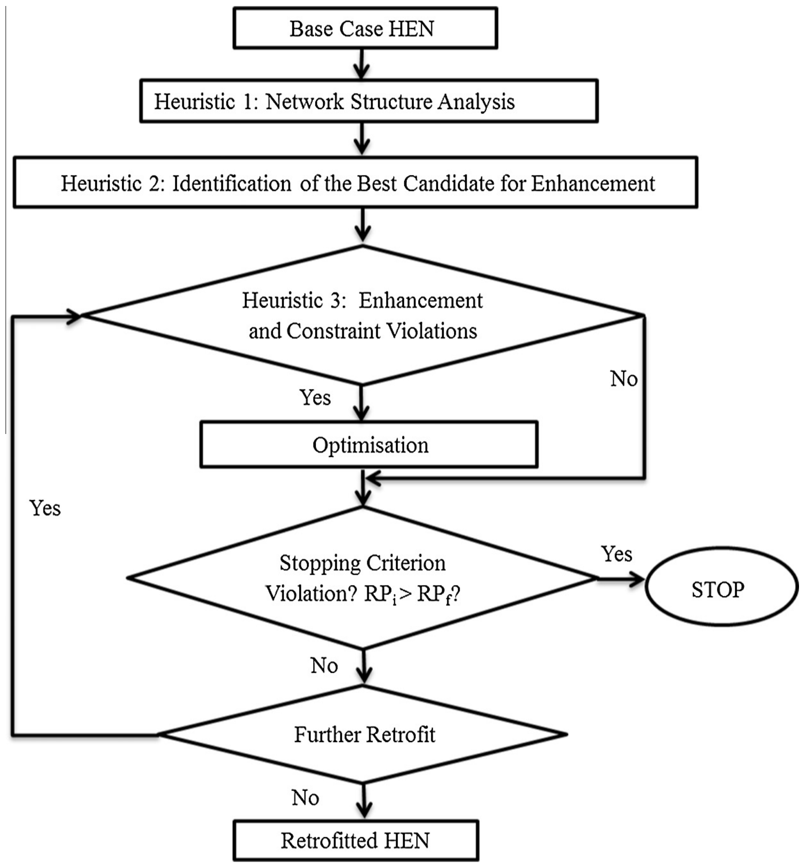

Fig. 1. Proposed retrofit methodology.

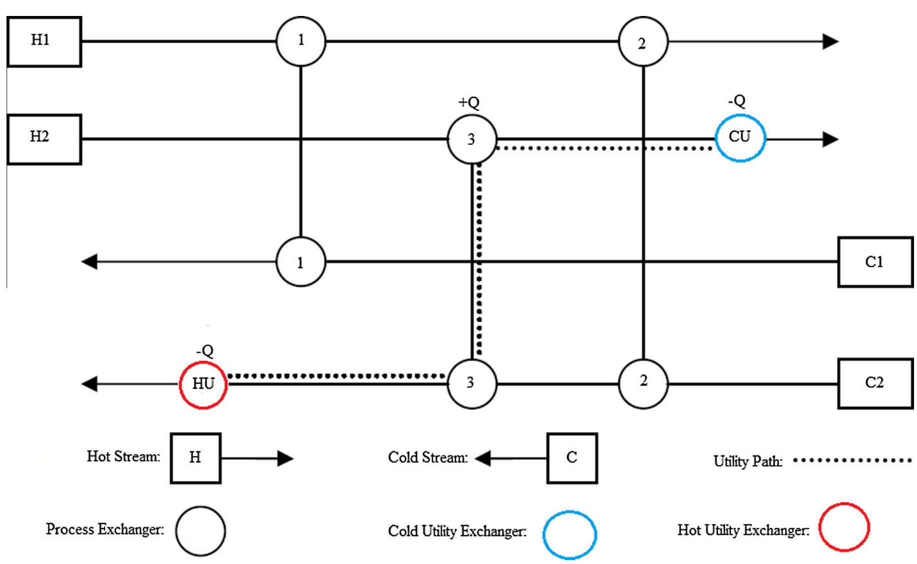

Fig. 2. Utility path.

candidate heat exchanger will be proposed and a comparison made between both methods.

3.2.1. Sensitivity analysis

This method was first proposed by Kotjabaskis and Linnhoff [33] for the purpose of enhancing the flexibility of HENs. This work was restricted to countercurrent heat exchangers. It can identify the passive response in a HEN when design changes are made. Later the approach was extended to non-countercurrent heat exchangers by Jiang et al. [27]. Sensitivity analysis is based on the well-known heat transfer equation (Eq. (1)):

$$Q = UA\Delta T_{LM}F_T \tag{1}$$

In order to perform sensitivity analysis, the only information needed is the base case stream data and the HEN structure. Sensitivity analysis identifies the energy saving potential of candidate heat exchangers based on their effect on the inlet temperature of the key utility heat exchanger. This is done by varying the product of the overall heat transfer coefficient (U), heat transfer area (A) and the correction factor (F_T) against the inlet temperature of the key utility exchanger. The best candidate heat exchanger is one which can bring about the greatest increase in the inlet temperature of the key utility exchanger.

With sensitivity analysis, the best candidate is identified from an unbalanced heat exchanger network, as the energy balance is not maintained during analysis. Also, in a case of multiple utilities, sensitivity analysis has to be carried out separately for different key utilities within the HEN. This is because sensitivity analysis is solely based around a single temperature; that of the inlet temperature of the key utility exchanger in the same utility path as the candidate heat exchangers under investigation. This can result in a tedious and computationally expensive process in large networks. Another drawback with the use of sensitivity analysis for the identification of the best candidate heat exchanger for enhancement is down to its inability to examine if a suggested level enhancement for the best candidate heat exchanger is feasible, based on the exchanger geometry.

3.2.2. Area ratio

Area ratio can be used in identifying the best candidate heat exchanger for enhancement. This is based on the ability of existing heat exchangers to accommodate additional heat transfer area based on their geometries. In retrofit, additional heat transfer area might be used in reducing the utility consumption in the HEN. It follows that decrease in utility consumption is directly proportional to the rate of increase in heat transfer area in existing heat exchangers as shown in Eq. (2).

$$\downarrow Q_{\text{utility}} \propto \uparrow A_{\text{existing}} \tag{2}$$

If the increased duty, the new log mean temperature difference obtained as a result of increasing the heat transfer area in a heat exchanger are fixed, the relationship between the heat duty and the additional heat transfer area is given by:

$$Q = U(A_{\text{existing}} + \Delta A)\Delta T_{\text{LM}} F_T \tag{3}$$

A benefit of heat transfer enhancement is that an enhanced heat exchanger has a higher heat transfer coefficient to exchange the same duty under smaller heat transfer area requirement. In other words, an enhanced heat exchanger at the same duty might be able to maintain an existing heat transfer area requirement. This relationship is given by:

$$Q = U_E A_{\text{existing}} \Delta T_{\text{LM}} F_T \tag{4}$$

Assuming heat transfer enhancement can completely accommodate the need for additional heat transfer area:

$$U(A_{\text{existing}} + \Delta A)\Delta T_{\text{LM}} F_T = U_{\text{enhanced}} A_{\text{existing}} \Delta T_{\text{LM}} F_T \tag{5}$$

The initial design equation for U is given by:

$$U = \left(\frac{1}{h_s} + \frac{1}{h_{\text{SF}}} + \frac{D_o \ln(D_o/D_i)}{2k_{\text{tube}}} + \frac{D_o}{D_i h_{\text{TF}}} + \frac{D_o}{D_i h_T}\right)^{-1} \tag{6}$$

The overall heat transfer coefficient after enhancement U_E is dependent on the enhancement location. Considering a shell-and-tube heat exchanger, enhancement can either be applied on the shell-side (Eq. (7)), tube-side (Eq. (8)) or on both sides (Eq. (9)).

$$U_E = \left(\frac{1}{h_{s,E}} + \frac{1}{h_{\text{SF}}} + \frac{D_o \ln(D_o/D_i)}{2k_{\text{tube}}} + \frac{D_o}{D_i h_{\text{TF}}} + \frac{D_o}{D_i h_T}\right)^{-1} \tag{7}$$

$$U_E = \left(\frac{1}{h_s} + \frac{1}{h_{\text{SF}}} + \frac{D_o \ln(D_o/D_i)}{2k_{\text{tube}}} + \frac{D_o}{D_i h_{\text{TF}}} + \frac{D_o}{D_i h_{T,E}}\right)^{-1} \tag{8}$$

$$U_E = \left(\frac{1}{h_{s,E}} + \frac{1}{h_{\text{SF}}} + \frac{D_o \ln(D_o/D_i)}{2k_{\text{tube}}} + \frac{D_o}{D_i h_{\text{TF}}} + \frac{D_o}{D_i h_{T,E}}\right)^{-1} \tag{9}$$

Rearranging Eq. (5) gives an equation for calculating the area ratio:

$$A_R = \frac{A_{\text{existing}}}{(A_{\text{existing}} + \Delta A)} = \frac{U}{U_E} \tag{10}$$

The best candidate heat exchanger is that with the smallest area ratio. From Eq. (10), it follows that the smaller the area ratio, the greater the additional heat transfer area of a particular heat exchanger. In retrofit, area ratio is a more tailored method for the identification of the best candidate heat exchanger for enhancement. This is because, it not only identifies the best candidate heat exchanger for enhancement but also the maximum allowable enhancement that still maintains a balanced network. Also, area ratio is computationally inexpensive, encourages good user interaction and it easy to perform and can therefore be applied to large networks. Given that area ratio is numerically determined based on the geometry of exchangers; it can easily be automated as part of a retrofit methodology for HENs with heat transfer enhancement.

3.3. Heuristic 3: Enhancement and constraint violations

This paper focuses on tube-side enhancement techniques. Models for the two commonly used inserts i.e. twisted-tape and coiled-wire, will be presented. A comparison between both inserts will be illustrated by the use of a simple example involving the enhancement of a single heat exchanger.

3.3.1. Twisted-tape inserts

Twisted-tape inserts are the most commonly used form of tube-side heat transfer enhancement in industries. They are frequently used in the retrofit of existing shell-and-tube heat exchangers to increase tube-side heat transfer coefficient. Fig. 3 shows the geometry of twisted tape inserts. Enhancement using twisted tape inserts is defined geometrically by the thickness of the tape δ and its twist ratio y. Twist ratio is defined as the axial length for a 180° turn of the tape (H) divided by the internal diameter of the tube (D_i). For heat transfer purposes, the surface area of the twisted tape itself is not taken into account. Only the effect on the heat transfer coefficient of the tube's inner surface is considered.

The following procedure is used to model a twisted tape insert for a tube:

1. Specify the twisted tape insert size: twist ratio $y = H/D_i$, tape thickness ratio δ/D_i (or H, δ).
2. Calculate the swirl number (Sw) using correlation proposed by Manglik and Bergles [35]:

$$Sw = \frac{Re}{\sqrt{y}} \frac{\pi}{\pi - 4(\delta/D_i)} \left[1 + \left(\frac{\pi}{2y}\right)^2\right]^{\frac{1}{2}} \tag{11}$$

where

$$Re = Reynoldsnumber = \frac{\rho u D_i}{\mu} \tag{12}$$

3. Determine the enhanced heat transfer coefficient $h_{T,E}$: taking into account only fully developed tape-induced swirl flows at a uniform wall temperature (UWT) and neglecting thermal entrance effects and convection effects, the mean Nusselt number (Nu) for twisted tape inserts for laminar flow ($Sw \leqslant 2000$) is given by [35]:

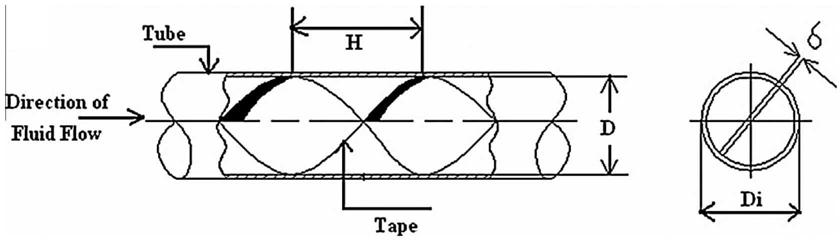

Fig. 3. Twisted tape geometry [34].

$$Nu_{T,UWT} = \frac{h_{T,E}D_i}{k} = 4.612\left(\frac{\mu_b}{\mu_w}\right)^{0.14}\left[6.413\times10^{-9}\left(SwPr^{0.391}\right)^{3.835}\right]^{0.2} \quad (13)$$

where

$$Pr = \text{Prandtl number} = \frac{C_p\mu}{k} \quad (14)$$

For turbulent flow heat transfer, ($Re \geqslant 10{,}000$), the Nusslet number for twisted tape under UWT condition is given by [36]:

$$Nu_{T,UWT} = \frac{h_{T,E}D_i}{k} = 0.023Re^{0.8}Pr^{0.4}\left(1+\frac{0.769}{y}\right)\left[\frac{\pi}{\pi-4(\delta/D_i)}\right]^{0.8}\left[\frac{\pi+2-2(\delta/D_i)}{\pi-4(\delta/D_i)}\right]^{0.2}\varphi \quad (15)$$

where φ is the physical correction factor.

In situations where by $Sw > 2000$ and $Re < 10{,}000$, the algebraic average of Eqs. (13) and (15) is used.

3.3.2. Coiled-wire Inserts

Coiled-wire inserts are currently used in application such as preheaters and oil cooling devices. This is because they exhibit advantages in relation to other enhancement devices such as preserving the mechanical strength of an existing tube, cheap, easy to install and remove in/from an existing plain tube heat exchanger. Coiled-wire inserts are defined by geometries shown in Fig. 4: the axial roughness pitch (p), the wire-diameter (e) and the tube inner diameter (D_i). These geometries can also be defined in dimensionless forms: dimensionless pitch p/D_i, dimensionless wire-diameter e/D_i and, pitch to wire-diameter ratio p/e.

The following procedure is used to model a coiled-wire insert for a tube:

1. Specify the coiled wire insert size: p, e (or p/D_i, e/D_i; or p/D_i, p/e).
2. Determine the enhanced heat transfer coefficient $h_{T,E}$:

For laminar regime ($Re \leqslant 1000$), the correlation shown in Eq. (16) is recommended.

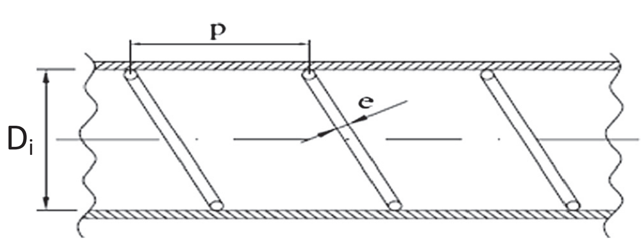

Fig. 4. Wire coil geometry.

$$Nu_T = \frac{h_{T,E}D_i}{k} = 1.86Re^{1/3}Pr^{1/3}\left(\frac{p}{D_i}\right)^{1/3}\left[\frac{\cos\alpha-(e/D_i)^2}{\cos\alpha+(e/D_i)}\right]^{-1/3}\left(\frac{\mu_b}{\mu_w}\right)^{0.14} \quad (16)$$

where

$$\cos\alpha = \sqrt{\frac{1}{\left[\frac{\pi}{\left(\frac{p}{D_i}\right)}\right]^2+1}} \quad (17)$$

For $1000 \leqslant Re \leqslant 80{,}000$ turbulent regimes, the correlation proposed by Garcia et al. [17] is recommended.

$$Nu_T = \frac{h_{T,E}D_i}{k} = 0.132Re^{0.72}Pr^{0.37}\left(\frac{p}{D_i}\right)^{-0.372} \quad (18)$$

For Re = 80,000–250,000 turbulent regime, Ravigururajan and Bergles [37] proposed a correlation that is considered to be the most general and accurate method for the performance prediction of heat transfer in single phase turbulent flow in a wide range of rough tubes.

$$Nu_T = \frac{h_{T,E}D_i}{k} = Nu_S\left\{1+\left[2.64Re^{0.036}\left(\frac{e}{D_i}\right)^{0.212}\left(\frac{p}{D_i}\right)^{-0.21}\left(\frac{\alpha}{90}\right)^{0.29}Pr^{-0.024}\right]^7\right\}^{\frac{1}{7}} \quad (19)$$

where

$$Nu_S = \frac{h_S D_i}{k} \quad (20)$$

The example case study presented in Table 1 will be used to perform calculations to examine the performance of both twisted-tape and coiled-wire inserts. It is assumed that a twist ratio, tape thickness and physical property correction factor of 5, 0.001 m and 1 respectively for twisted-tape insert. Also, an axial roughness pitch and roughness height of 0.0425 m and 0.0016 m respectively for coiled-wire insert are used.

From Table 2, it can be noted that both enhancement techniques show an increase in tube-side heat transfer coefficient. It is important to point out that in this example, pressure drop has not been considered. Coiled-wire inserts can present a higher increase in heat transfer coefficient compared to twisted-tape inserts, depending on their geometry. However, when considering a heat exchanger as part of a network, the increase in heat transfer coefficient can result in the elimination of the utility heat exchanger if the increased duty, exceeds that of the utility exchanger. This can lead to violations in stream target temperatures, which in the context of retrofit, could be considered unacceptable. Therefore, if pressure drop is not considered, the enhancement device that

Table 1
Exchanger data.

Fluids	Shell-side	Tube-side
Heat capacity flowrate C_p (J/kg K)	2273	2303
Thermal conductivity k (W/m K)	0.08	0.0899
Viscosity μ (Pa s)	1.89E−02	9.35E−04
Density ρ (kg/m^3)	966	791
Mass flow rate m (kg/s)	46.25	202.54
Inlet temperature T_{in} (°C)	227	131
Fouling resistance (m^2 K/W)	0.00176	0.00053

Heat exchanger geometry	
Tube pitch P_T (m)	0.03125
Number of tubes n_t	612
Number of passes n_p	2
Tube length L (m)	6
Tube effective length L_{eff} (m)	5.9
Tube conductivity k_{tube} (W/m K)	51.91
Tube layout angle	90
Bundle configuration	Straight tube bundle
Tube inner diameter D_i (m)	0.02
Tube outer diameter D_o (m)	0.025
Shell inner diameter D_s (m)	0.97
Number of baffles n_b	25
Baffle spacing B (m)	0.22
Inlet baffle spacing B_{in} (m)	0.3117
Outlet baffle spacing B_{out} (m)	0.3117
Baffle cut B_c	20%
Inner diameter of tube-side inlet nozzle $D_{i,inlet}$ (m)	0.336
Inner diameter of tube-side outlet nozzle $D_{i,outlet}$ (m)	0.336
Inner diameter of shell-side inlet nozzle $D_{o,inlet}$ (m)	0.154
Inner diameter of tube-side outlet nozzle $D_{o,outlet}$ (m)	0.154
Shell-bundle diametric clearance L_{sb} (m)	0.069

Table 2
Enhancement results.

	Base case	Twisted-tape	Coiled-wire
Tube-side heat transfer coefficient (kW/m^2 K)	1.58	2.64	3.26

should be chosen must be capable of providing the best enhancement subject to maintaining existing utility paths in the HEN.

3.3.3. Constraint violations

In retrofit, increasing the duty of an enhanced heat exchanger will have an effect on downstream heat exchangers and stream target temperatures in a HEN. After enhancement, a change in the driving force of other heat exchangers in the network will be observed. This can result in minimum temperature approach, stream target temperature and, heat transfer area violations. A constraint has not been placed on temperature approach in this case but it is useful to include it in order to avoid making existing heat exchangers inefficient as a result of small temperature differences [27]. For the retrofit objective of maximising retrofit profit without topology modifications and additional heat transfer area. Stream target temperature and heat transfer area constraints are particularly important. These violations can be corrected using optimisation.

3.4. Optimisation

This is a key step in the proposed retrofit methodology, as the heat transfer area after enhancement and the stream target temperatures can be maintained. This requires a certain heat load to be shifted through a utility path for heat exchangers requiring additional area on a utility path. For heat exchangers not on a utility path, enhancement can be implemented at constant duty when additional area is required or a bypass can be implemented in the case of reduced area use. The amount of heat load that needs to be shifted, degree of enhancement and the degree of overall heat transfer coefficient reduction through bypass to satisfy heat transfer area and stream target temperature constraints can be determined using a non-linear optimisation model. The non-linearity of the model is as a result of the logarithmic mean temperature difference (ΔT_{LM}) and the heat exchanger area (A). Eq. (21) represents the logarithmic mean temperature difference of all heat exchangers ($\Delta T_{LM,ex}$), where, THI_{ex}, THO_{ex}, TCI_{ex}, TCO_{ex} are inlet and outlet temperatures of hot and cold streams in exchanger ex and, EX is the set of all heat exchangers.

$$\Delta T_{LM_{ex}} = \frac{(THI_{ex} - TCO_{ex}) - (THO_{ex} - TCI_{ex})}{\ln\frac{(THI_{ex}-TCO_{ex})}{(THO_{ex}-TCI_{ex})}} \quad \forall_{ex} \in EX \tag{21}$$

The heat transfer area of all process heat exchangers (A_{ex}) in the network should be constant during retrofit. Eq. (22) represents the equation used in calculating the heat transfer area based on the duty of heat exchangers (Q_{ex}), overall heat transfer coefficient of exchangers (U_{ex}), correction factor (F_{Tex}) and $\Delta T_{LM,ex}$. After enhancement, heat transfer area should be the same. This is compensated for by the change in Q_{ex}, U_{ex}, F_{Tex}, and $\Delta T_{LM,ex.}$ The constraint shown in Eq. (23) is used where E represents the value after enhancement.

$$A_{ex} = \frac{Q_{ex}}{U_{ex}\Delta T_{LM_{ex}} F_{T,ex}} \quad \forall_{ex} \in EX \tag{22}$$

$$A_{ex} = A_E \quad \forall_{ex} \in EX_E \tag{23}$$

After enhancement, there will be changes in the stream temperatures for process streams of the enhanced heat exchanger. However, similar to heat transfer area, this value should be constant during retrofit. Eqs. (24)–(27) represents the constraint for all cold and hot streams, CS and HS. $EX^i{}_{CS}$, $EX^o C_S$, $EX^i{}_{HS}$, $EX^o{}_{HS}$ describe the set of all exchangers located in the inlet and outlet of all cold and hot streams respectively. $TCIS_{CS}$ and $TCOS_{CS}$, $THIS_{HS}$ and $THOS_{HS}$ represent the cold and hot inlet and outlet temperatures of all cold and hot streams.

$$TCI_{ex} = TCIS_{CS} \quad \forall_{ex} \in EX^i_{CS} \tag{24}$$

$$TCO_{ex} = TCOS_{CS} \quad \forall_{ex} \in EX^o_{CS} \tag{25}$$

$$THI_{ex} = THIS_{HS} \quad \forall_{ex} \in EX^i_{HS} \tag{26}$$

$$THO_{ex} = THOS_{CS} \quad \forall_{ex} \in EX^o_{HS} \tag{27}$$

To satisfy the aforementioned constraints, the duty of all heat exchangers on a utility path in the network can then be varied based on path analysis. The overall heat transfer coefficient of all heat exchangers not on a utility path can also varied at constant duty. It is important to note that the F_{Tex} depends on the value of U_{ex}. Therefore, after the application of enhancement, the change in the inlet and outlet temperatures in both the hot and cold streams, and U_{ex} will result in a change in the F_{Tex} value of the enhanced exchanger. A correlation used in determining the value of F_{Tex} can be found in a study by Jiang et al. [38]. The retrofit objective is to maximise the retrofit profit (RP). This is based on the difference between the base case utility cost (UC_B) and the sum of the utility cost after enhancement (UC_E) and the retrofit cost of all heat exchangers (RC_{ex}) as shown in Eq. (28).

$$RP = UC_B - \left[UC_E + \sum_{ex \in EX} RC_{ex} \right] \tag{28}$$

The utility costs for the base case and after enhancement are shown in Eqs. (29) and (30) where, CCU and CHU are the yearly cost parameter for cold and hot utility, Q_B and Q_E are the duty before and after enhancement and OT is the operating time.

$$UC_B = OT \times \left[CCU \times \sum_{ex \in EX_{CU}} Q_{B,ex} + CHU \times \sum_{ex \in EX_{HU}} Q_{B,ex} \right] \quad (29)$$

$$UC_E = OT \times \left[CCU \times \sum_{ex \in EX_{CU}} Q_{E,ex} + CHU \times \sum_{ex \in EX_{HU}} Q_{E,ex} \right] \quad (30)$$

The retrofit cost is dependent on the cost of enhancement, the cost of additional heat transfer area and the cost of implementing a bypass. It is important to note that the cost for additional heat transfer area after optimisation should be zero based on the constraint highlighted in Eq. (23). The cost of enhancement depends on the type of enhancement chosen, and is mostly a function of the heat transfer area of the existing heat exchanger. The cost of bypass is only applied if there is a decrease in the duty of heat exchangers below their base case values. This cost is given by a fixed value. However, an enhancement factor, EF, is assigned to each individual cost. If a heat exchanger is enhanced, additional area is required or bypass is required this value is one otherwise, zero. Eq. (31) shows the equation used to calculate the retrofit cost where, EC_{ex} is the enhancement cost of exchangers, AC_{ex} is the additional area cost and BC_{ex} is the cost of bypass.

$$RC_{ex} = EC_{ex} \times EF_{ex} + AC_{ex} \times EF_{ex} + BC_{ex} \times EF_{ex} \quad \forall_{ex} \in EX \quad (31)$$

In summary, the new NLP model consists of an objective function given in Eq. (28) and the model constraints are given in Eqs. (23) and (24)–(27). The model proposed is able to find the optimal heat load that needs to be shifted along a utility path to meet set constraints for heat exchangers on a utility path, and also the increase in the overall heat transfer coefficient of heat exchangers not on a utility path. This is done by identifying heat exchangers after the application of enhancement that violates the constraints imposed on the network.

3.5. Stopping criterion violation

The optimisation model is based on a trade-off between utility consumption and capital cost (allocated to additional area). Therefore, a stopping criterion is necessary to ensure that the retrofit objective is met while meeting set constraints. The proposed retrofit methodology stopping criterion is based on comparison between the initial retrofit profit and the final retrofit profit after a heat exchanger is enhanced. If the retrofit profit before enhancement (RP_i) is greater than that after (RP_f), the retrofit process is stopped. This means that the utility savings attained by enhancing that particular heat exchanger is not enough to cover the cost of retrofit required.

The heat exchanger network can then be explored to further increase energy recovery and retrofit profit by repeating the proposed methodology until the stopping criterion is violated and, there are no other eligible candidate heat exchangers for enhancement.

4. Illustrative example

The stream and process exchanger data for this example are shown in Tables 3 and 4 respectively. The fouling coefficient for all process heat exchangers are 5 kW/°C and 6 kW/°C for the shell and tube side respectively. The HEN shown in Fig. 5 has 13 heat exchangers (6 process and 7 utility heat exchangers), 10 process streams (5 hot streams and 5 cold streams) and 2 utility streams (1 hot utility and 1 cold utility stream). The proposed retrofit methodology is applied to this example with the following assumptions:

Table 3
Stream details.

Stream	CP (kW/°C)	TS (°C)	TT (°C)	Q (kW)
H1	300	330	210	36,000
H2	150	450	220	34,500
H3	150	300	135	24,750
H4	200	380	190	38,000
H5	125	340	75	33,125
C1	210	240	430	39,900
C2	340	55	150	32,300
C3	220	70	210	30,800
C4	120	150	365	25,800
C5	180	200	370	30,600
HU	–	850	500	–
CU	–	15	25	–

Table 4
Heat exchanger data for illustrative example.

Exchanger	h_T (kW/°C)	h_s (kW/°C)	U (kW/°C)	A (m^2)	Q (kW)	N_s	F_T
1	1.61	3.53	0.72	439.52	25,800	8	0.99
2	0.97	2.34	0.51	939.05	32,300	2	0.82
3	2.75	6.23	1.03	1189.91	23,777	5	0.81
4	2.56	4.36	0.93	981.08	21,237	3	0.78
5	3.36	9.94	1.19	262.73	24,750	2	0.89
6	0.86	1.03	0.37	117.53	3368	1	0.99

1. The overall heat transfer coefficient of all heat exchangers can be reduced by implementing a bypass.
2. Constant temperature dependent stream properties specific heat capacity, thermal conductivity, viscosity, etc.
3. The cost parameters used in this case study are outlined in Table 5.
4. The operating time is assumed to be one year for the purpose of calculating the total profit.

4.1. Results and discussion

Based on the proposed retrofit methodology, the first step is to perform network structure analysis to find the candidate heat exchangers that can improve energy recovery (exchangers on a utility path). From Fig. 5, only exchangers 3, 4 and 6 are on a utility path. Therefore, for the purpose of increasing energy recovery, the other process heat exchangers (1, 2 and 5) have not been considered for the second phase of the retrofit methodology. The best candidate heat exchanger to enhance and the hierarchy for performing enhancement are obtained using both sensitivity analysis and area ratio.

With sensitivity analysis, the first step is the identification of the most expensive utility heat exchangers that can bring about large retrofit profit. As indicated in Table 5, the hot utility cost is more expensive that the cold utility cost hence, the hot utility heat exchangers, 7, 8 and 9 are chosen. Given that utility exchanger 8 is not on a utility path, opportunities for energy savings are not viable. Therefore, focus has been placed on reducing the energy consumption of utility exchangers 7 and 9. The second step is the identification of the most expensive utility exchanger (one with the higher duty) as there is a greater opportunity for more energy saving. The initial duty of exchanger 7 is 12755 kW as opposed to exchanger 9 with a duty of 9363 kW. Therefore, sensitivity analysis will be conducted around exchanger 7 first.

The first sensitivity analysis is then performed along the utility paths 7–6–11 and 7–3–12. The analysis is centred on the inlet temperature of exchanger 7. Fig. 6 shows that exchanger 6 is the most sensitive heat exchanger and should be enhanced first. The second utility is then explored. From Fig. 5, it is clear that only exchanger 4

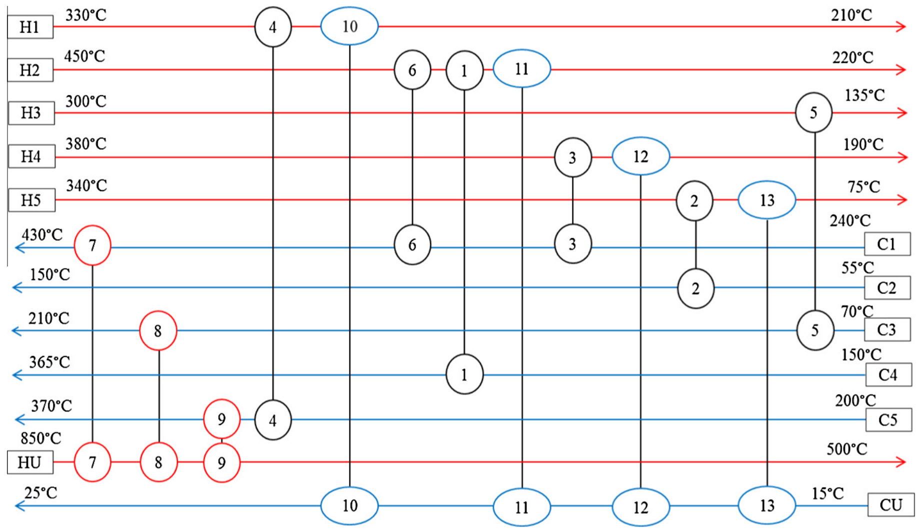

Fig. 5. Original HEN.

Table 5
Cost data.

Utility cost data	Retrofit cost data
Hot utility cost: 400 ($/kW y)	Cost of inserts: $500 + 10 * A$ ($)
Cold utility cost: 15 ($/kW y)	Implementing by-pass: 500 ($) Cost of increasing heat exchanger area: $400 + 200 * A$ ($)

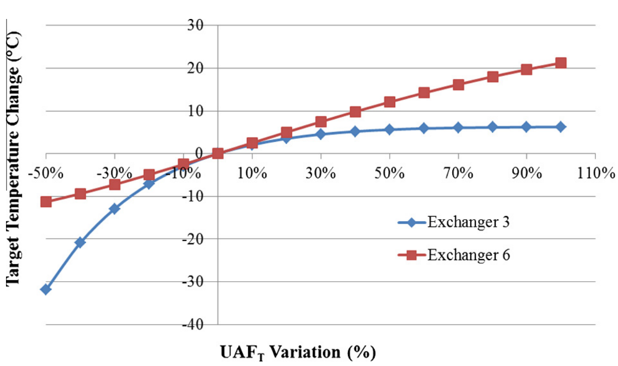

Fig. 6. Sensitivity analysis based on first utility.

Table 6
Area ratio result.

Heat exchangers	Coiled-wire	Twisted-tape
3	0.76	0.79
4	0.77	0.80
6	0.69	0.77

is on a utility path and as such, there is no need to perform sensitivity analysis. The hierarchy for enhancement based on sensitivity analysis is 6–3–4.

In terms of area ratio, it follows that the heat exchanger with the smallest area ratio translates to the heat exchanger that can bring about the greatest decrease in energy consumption. This is because the heat exchanger has the capability of accommodating the greatest additional heat transfer area. Considering only tube-side enhancement techniques, twisted-tape and coiled-wire inserts, the area ratio of all candidate heat exchangers found are shown in Table 6. Therefore, the hierarchy for enhancement based on area ratio is identified as 6–3–4.

Based on the retrofit methodology, exchanger 6 is then enhanced first. Coiled-wire inserts have been chosen as the enhancement device as compared to twisted-tape inserts, a greater degree of enhancement is observed as shown in Table 7. The values were obtained using a twist ratio and tape thickness of 10 and 0.005 m for twisted-tape insert and; axial roughness pitch and roughness height of 0.025 m and 0.0016 m for the three heat exchangers.

After enhancing exchanger 6, the network was then checked for constraint violations. There was an area violation in exchanger 1 and the target temperatures of Streams H2 and C1 as shown in Fig. 7. Therefore, optimisation was conducted. This was performed using the global solver in LINDO Systems What's Best! [39]. Results obtained after enhancing exchanger 6 and performing optimisation are shown in Table 8 where subscripts E and E, O represents enhanced, and enhanced and optimised respectively. It is important to point out that to maintain the area constraints imposed on the network, exchanger 1 had to be enhanced at constant duty.

The proposed retrofit methodology is then repeated for the next heat exchanger with the smallest area ratio i.e. exchanger 3. The stopping criterion was violated as the retrofit profit after enhancing exchanger 6 ($9261) was more than double that after

Table 7
Enhancement performance for candidate heat exchangers.

Options	Exchanger 3		Exchanger 4		Exchanger 6	
	h_s (kW/m^2 °C)	h_T (kW/m^2 °C)	h_s (kW/m^2 °C)	h_T (kW/m^2 °C)	h_s (kW/m^2 °C)	h_T (kW/m^2 °C)
Base case	6.08	2.77	4.36	2.56	1.03	0.86
Coiled-wire		6.59		5.81		2.33
Twisted-tape		5.45		5.06		1.66

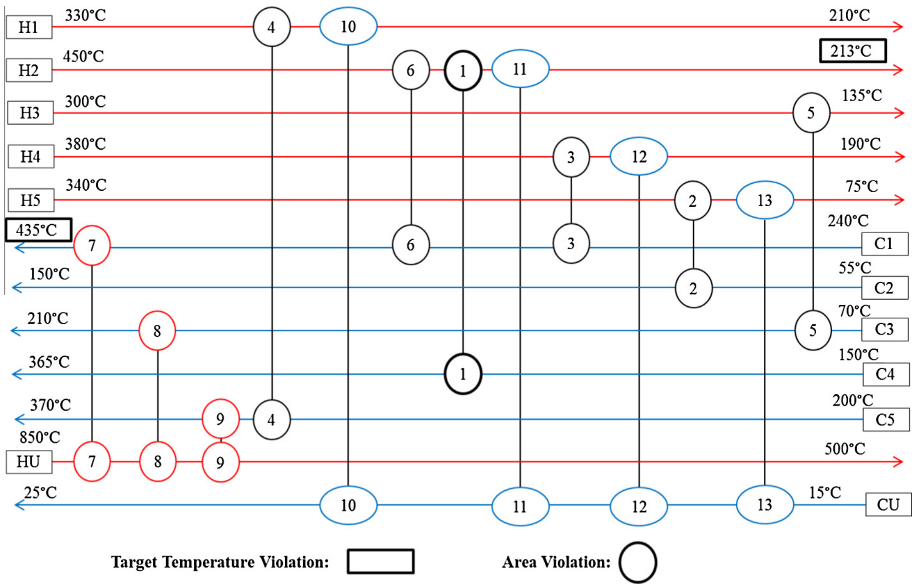

Fig. 7. After enhancing exchanger 6.

Table 8
Enhancement results after enhancement and optimisation of exchanger 6.

Exchangers	Q (kW)	A (m²)	U (kW/m² °C)	Q_E (kW)	A_E (m²)	U_E (kW/m² °C)	$Q_{E,O}$ (kW)	$A_{E,O}$ (m²)	$U_{E,O}$ (kW/m² °C)
1	25,800	440	0.76	25,800	482	0.76	25,800	440	0.79
2	32,300	939	0.51	32,300	939	0.51	32,300	939	0.51
3	23,777	1190	1.03	23,777	1190	1.03	23,777	1190	1.03
4	21,237	981	0.93	21,237	981	0.93	21,237	981	0.93
5	24,750	263	1.19	24,750	263	1.19	24,750	263	1.19
6	3368	118	0.37	4424	118	0.54	4424	118	0.54
7	12,755	–	–	12,755	–	–	11,699	–	–
8	6050	–	–	6050	–	–	6050	–	–
9	9363	–	–	9363	–	–	9363	–	–
10	14,763	–	–	14,763	–	–	14,763	–	–
11	5332	–	–	5332	–	–	4276	–	–
12	14,223	–	–	14,223	–	–	14,223	–	–
13	825	–	–	825	–	–	825	–	–

Table 9
Exchanger details of original HEN and retrofitted HEN.

Exchangers	THI_{ex} (°C)	THO_{ex} (°C)	TCI_{ex} (°C)	TCO_{ex} (°C)	$\Delta T_{LM,ex}$ (°C)	A_{ex} (°C)	U_{ex} (kW/m² °C)	F_{Tex}	Q (kW)	RC_{ex} ($)	ES (kW)	RP ($)
Original												
1	427.54	255.54	150.00	365.00	82.18	439.52	0.72	0.99	25,800			
2	340.00	81.60	55.00	150.00	83.11	939.05	0.51	0.82	32,300			
3	380.00	261.12	240.00	353.22	23.83	1189.91	1.03	0.81	23,777			
4	330.00	259.21	200.00	317.99	29.59	981.08	0.93	0.78	21,237			
5	300.00	135.00	70.00	182.50	88.67	262.73	1.19	0.89	24,750			
6	450.00	427.54	353.22	369.26	77.48	117.53	0.37	0.99	3368			
Retrofit												
1	420.51	248.51	150.00	365.00	74.96	439.52	0.79	0.99	25,800	4895	2111	9261
2	340.00	81.60	55.00	150.00	83.11	939.05	0.51	0.82	32,300	–		
3	380.00	261.12	240.00	353.22	23.83	1189.91	1.03	0.81	23,777	–		
4	330.00	259.21	200.00	317.99	29.59	981.08	0.93	0.78	21,237	–		
5	300.00	135.00	70.00	182.50	88.67	262.73	1.19	0.89	24,750	–		
6	450.00	420.51	353.22	374.29	71.41	117.53	0.54	0.98	4425	1675		

enhancing exchanger 3 ($3794). Therefore, enhancement was stopped. Table 9 shows the final exchanger details after retrofit.

5. Case study

The case study is a simplified pre-heat train studied by Akpomiemie and Smith [28]. The assumptions made in that paper still remains valid in this case. Fig. 8 shows the HEN and the exchanger data are shown in Table 10.

5.1. Results and discussion

From network structure analysis, it is clear that all process heat exchangers in the network shown in Fig. 8 are on a utility path

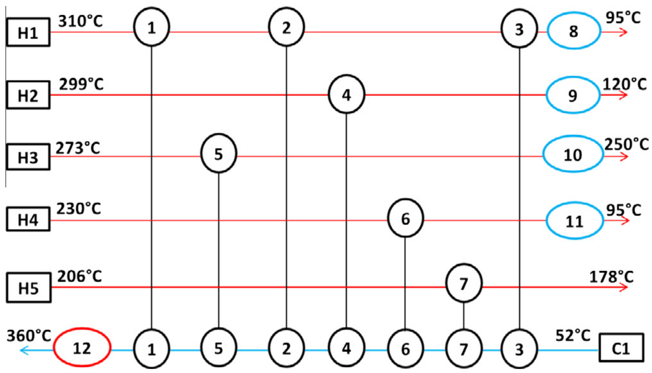

Fig. 8. HEN [28].

with the exception of exchanger 7. As such, exchanger 7 is left out from the next analysis. Both sensitivity analysis and area ratio approach are then applied to identify the best heat exchanger to enhance and the enhancement hierarchy. With sensitivity analysis, the first step is the identification of the key utility heat exchanger. In this case, the hot utility exchanger 12 is chosen as the key utility exchanger. This leaves us with 6 process heat exchangers located on the same utility path as this key utility exchanger. Fig. 9 shows the result obtained by using sensitivity analysis. From sensitivity analysis, exchanger 5 is clearly the most sensitive heat exchanger and should be enhanced first.

In terms of area ratio, twisted-tape inserts are used as the chosen enhancement device as it provided a greater increase in the heat transfer coefficient than coiled-wire inserts based on the exchanger geometry [28]. Table 11 shows the area ratio of all candidate heat exchangers for enhancement. From Table 11, exchanger 5 has the smallest area ratio. This means that exchanger 5 should be enhanced first based on the proposed methodology.

Table 11
Area ratio results.

Exchangers	U (kW/m^2 °C)	U_E (kW/m^2 °C)	A_R
1	0.517	0.669	0.773
2	0.475	0.597	0.795
3	0.158	0.198	0.798
4	0.0963	0.108	0.891
5	0.325	0.448	0.725
6	0.610	0.674	0.905

The steps outlined in the proposed methodology are then followed i.e. identifying any constraints violations, if there are, solving the problem using the NLP optimisation model. The procedure is repeated using both methods until the stopping criterion is violated. Again the result obtained by the use of area ratio is the same as that of sensitivity analysis. The final enhancement sequence is shown in Fig. 10. The stopping criterion was violated after enhancing exchanger 6 [28]. The final decrease in utility consumption was found to be ∼7%. Table 12 shows the final retrofit result based on this case study.

In conclusion, although both methods identified the same hierarchy for enhancement in both the illustrative example and the case study, a judgement on whether this will always be the case cannot be made. However, the benefits of area ratio over sensitivity analysis can be highlighted. It is clear that area ratio method as a one-step approach is more computationally inexpensive compared with sensitivity analysis. The area ratio approach is not also restricted by the presence of multiple utilities, as the decision is based solely on the geometry of exchangers and the maximum allowable additional area of existing heat exchangers. The effectiveness of the area ratio approach in comparison with sensitivity analysis is that the decision is not based on a single utility exchanger. With that, further identification procedures for the hierarchy, as necessary with sensitivity analysis, is not required.

Table 10
Heat exchanger data for case study.

Exchanger	A (m^2)	h_s (kW/m^2 °C)	h_T (kW/m^2 °C)	U (kW/m^2 °C)	Q (kW)	N_s	F_T
1	396.72	2.07	1.33	0.52	6141.33	2	0.88
2	545.45	2.31	1.40	0.48	6134.83	2	0.82
3	633.85	4.54	0.78	0.16	5556.61	1	0.88
4	354.64	1.27	0.62	0.10	2688.79	1	0.94
5	183.85	2.56	0.78	0.32	3431.16	1	0.98
6	843.73	0.96	0.49	0.06	2291.88	1	0.97
7	114.28	3.38	0.98	0.36	3623.20	1	0.98
8	–	–	–	–	657.23	–	–
9	–	–	–	–	1141.81	–	–
10	–	–	–	–	816.94	–	–
11	–	–	–	–	880.62	–	–
12	–	–	–	–	14455.41	–	–

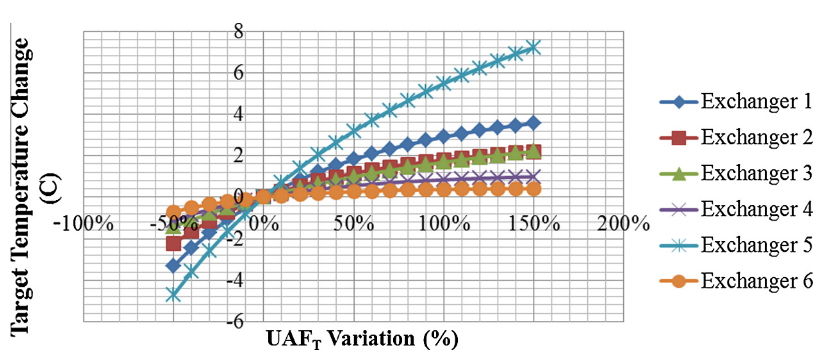

Fig. 9. Sensitivity analysis result.

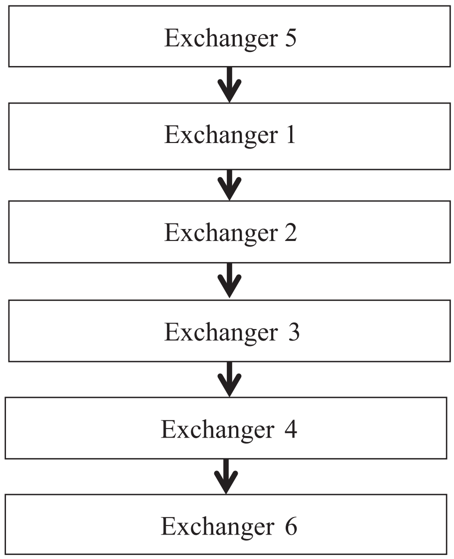

Fig. 10. Enhancement sequence.

Table 12
Retrofit results.

Parameters	Costs
Retrofit cost	
Enhancement	$25,288
Increasing area	$0
Implementing by-pass	$1000
Total cost	**$26,288**
Retrofit profit	
Utility savings	**$409,154**
Net saving (utility savings – total cost)	**$382,866** (~6.6% of initial utility cost $5,801,396)

The numerical based determination of the best heat exchanger for enhancement is an advantage as it can be automated as part of a retrofit methodology for HENs with heat transfer enhancement. Therefore, for large HEN with multiple utilities, the area ratio approach is more robust for the identification of the best heat exchangers for enhancement in retrofit.

6. Conclusions

A methodology for the retrofit of heat exchanger networks (HENs) without the need for topology modifications and additional heat transfer area has been proposed. This new methodology is able to tackle the key issues posed by the use of enhancement techniques in HEN retrofit. The key issues include: (1) identifying the best heat exchanger in the network to enhance, (2) obtaining the level of enhancement for each heat exchanger based on their geometry, and (3) dealing with downstream effects after enhancement.

A comparison between two methods i.e. sensitivity analysis and area ratio was made for the identification of the best candidate heat exchanger for enhancement. Although both methods identified the same hierarchy of heat exchangers for enhancement, the area ratio method was observed to be a more robust and computationally inexpensive method of identifying the best candidate heat exchangers for enhancement based on the exchanger geometry. Two enhancement techniques have been considered; twisted-tape and coiled-wire inserts. For the illustrative example, coiled-wire inserts were chosen as the enhancement device because, as opposed to twisted-tape inserts, a greater degree of enhancement was attained. The opposite was the case with the case study (pre-heat train). A profit based non-linear optimisation framework was used to ensure the constraints imposed on the network i.e. stream target temperature and heat transfer area constraints are met. The objective in the framework was to maximise retrofit profit, which is the difference between the initial cost of utilities and the sum of the utility cost and retrofit cost after enhancement.

Future research will consider other forms of enhancement. Although heat transfer enhancement using tube inserts provides an adequate degree of energy savings (~8% and ~7% of hot utility based for the illustrative example and case study respectively), it is not always applicable. It will be worthwhile to consider other heat transfer enhancement devices. In addition, future research can also consider the application of heat transfer enhancement in other types of heat exchangers such as plate heat exchangers. The use of heat transfer enhancement with topology modifications and additional heat transfer area to maximise the retrofit profit will be considered in a future paper.

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4.4 Non-Linear Optimisation Model Validation

To authenticate the robustness of the non-linear optimisation model presented in Publications 1 and 2, it is applied on examples presented by Pan et al. (2012). Unlike the proposed non-linear optimisation model, the optimisation carried out by Pan et al. (2012) is a mixed integer linear programming (MILP) model based on two iteration loops. The main aim of this section is to highlight the benefits of using the exact values of nonlinear terms in retrofit as opposed to linearization of these terms to obtain a feasible design. The examples are shown in Figures 4.1 and 4.2 respectively. The full details of the HENs can be found in Pan et al. (2012).

In this work, the LINDO Systems What'*sBest!* Global Solver is used as the optimisation tool for solving the proposed non-linear optimisation model. This solver has not been used in the context of HEN retrofit. What'*sBest!* capitalises on the flexibility of the Excel environment and ease of use. Constraints and relationships for the model are expressed using standard Excel style functions. This makes the models visual and interactive (constraints display their status in forms of violated, satisfied, or precisely satisfied). This makes tracking down any problems with the optimisation model easy. The Global Solver converts the original non-convex, nonlinear problem into several convex, linear sub-problems. The solver makes use of the branch-and-bound technique to ensure the global solution is obtained (LINDO Systems, 2013).

In contrast, the solver employed by Pan et al. (2012) is the CPLEX solver in GAMS. GAMS software, allows the user to develop and work with models that are more complicated. This is due to the presence of large sets of solution algorithms. Therefore, all that is required is the formulation of a good model.

Both models are employed for two objective functions i.e. maximising the retrofit profit, RP (the difference between the profit from energy savings over a specified payback time and the total cost of retrofit) and maximising the energy savings ES. These analyses are carried out by varying the duties and overall heat transfer coefficients of all heat exchangers in the HENs subject to the target temperatures of all streams and the heat transfer area of all heat exchangers being maintained. This is also subject to a fixed minimum temperature approach of 5°K for both examples. Tables 4.1 and 4.2 shows the results obtained for Example 1. From both tables, it can be noted that both solvers identified the same heat exchangers to enhance. This is true for both objective functions. This is also true when applied to the second example HEN. The results obtained are shown in Tables 4.3 and 4.4.

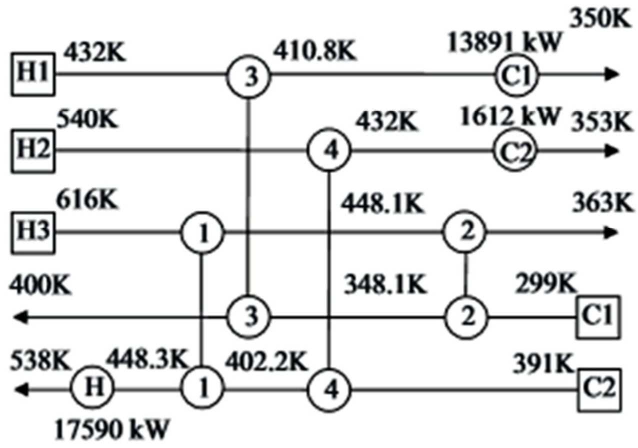

Figure 4.1: Network 1 curled from Pan et al. (2012)

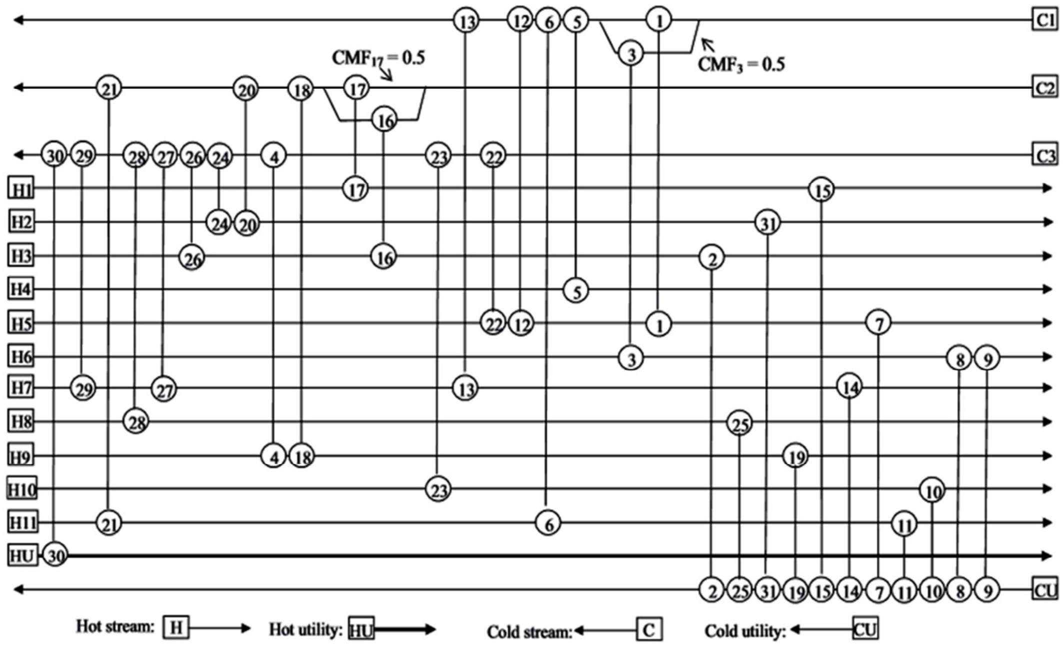

Figure 4.2: Network 2 curled from Pan et al. (2012)

Table 4.1: Maximum retrofit profit (Network 1)

Solver	Enhanced Heat Exchangers	Maximum ES (kW)	Maximum RP ($)
CPLEX: GAMS	1, 3 and 4	5,240	132,747
What's Best!: LINDO System	1, 3 and 4	5,288	132,956

Table 4.2: Maximum duty savings (Network 1)

Solver	Enhanced Heat Exchangers	Maximum ES (kW)	Maximum RP ($)
CPLEX: GAMS	1, 3 and 4	5,462	129,044
What's Best!: LINDO System	1, 3 and 4	5,462	129,032

Table 4.3: Maximum retrofit profit (Network 2)

Solver	Enhanced Heat Exchangers	Maximum ES (kW)	Maximum RP ($)
CPLEX: GAMS	3, 6, 20, 22 – 24, 26 – 28	8,615	204,558
What's Best!: LINDO System	3, 6, 20, 22 – 24, 26 – 28	8,723	222,384

Table 4.4: Maximum duty savings (Network 2)

Solver	Enhanced Heat Exchangers	Maximum ES (kW)	Maximum RP ($)
CPLEX: GAMS	3 – 6, 13,17, 18, 20 – 24, 26 – 29	10,673	107,331
What's Best!: LINDO System	3 – 6, 13,17, 18, 20 – 24, 26 – 29	10,676	102,706

It can be noted from the results presented that the non-linear optimisation model used in this work identifies a better solution compared to the MILP presented by Pan et al. (2012). This is because, the exact correlation for the non-linear terms such as log mean temperature difference have been used as opposed to the linearized version used in the work by Pan et al. (2012). The computational times required for the work by Pan et al. (2012) were around 20 seconds for the first example and less than 40seconds for the second. In contrast, the times for this work are less than a second for the first example and 32 seconds for the second. To conclude, the non-linear optimisation model presented and solved using the Global Solver using LINDO System What's*Best!* is proficient with regards to the retrofit of both small and large scale HENs.

4.5 Summary

Publications 1 and 2 highlight the benefits of heat transfer enhancement in HEN retrofit. The case studies examined in both publications show that energy recovery could be attained without structural modifications and additional heat transfer area. For small scale HENs, the use of sensitivity analysis can be employed. In the case of large HENs, the use of the area ratio approach is recommended, as it is computationally inexpensive and easy to perform. Although an objective function of retrofit profit is employed in both publications, this can be adjusted to suite other retrofit objectives such as maximum energy recovery, minimum operating cost. It is also important to point out that the cost functions used in determining the retrofit cost does not include the engineering costs that may be required with the application of enhancement.

The non-linear optimisation model and solver used in this work has been compared against the work of Pan et al. (2012) for the application of heat transfer enhancement in retrofit and the results show that it is capable for dealing with downstream effects after enhancement, and can identify the best heat exchangers to enhance if an optimisation approach is used. In Publications 1 and 2, only heat transfer area and target temperature are considered as constraints, as the objective is to present a method for the application of heat transfer enhancement. Other practical constraints for the application of heat transfer enhancement are not accounted for (e.g. pressure drop). In Chapter 5, the methodologies with heat transfer enhancement are extended to consider pressure drop.

Chapter 5 Pressure Drop Considerations with Heat Transfer Enhancement

5.1 Introduction to Publication 3

This section tackles the second research objective in Section 1.3 of this thesis and answers the corresponding questions. Pressure drop consideration in retrofit is important, as failure to consider it might lead to an unachievable decrease in energy consumption because pumps or compressors are unable to cope with the increased pressure drop after retrofit. In worst-case scenario, the pumps and compressors might need to be replaced and this may outweigh the profit obtained from energy saving. Publication 3 presents a methodology for considering pressure drop in retrofit.

5.1.1 Pressure Drop Mitigation

This section addresses the question posed in "Objective 2, Question a". Nie and Zhu (1999) presented useful methods for mitigating pressure drop in retrofit. In their work, pressure drop is considered with structural modifications and heat transfer enhancement was only considered as a way of reducing the additional heat transfer area in retrofit. Therefore, Publication 3 employs the methods presented by Nie and Zhu (1999) for pressure drop mitigation with heat transfer enhancement. Publication 3 presents correlations that accurately predict the effect of the enhancement devices studied in Publications 1 and 2. As such, the correct influence of the enhancement devices on pressure drop is known.

5.1.2 Retrofit Methodology

This section addresses the question posed in "Objective 2, Question b". The new method is an extension of the retrofit methodology presented in Publications 1 and 2. A new retrofit methodology that incorporates pressure drop as a constraint, together with heat transfer area and target temperature constraint is presented in the third publication. For a given heat exchanger, there might be various methods for mitigating the increase in pressure drop with enhancement. Therefore, the new methodology includes the definition of a selection factor that identifies the best mitigation technique to use for a given heat exchanger. The final retrofit methodology with the use of heat transfer enhancement is presented in this publication. Although the area ratio approach is used in this work for identifying the best heat exchanger to enhance, sensitivity analysis can also be used, depending on the size of the retrofit problem.

5.2 Publication 3:

Akpomiemie, M. O., and Smith, R., (2016). Pressure drop considerations with heat transfer enhancement in heat exchanger network retrofit.

Pressure drop considerations with heat transfer enhancement in heat exchanger network retrofit

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Abstract

The success of heat exchanger network (HEN) retrofit not only lies in the amount of energy savings that can be obtained but also being able to comply with any pressure drop constraints imposed on the network. The techniques used for heat transfer enhancement increase the performance of the heat exchanger but at a penalty of increased pressure drop. In order for a retrofit design with heat transfer enhancement to be realistic, pressure drop must be considered. The effects of heat transfer enhancement on pressure drop can be mitigated by applying different techniques. For shell and tube heat exchangers, the decision on which technique to apply is dependent on the side that is constrained i.e. shell side or tube side. The variety of options available for pressure drop mitigation can make the process more complex. To effectively solve the problem, a step wise approach for the application of heat transfer enhancement with pressure drop consideration is proposed. The first step is the identification of the heat exchangers that bring about pressure drop violation when enhanced. Pressure drop mitigation techniques can then be applied. Considering there might be multiple mitigation techniques that can be used for a given heat exchanger, a ranking criterion has been defined for the identification of the best modification required. After mitigation techniques have been applied to candidate heat exchangers and the network is no longer constrained by pressure drop, a simple nonlinear optimisation based model is then used, together with the new geometry of modified heat exchangers to apply heat transfer enhancement. Heat transfer enhancement is conducted subject to the target temperatures of all streams being met and no additional heat transfer area required. Heat transfer enhancement, even with pressure drop considerations remains an attractive option for HEN retrofit

as the costs associated with changing the network topology are eliminated, and it requires reduced time for implementation.

Highlights:

- New systematic methodology for consideration pressure drop consideration in heat exchanger networks.
- Pressure drop constraints reduce the degree of enhancement in heat exchangers.
- Energy saving can be accommodated with pressure drop constraints in network retrofit with heat transfer enhancement.

1 Introduction

Environmental concerns regarding global warming and declining energy resources create an urgent need to improve the energy efficiency in process plants. There has been significant research performed on the retrofit of HENs. The objective has been to develop ways of optimising the use of existing exchangers and identifying attractive structural modifications that can be applied to an existing HEN. Recently, there has been increased interest in the use of heat transfer enhancement for retrofit. Retrofit methods can be broadly divided into groups: pinch analysis, mathematical programming and hybrid methods.

In terms of pinch design method, early research on the retrofit of HEN focused on estimating the cost and area requirements for additional exchangers to achieve a retrofit target. Tjoe and Linnhoff [1] first proposed a two-step approach for the retrofit of HENs. In the first step, a retrofit target was established in terms of energy reduction and additional area required. To improve the energy efficiency of the process, modifications were then carried out in the second step. The drawback of this approach is that there is no method for identifying the area distribution within a given HEN. Subsequent research conducted based on the pinch design method overcame this limitation by integrating the area distribution of the existing HEN into the targeting stage [2]. The design method was further modified to include the costs of structural modifications required with each match [3]. This was based on the development of a cost matrix. The cost matrix is used together with a set of heuristic rules, and the capital -energy trade-off is evaluated by producing different design options at varying energy reduction levels. The advantage of pinch analysis is that it encourages user interaction and provides physical insights to the retrofit problem. On the other hand, the heuristic nature results in a very time consuming process, which can be difficult to implement in large HENs.

Mathematical programming methods formulate the retrofit problem as an optimisation task and solves. Ciric and Floudas [4] first proposed a two-step approach which consisted of a match selection and an optimisation step. A mixed integer linear programming (MILP) model was used in the match selection stage to determine the process stream matches, which was then optimised in the optimisation stage using a nonlinear programming (NLP) model to determine the flow configurations in terms of capital cost. The proposed method was later combined into a single step consisting of a mixed integer nonlinear programming (MINLP) model for the retrofit of HENs [5]. This formulation is used in simultaneously optimising all the aspects of retrofit. Yee and Grossmann [6] produced a pre-screening and an optimisation stage for solving retrofit problems with mathematical programming. In the pre-screening stage, the optimal energy recovery and the economic feasibility of the retrofit design were determined using an MILP model. The network was then optimised in the optimisation stage using a detailed MINLP model to determine the number of units required to achieve the optimal retrofit investment. The amount of detail incorporated in the MINLP model restricts it from being applied to large scale problems as a result of the presence of binary variables. Abbas et al. [7] developed a new method based on heuristic rules to solve the retrofit problem based on constraint logic programming (CLP). The heuristic rules used in this method involved shifting a certain amount of heat load between utilities and process heat exchangers by the addition of a new shell to the existing unit, and creating a new utility path by adding a new heat exchanger between utilities. Ma et al. [8] proposed a two-step approach which included a constant approach temperature (CAT) model to optimise the HEN structure in the first step, and an MINLP model, which includes additional variables for exchanger area and takes into account the actual approach temperatures of all heat exchangers, is used in the second step. Sorsak and Kravanja [9] proposed a simultaneous MINLP model based on the original superstructure [10] consisting of different heat exchangers types. The superstructure is updated with heat transfer area of heat exchangers, the type and the location of the heat exchanger in the HEN. Although being automated is a benefit of the mathematical programming method, its lack of user interaction and prolonged computational time required are drawbacks that readily restrict its practical application in industry.

To capitalise on the benefits of pinch analysis and mathematical programming, both methods have been combined to solve the retrofit problem. Briones and Kokossis [11] proposed a three step approach. The first step, the screening stage, involves area targeting and minimisation of modifications simultaneously. In the second stage, an MILP model is developed, taking into account the topology identified in the first stage, to simultaneously optimise heat transfer area and modifications to the existing HEN. A NLP model is then solved using the structure developed in the second stage. Asante and Zhu [12, 13] proposed a two-step approach for solving the HEN problem that combined pinch analysis and mathematical programming. The new method aimed to simplify the retrofit procedure by the use of the network pinch. The network pinch defines the bottleneck of the existing network that limits energy recovery. To overcome the network pinch, structural modifications must be performed on the existing network. In the first step, the diagnosis step, promising structural modifications are identified. The modifications identified are then optimised based on an energy-capital cost trade-off. Smith et al. [14] presented a modified network pinch concept for solving retrofit problems. The novelty of this work is its ability to handle temperature-dependent thermal properties of streams. The diagnosis stage and optimisation stage were combined to eliminate the likelihood of missing cost effective designs. A simulated annealing algorithm is then used in solving the formulated NLP model, together with a feasibility solver.

The methods discussed so far all depend on the need for additional heat transfer area or structural modifications. In retrofit, this might not be ideal as a result of the cost associated with these modifications, layout restrictions and difficulty in implementation. This gave rise to research into the use of heat transfer enhancement techniques in retrofit. The benefits of heat transfer enhancement include its ability to improve the performance of existing heat exchangers without altering the network structure. It is easy to implement, and as such can be done during normal shut down periods. It is generally cheaper to implement heat transfer enhancement than additional heat transfer area or structural modifications. Zhu et al. [15] presented a two-step approach for the implementation of heat transfer enhancement in retrofit. In the first step, the network pinch method is used to identify structural stages for a given HEN. The different enhancement techniques are applied depending on the controlling side (given a shell and tube heat exchanger; shell side or tube side). Up to this point, enhancement has been looked as a way of reducing or eliminating the area requirement after structural modifications are applied. To highlight the benefit of heat transfer enhancement, Pan et al. [16] presented an MINLP model for solving the retrofit problem considering only enhancement. To reduce the computational difficulties associated with the MINLP model, an MILP model was developed to solve the problem. Pan et al. [17] then presented an MILP optimisation model taking into account only tube-side enhancement. The novelty of this work was presenting a way of overcoming the difficulty faced in optimisation as due to the nonlinearities of the log mean temperature difference and the correction factor. The work was then extended by including two iteration loops for solving the retrofit problem with heat transfer enhancement using a simple MILP model [18]. The first loop is solved based on an objective function of energy saving or retrofit profit i.e. the difference between the profit from energy savings and the total cost of retrofit. The maximum energy savings and retrofit profit is then obtained using the second loop. The advantage of this method is that it is able to considerably reduce the computational difficulties due to the nonlinear formulation in the existing HEN retrofit formulations. However, the mathematical approach used limits its application in industry as insights into the interactions within the HEN are not known. To tackle this problem, Wang et al. [19] presented a method for the application of heat transfer enhancement techniques based on heuristics. The proposed methodology highlighted the benefits of network structure analysis and sensitivity analysis in identifying the best heat exchanger to enhance. However, the degree of enhancement in this study cannot be guaranteed, as detailed modelling of heat exchangers was not considered. Jiang et al. [20] extended the proposed method to take into account detailed heat exchanger design. Although a systematic methodology for the application of heat transfer enhancement was presented in both publications [19, 20], ways of dealing with the downstream effects after enhancement was not provided. This is essential as a result of the close interactions between units in the HEN. To tackle this issue Akpomiemie and Smith [21] presented a novel method based on the combination of heuristic rules and a NLP model to solve the retrofit problem with heat transfer enhancement. The methodology presented was based on sensitivity analysis for the identification of the best heat exchanger to enhance. The NLP model was used in eliminating the need for additional heat transfer area after the application of enhancement. Although sensitivity analysis is an efficient method for the identification of the best heat exchanger to enhance, the procedure can be computationally expensive if applied to large scale networks. This is because, the determination of the best heat exchanger to enhance is dependent on a key utility exchanger, and only heat exchangers located on a utility path with the key utility exchanger are considered. This can be problematic if there is more than one utility exchanger. Therefore, to tackle this issue a more robust method i.e. the area ratio approach was developed [22]. The area ratio approach identifies the best heat exchangers to enhance based on the ability of candidate heat exchangers to accommodate for additional heat transfer area. This lends itself to being applicable in large scale HEN for retrofit.

One of the major drawbacks as to why heat transfer enhancement is not readily used in industry is as a result of the pressure drop penalty of enhancement devices. Many studies do not consider pressure drop, which may present a false sense of energy efficiency in existing HEN. A typical assumption made with the use of enhancement is that the existing pumps have enough capacity to cope with the increase in pressure drop due to the application of heat transfer enhancement techniques. This work presents methods that can be used in mitigating pressure drop when heat transfer enhancement is used. A systematic approach that makes use of exchanger modifications with heat transfer enhancement methodology [21, 22] is used. A ranking criterion is presented that helps in identifying the best modification when there are multiple viable options. The new approach presents a more realistic representation of energy saving that can be attained when pressure drop constraints are imposed on process streams. First the retrofit problem with heat transfer enhancement is defined in Section 2. This section also includes the correlations used for detailed modelling of shell and tube heat exchangers with two commonly used tube side enhancement techniques i.e. twisted tape and wire coil inserts. A simple example is used in highlighting the effects of the enhancement techniques on pressure drop. Section 3 then presents the various methods that can be used for pressure drop mitigation. Section 4 presents the retrofit methodology for the application of heat transfer enhancement with pressure drop considerations. This methodology is then applied to the case study and the results obtained discussed. Finally, conclusions and recommendations for improving the proposed methodology are presented in Section 5.

2 Retrofit problem

Although heat transfer enhancement has the ability to provide a good degree of energy saving in an existing network, it is not so readily applied in process industries. This is due to the pressure drop penalty associated with the use of heat transfer enhancement techniques. In an existing HEN, each stream is constrained by a maximum allowable pressure drop. If enhancement is applied, this constraint might be violated. This work is an extension of the novel methodologies for the application of tube side heat transfer enhancement techniques [21, 22]. First it is important to examine the effect of the use of tube side enhancement techniques. Two tube side enhancement techniques commonly used i.e. twisted tape and wire coil inserts, and the correlations for modelling the respective heat transfer coefficients for both inserts are provided in Akpomiemie and Smith [22]. Outlined below are correlations used in calculating the pressure drop when both enhancement techniques are used.

2.1 Twisted tape inserts:

The total pressure drop (ΔP_T) is given by the sum of the pressure drop in the straight tube with twisted tape inserts (ΔP_{TTI}), pressure drop in the tube entrances, exits and reversals (ΔP_{TE}) and the pressure drop in the inlet and outlet nozzle (ΔP_{TN}). To calculate ΔP_{TTI}, Manglik and Bergles [23] proposed a correlation to predict the isothermal Fanning friction factor (cf_T) for a fully developed laminar flow (see Equation 1). The equation is subject to $0 \leq$ Swirl number (Sw) ≤ 2000; $1.5 \leq$ twist ratio (y) $\leq \infty$; $0.02 \leq$ ratio of thickness of tape to tube inner diameter (δ/Di) ≤ 0.12 [23, 24, 25].

$$cf_T = \frac{15.767}{Re_{sw}} \left[\frac{\pi + 2 - 2(\delta/D_i)}{\pi - 4(\delta/D_i)} \right]^2 \left(1 + 10^{-6} Sw^{2.55}\right)^{\frac{1}{6}} \qquad \text{Equation 1}$$

where $$Re_{sw} = \frac{\rho_T u_{sw} D_i}{\mu_T} = Re \frac{\pi}{\pi - 4(\delta/D_i)} \left[1 + \left(\frac{\pi}{2y} \right)^2 \right]^{\frac{1}{2}} \qquad \text{Equation 2}$$

$$u_{sw} = v_T \frac{\pi}{\pi - 4(\delta/D_i)} \left[1 + \left(\frac{\pi}{2y}\right)^2\right]^{\frac{1}{2}} \quad \text{Equation 3}$$

For turbulent flow, [26] proposed the correlation shown in Equation 4. The equation is valid for Re ≥ 10000; and twist ratio (y) of between 2.5 and 10.

$$cf_T = \frac{0.0791}{Re^{0.25}} \left(1 + \frac{2.752}{y^{1.29}}\right) \left[\frac{\pi}{\pi - 4(\delta/D_i)}\right]^{1.75} \left[\frac{\pi + 2 \ - 2(\delta/D_i)}{\pi \ - 4\ (\delta/D_i)}\right]^{1.25} \quad \text{Equation 4}$$

ΔP_{TTI} is given by:

$$\Delta P_{TTI} = 4cf_T \left(\frac{L}{D_i}\right)\left(\frac{\rho_T\, v_T^2}{2}\right) \quad \text{Equation 5}$$

Serth [27] presented a correlation for calculating the pressure drop in the tube entrance, exit and reversal ΔP_{TE} and the pressure loss in the inlet and outlet nozzles ΔP_{TN} (see Equation 6 and 9).

$$\Delta P_{TE} = 0.5\alpha_R \rho_T v_T^2 \quad \text{Equation 6}$$

where

$$\alpha_R = 2N_P - 1.5 \text{ for } Re > 2100 \quad \text{Equation 7}$$

$$\alpha_R = 3.25N_P - 1.5 \text{ for } 500 \leq Re \leq 2100 \quad \text{Equation 8}$$

$$\Delta P_{TN} = \Delta P_{TN,inlet} + \Delta P_{TN,outlet} = C_{TN,inlet}\rho_T v^2_{TN,inlet} + C_{TN,outlet}\rho_T v^2_{TN,outlet} \quad \text{Equation 9}$$

where

$C_{TN,\,inlet} = 0.375$ for $Re_{TN,\,inlet} > 2100$; and $C_{TN,\,inlet} = 0.75$ for $100 \leq Re_{TN,\,inlet} \leq 2100$

$C_{TN,\,outlet} = 0.375$ for $Re_{TN,\,outlet} > 2100$; and $C_{TN,outlet} = 0.75$ for $100 \leq Re_{TN,\,outlett} \leq 2100$

The Reynolds number for the inlet ($Re_{TN,\,inlet}$) and outlet ($Re_{TN,\,outlet}$) and velocity for the inlet ($v_{TN,\,inlet}$) and outlet ($v_{TN,\,outlet}$) nozzle are given in Equations 10 – 13. Both equations are a function of the inner diameter of the inlet and outlet nozzle for the tube-side fluid ($D_{TN,\,inlet}$ and $D_{TN,\,outlet}$ respectively).

$$Re_{TN,\ inlet} = \frac{\rho_T v_{TN,\ inlet} D_{TN,\ inlet}}{\mu_T}$$ Equation 10

$$v_{TN,\ inlet} = \frac{m_T}{\rho_T \left(\frac{\pi D_{TN,\ inlet}^2}{4}\right)}$$ Equation 11

$$Re_{TN,\ outlet} = \frac{\rho_T v_{TN,\ outlet} D_{TN,\ outlet}}{\mu_T}$$ Equation 12

$$v_{TN,\ outlet} = \frac{m_T}{\rho_T \left(\frac{\pi D_{TN,outlet}^2}{4}\right)}$$ Equation 13

The total pressure drop is given by:

$$\Delta P_T = \Delta P_{TTI} + \Delta P_{TE} + \Delta P_{TN}$$ Equation 14

For heat exchangers with multiple shells connected in series, the total pressure drop is the pressure drop calculated using Equation 14 multiplied by the total number of shells.

2.2 Wire coil inserts:

The total pressure drop (ΔP_T) is given by the sum of the pressure drop in the straight tube with wire coil inserts (ΔP_{WCI}), pressure drop in the tube entrances, exits and reversals (ΔP_{TE}) and the pressure drop in the inlet and outlet nozzle (ΔP_{TN}). ΔP_{WCI} is calculated using the pressure drop equation (see Equation 5). However, the friction factor is different in the case of wire coil inserts.

Garcia et al. [28] proposed a correlation for calculating the Fanning friction factor (cf_W) for 2000 < Re < 30000 (see Equation 15).

$$cf_W = 9.35 \left(\frac{p}{e}\right)^{-1.16} Re^{-0.217}$$ Equation 15

Ravigururajan and Bergles [29] proposed a correlation for calculating the Fanning friction factor for 30000 < Re < 250000 in augmented tube with structured roughness (see Equation 16).

$$cf_W = cf_s \left\{1 + \left[29.1 Re^{a1} \left(\frac{e}{D_i}\right)^{a2} \left(\frac{p}{D_i}\right)^{a3} \left(\frac{\alpha}{90}\right)^{a4}\right]^{\frac{15}{16}}\right\}^{\frac{16}{15}}$$ Equation 16

where $a_1 = 0.67 - 0.06\left(\frac{p}{D_i}\right) - 0.49\left(\frac{\alpha}{90}\right)$ Equation 17

$$a_2 = 1.37 - 0.157\left(\frac{p}{D_i}\right) \quad \text{Equation 18}$$

$$a_3 = -1.66 \times 10^{-6}Re - 0.33\left(\frac{\alpha}{90}\right) \quad \text{Equation 19}$$

$$a_4 = 4.59 + 4.11 \times 10^{-6}Re - 0.15\left(\frac{p}{D_i}\right) \quad \text{Equation 20}$$

$$\left(\frac{\alpha}{90}\right) = \frac{2}{\pi}\tan^{-1}\frac{\pi}{\left(\frac{p}{D_i}\right)} \quad \text{Equation 21}$$

Filonenko [30] defined a correlation for the smooth tube friction factor (cf_s):

$$cf_s = (1.58\ln Re - 3.28)^{-2} \quad \text{Equation 22}$$

The total pressure drop is given by:

$$\Delta P_T = \Delta P_{WCI} + \Delta P_{TE} + \Delta P_{TN} \quad \text{Equation 23}$$

Similar to twisted tape inserts, heat exchangers with multiple shells connected in series, the total pressure drop is the pressure drop calculated in Equation 23 multiplied by the total number of shells.

2.3 Example

Table 1 shows the details of an example heat exchanger. The heat exchanger was modelled using the correlations provided for twisted tape and wire coil inserts to calculate the pressure drop of the heat exchanger before [22] and after enhancement. Table 2 shows the results obtained. Assumed parameters for twisted tape insert include a twist ratio of 5 and a tape thickness of 0.001m. In terms of wire coil insert, an axial roughness pitch (p) and roughness height (e) of 0.0425 and 0.0016m respectively are used.

Table 1: Exchanger Data

Fluids		Shell side		Tube Side
Heat Capacity Flowrate C_p (J/kg °C)		2273		2303
Thermal Conductivity k (W/m °C)		0.08		0.0899
Viscosity μ (Pa s)		1.89E-04		9.35E-04
Density ρ (kg/m^3)		966		791
Mass Flow rate m (kg/s)		46.25		202.54
Inlet Temperature T_{in} (°C)		227		131
Fouling Resistance (m^2 °C /W)		0.00053		0.00053
Heat exchanger geometry				
Tube Pitch P_T (m)	0.03125	Number of Baffles n_b		25
Number of Tubes N_t	612	Baffle Spacing B (m)		0.22
Number of Passes N_p	2	Inlet Baffle Spacing B_{in} (m)		0.3117
Tube Length L (m)	6	Outlet Baffle Spacing B_{out} (m)		0.3117
Tube Effective Length L_{eff} (m)	5.9	Baffle cut B_c		20%
Tube Conductivity k_{tube} (W/m K)	51.91	Inner Diameter of Tube-side Inlet Nozzle $D_{T,inlet}$ (m)		0.336
Tube Layout Angle	90	Inner Diameter of Tube-side Outlet Nozzle $D_{T,outlet}$ (m)		0.336
Bundle Configuration	Straight Tube Bundle	Inner Diameter of Shell-side Inlet Nozzle $D_{S,inlet}$ (m)		0.154
Tube Inner Diameter D_i (m)	0.02	Inner Diameter of Shell-side Outlet Nozzle $D_{S,outlet}$ (m)		0.154
Tube Outer Diameter D_o (m)	0.025	Shell-Bundle Diametric Clearance L_{sb} (m)		0.069
Shell Inner Diameter D_s (m)	0.97	Shell arrangement (series x parallel)		2 x 1

Table 2: Enhancement Results

	Tube Side		Shell side	
	h_T (kW/m^2 °C)	ΔP_T (kPa)	h_S (kW/m^2 °C)	ΔP_S (kPa)
Base Case	1.58	95.23	1.91	69.09
Twisted Tape	2.64	130.32	1.91	69.09
Wire Coil	3.26	111.51	1.91	69.09

From the result shown in Table 2, the use of both enhancement techniques led to an increase in the pressure drop by 36.9% for twisted tape and 17.1% for wire coil inserts. In this case, the existing pumps might not be able to cope with the increase in pressure drop. This problem can be solved by installing additional pumps either as replacements or in series with existing ones or retrofitting the existing pumps. However, in retrofit, it might not be economic to consider the installation of pumps with increased capacity. Therefore, presenting different methods for mitigating the increase in pressure drop with enhancement is vital.

3 Pressure drop mitigation

The example studied in the previous section highlights the effect of heat transfer enhancement on both heat transfer coefficient and pressure drop. Not only does the heat transfer enhancement techniques used increase the heat transfer coefficient, but also the pressure drop. With the exception of installing a pump to cope with the increase in pressure drop, other methods can be considered for pressure drop mitigation. Methods used in mitigating pressure drop are discussed in more detail in the following sections.

3.1 Tube passes:

Modifying the tube passes in existing heat exchangers is one way of reducing the pressure drop. Reducing the tube passes in existing heat exchangers results in a decrease in the tube-side flow velocity but the overall performance of the heat exchanger can still be improved with the use of heat transfer enhancement. Examples of common tube passes used in the design of shell and tube heat exchangers are one, two, four, six, eight, ten and twelve. Based on this existing number of tube passes, there are different possible options for the tube pass reduction (see Table 3). The proposed modifications are relatively simple to implement. From the majority of the retrofit options proposed in Table 3, two underlying principles that can be stated are that the tubes for each pass should be the same after decreasing tube passes and no new partition installation channels can be installed.

Table 3: Options for reducing tube passes

Tube passes	Retrofit options	Actions required
One	None	None
Two	Reduce the number of tube passes to one	1) Remove all the partitions; 2) Replace the existing heads with two new heads; 3) Rearrange or repipe the flows if necessary
Four or Eight	Reduce the number of tube passes to two	1) Remove all the partitions; 2) Replace the existing heads with two new heads; 3) Install a new partition in the middle of the front head; 4) Rearrange or repipe the flows if necessary
	Reduce the number of tube passes to one	1) Remove all the partitions; 2) Replace the existing heads with two new heads; 3) Rearrange or repipe the flows if necessary
Six or Ten	Reduce the number of tube passes to two	Remove all partitions except the middle one in the front head
	Reduce the number of tube passes to one	1) Remove all the partitions; 2) Replace the existing heads with two new heads; 3) Rearrange or repipe the flows if necessary
Twelve	Reduce the number of tube passes to four	Remove some partitions and retain those in the typical 4-tube-pass layout

	Reduce the number of tube passes to two	1) Remove all the partitions; 2) Replace the existing heads with two new heads; 3) Install a new partition in the middle of the front head; 4) Rearrange or repipe the flows if necessary
	Reduce the number of tube passes to one	1) Remove all the partitions; 2) Replace the existing heads with two new heads; 3) Rearrange or repipe the flows if necessary

This technique is used in reducing the tube side pressure drop. Therefore, considering the example heat exchanger provided in Table 1, the pressure drop after the application of heat transfer enhancement can be reduced by modifying the tube passes. There are two tube passes in this example heat exchanger. From Table 3, the only option available is to reduce the number of tube passes from two to one. Table 4 shows the result obtained when this procedure was applied.

Table 4: Result from tube pass reduction

	Before Modification		After Modification	
	h_T (kW/m^2 °C)	ΔP_T (kPa)	h_T (kW/m^2 °C)	ΔP_T (kPa)
Base Case	1.58	95.23	0.905	21.26
Twisted Tape	2.64	130.32	1.51	42.23
Wire Coil	3.26	111.51	1.98	49.77

From Table 4, it can be noted that the heat transfer coefficient in the base case scenario decreases as a result of the decrease in the number of tube passes. However, the decrease in performance can be compensated for with the use of enhancement in particular. In this case, a wire coil insert has been used, which was still able to provide a degree of enhancement compared to the base case but at a lower pressure drop. In summary, this example shows that modifying the number of tube passes can mitigate the increase in pressure drop with the use of heat transfer enhancement.

However, this comes at a penalty of decreased level of enhancement when compared to the scenario where pressure drop is not considered.

3.2 Modification of shell arrangement:

In retrofit, the presence of more than one shell in a heat exchanger allows for an opportunity to reduce its pressure drop requirement. The total pressure drop of the heat exchanger is dependent on the shell arrangement of the total number of shells. Different shell arrangements have a significant impact on pressure drop. For example, for a two shell heat exchanger, the shells can either be arranged in series or in parallel (see Figure 1). In the case of the series arrangement of shells, the total pressure drop is the sum of pressure drop of both shells. In the series arrangement, the entire flow goes through both shells resulting in pressure drop and heat transfer coefficient that are relatively high. On the other hand, with parallel arrangement, the total pressure drop is given by the maximum pressure drop in either of the shells. With a parallel arrangement, the heat transfer coefficient and pressure drop are lower as the flow going through each shell is lower than that of series arrangement.

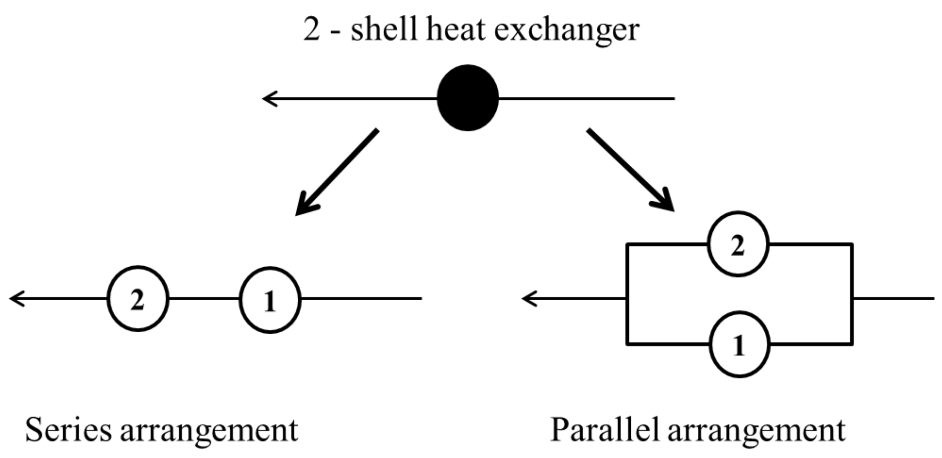

Figure 1: Shell arrangement

In the case where there are more than two shells in a heat exchanger, a mixed arrangement can be used (see Figure 2). In this case, each shell has intermediate heat transfer coefficients and pressure drops compared to the series and parallel arrangements.

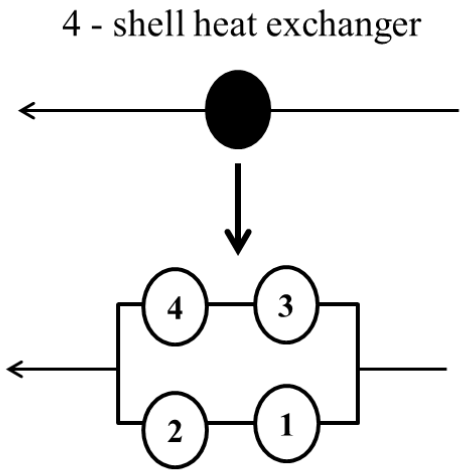

Figure 2: Mixed arrangement (2series, 2 parallel)

This technique can be used in reducing both the shell and tube side pressure drop requirement. Again, considering the example heat exchanger provided in Table 1, it is assumed that the two shells are in series. Therefore, to reduce the pressure drop we can modify the shell arrangement from series to parallel. A split ratio of 0.5 is assumed for both the shell and tube side analysis. Tables 5 and 6 show the result obtained when this approach was applied to reduce the shell and tube side pressure drop respectively.

Table 5: Shell side mitigation

	Before Modification		After Modification	
	h_S (kW/m^2 °C)	ΔP_S (kPa)	h_S (kW/m^2 °C)	ΔP_S (kPa)
Base Case	1.91	69.09	1.21	18.92
Twisted Tape	1.91	69.09	1.21	18.92
Wire Coil	1.91	69.09	1.21	18.92

Table 6: Tube side mitigation

	Before Modification		After Modification	
	h_T (kW/m^2 °C)	ΔP_T (kPa)	h_T (kW/m^2 °C)	ΔP_T (kPa)
Base Case	1.58	95.23	0.905	27.31
Twisted Tape	2.64	130.32	1.51	37.61
Wire Coil	3.26	111.51	1.98	45.16

The results show that modifying the shell arrangement resulted in a decrease in both the heat transfer coefficients and the pressure drop for both cases. Also, the result obtained in Table 6 is the same as that obtained for reducing the number of tube passes from two to one (see Table 4) in terms of heat transfer coefficients. This result is expected as the velocity of the tube-side in both cases decreases by a factor of half. However, the pressure drop is different from that of reducing the number of tube passes due to the tube-side entrance and exit pressure drop losses, which is a factor of the number of tube passes (see Equations 7 and 8).

3.3 Heat transfer enhancement

The general perception of heat transfer enhancement is that it not only increases the performance of heat exchangers, but also increases pressure drop. This assertion is true for most enhancement devices but not all. An example of enhancement device that can aid in reducing the pressure drop in heat exchangers is helical baffles. Helical baffles are known to actually have a greater impact in terms of reducing pressure drop than increasing heat transfer coefficient [31]. They are also known to reduce the heat transfer coefficient in some cases. Helical baffles are mostly used when there is a need to reduce the pressure drop in the shell side as it is a form of shell side enhancement technique. Zhang et al. [32] presented useful correlations in calculating the shell side heat transfer coefficient with helical baffles (h_{SHB}) and pressure drop using helical baffles (ΔP_{SHB}). The shell side heat transfer coefficient is determined from the Nusselt number (Nu_{SHB}) correlation shown in Equation 24 where A and B are constants that depends on the type of baffle used.

$$Nu_{SHB} = \frac{h_{SHB} D_o}{k_s} = A\, Re_s^B\, Pr_s^{1/3} \qquad \text{Equation 24}$$

where $\quad Re_s = \text{Shell side Reynolds number} = \frac{\rho_s u_s D_o}{\mu_s} \qquad$ Equation 25

$$Pr = \text{Shell side Prandtl number} = \frac{C_{ps} \mu_s}{k_s} \qquad \text{Equation 26}$$

The friction factor (cf_{SHB}) is dependent on the shell side Reynolds number, as shown in Equation 27, where C and D are constants dependent on the baffle type.

$$cf_{SHB} = C\, Re_s^D \qquad \text{Equation 27}$$

The pressure drop for helical baffles can then be calculated using the correlation shown in Equation 28. Variables for each constant (A, B, C and D) are given in Table 7.

$$\Delta P_{SHB} = \frac{2\, cf_{SHB}\, N_t\, L\, \rho_s\, u_s^2}{X} \qquad \text{Equation 28}$$

where $$X = \sqrt{2D_s}\, \tan\beta \qquad \text{Equation 29}$$

Table 7: Coefficients of constants A, B, C and D [32]

Baffle type	A	B	C	D
Helical baffles, β = 20°	0.275	0.542	11.0	-0.715
Helical baffles, β = 30°	0.365	0.516	13.5	-0.774
Helical baffles, β = 40°	0.455	0.488	34.7	-0.806
Helical baffles, β = 50°	0.326	0.512	47.9	-0.849

The total pressure drop when helical baffles are used is the sum of the pressure drop in the straight section with helical baffles and the pressure drop in the nozzles (ΔP_{SN}).

$$\Delta P_S = \Delta P_{SHB} + \Delta P_{SN} \qquad \text{Equation 30}$$

For heat exchangers with multiple shells, the pressure drop calculated using Equation 30 is multiplied by the total number of shells.

To examine the influence on helical baffles on heat transfer coefficient and pressure drop; helical baffles are implemented in the example heat exchanger shown in Table 1. Table 8 confirms that helical baffles not only reduce the shell side pressure drop but also the heat transfer coefficient. Based on this example, the best baffle type to use will be 30°, as the degree of enhancement between this baffle and that at 40° is close, but the difference in pressure drop is considerable.

Table 8: Application of helical baffles

	Shell side	
	h_S (kW/m^2 °C)	ΔP_S (kPa)
Base Case	1.91	69.09
Helical baffles, β = 20°	0.848	67.87
Helical baffles, β = 30°	0.832	32.27
Helical baffles, β = 40°	0.748	37.23
Helical baffles, β = 50°	0.709	25.86

3.4 Other practical methods

Nie and Zhu [33] identified four other opportunities that can be applied in practice to tackle pressure drop problems when looking at a HEN. The opportunities identified are as follows.

Option 1: Exploiting streams with spare pressure drop capacity:

This opportunity arises from the fact that in a given HEN, not every stream will have a pressure drop constraint. Therefore, a certain amount of heat load can be shifted between exchangers on constrained and unconstrained streams.

Option 2: Releasing pressure drop from existing heat exchangers on the same stream:

The shell arrangements of each heat exchanger on the stream can be manipulated to reduce the pressure drop requirement of the stream. This releases the pressure drop and allows for heat transfer enhancement techniques to be applied, while still maintaining the pressure constraint of the stream. Also, if the shell arrangement of a heat exchanger is modified from series to parallel, this not only reduces the pressure drop requirement, but also increases the performance of heat exchangers located downstream. As such, the overall energy performance is improved.

Option 3: Modifying the existing pumps to increase the allowable pressure drop requirement:

This is often not a desirable option in retrofit due to the cost associated with pump modification. However, if this is an option the pump capacity can be improved by methods such as increasing the impeller size or increasing the rotating speed of the pump. This increases the discharge pressure and the allowable pressure drop of the HEN.

Option 4: Exploiting utility conditions:

Modifications made to a heat exchanger might result in the violation of target temperatures of streams which contain that heat exchanger. Ordinarily, additional heat transfer area can be added to existing heat exchangers in order to maintain the energy balance. However, this might result in an increase in the pressure drop beyond the allowable limit of the existing pump. With this method, utilities are either replaced with higher temperature utility or one with a higher heat transfer coefficient, instead of increasing the heat transfer area of existing heat exchangers.

In addition to the practical methods presented by Nie and Zhu [33], other methods can be used in mitigating pressure drop in the shell and tube sides. In terms of shell side pressure drop mitigation, the baffle cut, baffle spacing and tube pitch can be increased. Other methods include changing the tube pitch configuration from triangular to square or rotated to in-line or use an alternative baffle design. For tube side mitigation, the tube length can be decreased; the shell diameter and tube diameter can be increased. In summary, it is important to point out that although these methods might be able to mitigate pressure drop requirement, it is always advisable to explore the effect of performing these modifications in terms of cost.

4 Retrofit methodology

The methodology shown in Figure 3 shows the proposed approach for considering pressure drop with heat transfer enhancement in retrofit. Given that this is a retrofit problem, it is assumed that the heat exchanger data are available.

Step 1: Given the base case heat exchanger data, the first step is the identification of the best heat exchanger to enhance. This procedure is a two-step approach as described in [21, 22]. The first step is the identification of heat exchangers on a utility path. Then either sensitivity analysis [19, 20 and 21] or the area ratio approach [22] can be used in determining the best heat exchanger to enhance.

Step 2: In the second step, the chosen enhancement technique is then applied to the best heat exchanger identified in Step 1.

Step 3: The stream pressure drop is then checked after enhancement. If there are pressure drop violations, the mitigation techniques described in Section 3 is applied (Step 3.1). If not continue to Step 4. The decision on what technique to apply depends on the stream that is constrained. For example, if the shell side is constrained, helical baffles or changing the shell arrangements could be considered. If on the other hand, the constraint is on the tube side, then reduction in the number of tube passes or change in the shell arrangement could be considered. Given the new exchanger geometry and data, the new heat transfer coefficient and pressure drop for the new base case and enhanced conditions could be determined. In situations where there is more than one mitigation option, a ranking criterion is required to determine the best modification option. The ranking criterion (SF) is defined as the change in pressure drop with respect to the change in the degree of enhancement before and after applying modifications (Equation 31). The best option is one with the smallest selection factor, as this signifies the modification that can still provide a higher degree of enhancement with the lowest pressure drop penalty.

$$SF = \left(\frac{\Delta P_{N,E} - \Delta P_N}{\Delta P_{B,E} - \Delta P_B}\right)\left(\frac{U_{B,E} - U_B}{U_{N,E} - U_N}\right) \qquad \text{Equation 31}$$

Step 4: After satisfying the pressure drop constraint, the network is then checked for heat transfer area and target temperature constraint violations. This is essential, as the aim is to apply heat transfer enhancement without the need for additional heat transfer area, while ensuring energy balance is maintained. If the constraints are not violated, continue to Step 6 otherwise continue to Step 5.

Step 5: In case of constraint violations, a non-linear optimisation model can then be applied. The non-linear optimisation model is similar to that presented in [21, 22]. However, it has been modified to take into account the cost associated with the application of the mitigation techniques. The objective function is still to maximise the retrofit profit (RP) where:

$$RP = UC_B - \left[UC_E + \sum_{ex \in EX} RC_{ex} \right] \quad \text{Equation 32}$$

In this case, the retrofit cost includes the cost of modifications and is given by:

$$RC_{ex} = EC_{ex} \times EF_{ex} + AC_{ex} \times EF_{ex} + BC_{ex} \times EF_{ex} + MC_{ex} \times EF_{ex} \qquad \forall_{ex} \in EX \quad \text{Equation 33}$$

where, EC_{ex} is the enhancement cost of exchangers, AC_{ex} is the additional area cost, BC_{ex} is the cost of bypass, and MC_{ex} is the modification cost. An enhancement factor, EF, is assigned to each individual cost. If a heat exchanger is enhanced, additional area is required, bypass is required or modifications are made to the exchanger geometry then this value is one otherwise, zero. Correlations shown in Equations 34 and 35 are used in calculating the utility cost before and after enhancement a CCU and CHU are the yearly cost parameter for cold and hot utility, Q_B and Q_E are the duty before and after enhancement and OT is the operating time.

$$UC_B = OT \times \left[CCU \times \sum_{ex \in EX_{CU}} Q_{B,ex} + CHU \times \sum_{ex \in EX_{HU}} Q_{B,ex} \right] \quad \text{Equation 34}$$

$$UC_E = OT \times \left[CCU \times \sum_{ex \in EX_{CU}} Q_{E,ex} + CHU \times \sum_{ex \in EX_{HU}} Q_{E,ex} \right] \quad \text{Equation 35}$$

The aim of the optimisation model is to be able to apply heat transfer enhancement without the need for additional heat transfer area and ensuring the target temperatures of all streams are met (see Equations 36 – 38). Equations 36 to Equation 38 represent the constraints for heat transfer area requirement, for all cold and hot streams, CS and HS. A_{ex} and A_E represent the heat transfer area of all process heat exchangers before and after the application of enhancement. EX^{i}_{CS}, EX^{o}_{CS}, EX^{i}_{HS}, EX^{o}_{HS} describe the set of all exchangers located at the inlet and outlet of all cold and hot streams respectively. $TCOS_{CS}$ and $THOS_{HS}$ represent the cold and hot outlet stream temperatures.

$$A_{ex} = A_E \qquad \forall_{ex} \in EX_E \quad \text{Equation 36}$$

$$TCO_{ex} = TCOS_{CS} \qquad \forall_{ex} \in EX^{o}_{CS} \quad \text{Equation 37}$$

$$\mathrm{THO_{ex} = THOS_{CS}} \qquad \forall_{\mathrm{ex}} \in \mathrm{EX_{HS}^{o}} \qquad \text{Equation 38}$$

Variables used in this model are the overall heat transfer coefficient of all process heat exchangers, subject to this value not exceeding the maximum determined based on the exchanger geometry. The duty of all heat exchangers on a utility path is another variable used in this model. It is important to point out that although the overall heat transfer coefficients of heat exchangers not on a utility path are varied, this is done at constant heat exchanger duty.

Step 6: Given that the retrofit objective is to maximise the retrofit profit, after the application of the non-linear optimisation model, if the retrofit profit before enhancement is greater than that after, the procedure is stopped. This means that the profit obtained from applying enhancement is less than the cost of retrofit. As such, it is uneconomic. If this is not the case, proceed to Step 7.

Step 7: There might be more than one heat exchanger that can improve energy recovery. If so, other candidate heat exchangers are sorted and the procedure is repeated. If all potential for energy recovery has been explored, the procedure can then be terminated.

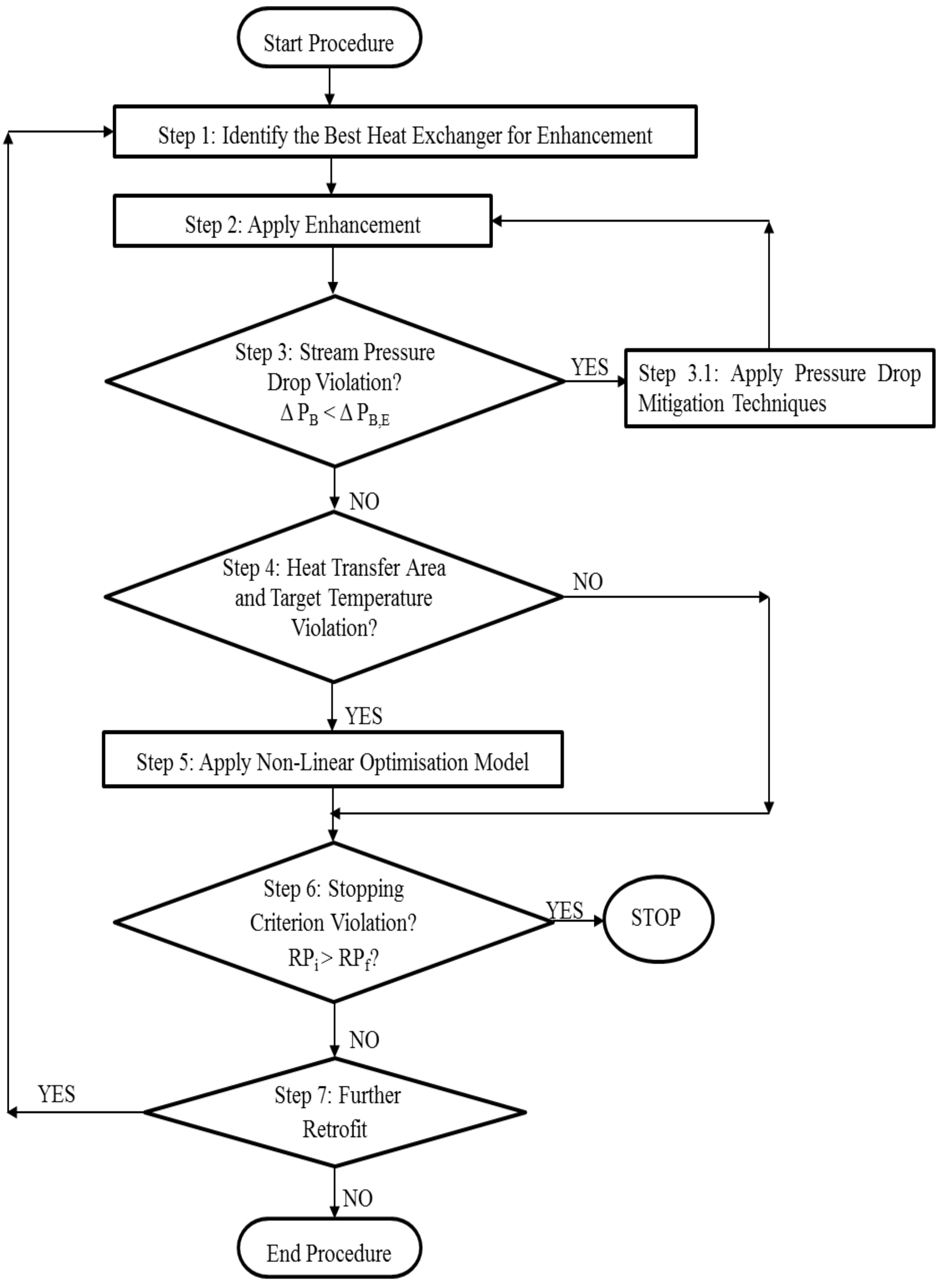

Figure 3: Retrofit methodology with pressure drop and heat transfer enhancement

5 Case Study

The case study shown in Figure 4 depicts a simplified crude-oil pre heat train [21, 22]. Table 9 shows the data for each process heat exchanger in the network. The objective is to present a retrofit design with the maximum retrofit profit while minimising the energy consumption of the hot utility (exchanger 12) and maintaining the pressure drop, heat transfer area and target temperature constraints in the network. Table 9 and 10 shows the original heat exchanger and stream data for the case study, including the maximum pressure drop of each process stream in the HEN.

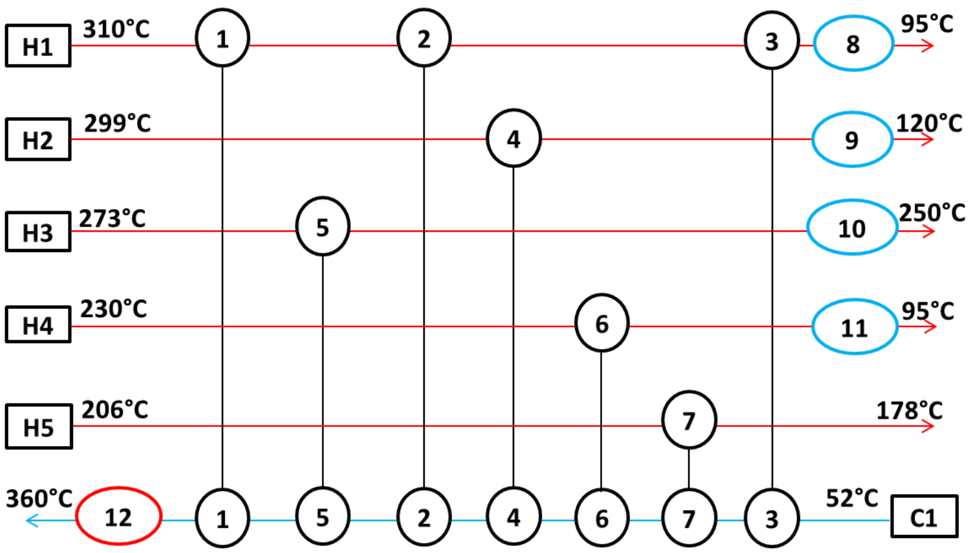

Figure 4: Case study

Table 9: Original Heat Exchanger Data

Ex.	A (m^2)	h_s (kW/m^2°C)	ΔP_S (kPa)	h_T (kW/m^2°C)	ΔP_T (kPa)	U (kW/m^2°C)	Q (kW)
1	396.72	2.07	78.49	1.33	167.29	0.52	6141.33
2	545.45	2.31	100.80	1.40	131.40	0.48	6134.83
3	633.85	4.54	75.76	0.78	73.43	0.16	5556.61
4	354.64	1.27	4.27	0.62	45.38	0.10	2688.79
5	183.85	2.56	98.38	0.78	15.73	0.32	3431.16
6	843.73	0.96	14.66	0.49	146.74	0.06	2291.88
7	114.28	3.38	91.09	0.98	88.54	0.36	3623.20
8	-	-		-		-	657.23
9	-	-		-		-	1141.81
10	-	-		-		-	816.94
11	-	-		-		-	880.62
12	-	-		-		-	14455.41

Table 10: Stream Details

Stream	CP [kW/°C]	TS [°C]	TT [°C]	Q [kW]	Maximum ΔP (kPa)
H1	86	310	95	18,490.0	400
H2	21.4	299	120	3,830.6	200
H3	184.7	273	250	4,248.1	200
H4	23.5	230	95	3,172.5	200
H5	129.4	206	178	3,623.2	100
C1	143.91	52	360	44,323.2	700

The first step is the identification of the best heat exchangers to enhance. In this work, only tube side enhancement techniques are considered and in particular, twisted tape inserts are used, as they brought about the greatest degree of enhancement in all candidate process heat exchangers. The geometric details of all candidate heat exchangers are given in Table 11. The area ratio approach [22] is used in determining the enhancement sequence for this case study. Table 12 shows the results obtained for each candidate heat exchanger. It is important to point out that result for Exchanger 7 is not provided as it is the only process heat exchanger not on a utility path. From Table 12, the best heat exchanger for enhancement is Exchanger 5, as it has the smallest area ratio (i.e. signifies the heat exchanger that can accommodate for the greatest increase in heat transfer area, and as such greatest decrease in utility consumption).

After enhancing Exchanger 5, the pressure drop on stream C1 is then checked for pressure drop violation. Applying enhancement to Exchanger 5, results in an increase in its tube side pressure drop from 15.73kPa to 37.67kPa. Initially, the total pressure drop of stream C1 was 668.51kPa. After enhancement, this value increases to 690.45kPa, which is below the maximum allowable pressure drop in stream C1. Therefore, the next step in the retrofit process is to check for heat transfer area and target temperature violations.

Enhancing Exchanger 5 resulted in a decrease in the driving force for Exchanger 1. At constant duty, additional heat transfer area is required in Exchanger 1 to maintain the target temperatures. Therefore, the non-linear optimisation model is applied. The optimisation was carried out using the LINDO system What’s Best global solver

[34]. Table 13 shows the cost data for the utilities and cost of modifications. Table 14 shows the result obtained after enhancing Exchanger 5 and applying the non-linear optimisation model. From Table 14, enhancing exchanger 5 can bring about a total retrofit profit of ~3% of the initial utility cost of $5,801,395.

Table 11: Detailed exchanger geometry

Heat exchanger geometry	Ex.1	Ex.2	Ex.3	Ex.4	Ex.5	Ex.6
P_T (m)	0.025	0.025	0.025	0.025	0.025	0.025
N_t	1032	985	1192	798	665	985
N_p	4	2	2	2	2	2
L (m)	6.4	9.3	8.5	7.4	4.4	13.6
k_{tube} (W/m°C)	51.91	51.91	51.91	51.91	51.91	51.91
Tube Layout Angle	90	90	90	90	90	90
D_i (m)	0.015	0.015	0.016	0.016	0.016	0.016
D_o (m)	0.019	0.019	0.020	0.020	0.020	0.020
D_s (m)	1.02	1.00	1.10	0.90	0.82	1.00
n_b	41	41	41	41	41	41
B (m)	0.3	0.3	0.3	0.3	0.488	0.25
B_{in} (m)	0.127	0.127	0.127	0.127	0.488	0.127
B_{out} (m)	0.127	0.127	0.127	0.127	0.488	0.127
B_c	20%	20%	20%	20%	25%	20%
$D_{T,inlet}$ (m)	0.1023	0.1023	0.1023	0.1023	0.3048	0.1023
$D_{T,outlet}$ (m)	0.1023	0.1023	0.1023	0.1023	0.3048	0.1023
$D_{S,inlet}$ (m)	0.079	0.079	0.079	0.079	0.3048	0.079
$D_{S,outlet}$ (m)	0.079	0.079	0.079	0.079	0.3048	0.079
L_{sb} (m)	0.074	0.074	0.071	0.071	0.041	0.071

Table 12: Area Ratio Result

Exchangers	U (kW/m^2°C)	U_E(kW/m^2°C)	A_R
1	0.517	0.669	0.773
2	0.475	0.597	0.795
3	0.158	0.198	0.798
4	0.0963	0.108	0.891
5	0.325	0.448	0.725
6	0.610	0.674	0.905

Table 13: Cost Data

Utility Cost Data	Retrofit Cost Data
Hot Utility Cost: 400 ($/kW y)	Cost of Inserts: 500 + 10*A ($)
Cold Utility Cost: 5.5 ($/kW y)	Implementing By-Pass: 500 ($)
	Cost of Increasing Heat Exchanger Area: 4000 + 200*A ($)
	Cost of modifying shell arrangement: 10,000($)
	Cost of modifying tube passes: 5,000 ($)

Table 14: Enhancement Result after Enhancing Exchanger 5

Retrofit Cost	Enhancement	$2,338
	Modification for Pressure Drop Mitigation	$0
	Increasing Area	$0
	Implementing By-pass	$500
	Total Cost	$2,838
Retrofit Profit	Utilities Savings	$178,076
	Net Saving (Utility Savings - Total Cost)	**$175,238 (~3.0% of initial utility cost)**

The next step is to explore other opportunities for energy recovery. The next candidate heat exchanger for enhancement is Exchanger 1. Applying tube side enhancement to Exchanger 1 not only results in an increase of its overall heat transfer coefficient from 0.52 kW/m^2°C to 0.67 kW/m^2°C, but also the pressure drop from 167.29kPa to 169.25kPa. The total pressure drop of stream C1 has now increased to 692.41kPa. Again this is below the maximum allowable pressure drop, and as such the retrofit procedure can proceed to the next step which is dealing with heat transfer area and target temperature violations. The final result obtained after enhancing Exchanger 1 is given in Table 15.

Table 15: Enhancement Result after Enhancing Exchanger 5 and 1

Retrofit Cost	Enhancement	$8,448
	Modification for Pressure Drop Mitigation	$0
	Increasing Area	$0
	Implementing By-pass	$1,500
	Total Cost	$9,948
Retrofit Profit	Utilities Savings (relative to initial utility cost)	$321,924
	Net Saving (Utility Savings - Total Cost)	**$311,976 (~5.4% of initial utility cost)**

The procedure is repeated for the next best heat exchanger i.e. Exchanger 2. In the case of Exchanger 2, the pressure drop after enhancement increased from 131.40kPa to 163.31kPa. This increased the total pressure drop of Stream C1 to a value of 724.32kPa. Therefore, pressure drop mitigation techniques must be applied. Exchanger 2 has two shells arranged in series and two tube passes. In this case, there are two options available i.e. reducing the number of tube passes from two to one and changing the shell arrangement from series to parallel. A split fraction of 0.5 is assumed for the case of changing shell arrangement. In this case, the selection of the best modification is based on the ranking criterion (SF). From the result shown in Table 16, the modification of the shell arrangement is the best, as it has the lowest value for SF.

Table 16: Modification for Exchanger 2

	Base Case				After Modification				SF
	U_B (kW/m^2°C)	$U_{B,E}$ (kW/m^2°C)	ΔP_B (kPa)	$\Delta P_{B,E}$ (kPa)	U_N (kW/m^2°C)	$U_{N,E}$ (kW/m^2°C)	ΔP_N (kPa)	$\Delta P_{N,E}$ (kPa)	
Original Design	0.475	0.597	131.40	163.31	-	-	-	-	-
Tube pass reduction (two to one)	0.475	0.597	131.40	163.31	0.356	0.490	113.80	125.48	0.33
Shell Modification (series to parallel)	0.475	0.597	131.40	163.31	0.361	0.494	33.77	43.22	0.27

The modification is applied based on the degree of enhancement after shell modification to Exchanger 2 is applied. The network is checked for violations and if there are any, the violations are corrected using the non-linear optimisation model. The retrofit profit obtained after enhancing Exchanger 2 (see Table 17) is less than that before. Therefore, the result obtained is discarded, as it is not economic to apply enhancement. The final details of all heat exchangers after enhancement with pressure drop consideration are given in Table 18.

Table 17: Enhancement Result after Enhancing Exchanger 5, 1 and 2

Retrofit Cost	Enhancement	$14,323
	Modification for Pressure Drop Mitigation	$10,000
	Increasing Area	$0
	Implementing By-pass	$1,500
	Total Cost	$25,823
Retrofit Profit	Utilities Savings (relative to initial utility cost)	$242,017
	Net Saving (Utility Savings - Total Cost)	**$216,194 (~3.9% of initial utility cost)**

Table 18: Final Heat Exchanger Data

Ex	A (m^2)	U_F ($kW/m^2°C$)	ΔT_{LM} (°C)	F_T	Q (kW)	ΔP_T (kPa)	ΔP_S (kPa)
1	396.72	0.67	28.29	0.88	6104.73	169.25	78.49
2	545.45	0.48	29.00	0.82	6162.68	131.40	100.80
3	633.85	0.16	62.80	0.88	5561.54	73.43	75.76
4	354.64	0.10	84.06	0.94	2688.32	45.38	4.27
5	183.85	0.45	53.53	0.96	4230.13	37.67	98.38
6	843.73	0.06	46.00	0.97	2291.21	146.74	14.66
7	114.28	0.36	88.76	0.97	3623.20	88.54	91.09
8	-	-	-	-	661.04	-	-
9	-	-	-	-	1142.28	-	-

10	-	-	-	-	17.97	-	-
11	-	-	-	-	881.29	-	-
12	-	-	-	-	13661.52	-	-

A comparative analysis (see Figure 5) shows that with pressure drop consideration, only a decrease in utility consumption of ~5.5% can be achieved, compared to the 7% achieved without pressure drop consideration [21, 22]. Compared to the result obtained without pressure drop [21, 22], the retrofit profit obtained with pressure drop consideration represents a decrease of ~18.5%. This result was obtained even though the retrofit cost with pressure drop was considerably lower than that without. The higher retrofit profit without pressure drop is obtained as there was more opportunity for increasing energy recovery by enhancing more candidate heat exchangers.

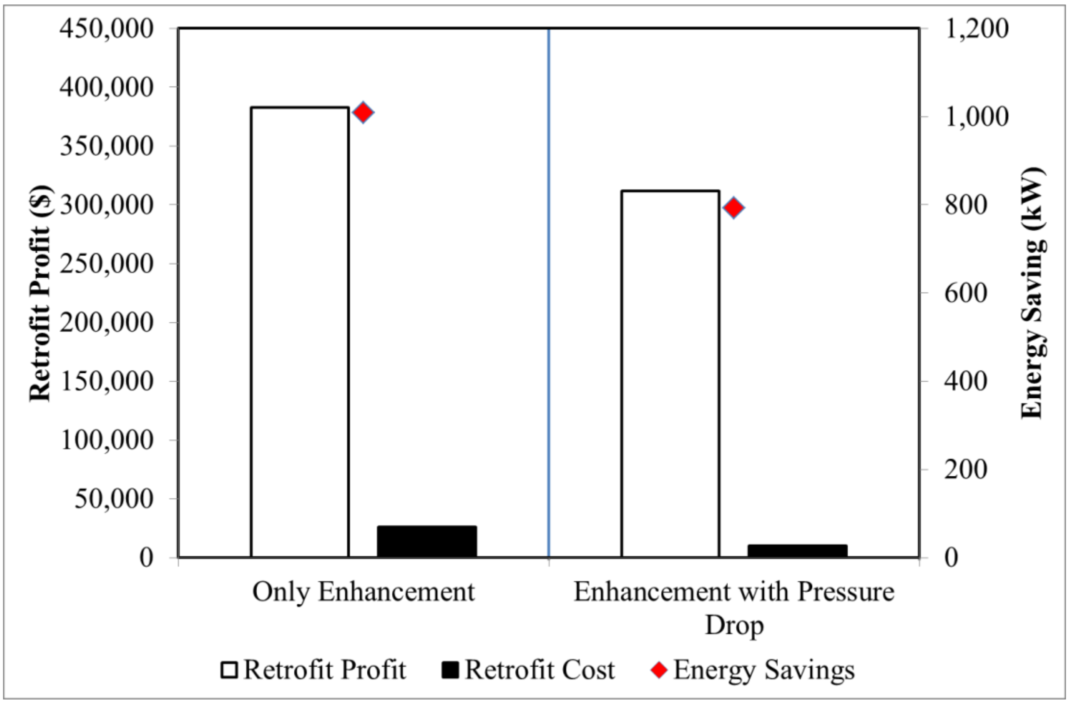

Figure 5: Comparative Analysis

6 Conclusions

Pressure drop consideration is important in retrofit, especially when heat transfer enhancement is considered. The use of heat transfer enhancement techniques results in an increase in the pressure drop of enhanced heat exchangers. In retrofit, the modifications made are restricted by pressure drop constraints imposed by the existing pumps. Correlations used in calculating the increase in pressure drop for twisted tape and wire coil inserts have been presented. In this work, a combination of heuristics and optimisation for pressure drop consideration is proposed. The method first identifies the heat exchangers for enhancement. Then the network is checked for pressure drop violations. If there are violations, pressure drop mitigation techniques are used to solve the problem. For tube side pressure drop violation, modification of the number of tube passes and the shell arrangement can be considered. In terms of shell side violation, the use of helical baffles or the modification of shell arrangement can be considered. In the case, where there are no pressure drop violations, other constraints such as heat transfer area and target temperature constraints, are examined. Heat transfer area and target temperature violations are corrected using a non-linear optimisation model. The aim in retrofit is not only to present a feasible design methodology that incorporates all network constraints, but also an economic design. Therefore, a stopping criterion of retrofit profit is included in the methodology. The procedure is stopped when the application of enhancement, subject to all constraints being met, becomes uneconomic.

This procedure was applied to a case study and the result obtained demonstrated that pressure drop consideration can be vital in order to be able to present a more realistic retrofit design. The results showed that the level of energy saving when pressure drop is constraining is less than that without. As such, the retrofit profit obtained is reduced compared to the case without pressure drop considerations. It still needs to be emphasized that, although there is a decrease in the projected level of energy saving that can be achieved, heat transfer enhancement can still be an attractive option in HEN retrofit. This is as a result of the ease in which it can be applied. It is generally cheaper to implement than conventional retrofit methods as it requires reduced civil and piping work. However, the amount of energy savings that can be achieved by the application of conventional retrofit methods (i.e resequencing, stream splitting, adding a new heat exchanger to create a path or loop) cannot be ignored. Current methodologies for the application of conventional retrofit methods do not support user interaction Future work will look into developing a step-wise approach for the application of conventional retrofit methods in HEN retrofit that provides useful insights into the identification of the best network modification to make.

Nomenclature

Symbols	Definitions	Units
ΔP_T	Total tube-side pressure drop	kPa
ΔP_{TTI}	Pressure drop in the straight tubes with twisted tapes	kPa
ΔP_{TE}	Pressure drop in the tube entrances, exits and reversal	kPa
ΔP_{TN}	Pressure drop in tube side nozzles	kPa
y	Twist ratio	-
D_i	Tube inner diameter	m
c_{fT}	Tube-side friction factor for twisted tape	-
u_{SW}	Effective swirl velocity	ms^{-1}
u_T	Mean fluid velocity inside the tubes	ms^{-1}
L	Length	m
N_P	Number of tube passes	-
$v_{TN,inlet}$	velocity of the inlet nozzle for the tube-side fluid	ms^{-1}
$v_{TN,outlet}$	velocity of the outlet nozzle for the tube-side fluid	ms^{-1}
$D_{TN,inlet}$	Inner diameter of the inlet nozzle for the tube-side fluid	m
$D_{TN,outlet}$	Inner diameter of the outlet nozzle for the tube-side fluid	m
$D_{SN,inlet}$	Inner diameter of the inlet nozzle for the shell-side fluid	m
$D_{SN,outlet}$	Inner diameter of the outlet nozzle for the shell-side fluid	m
m_T	Mass flowrate on the tube-side	kg s^{-1}
ΔP_{WCI}	Pressure drop in the straight tubes with wire coil	kPa
c_{fW}	Tube-side friction factor for wire coil	-
p	Roughness pitch	m
e	Wire diameter	m
c_{fS}	Smooth tube friction factor	-
C_P	Heat capacity	$Jkg^{-1}°C^{-1}$
k	Fluid thermal conductivity	$kWm^{-1}°C^{-1}$
m	Mass flowrate	kgs^{-1}
N_P	Number of tube passes	-
k_{tube}	Tube thermal conductivity	$kWm^{-1}°C^{-1}$

L_{eff}	Effective tube length	m
p_T	Tube pitch	m
B	Baffle spacing	m
D_S	Shell inside diameter	m
D_o	Tube outer diameter	m
N_B	Number of baffles	-
B_C	Baffle cut	-
B_{in}	Inlet baffle spacing	m
B_{out}	Outlet baffle spacing	m
h_T	Tube-side heat transfer coefficient	$kWm^{-2}°C^{-1}$
h_S	Shell-side heat transfer coefficient	$kWm^{-2}°C^{-1}$
ΔP_S	Total shell-side pressure drop	kPa
h_{SHB}	Shell-side heat transfer coefficient with helical baffles	$kWm^{-2}°C^{-1}$
ΔP_{SHB}	Total shell-side pressure drop using helical baffles	kPa
u_S	Mean fluid velocity inside the shell	ms^{-1}
k_s	Shell thermal conductivity	$kWm^{-1}°C^{-1}$
cf_{SHB}	friction factor for helical baffles	-
ΔP_{SHB}	Shell-side pressure drop with helical baffles	kPa
ΔP_{SN}	Pressure drop in shell side nozzles	kPa
SF	Selection factor	-
$\Delta P_{N,E}$	New total pressure drop after enhancement	kPa
$\Delta P_{B,E}$	Base total pressure drop after enhancement	kPa
ΔP_N	New total pressure drop	kPa
ΔP_B	Base total pressure drop	kPa
$U_{B,E}$	Base overall heat transfer coefficient after enhancement	$kWm^{-2}°C^{-1}$
$U_{N,E}$	New overall heat transfer coefficient after enhancement	$kWm^{-2}°C^{-1}$
U_B	Base overall heat transfer coefficient	$kWm^{-2}°C^{-1}$
U_N	New overall heat transfer coefficient	$kWm^{-2}°C^{-1}$
RP	Retrofit Profit	$
RC	Retrofit cost	$

UC	Utility cost	$
EC	Enhancement cost	$
AC	Area cost	$
BC	Bypass cost	$
MC	Modification cost	$
CCU	Cost parameter for cold utility	$/y
CHU	Cost parameter forhot utility	$/y
OT	Operating time	y
EF	Enhancement Factor	-
Q	Heat duty	kW
A	Heat transfer area	m^2
THO	Hot outlet temperature	°C
TCO	Cold outlet temperature	°C
THOS	Hot outlet temperature of stream	°C
TCOS	Cold outlet temperature of stream	°C
TT	Target temperature	°C
TS	Supply temperature	°C
ΔT_{LM}	Log Mean Temperature Difference	°C
F_T	Correction factor	-
AR	Area ratio	-
U_E	Enhanced overall heat transfer coefficient	$kWm^{-2}°C^{-1}$
U_F	Final overall heat transfer coefficient	$kWm^{-2} °C^{-1}$

Greek letters

μ	Viscosity	Pa s
ρ	Fluid density	kgm^{-3}
δ	Tape thickness	m
β	Helical baffles angle type	°
α	Function of number of tube passes	-

Dimensionless groups:

Nu: Nusselt number $= \frac{hD_i}{k}$

Pr: Prandtl number $= \frac{C_p \mu}{k}$

Re: Reynolds number $= \frac{\rho u D_i}{\mu}$

Sw: Swirl number $= \frac{Re}{\sqrt{y}} \frac{\pi}{\pi - 4(\delta/D_i)} \left[1 + \left(\frac{\pi}{2y}\right)^2\right]^{\frac{1}{2}}$

Subscripts:

TT	Twisted Tape
WC	Wire coil
B	Base
E	Enhanced
T	Tube
S	Shell
SHB	Shell helical baffles
ex, EX	Exchanger
HS	Hot stream
CS	Cold stream
CU	Cold utility
HU	Hot utility
F	Final
N	New

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5.3 Summary

The use of heat transfer enhancement in retrofit can have a negative impact on pressure drop. This is not the case for all enhancement devices e.g. helical baffles for shell side enhancement. However, this work focuses on the use of tube-side enhancement devices that have a negative impact on pressure drop. Publication 3 shows that the consideration of pressure drop in retrofit resulted in the decrease in the energy recovery and retrofit profit compared with the results presented in Publications 1 and 2, where pressure drop is not considered. The decrease in energy recovery is due to the decrease in the performance of heat exchangers where pressure drop mitigations are applied. In terms of retrofit profit, the decrease in energy recovery and the cost required for heat exchanger modifications used in pressure drop mitigation are contributing factors. However, this result paints a more realistic picture of the effects of heat transfer enhancement in retrofit.

Structural modifications are not usually ideal in retrofit due to the cost associated with the modifications required to achieve a degree of energy savings and the constraints that might be imposed on the existing network. Although these are drawbacks, the benefits of the reduced energy consumption cannot be ignored. The goal in retrofit is to be able to present low cost techniques by minimising the amount of structural modifications required in retrofit. Therefore, a new interactive method needs to be developed considering structural modifications that results in a less complex retrofit. Chapter 6 addresses this issue.

Chapter 6 Structural Modifications

6.1 Introduction to Publication 4

This section tackles the third research objective of this thesis given in Section 1.3. As mentioned previously, structural modifications and additional heat transfer area are not desirable in retrofit. This has a direct impact on the cost associated with the retrofit process and hence, the retrofit profit. However, the degree of energy savings that can be obtained by applying structural modifications cannot be ignored.

The uncertainty associated with applying structural modifications is addressed in Publication 4. However, before the application of structural modifications, this publication highlights the benefit of pinching the existing network by adjusting the degrees of freedom to minimise energy consumption, subject to a minimum temperature approach. Pinching the existing network identifies the network bottleneck that restricts energy recovery (network pinch). By pinching the network, additional heat transfer area might be required to maintain the network energy balance. If there are still opportunities for energy recovery, structural modifications can then be carried out. The structural modifications analysed in this publication are resequencing heat exchangers, introducing stream splitting, and adding new heat exchangers or new matches to create a loop and/or a utility path.

6.1.1 Guidelines and Algorithm for Structural Modifications

This section addresses the questions posed in "Objective 3, Questions 'a' and 'b'". The guidelines for identifying the most suitable location for applying structural modifications are based on key features of the heat exchanger network (HEN) such as the presence of utility exchangers that are not fully utilised, and the location and number of pinched heat exchangers in a given network. The guidelines present new insights and form the basis of the new interactive method that could lead to reduced complexity in retrofit. Questions such as, why is it that the application of resequencing provides a greater decrease in energy consumption for a given network than stream splitting, are answered. With the new method, the best modification at each stage in the retrofit process can be obtained.

6.1.2 Validation

The proposed method has been applied to five case studies for both single and multiple modifications. To validate the robustness of the new method, the results obtained have been compared with that obtained with the use of a stochastic optimisation method i.e. simulated annealing in terms of energy recovery, number of modifications required and additional heat transfer area required.

6.2 Publication 4:

Akpomiemie, M. O., Ambakkaden, D.M., Ajenifuja, A., and Smith, R., (2016). New step-by-step method for heat exchanger network retrofit based on network pinch approach.

New step-by-step method for heat exchanger network retrofit based on network pinch approach

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Abstract

In this work, new guidelines and retrofit methodologies are presented for carrying out structural modifications in heat exchanger network (HEN) retrofit. Structural modifications considered in this work are resequencing heat exchange matches, stream splitting and adding new heat exchangers. The guidelines and methodology presented are based on new insights that capitalise on the interactions between the different components in the networks. This provides useful insights into determining the best structural modification(s) for a given HEN. It has been found that the decision on the best network modification depends on four key factors; (1) location of cross pinch exchangers, (2) the number of pinched exchangers, (3) the location of pinched exchangers relative to each other and in the network, and (4) the location of viable utilities (utility with non-zero duty). The benefits of the new approach are demonstrated with the use of five case studies by comparing the results obtained against that of a well-established stochastic optimisation method i.e. simulated annealing.

Highlights:

- New guidelines and methodologies for retrofit of heat exchanger networks.
- Best network modification is based on energy saving potential.
- The new approach highlights the interactions and key features of an existing network.
- Simulated annealing is used in validating the retrofit results.

Keywords: Retrofit; Heat Exchanger Networks; Structural Modifications; Network Pinch; Energy Recovery, Simulated Annealing

1 Introduction

The retrofit of heat exchanger networks (HENs) plays an important role in reducing energy consumption in the process industries. Strategies employed in retrofit have been centred on the modification of existing HEN structures and the application of heat transfer enhancement techniques to indirectly add heat transfer area by increasing heat transfer coefficients. This paper will concentrate on modifications to the network structure. These modifications include adding new heat exchangers or new matches, resequencing heat exchangers, repiping process streams and introducing stream splitting. This is usually carried out with an objective of a minimum return on capital investment and minimising the energy consumption of the network subject to process constraints being met. The three methods used for HEN retrofit can be classified as pinch analysis, mathematical programming, and hybrid methods.

Pinch analysis is based on thermodynamic rules. Whilst these rules are fundamental, it requires an expert user for its application. The use of pinch analysis in retrofit was first introduced by Tjoe and Linnhoff [1]. The proposed approach involved establishing targets for energy consumption and heat transfer area. Cross-pinch heat exchangers in the existing HEN were identified, disconnected, and reconnected to obey pinch decomposition. The disadvantage of this approach was that the solution did not reflect the true state of area distribution within the existing HEN. Shokoya and Kotjabasakis [2] presented a method that takes into account the area distribution of the existing HEN to provide a more realistic area target and retrofit design compared to that proposed by Tjoe and Linnhoff [1]. Lack of rules for retrofit rendered the approach impractical when applied to large scale problems, due to the increased number of design alternatives and decisions that needs to be made. This often leads to complex and uneconomic retrofits as it uses an ideal new design as a reference. Also, its dependence on an expert user means that the quality of the final retrofit design may be compromised.

Mathematical programming methods can be further subdivided into deterministic and stochastic search optimisation methods. These methods convert the retrofit problem into an optimisation task to solve the problem. The mathematical programming models used in the optimisation can be classified on the basis of the presence or absence of non-linear and discrete variables as linear programming (LP), non-linear programming (NLP), mixed integer linear programming (MILP), or mixed integer non-linear programming (MINLP). These deterministic optimisation approaches optimise a superstructure to obtain a design. However, it is unable to guarantee finding the global optimal solution due to the non-convexity of the problem if formulated as NLP or MINLP. Other disadvantages include: it does not allow user interaction, and is not suited to the solution of large networks and including rigorous heat exchanger models. The stochastic search optimisation methods on the other hand, have an increased chance of finding the global optimum due to the random search nature. These methods allow more detailed models to be included in the optimisation and are suited to solve large scale problems. However, a longer computational time compared to the deterministic based approach is required.

An MILP assignment-transhipment model was first developed by Yee and Grossmann [3] for solving retrofit problems based on mathematical programming. The model was used in predicting the minimum number of network modifications that can be carried out in an existing HEN. Based on the set objective, they were able to present a HEN structure that was very close to the existing one after performing the network modifications. Ciric and Floudas [4] proposed an MILP model used for the identification of structural modifications that can be applied in HEN retrofit. This was then optimised by generating a superstructure that contains all the possible structural modifications and solved as an NLP problem. The drawback of this model is the complexity in the proposed superstructure. This could result in prolonged computational times to obtain a feasible solution. Ciric and Floudas [5] then presented a single stage MINLP model that accounted for the trade-offs between the energy and capital costs by simultaneously optimising the HEN retrofit problem. Yee and Grossmann [6] proposed a new method where, firstly the optimal energy recovery level and economic feasibility of the retrofit design is determined. Then, an MILP model is formulated and solved taking into account all the possible retrofit designs embedded within a superstructure. An advantage of mathematical programming methods is that they are fully automated. This is beneficial as the retrofit solution is less sensitive to the need for an expert user. This ensures the reliability and consistency of the retrofit solution. However, this can also be a disadvantage as sub-optimal results, or infeasible solutions might be obtained. This is because the model may not be able to include key aspects of the HEN during the optimisation stage.

The hybrid methods stemmed from the desire to combine the advantages of both the pinch analysis and mathematical programming methods. Asante and Zhu [7] first introduced the concept of network pinch. This method identifies the bottleneck of the existing HEN that limits energy recovery subject to a minimum temperature approach and overcomes this by performing structural modifications. Structural modifications were identified by MILP and then the capital-energy trade-off carried out using NLP. Structural modifications were explored sequentially. This is a fully automated process, but also allows for user interaction during the design phase. This ensures that a more robust procedure that takes into account positive aspects of pinch analysis and mathematical programming methods, while minimising their respective drawbacks. A disadvantage of the method is that there is no guarantee that choosing a sequence of modifications in turn leads to choosing the best combination. This method was later modified by Smith et al. [8] by combining the structural modifications and capital-energy optimisation into a single step. The new method also considered adjusting both the heat loads and split fractions for stream split to ensure that the network pinch is caused by the existing network structure and not by the heat transfer area limits or split fractions.

As opposed to pinch analysis and mathematical programming methods, the network pinch approach has the benefit of user interaction while ensuring a good retrofit design. While there have been successful applications of the network pinch approach in solving retrofit problems that leads to improved energy recovery, there have not been much investigation into why the modification choices are made. Also, there has been little research into explaining why a modification may be better than another when applied to an existing HEN.

The main objective of this paper is to present insights into the decisions involved in retrofit based on the application of the network pinch approach. The new step-by-step approach presented in this work, includes guidelines that aid in identifying the most suitable modifications to a given HEN and the best location to apply such modifications. Modifications such as resequencing, stream splitting and adding a new heat exchanger to create a loop and path are considered. This approach has an advantage of early identification of unfavourable modification options, which can then be eliminated without the need for comprehensive calculations. Computational time is considerably reduced, whilst also improving the quality of the solutions obtained in the retrofit process. The guidelines that will be presented also serve as a basis for the development of a more robust retrofit design methodology that can be applied to a wider range of retrofit problems. In this work, energy recovery will be used as the major performance indicator. The proposed guidelines and methodology will be applied to five case studies for single network and multiple modifications. To further validate the proposed approach, the result obtained from the step-by-step approach will be compared to those of an optimisation based approach.

2 Background on network pinch

Before considering network modifications, it is always good practice to pinch the existing network by adjusting the degrees of freedom to minimise energy consumption subject to a minimum temperature approach. This ensures that all outstanding opportunities for energy recovery are utilised. Given an existing network, the network pinch can be used in reducing the existing energy consumption, while maintaining the network structure. This can be done by exploiting the degrees of freedom of the existing network. For example, Figure 1a shows an existing HEN with an energy recovery of 200MW and a minimum temperature difference (ΔT_{min}) of 20°C. The corresponding energy recovery based on the composite curves is obtained with a ΔT_{min} of 22.5°C (Figure 1b).

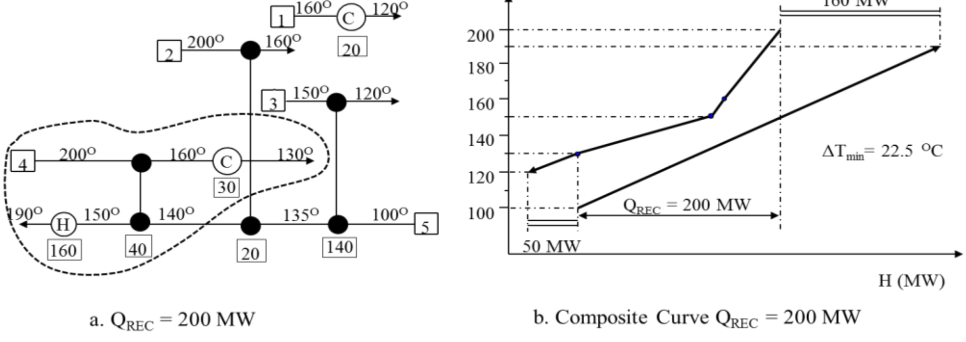


Figure 1: An existing network [7]

To reduce the energy consumption while maintaining the network structure, the only way possible is by exploiting the utility paths present in the existing network. The bubble overlaid on the HEN shown in Figure 1a highlights the only degree of freedom of the existing network. It shows the connection between the heater (H) and cooler (C) through a process heat exchanger. The matches outside of the bubble are constrained by the heat duties on individual streams. For the sake of illustration, the ΔT_{min} of the existing HEN is then set to 0°C. This corresponds to an increase in the energy recovery of 20MW as shown in Figure 2a. We can note that even by maximising the energy recovery down to 0°C the energy performance is worse than the energy target obtained using the composite curves shown in Figure 2b. The difference between both results for maximum energy recovery results from the fact that the existing HEN structure is not appropriate for maximum energy recovery.

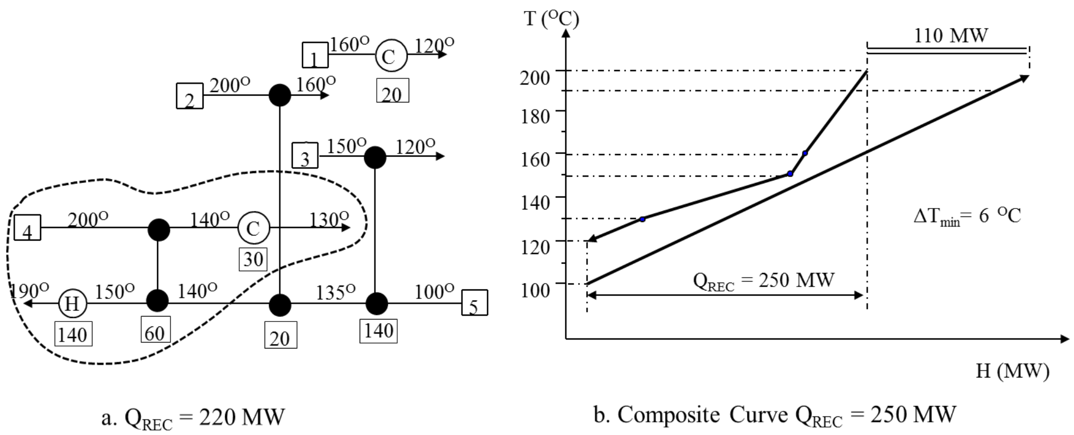
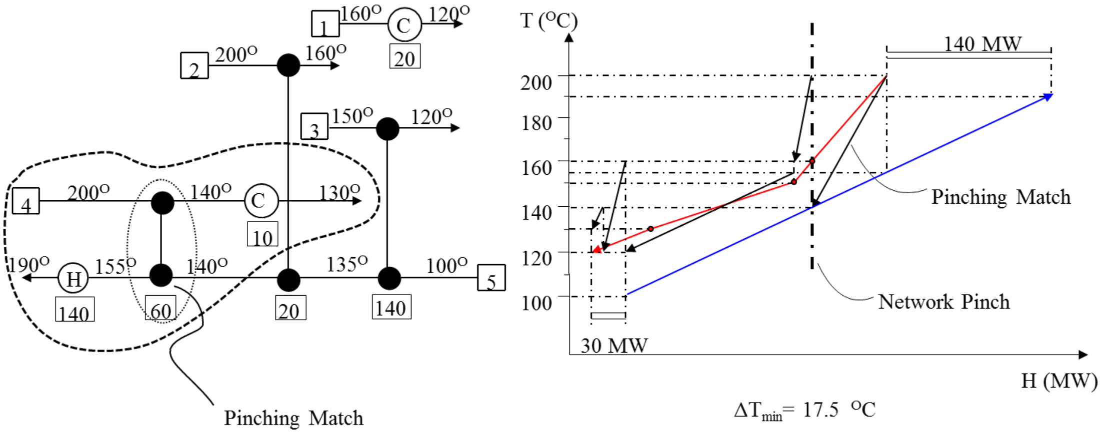


Figure 2: Maximum Energy Recovery [7]

From the network structure for maximum energy recovery based on a ΔT_{min} of 0°C, the exchanger that limits the energy recovery based on the existing network is identified. This heat exchanger is referred to as the pinching match (Figure 3a) and the point at which this occurs in the existing network is known as the network pinch. Note that this is still based on the minimum temperature difference of 0°C. In practice, if the network pinch is being identified in the design phase, a practical ΔT_{min} of say 10°C or 20°C is used [9]. The composite curves for the same energy recovery are shown in Figure 3b.



a. Maximum Heat Recovery Condition Q_{REC} = 220 MW

b. HEN Representation on Composite Curves Q_{REC} = 220 MW

Figure 3: Network Pinch

The only way to overcome the network pinch is by performing structural modifications. With this, there is always a trade-off between energy recovery and additional heat transfer area requirement (see Figure 4).

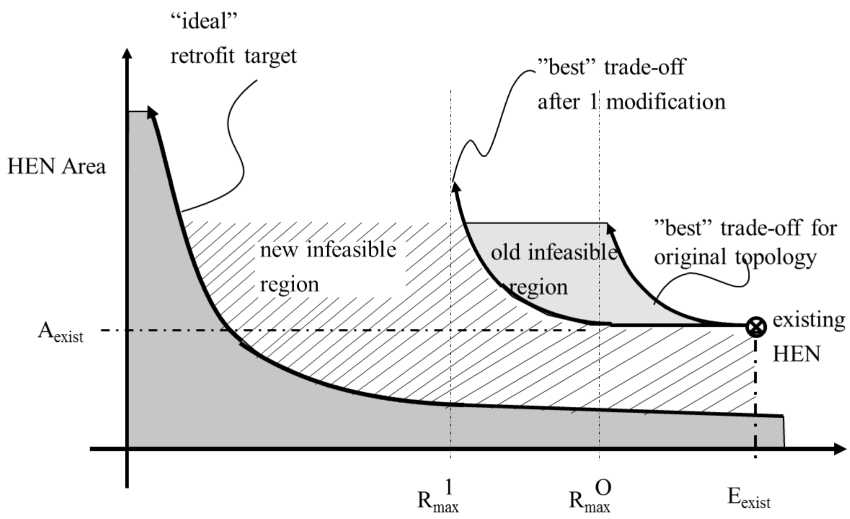


Figure 4: Energy – Area trade-off after each modification [7]

There are four structural modifications that can be carried out i.e. resequencing; repiping; adding a new heat exchanger; and stream splitting [9].

a. Resequencing: This is the relocation of an existing heat exchanger to a new location in the network, while maintaining the same streams as its original match. This allows for heat to be transferred from below to above the pinch thereby easing the constraints on the pinching match, allowing them to take up increased heat load, and reducing the energy consumption. From Figure 5, there is a cold stream being heated by two hot streams. There is one pinching match identified as the temperature profile tends to the minimum. Moving the process heat exchanger located upstream from the pinching match eases the constraint on the pinched exchanger. This allows for the pinched exchanger to take on more heat load (Q) by exploiting the utility path. If the utility path is exploited to its limit, then a new network pinch is created, but now at lower energy consumption for the network [9].

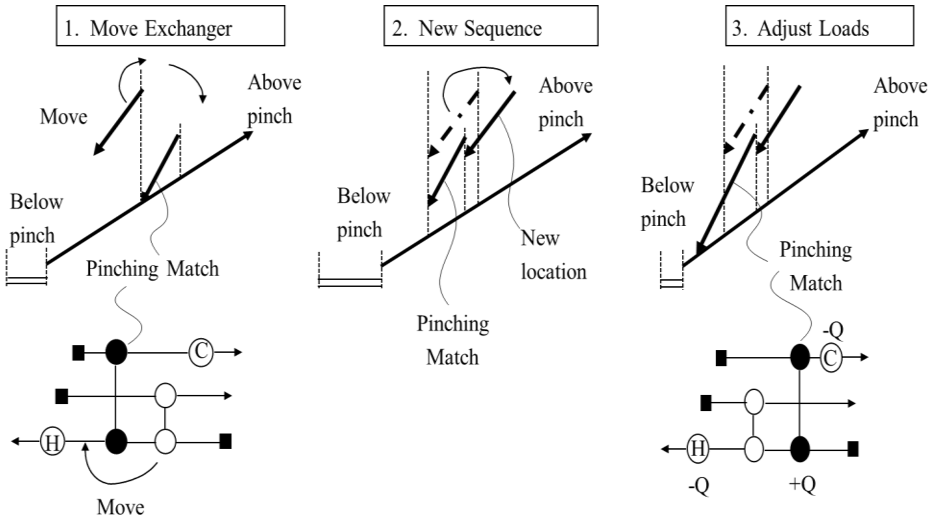


Figure 5: Resequencing to overcome network pinch

b. Repiping: This involves the movement of a heat exchanger to a new location in the existing HEN. With repiping, the streams of the original match for a heat exchanger are not maintained, as in the case of resequencing. In essence, repiping is a more general structural modification compared to resequencing, but might not be practical to implement especially in cases restricted by the materials of construction and pressure rating of equipment being unsuitable for other streams [9]. Repiping as a structural modification is not considered in this work.

c. Adding a new exchanger: As the name suggests, this involves adding a new heat exchanger or match in the existing network structure to allow for a certain amount of heat load to be transferred from below to above the network pinch. A new heat exchanger can be added to create a loop with an existing heat exchanger as shown in Figure 6. As with the case of resequencing, there are two hot streams and a cold stream. The pinching match is identified by the temperature profile. If the new match is inserted such that the duty of the hot stream adjacent to the pinching match is decreased and replaced by the new match, then the position of the pinching match can be changed such that it is no longer pinching [9]. This then allows for the utility path to be exploited and allows for the pinching match to take up more heat load to reduce the energy consumption in the network. Another option with the addition of a new heat exchanger is the creation of a new utility path. This option is only considered if there are utility exchangers that are not fully utilised and there is a clear scope for energy recovery that does not violate the constraints imposed by the network.

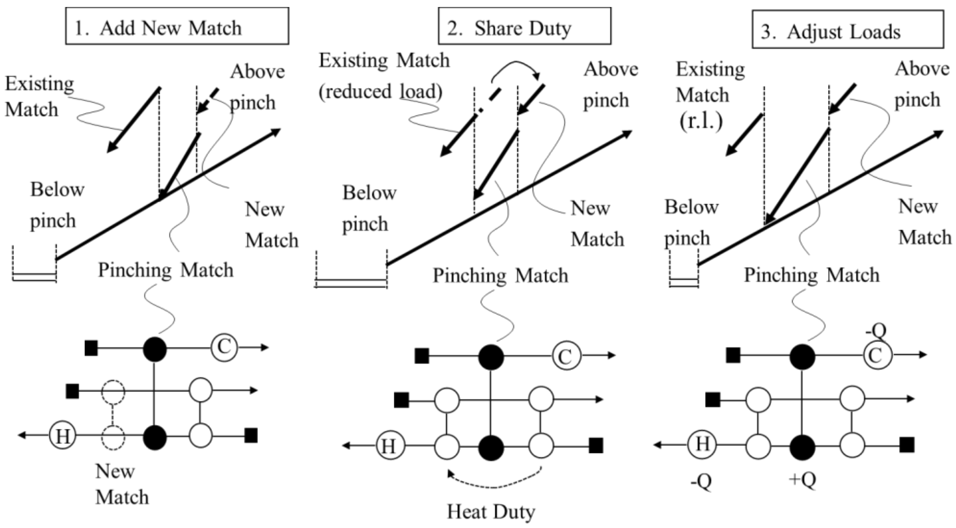


Figure 6: Adding a new heat exchanger to overcome network pinch

d. Stream Splitting: This is employed when there is more than one pinching match as shown in Figure 7. By introducing stream splits, the cold stream profiles in the two pinched exchangers are now such that one of the pinching matches is no longer pinched [9]. This creates an avenue for more energy recovery by exploiting a utility path by shifting a certain amount of heat load subject to the constraint of the network.

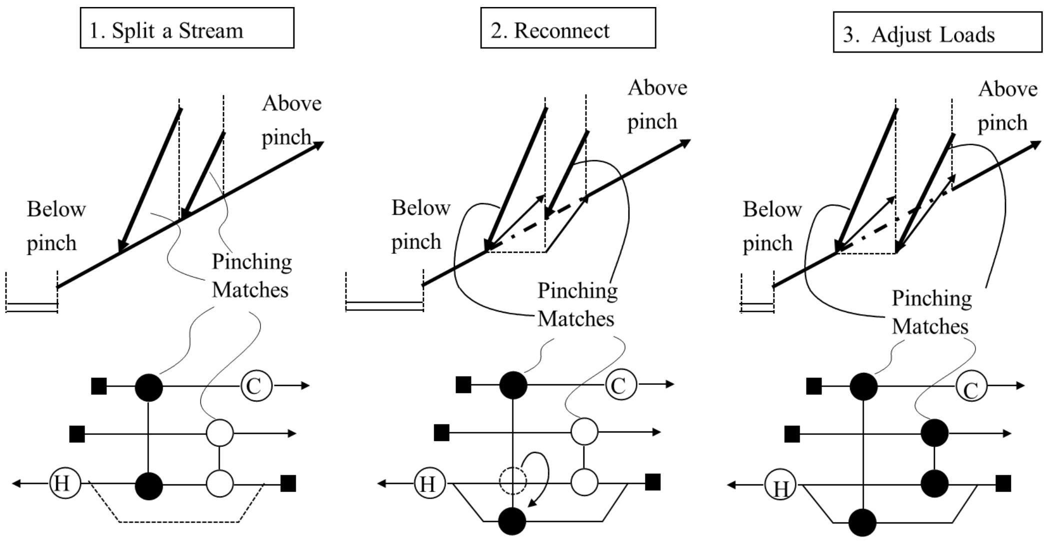


Figure 7: Stream splitting to overcome network pinch

3 Pinch Retrofit Method

As stated earlier, to overcome the network pinch, structural modifications need to be carried out. This paper provides guidelines that govern the placement of the different types of structural modifications in a given HEN to achieve maximum energy recovery. Novel methods for the identification of the best single modification and best multiple modifications to achieve maximum energy recovery are presented.

3.1 Guidelines for performing structural modifications

This section highlights guidelines and reasons for the placement of a given modification in a HEN. The guidelines are based on identifying the pinching matches and their location in the HEN; cross process pinch and cross utility pinch exchangers, which contribute to the excessive use of utilities; other process heat exchangers that are not pinched exchangers and does not transfer heat across the pinch. The properties of these exchangers such as their log mean temperature difference (ΔT_{LM}), heat duty (Q) and the total cross pinch heat transfer of either process or utility pinch heat exchangers (Q_{cp}). Graphical representations of the guidelines are provided in Figures 8 – 13. Structural modifications considered are resequencing, adding a new heat exchanger to create a loop, adding a new heat exchanger to create a utility path, and stream splitting.

3.1.1 Resequencing

Resequencing is considered only when there is cross utility pinch as opposed to cross process pinch heat transfer. There must also be at least one process heat exchanger that does not transfer heat across the pinch and is not pinched. This heat exchanger must be located upstream from the pinched exchanger(s) on both the hot and cold stream on which the pinched exchanger(s) is matched.

Step 1: If the pinched exchanger(s) is on a utility path then, on either the hot or cold stream(s), identify the exchanger upstream from the pinched exchanger(s) with the highest ΔT_{LM}. If there is more than one heat exchanger with the same ΔT_{LM}, then choose the one with the highest heat duty. Choosing the heat exchanger with the highest ΔT_{LM} provides the greatest potential to relax the temperature constraint of the pinched exchanger. Figure 8a (i) and 8a (ii) shows the case when exchanger with the highest ΔT_{LM} is on the cold and hot streams respectively.

Step 2: Move the identified heat exchanger downstream, along the stream on which the pinched exchanger(s) is matched, to the outlet of the pinched exchanger that is on a utility path. By doing this, the pinched exchanger becomes unconstrained and allows for the pinched exchanger to take up more heat load, while reducing the energy consumption of utilities (see Figure 8b (i and ii)).

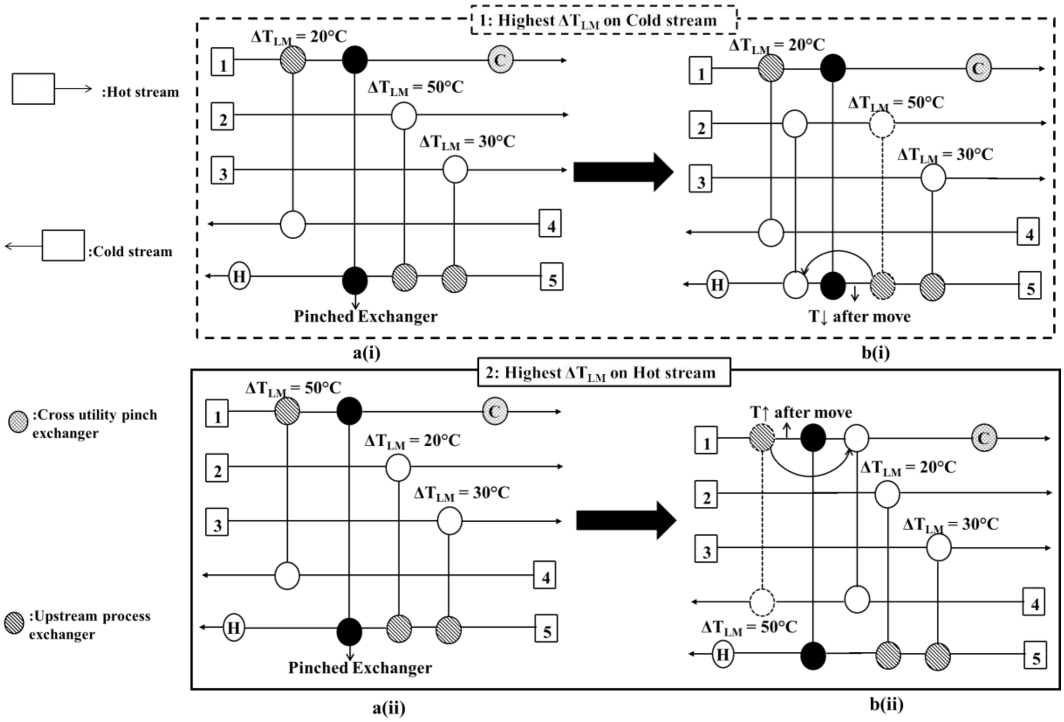


Figure 8: Guidelines for Resequencing

3.1.2 New exchanger to create a loop

There are two scenarios considered: (1) when cross process pinch exchanger(s) is present, and (2) when cross utility pinch exchanger(s) is present.

1. Cross process pinch exchanger(s):

A prerequisite is that there must be at least one cross process pinch heat exchanger in the network.

Step 1: Identify the cross process pinch with the highest cross pinch heat transfer. This represents the heat exchanger that provides the greatest potential to reduce or eliminate the total cross pinch heat transfer that restricts achieving maximum energy recovery. Figure 9a (i) and 9a (ii) shows the case when there are process heat exchangers and pinched exchangers respectively.

Step 2a: If there are other process exchangers on the same stream as the cross process pinch exchanger, add a new heat exchanger to create a loop with the identified cross process pinch exchanger by placing the new heat exchanger at the exit of the process exchanger if not on a utility path and the entrance of the process exchanger if on a utility path, and on the stream with the selected cross process pinch exchanger. This allows for the cross pinch heat transfer of the selected exchanger to be reduced or eliminated without violating the energy balance of the network (see Figure 9b (i)).

Step 2b: If there are pinched exchangers on the same stream as the cross process pinch exchanger in the network, add the new heat exchanger to create a loop with the identified cross process pinch exchanger by placing the new heat exchanger downstream, along the same stream on which the pinched exchanger on a utility path is matched. If the new heat exchanger is placed before the pinched exchanger, the heat load of the pinched heat exchanger will have to be reduced, which can result in either energy balance violation or more heat load requirement in the utility exchangers on a utility path with the pinched exchanger. Therefore, it is more beneficial to place the new heat exchanger at the exit of the pinched exchanger to prevent temperature constraint and energy balance violations. In addition, if the pinched exchanger identified transfers heat across the pinch, the new heat exchanger should be placed before the pinched exchanger. This provides an opportunity for reducing the total cross pinch heat transfer in the cross pinch heat exchanger (see Figure 9b (ii)).

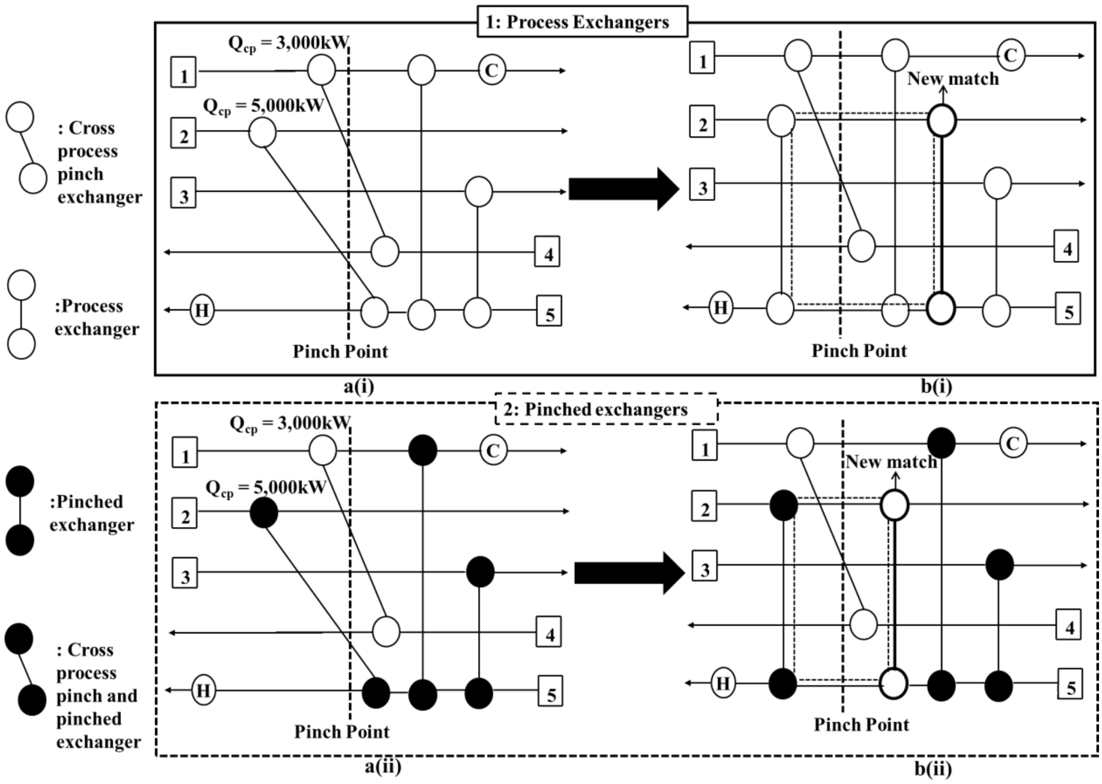


Figure 9: Guidelines for New Exchanger to Create a Loop (1)

2. Cross utility pinch exchanger(s):

A prerequisite is that there must be at least one process heat exchanger that does not transfer heat across the pinch and is not pinched. This heat exchanger must be located upstream from the pinched exchanger(s) on both the hot and cold stream on which the pinched exchanger(s) is matched.

Step 1: If the pinched exchanger(s) is on a utility path then, on either the hot or cold stream(s), identify the process heat exchanger upstream from the pinched exchanger(s) with the highest ΔT_{LM}. This represents the heat exchanger with the highest potential for energy recovery. Figure 10a (i) and 10a (ii) shows the case when exchanger with the highest ΔT_{LM} is on the cold and hot streams respectively.

Step 2: Add a new exchanger to create a loop with the identified upstream exchanger by placing the new heat exchanger at the exit of the pinched exchanger on a utility path. This allows for the temperature constraint on pinched exchanger to be relaxed to take up more heat load, while maintaining the energy balance of the network (see Figure 10b(i and ii)).

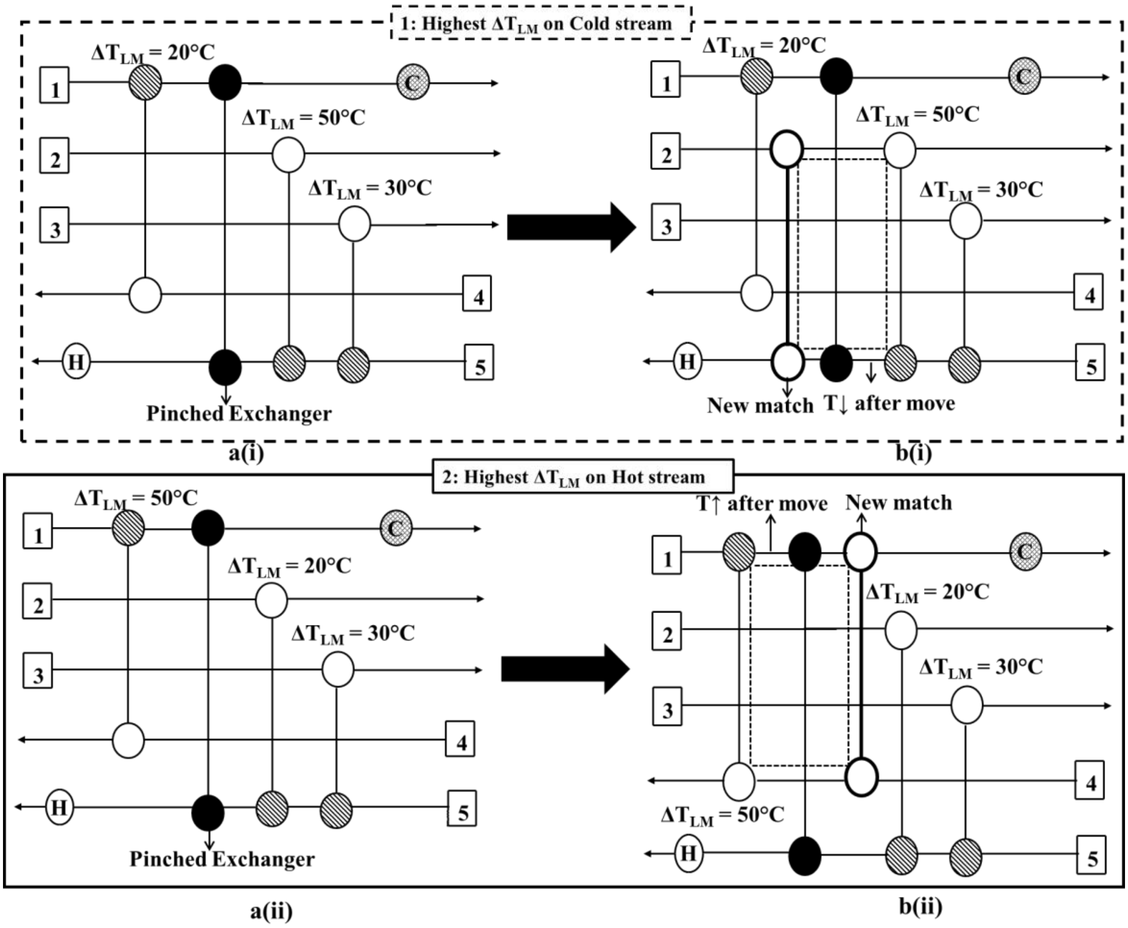


Figure 10: Guidelines for New Exchanger to Create a Loop (2)

3.1.3 New exchanger to create a utility path:

Similar to adding a new heat exchanger to create a loop, there are two scenarios considered: (1) when cross process pinch exchanger(s) is present, and (2) when cross utility pinch exchanger(s) is present.

1. Cross process pinch exchanger(s):

A prerequisite is that there must be at least one cross process pinch heat exchanger in the network.

Step 1: Identify hot and cold utility exchangers with the highest duty. These exchangers represent the highest potential for energy recovery. Figure 11a (i) and

11a (ii) shows the case when there are process heat exchangers and pinched exchangers respectively.

Step 2a: If there are upstream process exchangers on the same stream as the selected utilities, add a new heat exchanger to create a path by placing the new exchanger at the entrance of the process exchangers if on a utility path or loop, and at the exit if not on a utility path or loop. This allows for the cross pinch heat transfer of the selected exchanger to be reduced or eliminated. The energy consumption of the HEN is reduced without violating the energy balance of the network (see Figure 11b (i)).

Step 2b: If there are pinched exchangers on the same stream as the selected utilities, add a new heat exchanger to create a path by placing the new heat exchanger downstream, along the same stream on which the pinched exchanger on a utility path is matched. This is to prevent excessive use of utilities as a result of the reduction in the duty of pinched exchangers if the new exchanger is placed before. In addition, if the pinched exchanger identified transfers heat across the pinch, the new heat exchanger should be placed before the pinched exchanger. This provides an opportunity for reducing the total cross pinch heat transfer in the cross pinch heat exchanger (see Figure 11b (ii)).

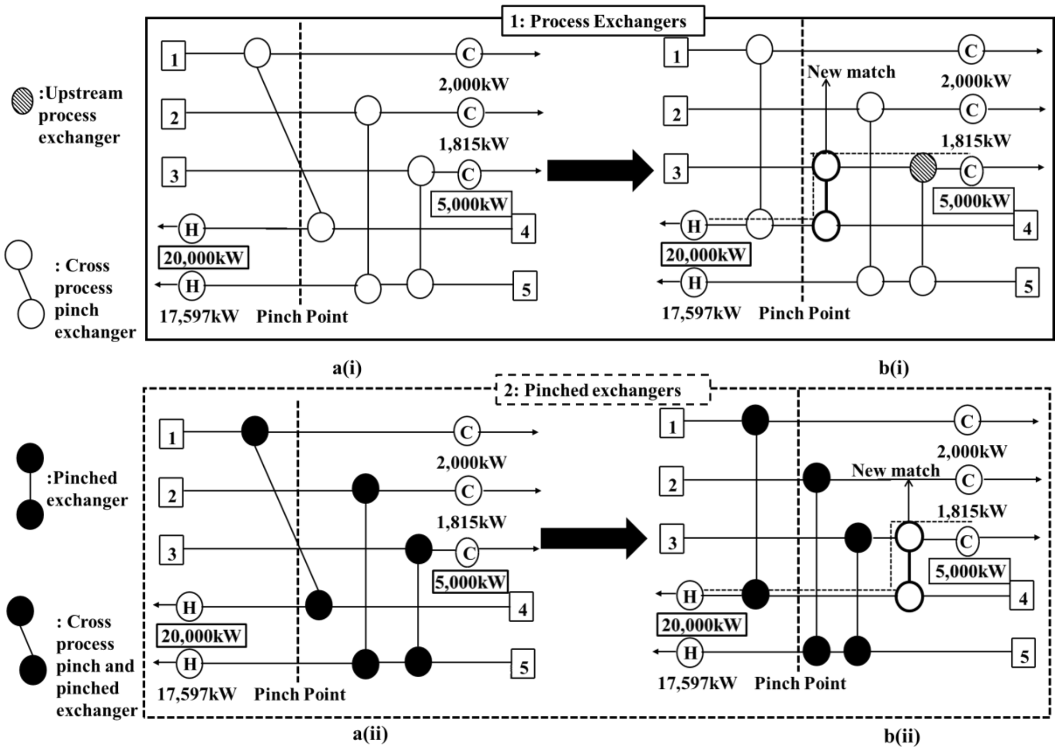


Figure 11: Guidelines for New Exchanger to Create a Utility Path (1)

2. Cross utility pinch exchanger(s):

A prerequisite is that there are only cross utility pinch exchangers.

Step 1: Identify hot and/or cold utility exchangers that transfer the most heat across the pinch and the hot and/or cold utility with the highest duty. These represent the utilities that provide the greatest potential to reduce/eliminate cross pinch heat transfer that restricts achieving maximum energy recovery. Figures 12a (i) and 12a (ii) show the case when there are hot utility pinch and cold utility pinch respectively.

Step 2: For the cases given in Step 1, if there are upstream process exchangers from the selected utilities, place the new exchanger at the entrance of the upstream process exchanger if the upstream exchanger is on a utility path or loop, and at the exit of the upstream process exchanger if not on a utility path or loop, on both the hot and cold streams. This allows for the process heat exchanger to be used in correcting the energy balance of the network, while the new exchanger takes up heat load. On the other hand, if there are pinched exchangers, the new exchanger should be placed downstream of the pinched exchanger to ensure that maximum energy recovery can be attained, on both the hot and cold streams. The cases for the presence of both process exchangers and pinched exchangers are shown in Figures 12b (i) and 12b (ii) for hot and cold utility pinch respectively.

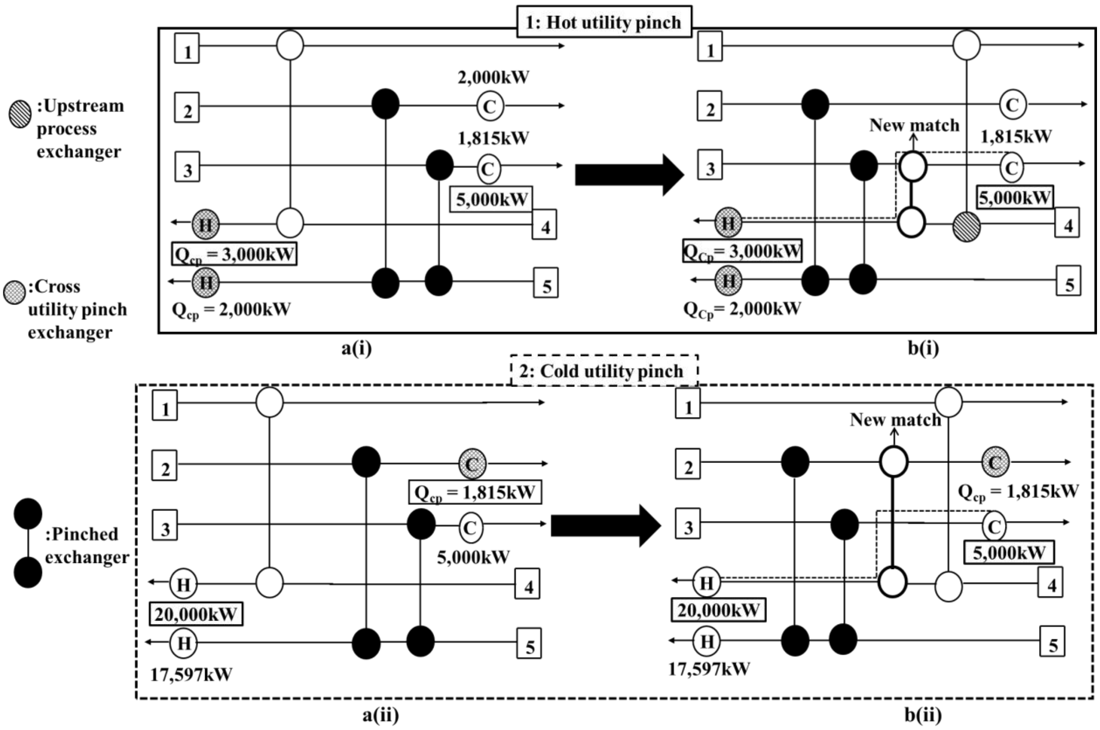


Figure 12: Guidelines for New Exchanger to Create a Utility Path (2)

3.1.4 Stream Splitting

Stream splitting is only possible if there are pinched exchangers located adjacent to one another in a HEN.

Step 1: Identify stream(s) with adjacent pinched exchangers. Select the one with the highest duty. This represents stream(s) with the highest potential for energy recovery (see Figure 13a).

Step 2: Arrange pinched exchangers that are on a viable utility path or loop on each branch. This is done so that as many of the originally downstream pinched exchangers as possible becomes unconstrained. Being on a viable utility path or loop allows for pinching matches to take up more heat load, without violating the network energy balance (see Figure 13b).

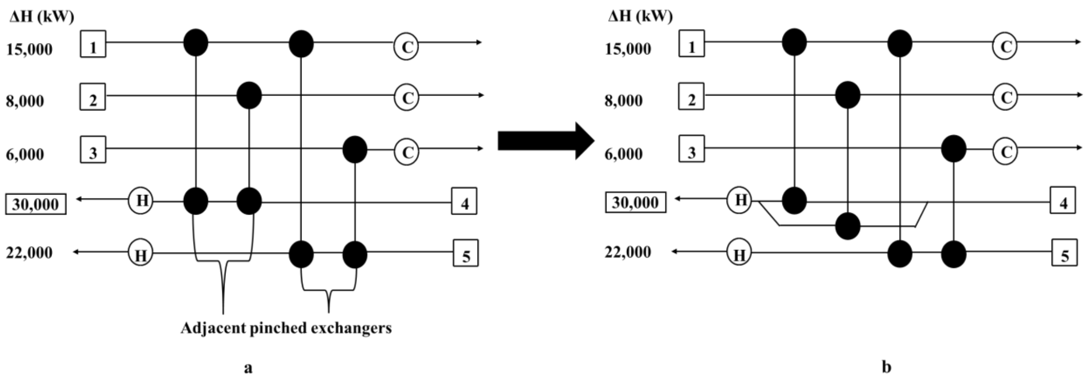


Figure 13: Guidelines for Stream Splitting

3.2 Single modification

To identify the best single network modification for a given HEN, the retrofit methodology shown in Figure 14 is proposed. Based on the proposed methodology, the first step is to pinch the network. This step is beneficial, as capital costs and process downtime are minimised as reduction in energy consumption is obtained, while maintaining the network structure. It also helps in identifying the location of heat exchangers that restrict energy recovery (pinched exchangers), and exchangers that contribute to excessive use of utilities (cross process pinch and cross utility pinch exchangers). The absence of any pinched exchangers indicates that the specified ΔT_{min} is not attained and that temperature driving forces do not limit the amount of energy recovery obtainable. Resequencing, stream splitting, and adding new exchangers to create a loop are modifications made to ease ΔT_{min} constraints on pinched exchangers. Therefore, in the absence of pinched exchangers these modifications are not beneficial. Such a situation indicates that the existing network does not have adequate utility paths through which the utility demand can be further reduced. Adding a new heat exchanger to create a utility path will be the most beneficial option in such a case as the heat transferred across the pinch either by utility exchangers or process exchangers can be reduced or eliminated. The presence of pinched exchangers indicates that the specified ΔT_{min} constraint is a limiting factor to additional energy recovery. Modifications such as resequencing, stream splitting and adding new heat exchangers will be beneficial.

The network is examined to identify process heat exchangers located upstream from pinched exchangers. If there are upstream process heat exchangers, the temperature constraint can be eased by directly moving heat from below to above the pinch by applying resequencing or adding a new heat exchanger to create a loop. The feasibility of moving heat load from the upstream heat exchanger across the pinch based on the temperature driving force is then examined. Doing this prevents futile attempts to implement modifications where an upstream process heat exchanger exists but heat load cannot be moved due to the temperature constraints. The decision on what modification to then apply is based on whether all the heat load of the chosen upstream heat exchanger can be moved. If the entire heat load of the upstream heat exchanger can be moved, it is more economic to apply resequencing than adding a new heat exchanger to create a loop. However, if moving all the heat load of the upstream heat exchanger is not an option, resequencing becomes less beneficial and adding a new heat exchanger to create a loop becomes the most beneficial option.

In cases where no process heat exchangers are found upstream of any pinched exchanger, the most beneficial options would be to implement stream splitting or to add a new heat exchanger to create a utility path. The implementation of stream splitting is only beneficial over adding a new heat exchanger to create a utility path if there are more than two pinched exchangers adjacent to each other and on a viable utility path or loop. By applying stream splitting the ΔT_{min} constraints is eased because, the pinched exchangers further downstream are exposed to lower cold stream and higher hot stream temperature than its original conditions. This allows for the pinched heat exchangers to take up more heat load, thereby reducing the energy consumption of the HEN. If the requirement for stream splitting is not satisfied then adding a new heat exchanger to create a utility path should be implemented.

However, this is subject to there not being any pinched exchangers on both streams of the viable utilities selected for analysis. There can be pinched exchangers on one but not both of the streams with the selected utility exchangers for analysis. If there are pinched exchangers on both streams as the viable utilities, the maximum energy recovery that can be obtained is constrained as although the new heat exchanger can take up more heat load and reduce the energy consumption of the utilities, more heat load will have to be added back to the utilities connected to the pinched exchangers. This is for the purpose of maintaining the network energy balance and the temperature constraints of the pinched exchangers. In this situation, it will be more beneficial to add a new exchanger to create a loop. The sequence of the flowchart suggests the existence of an inherent hierarchy of examining the modification options. However, this can always be modified to take into account other constraints that might be imposed on the existing network such as safety considerations.

To summarise, the key features that allow for structural modifications to overcome the network pinch are:

a. Resequencing: Presence of unconstrained process heat exchangers located upstream from pinched exchanger(s) and cross utility pinch exchangers.
b. New heat exchanger (Loop creation): Presence of cross process pinch heat exchanger(s) and upstream process heat exchangers from pinched exchangers.
c. New heat exchanger (Utility path creation): Presence of viable utility exchangers (i.e. utility exchangers with a duty greater than zero) and cross utility pinch exchanger(s).
d. Stream splitting: Location of pinching matches relative to one another and the duty of process streams in the network.

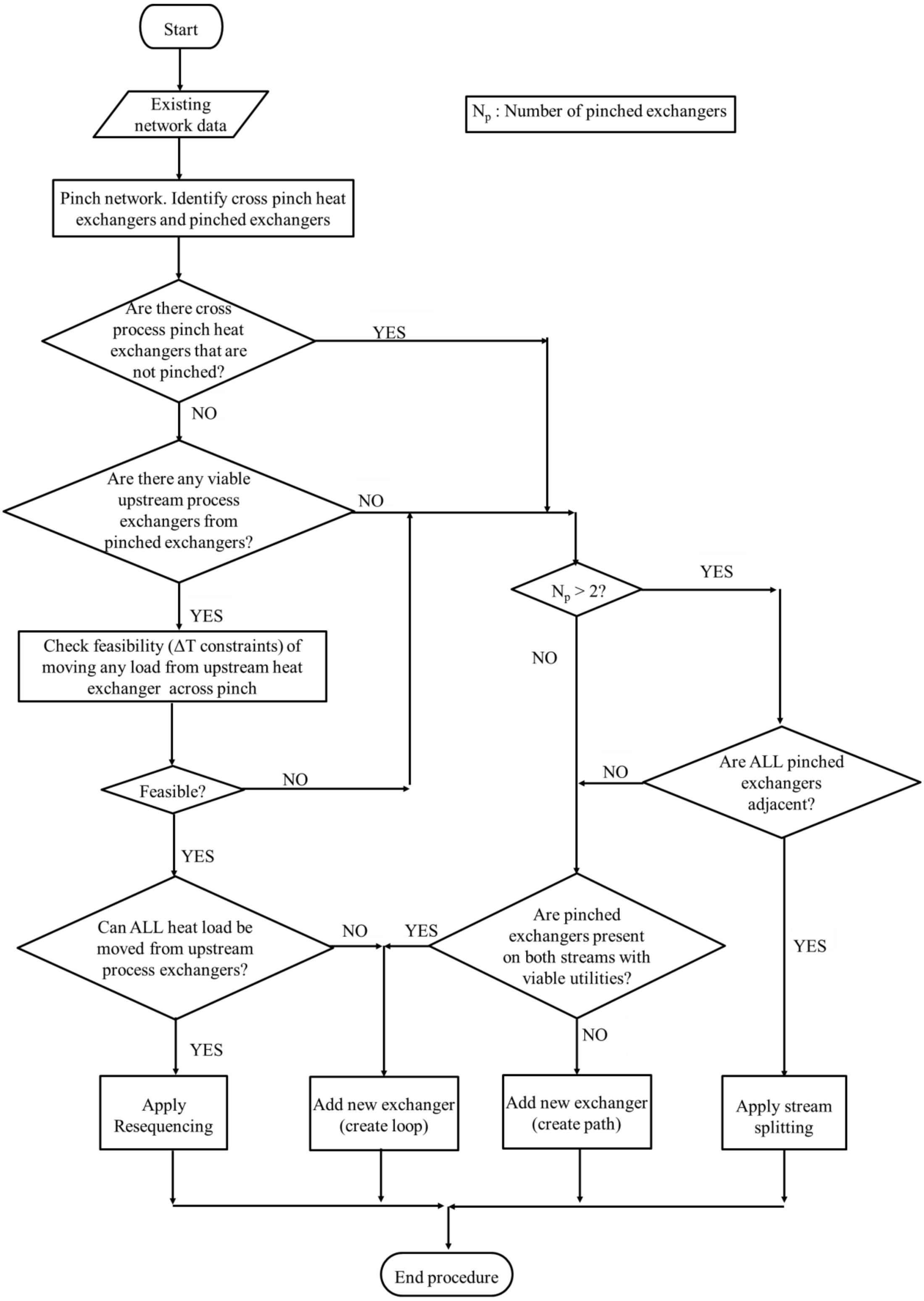


Figure 14: Proposed retrofit methodology for single modification

3.2.1 Case Study 1

The first case study was originally presented by Tjoe and Linnhoff [1]. The work by Li and Chang [10] identified inconsistencies in the original data set and modifications were made accordingly to correct them. The stream data after modifications are given in Table 1. The corresponding HEN is given in Figure 15. The goal is to reduce the energy consumption of the hot utility (H) subject to ΔT_{min} of 19°C. This corresponds to a minimum hot and cold utility consumption of 12,410kW and 10,323kW respectively. From network structure analysis, the heat exchanger network is made up of 3 hot and 2 cold process streams. There are 4 process heat exchangers, 2 cold utility and 1 hot utility heat exchangers. There are 2 degrees of freedom (2 utility paths present). Note that all analysis has been carried out using SPRINT v.2.9 [11].

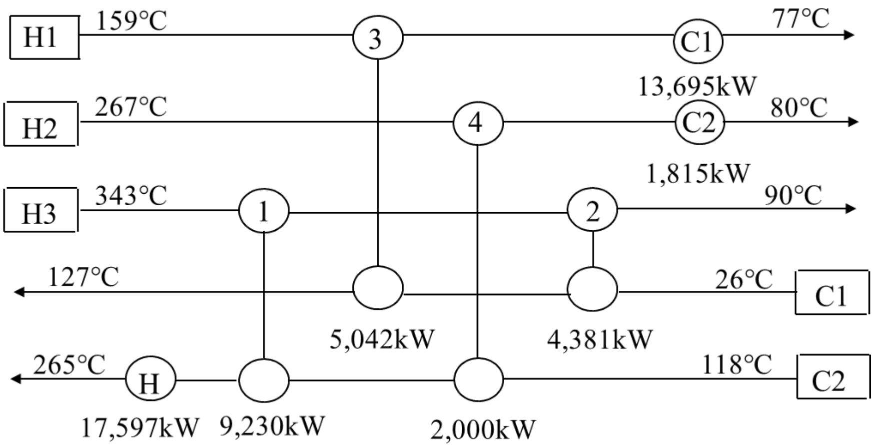


Figure 15: Original HEN for Case Study 1

Table 1: Stream Data for Case Study 1

Stream Name	T_S (°C)	T_T (°C)	Q (kW)	CP (kW/°C)	H.T.C.(kW/m^2°C)
H1	159	77	18,737.0	228.5	0.40
H2	267	80	3,841.8	20.4	0.30
H3	343	90	13,611.4	53.8	0.25
C1	26	127	9,423.3	93.3	0.15
C2	118	265	28,826.7	196.1	0.50

Pinching the network identified Exchangers 1 and 4 as both pinched exchangers and cross process pinch exchangers (see Figure 16). The pinch temperatures are 159°C (hot) and 140°C (cold).

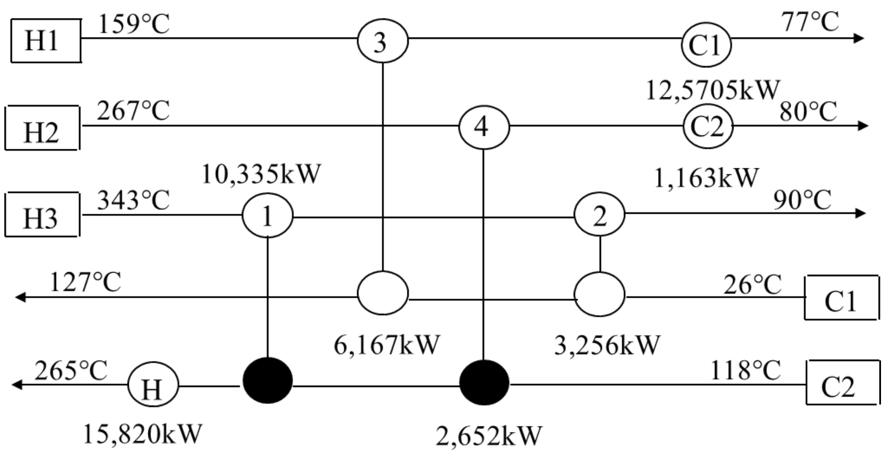


Figure 16: Pinched HEN for Case Study 1

Analysing the network structure shown in Figure 16 based on the proposed methodology shown in Figure 14, the best network modification should be adding a new heat exchanger to create a utility path. This is because:

1. There are no heat exchangers upstream from the pinched exchangers. This eliminates resequencing and adding a new heat exchanger to create a loop as beneficial options.
2. There are only two pinched exchangers present. So although a degree of energy saving can be obtained by applying stream splitting, it would not be the maximum for single modification.
3. Although there are pinched exchangers on the stream with the selected hot utility (H), there are no pinched exchangers on the stream with the selected cold utility (CI).

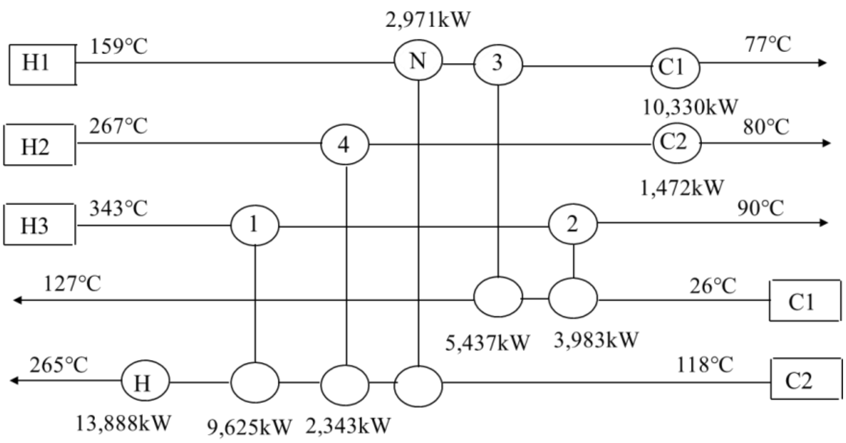


Figure 17: Best single modification for Case Study 1

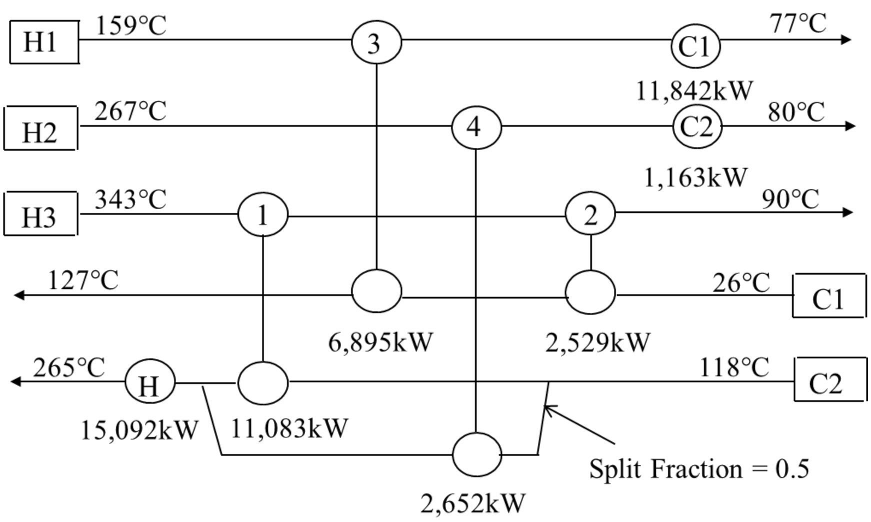


Figure 18: Alternative single modification for Case Study 1

Figure 17 shows the network structure after a new heat exchanger (Exchanger N) is added to form a utility path with the utilities with the highest duties i.e. Exchangers H and C1. It is important to point out that based on the guidelines, the new heat exchanger has been placed upstream of Exchanger 3, as exchanger 3 is on a utility path. The new exchanger has also been placed upstream of the pinched exchangers as both pinched exchanger transfers heat across the pinch. The network structure generated for the other viable structural modification option (stream splitting) is shown in Figure 18. A decrease in energy consumption of 21.1% for new heat exchanger as opposed to 14.2% for stream splitting is obtained.

3.2.2 Case Study 2

The second case study is the simplified crude oil pre-heat train studied in Akpomiemie and Smith [12]. The stream data and network structure are given in Table 2 and Figure 19 respectively. The goal is to reduce the energy consumption of the hot utility (H) subject to ΔT_{min} of 10°C. This corresponds to a minimum hot and cold utility consumption of 10,958kW and 0kW respectively. The heat exchanger network is made up of 5 hot and 1 cold process streams. There are 7 process heat exchangers, 4 cold utility and 1 hot utility heat exchangers. There are 9 degrees of freedom (6 utility paths and 3 loops present).

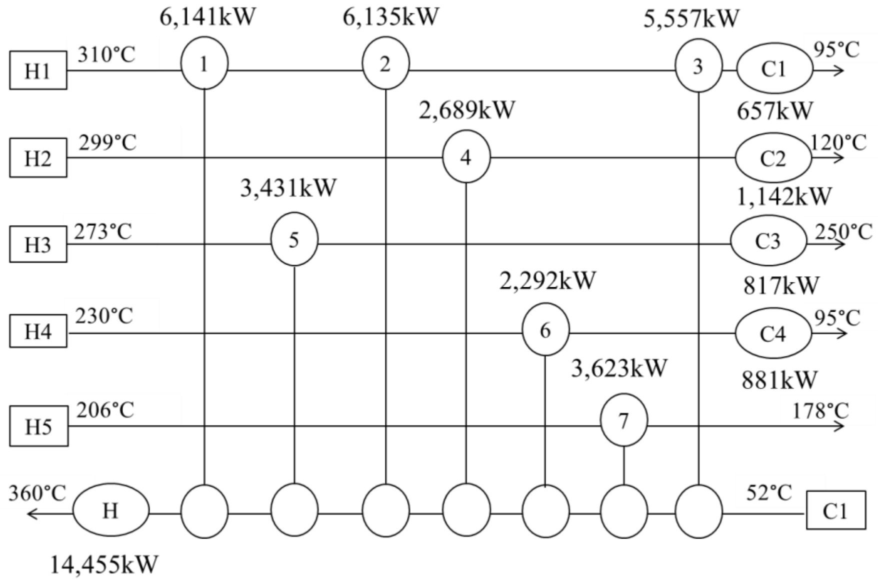


Figure 19: Original HEN for Case Study 2

Table 2: Stream Data

Stream Name	T_S (°C)	T_T (°C)	Q (kW)	CP (kW/°C)	H.T.C.(kW/m^2°C)
H1	310	95	18,490.0	86.0	0.5
H2	299	120	3,830.6	21.4	0.5
H3	273	250	4,248.1	184.7	0.5
H4	230	95	3,172.5	23.5	0.5
H5	206	178	3,623.2	129.4	0.5
C1	52	360	4,4321.2	143.9	0.5

In this case, pinching the network resulted in the elimination of 4 utility paths, as the duties of the cold utilities C1 and C3 became zero (see Figure 20).

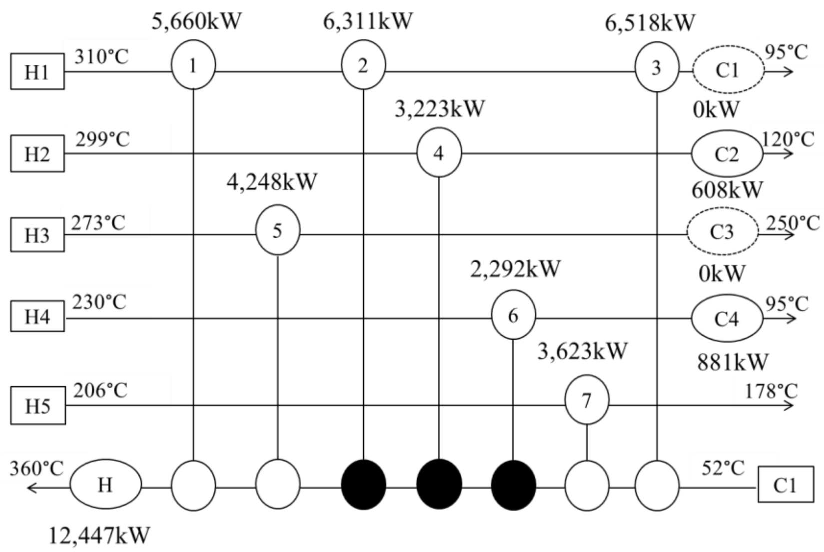


Figure 20: Pinched HEN for Case Study 2

There are two utility pinch temperatures. These are 62°C (hot) and 52°C (cold), and 40°C (hot) and 30°C (cold).The pinched exchangers identified in this case study are Exchangers 2, 4 and 6. There were no cross process pinch exchangers, but exchangers C2 and C4 were identified as cross utility pinch exchangers. Based on the proposed retrofit methodology, the most beneficial options for retrofit will be resequencing or adding a new heat exchanger to create a loop. This is as a result of the presence of heat exchangers 3 and 7 upstream from the pinched exchangers. Next, the network is analysed to determine the feasibility of moving the entire heat load of the heat exchanger with the highest ΔT_{LM} further downstream. The heat exchanger with the highest ΔT_{LM} was identified to be Exchanger 7. Moving Exchanger 7 downstream does not violate the network temperature constraint, as the inlet temperatures of the pinched exchangers on the cold stream C1 decreases, which in turn allows for them to take up more heat load. Therefore, the best single modification for this case study was to resequence Exchanger 7. Exchanger 7 is then moved to the outlet of the pinched exchanger furthest downstream and still on a viable utility path i.e. Exchanger 4 (Figure 21).

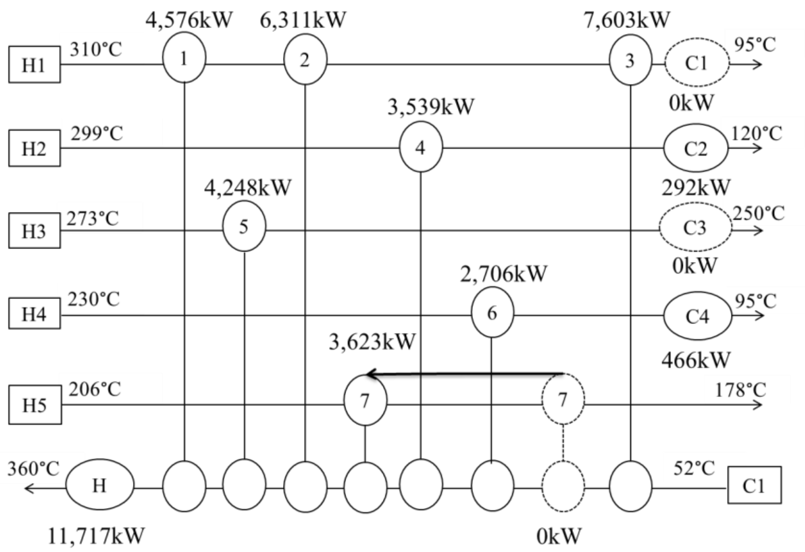


Figure 21: Best single modification for Case Study 2

Figures 22 – 24 show the network structures for other viable modification options. Adding a new heat exchanger to create a loop provided the same decrease in energy consumption as in the case of resequencing. However, in the case of adding a new heat exchanger to create a loop, exchanger 7 was left dormant as its entire load was moved to the new heat exchanger, effectively resequencing. Therefore, the best single modification for this HEN is the application of resequencing in terms of energy savings and cost. A decrease in energy consumption of 18.9% is achieved as opposed to 17.4% and 18.1% for stream splitting and adding a new heat exchanger to create a utility path.

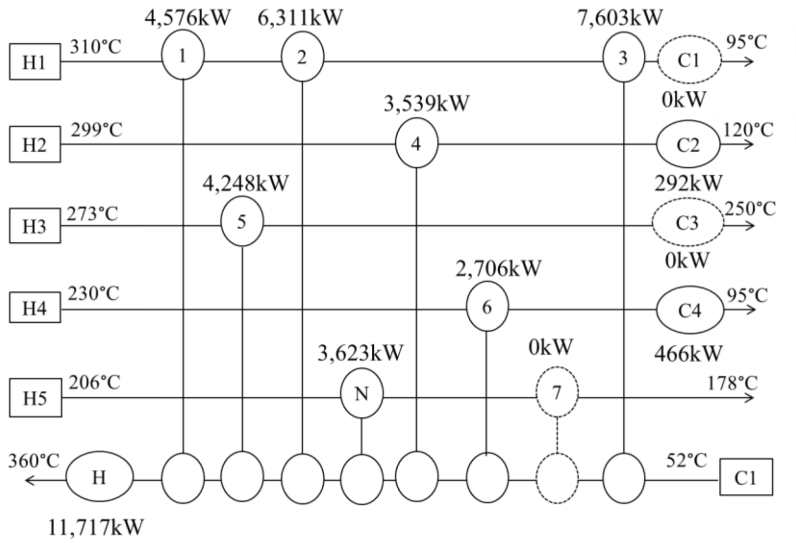


Figure 22: New exchanger to create a loop for Case Study 2

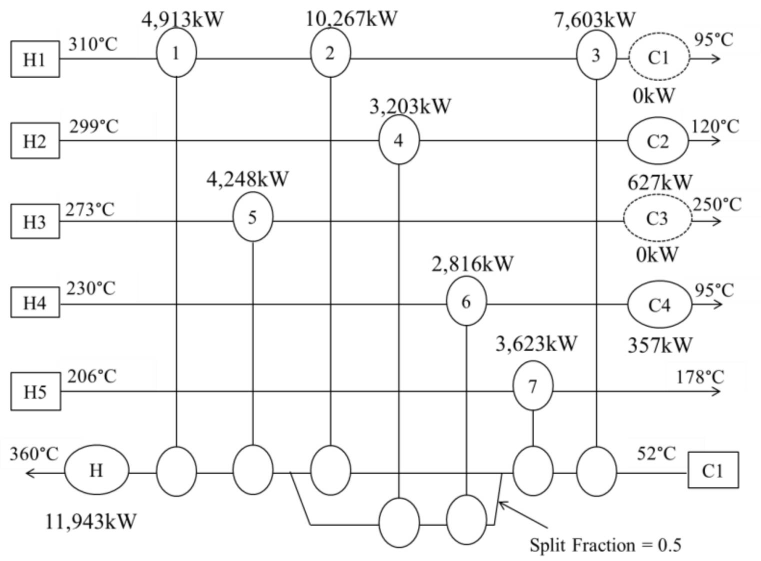


Figure 23: Stream splitting for Case Study 2

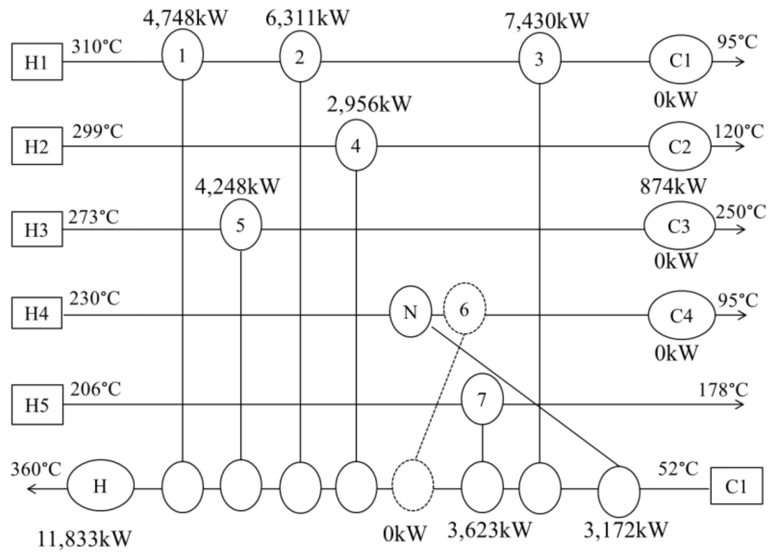


Figure 24: New exchanger to create a utility path for Case Study 2

3.2.3 Case Study 3

The third case study is curled from Akpomiemie and Smith, [13]. The network shown in Figure 25 is made up of 5 hot streams and 5 cold streams. The network consists of 5 process heat exchangers and 7 utility exchangers (3 hot and 4 cold utilities). The goal is to reduce the energy consumption of the hot utilities (H1, H2 and H3) subject to ΔT_{min} of 10°C. This corresponds to a minimum hot and cold utility consumption of 8,300kW and 15,275kW respectively. The stream data is shown in Table 3. This HEN has 3 degrees of freedom (3 utility paths).

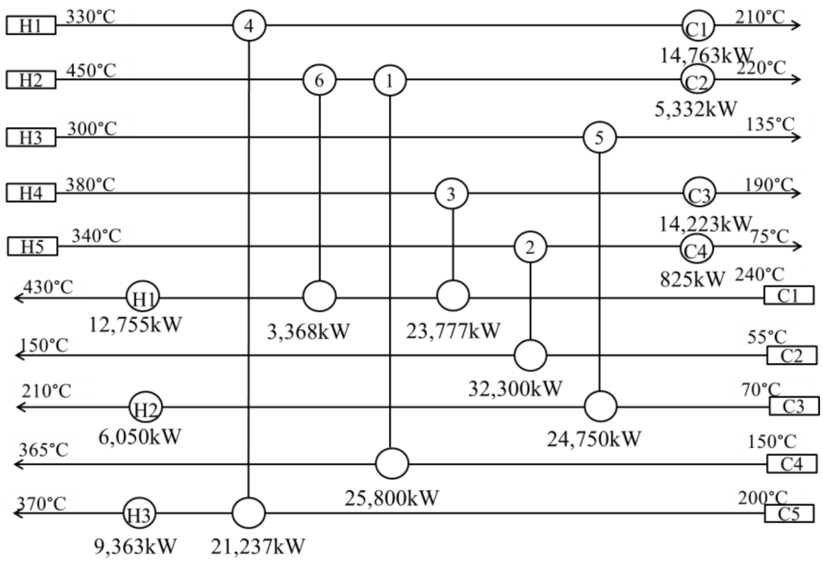


Figure 25: Original HEN for Case Study 3

Table 3: Stream Data

Stream Name	T_S (°C)	T_T (°C)	Q (kW)	CP (kW/°C)	H.T.C.(kW/m^2°C)
H1	330	210	36,000	300	0.5
H2	450	220	34,500	150	0.5
H3	300	135	24,750	150	0.5
H4	380	190	38,000	200	0.5
H5	340	75	33,125	125	0.5
C1	240	430	39,900	210	0.5
C2	55	150	32,300	340	0.5
C3	70	210	30,800	220	0.5
C4	150	365	25,800	120	0.5
C5	200	370	30,600	180	0.5

After pinching the network, the number of viable utility paths decreases to 2 (see Figure 26). Exchangers 3 and 4 were identified as pinched exchangers. The pinch temperatures are 330°C (hot) and 320°C (cold).

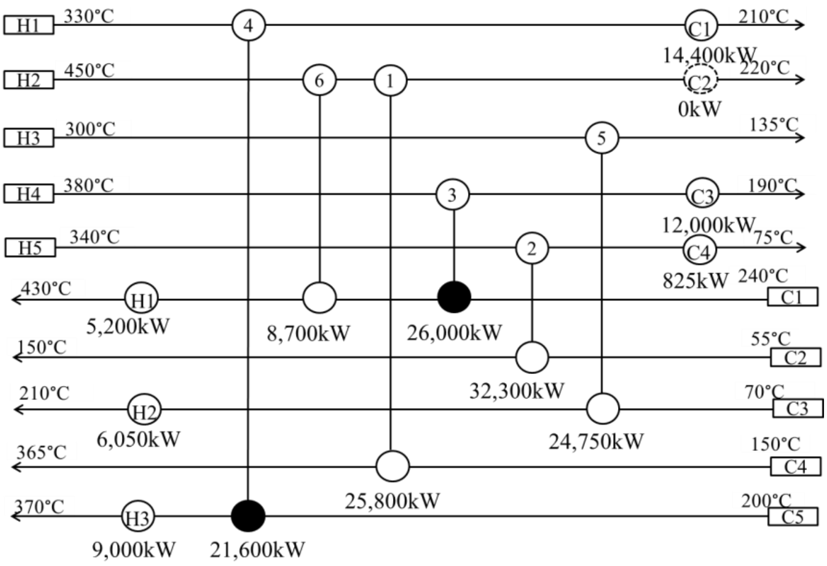


Figure 26: Pinched HEN for Case Study 3

There were 3 cross process pinch exchangers (Exchangers 1, 2 and 3) and 1 cross utility pinch exchanger (Exchanger H2). The best modification identified based on the proposed method is adding a new heat exchanger to create a path. This is because:

1. There are no process heat exchangers upstream from the pinched exchangers. This eliminates resequencing and adding a new heat exchanger to create a loop as beneficial options.
2. There are only two pinched exchangers, and none are adjacent. This makes the implementation of stream splitting not feasible.

Figure 27 shows the network structure for the best single modification (adding a new heat exchanger to create a path). The new exchanger has been added to create a path with the cross utility pinch exchanger with the highest duty (H2) and the cold utility exchanger with the highest duty (C1). Also, the new exchanger has been added after the pinched exchanger 4 and it does not transfer heat across the pinch as indicated in the guidelines. It has also been added after Exchanger 5 on stream C3 because Exchanger 5 is not on a utility path or loop. This ensures that the network energy balance is maintained. With this network there were no viable retrofit designs with the application of the other retrofit options.

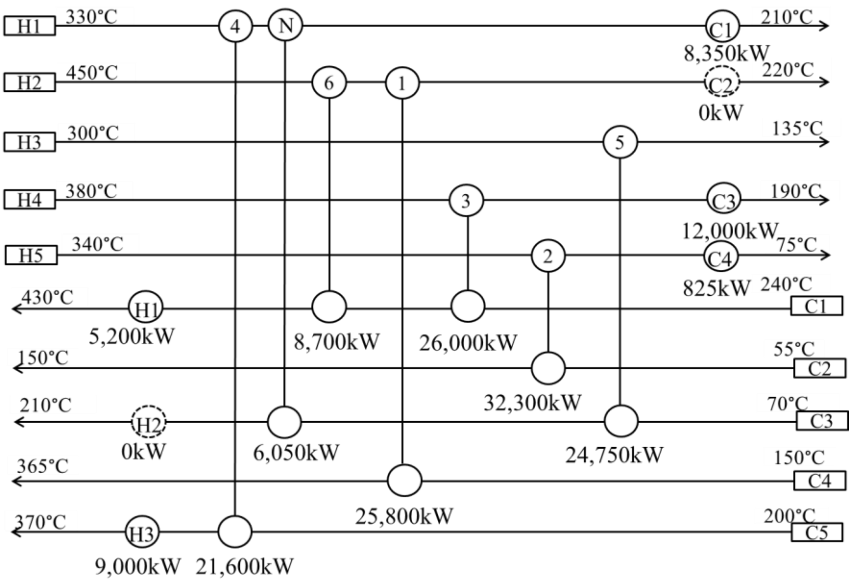


Figure 27: Best single modification for Case Study 3

3.2.4 Case Study 4

Case study 4 is from Wang, [14]. The network shown in Figure 28 is made up of 7 hot streams and 3 cold streams. The network consists of 11 process heat exchangers and 8 utility exchangers. The goal is to reduce the energy consumption of the hot utility (H) subject to ΔT_{min} of 10°C. This corresponds to a minimum hot and cold utility consumption of 13,906kW and 6,714kW respectively. The stream data is shown in Table 4. This HEN has 5 degrees of freedom (4 utility paths and 1 loop).

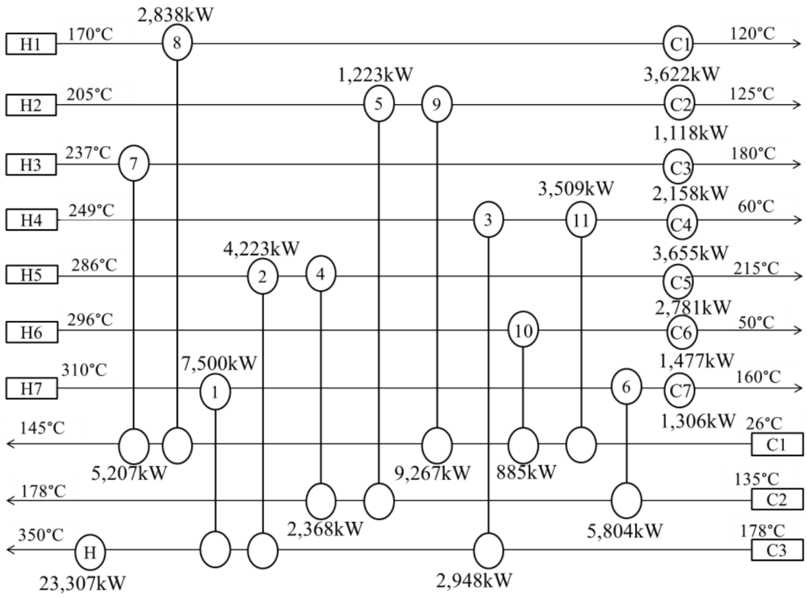


Figure 28: Original HEN for Case Study 4

Table 4: Stream Data

Stream Name	T_S (°C)	T_T (°C)	Q (kW)	CP (kW/°C)	H.T.C.(kW/m^2°C)
H1	170	120	6,460.0	129.2	1
H2	205	125	11,608.0	145.1	1
H3	237	180	7,364.4	129.2	1
H4	249	60	10,111.5	53.5	1
H5	286	215	9,372.0	132.0	1
H6	296	50	2,361.6	9.6	1
H7	310	160	14,610.0	97.4	1
C1	26	145	21,705.6	182.4	1
C2	135	178	9,395.5	218.5	1
C3	178	350	37,977.6	220.8	1

After pinching the network, there is only one viable utility path left as the duties of utility exchangers C3, C4, C5 and C7 becomes zero (see Figure 29). Pinched exchangers identified for in this case study are Exchangers 1 and 3. The pinch temperatures are 286°C (hot) and 276°C (cold).

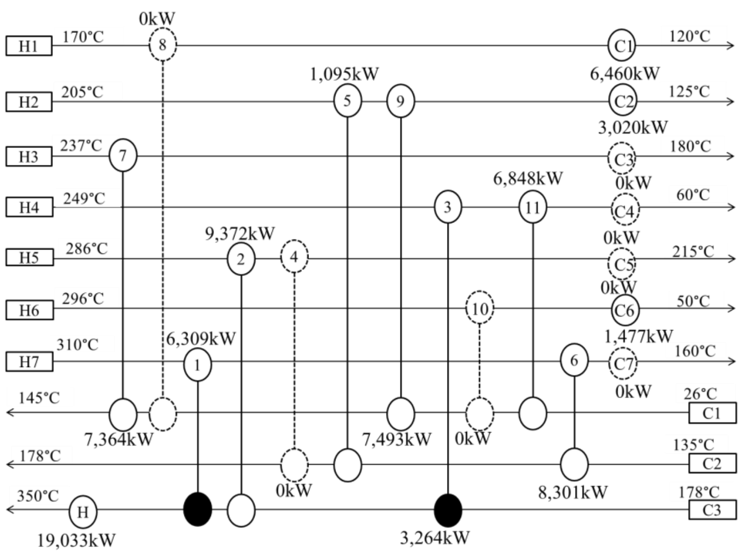


Figure 29: Pinched HEN for Case Study 4

There is one cross process pinch exchanger (Exchanger 1) and 2 cross utility pinch exchangers (Exchangers H and C6). Repeating the retrofit methodology identifies that adding a new heat exchanger to create a loop is the best option (see Figure 30).

A loop has been created with the only cross process pinch heat exchanger (Exchanger 1). Note that the new heat exchanger has been placed before Exchanger 2 on the cold stream (C3) and before Exchanger 6 on the hot stream (H7). This is because both Exchangers 2 and 6 are on a viable loop. The new exchanger has also been placed after Exchanger 3 as it is pinched and does not transfer heat across the pinch. The network structure generated for the other viable structural modification option (new exchanger to create a path) is shown in Figure 31. A decrease in energy consumption of 27.9% for new heat exchanger to create a loop as opposed to 22.9% of new heat exchanger to create a path is obtained.

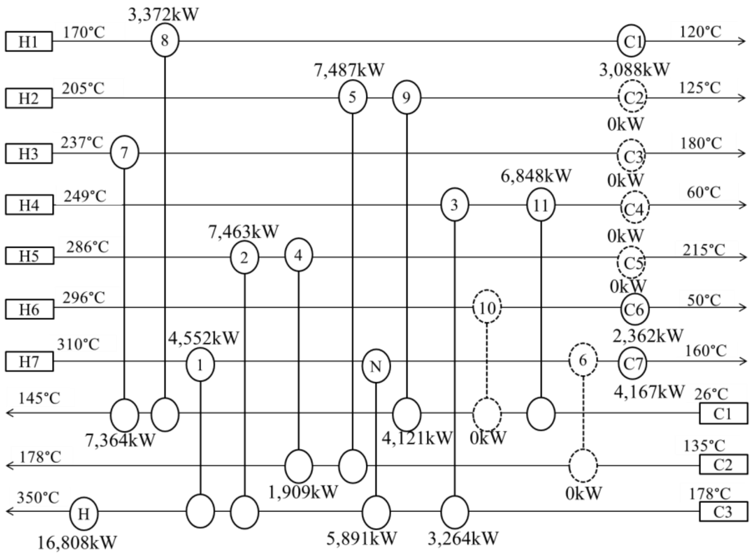


Figure 30: Best single modification for Case Study 4

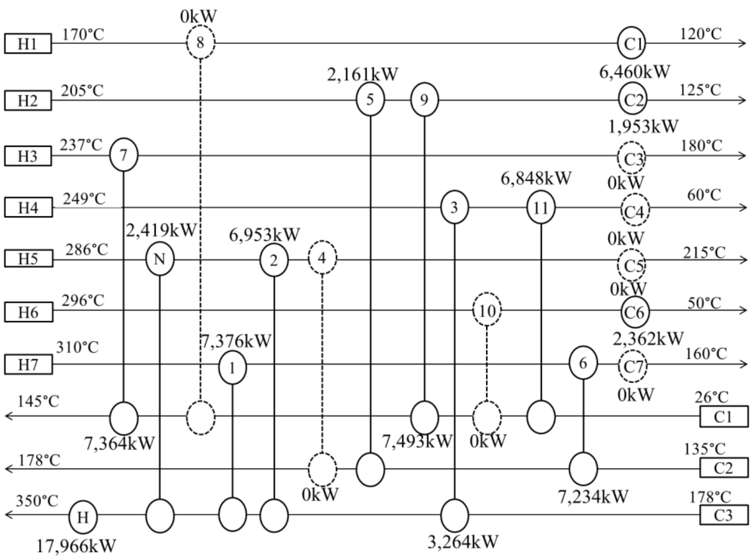


Figure 31: New Exchanger to create a path for Case Study 4

3.2.5 Case Study 5

The fifth case study is from Wang, [14]. The network shown in Figure 32 is made up of 6 hot streams and 3 cold streams. The network consists of 8 process heat exchangers and 7 utility exchangers. The goal is to reduce the energy consumption of the hot utility (H) subject to ΔT_{min} of 10°C. This corresponds to a minimum hot and cold utility consumption of 11,568 and 10,968kW respectively. The stream data is shown in Table 5. This HEN has 6 degrees of freedom (6 utility paths).

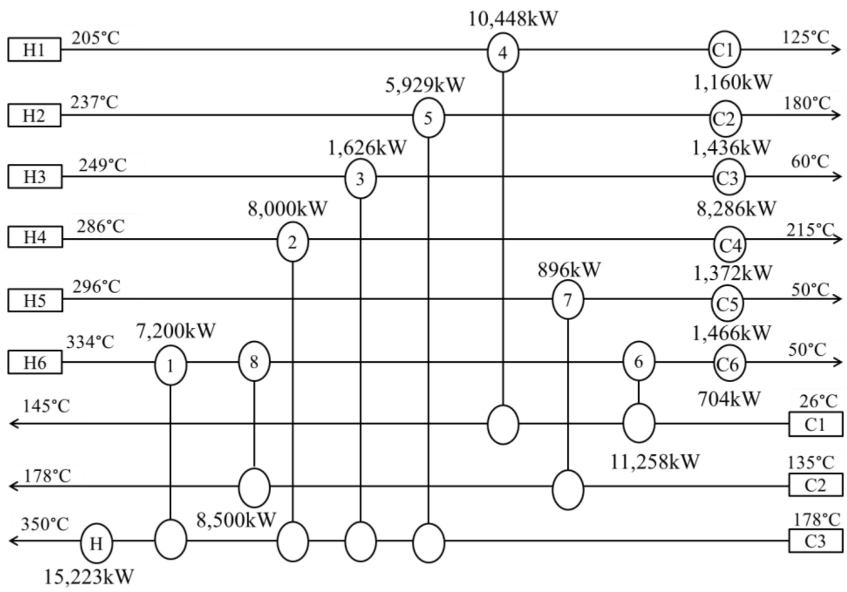


Figure 32: Original HEN for Case Study 5

Table 5: Stream Data

Stream Name	T_S (°C)	T_T (°C)	Q (kW)	CP (kW/°C)	H.T.C.(kW/m^2°C)
H1	205	125	11608.0	145.1	1.5
H2	237	180	7364.4	129.2	1.5
H3	249	60	10111.5	53.5	1.5
H4	286	215	9372.0	132.0	1.5
H5	296	50	2361.6	9.6	1.5
H6	334	50	27661.6	97.4	1.5
C1	26	145	21705.6	182.4	0.75
C2	135	178	9395.5	218.5	0.75
C3	178	350	37977.6	220.8	1.5

After pinching the network, the number of viable utility paths decreases to 4 (see Figure 33). Also, Exchangers 1, 2, 3 and 5 were identified as pinched exchangers. The pinch temperatures are 286°C (hot) and 276°C (cold). Exchangers 1 and C5 transfers heat across the pinch.

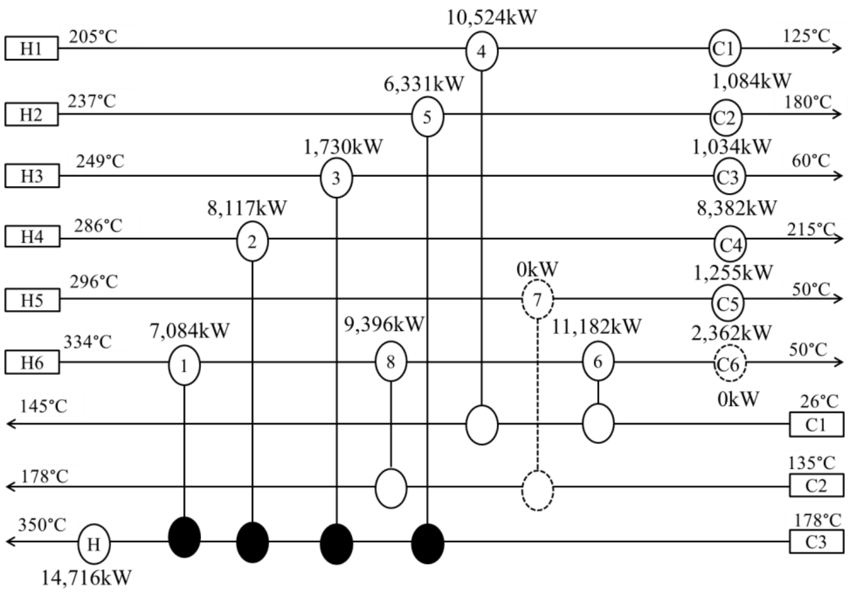


Figure 33: Pinched HEN for Case Study 5

The best modification identified based on the retrofit methodology is stream splitting. This is because:

1. There are no heat exchangers upstream from the pinched exchangers. This eliminates resequencing and adding a new heat exchanger to create a loop as beneficial options.
2. There are four pinching matches, all located adjacent to each other and on utility paths. Therefore, stream splitting will be more beneficial than adding a new heat exchanger to create a utility path.

Figure 34 shows the network structure after splitting stream C3. The network structure generated for the other viable structural modification, new heat exchanger to create a utility path is shown in Figure 35. A decrease in energy consumption of 22.9% for stream splitting as opposed to 4.6% for new heat exchanger to create a utility path is obtained.

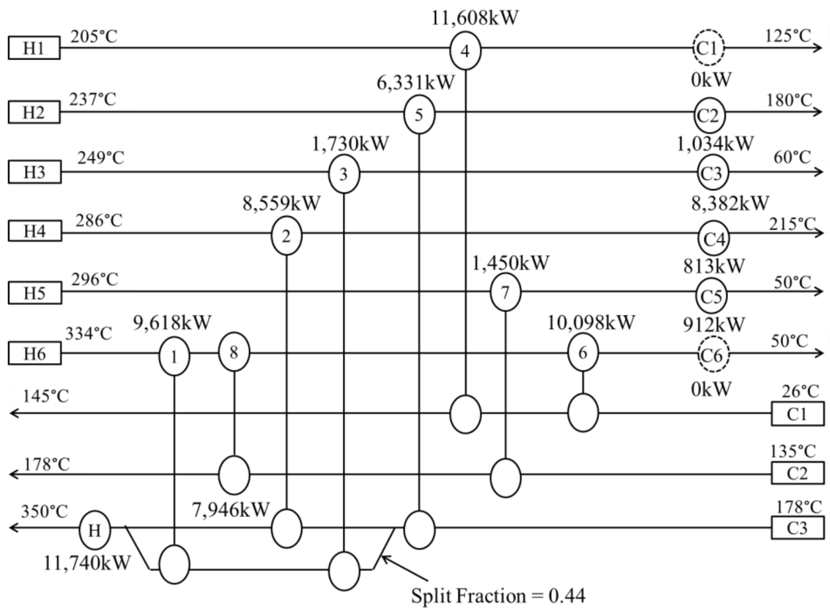


Figure 34: Best single modification for Case Study 5

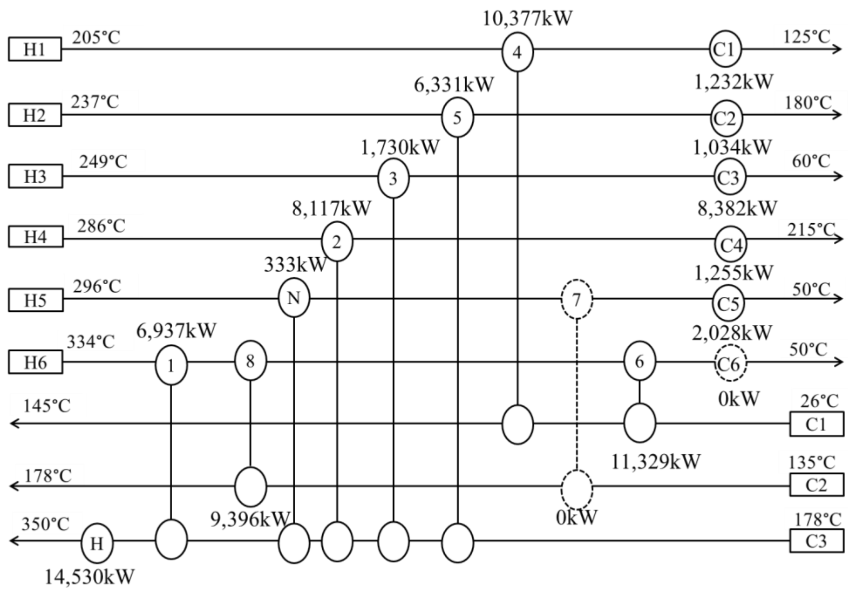


Figure 35: New Exchanger to create a utility path for Case Study 5

3.3 Multiple Modifications

Given the various options that can be employed for the retrofit of HENs, it is difficult to ascertain the correct order in which to apply multiple modifications. After applying a single network modification, the decision on what modification to apply next is unknown (see Figure 36a). From Figure 36b, it can be noted that selecting the best option at each stage of the retrofit process and repeating that same option, may not be the best strategy. A combination of retrofit options may need to be implemented to obtain the best retrofit results in terms of providing the greatest benefits with the fewest number of modifications.

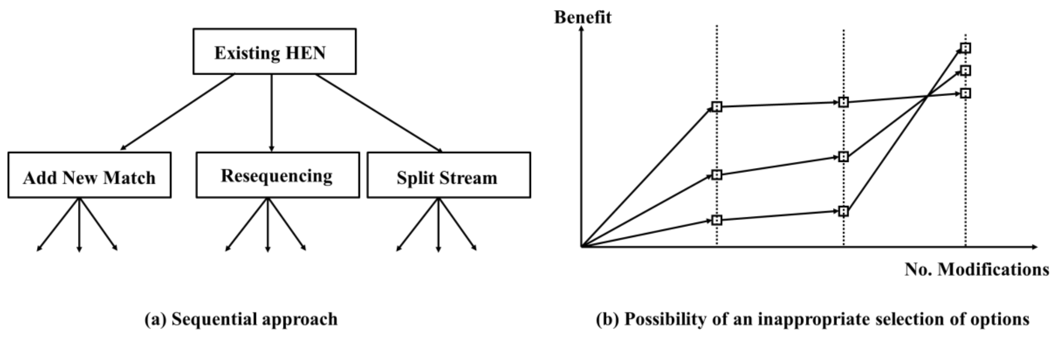


Figure 36: Paths for multiple modifications

To tackle this issue, the retrofit methodology proposed in Figure 37 is used. The only difference between the proposed methodology for single and multiple modifications is for resequencing and new heat exchanger to create a loop to be a beneficial option, upstream heat exchangers must not be on a utility path. If they are, it will be more beneficial to shift a certain amount of heat load along the utility path containing these heat exchangers. This not only reduces the energy consumption but also retrofit capital cost as investments in terms of structural modifications can be avoided. Also, in this situation, it will be more beneficial to consider either adding a new heat exchanger to create a utility path or splitting viable streams.

The network data is updated and the retrofit methodology repeated until the set stopping criteria such as maximum energy recovery or maximum number of modifications, is met. This methodology overcomes the premise that the best single modification if repeated will provide the maximum energy recovery. The best modification at each stage is obtained based on the updated network data and the key features of the new network.

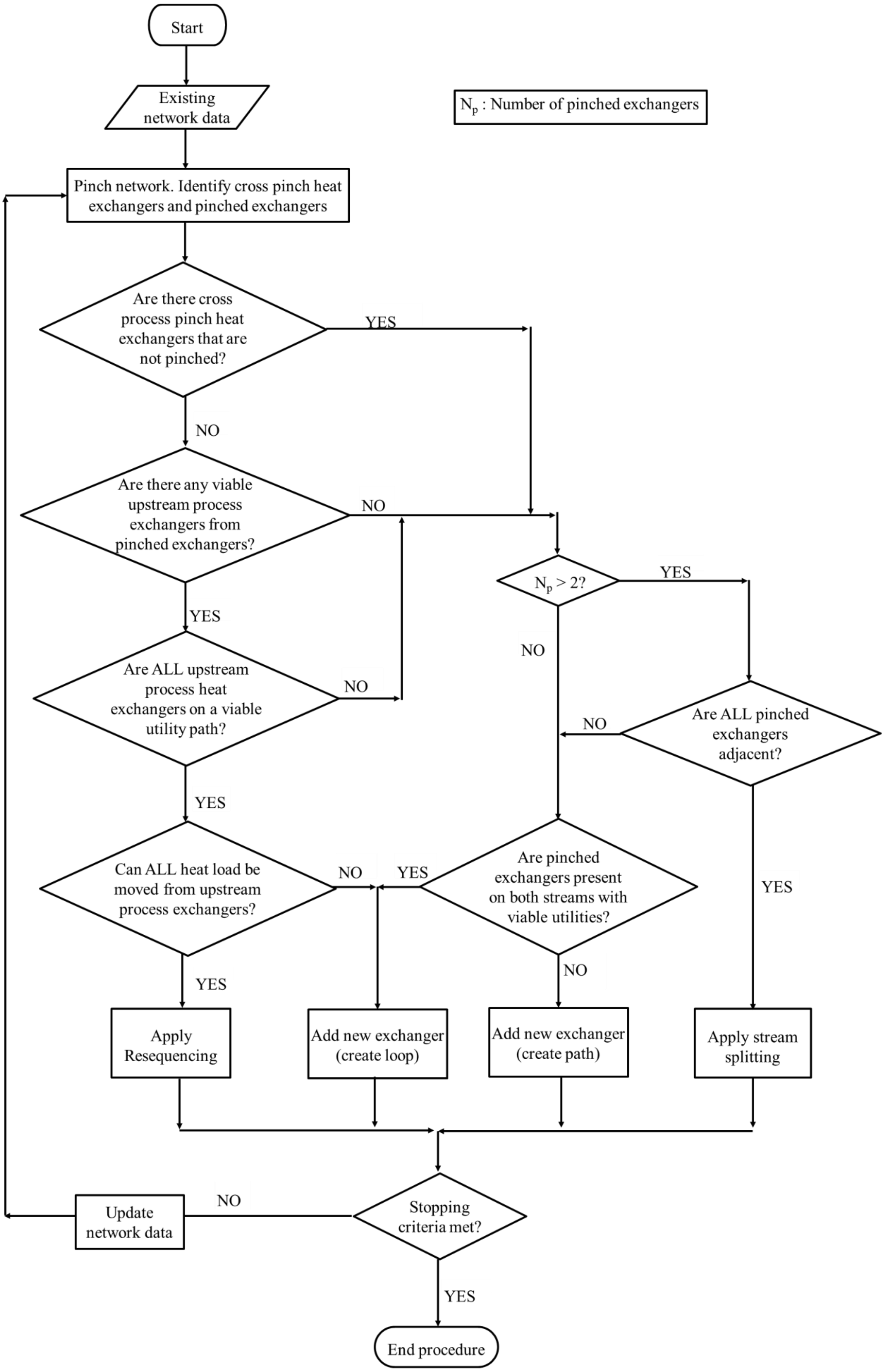


Figure 37: Proposed retrofit methodology for multiple modifications

3.3.1 Case Study 1

To validate the proposed retrofit methodology, the procedure is first applied to Case Study 1 analysed in the single modification. The stopping criteria used for the analysis of case study 1 is to reduce the consumption of the hot utility, H, to 12,410kW subject to ΔT_{min} of 19°C. The best single modification identified is the addition of a new heat exchanger to create a utility path (see Figure 17).

The network data is updated and after pinching the revised network, Exchangers 1, 3 and 4 are identified as pinched exchangers. Exchangers 2 and 4 are also identified as cross process pinch exchangers. From the retrofit methodology, adding a new heat exchanger to create a loop will be the most beneficial option. This is because:

1. From Figure 16, there are two exchangers upstream from the pinched exchangers 1, 3 and 4 (i.e. Exchangers 2 and 6). However, moving the upstream heat exchanger with the highest ΔT_{LM} (Exchanger 2) is not feasible. This eliminates resequencing as the most beneficial option.
2. Although the number of pinched exchangers is greater than 2, they are not located adjacent to one another. This eliminates stream splitting as the most beneficial option.
3. There are pinched heat exchangers on the streams with the utilities with the highest duty (stream C2 and H1). This eliminates adding a new heat exchanger to create a path as the most beneficial option.

Figure 38 shows the result of the best second modification for this case study. A new heat exchanger has been added to form a loop with the cross process pinch exchanger with the highest cross pinch heat transfer (Exchanger 2). Comparing this to performing stream splitting (see Figure 39), new heat exchanger to create a loop provided a further decrease in energy consumption of 873kW, as opposed to 643kW for stream splitting.

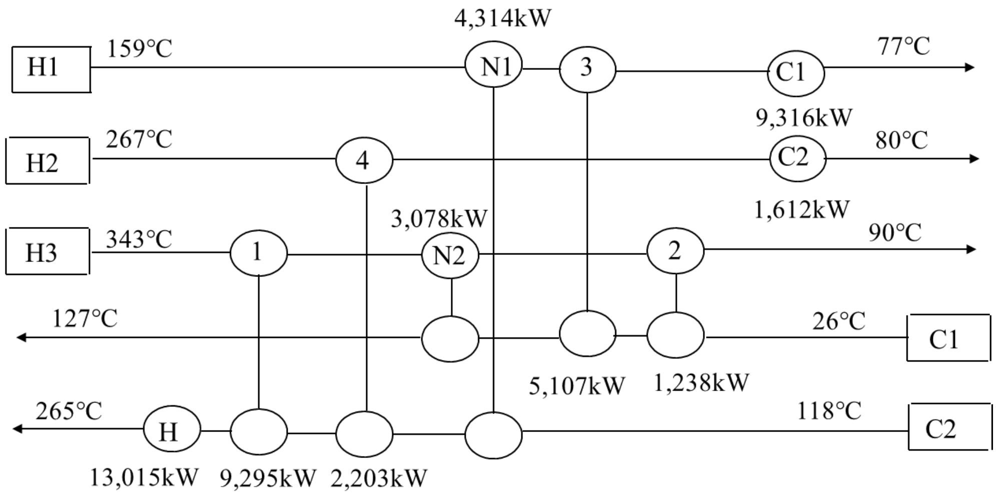


Figure 38: Best second modification for Case Study 1

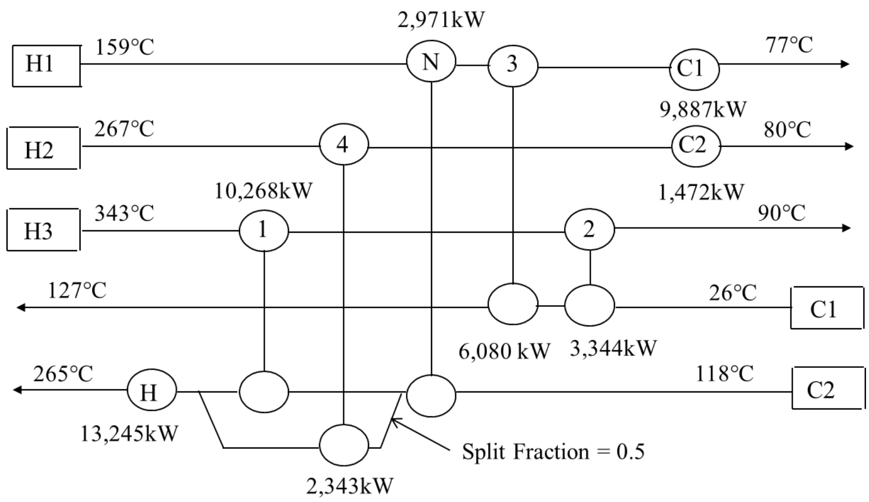


Figure 39: Stream splitting as second modification for Case Study 1

The best second modification does not meet the minimum energy requirement. Therefore, the network is updated and the procedure repeated. After the second modification, pinched exchangers identified are exchangers 1, 4 and N1. The new exchanger N1 is the only heat exchanger that transfers heat across the pinch. Considering there are no upstream process heat exchangers from all pinched exchangers, the only viable options will be to apply stream splitting or to add a new heat exchanger to create a path. Based on the proposed methodology, there are more than two pinched exchangers. Therefore, stream splitting will be the most beneficial option. Also, adding a new heat exchanger to add a utility path is eliminated as the most beneficial option due to the presence of pinched exchangers on the same streams as the viable utilities. Figure 40 shows the result obtained by applying stream splitting.

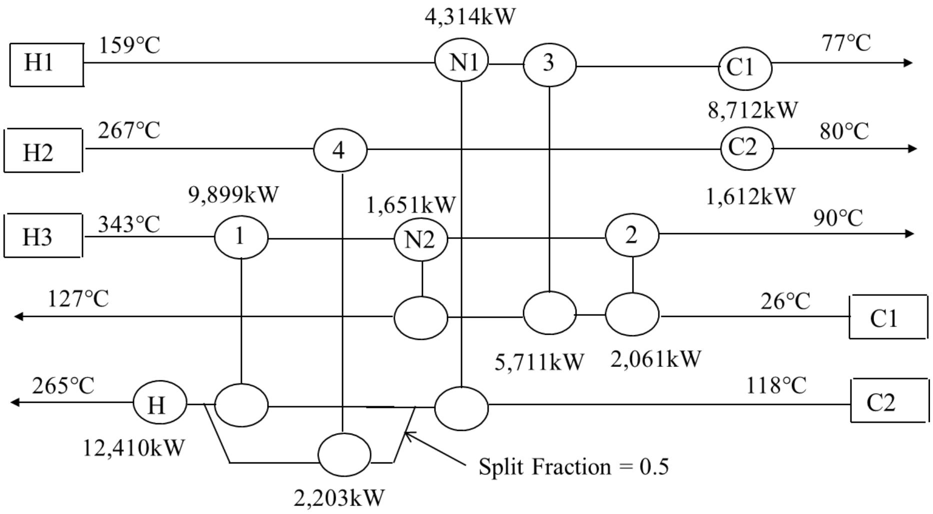


Figure 40: Best retrofit solution for Case Study 1

After the third modification, the minimum energy requirement is obtained. If the best single modification (addition of new heat exchanger to create a utility path) is repeated until the minimum energy requirement is obtained, following the logic presented in Figure 36b, 4 new heat exchangers will be required to achieve the same degree of energy savings as shown in Figure 41. This validates the proposed retrofit methodology in terms of identifying the best modifications in each stage of the retrofit process, which ultimately leads to the least number of modifications required to obtain maximum energy savings.

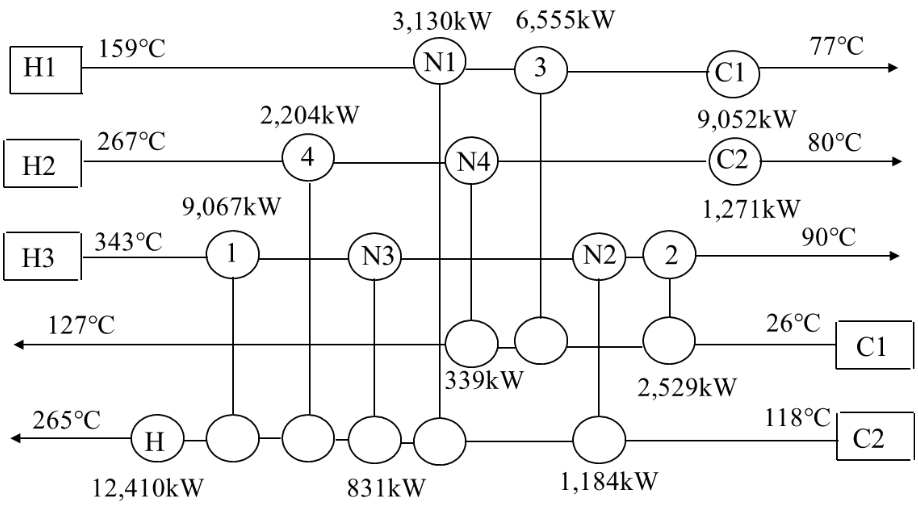


Figure 41: Alternative final solution for Case Study 1

3.3.2 Case Study 2

In this case, the best single modification identified is the application of resequencing (see Figure 21). The stopping criteria used for analysis is to achieve a minimum hot utility requirement of 10,959kW subject to a ΔT_{min} of 10°C.

Updating the network data and pinching the network after the single modification identified Exchangers 2, 4 and 6 as pinched exchangers. Utility exchangers C2 and C4 transfers heat across the pinch. From Figure 21, it can be noted that Exchanger 3 is located upstream from pinched exchangers. As such, both resequencing and adding a new heat exchanger to create a loop are the most beneficial options. Next the feasibility of moving all the heat load of Exchanger 3 is examined. By doing this, the network constraint is violated when Exchanger 3 is moved to the outlet of the pinched exchanger furthest downstream. Therefore, the most beneficial option is to add a new heat exchanger to create a loop with exchanger 3. Figure 42 shows the result of the best second modification for this case study. Comparing this to resequencing Exchanger 3 to the only feasible location, i.e. to the exit of the pinched exchanger, Exchanger 6 (see Figure 43). Adding a new heat exchanger to create a loop provides a further decrease in energy consumption of 758kW compared with 325kW for resequencing.

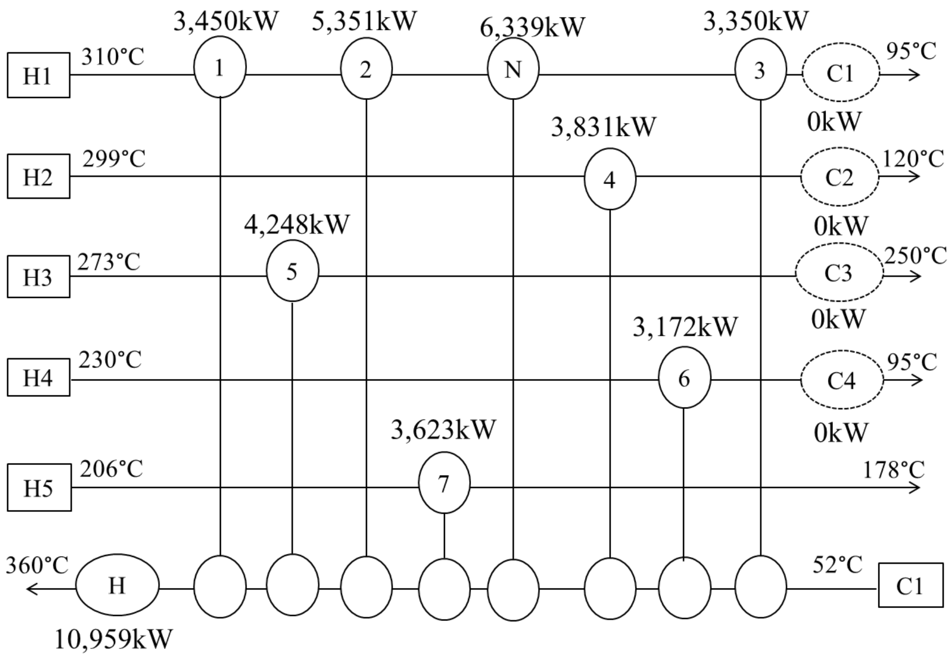


Figure 42: Best second modification for Case Study 2

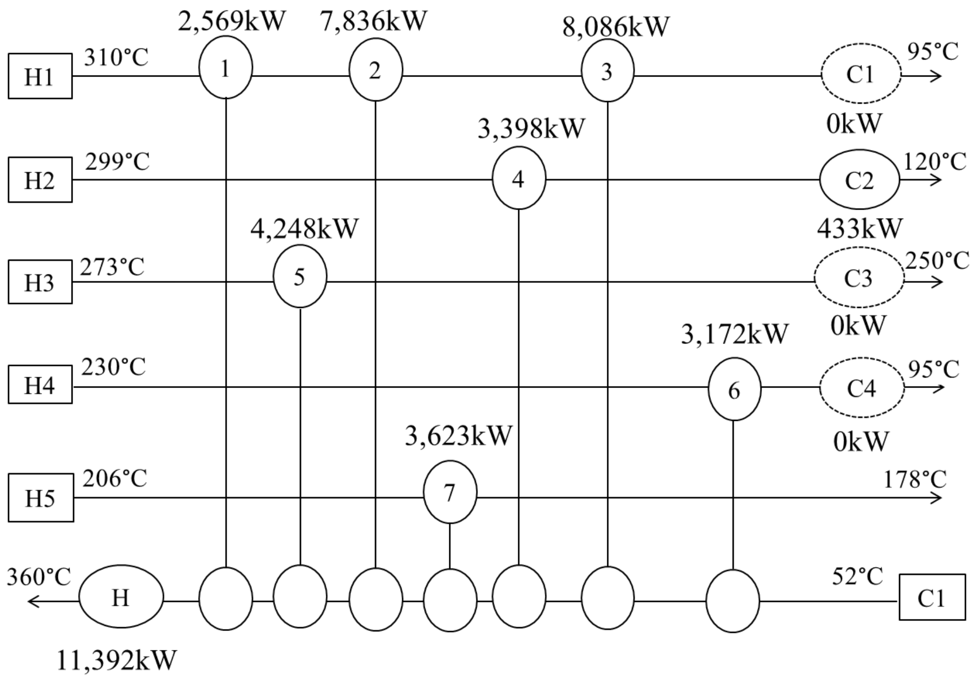


Figure 43: Resequencing as second modification for Case Study 2

3.3.3 Case Study 3

In this case, the best single modification identified is the addition of a new heat exchanger to create a path (see Figure 27). The stopping criteria used for analysis is a minimum hot utility requirement subject to a ΔT_{min} of 10°C. This is equivalent to a minimum hot utility requirement of 8,300kW. After the first modification, Exchangers 3 and 4 are still pinched. Also, Exchangers 1, 2 and 3 are identified as cross process pinch exchangers. Analysing the network structure in Figure 27 shows that there are no upstream heat exchangers from the pinched exchangers and the pinched exchangers are not adjacent to each other. However, due to the presence of a pinched exchanger on the streams as the most viable utilities (H3 and C4), adding a new exchanger to create a path will be infeasible as the temperature constraint of that heat exchanger will be violated. Therefore, to create a utility path, other placements might be required which will not provide the maximum energy recovery possible (for example Figure 44). From Figure 44, a new heat exchanger to create a path has been added to connect utility exchangers H3 and C4. This is because only the cold utility C4 is not connected to a pinched exchanger. Therefore, the best second modification will be to add a new heat exchanger to create a loop with the cross process pinch exchanger with the highest cross pinch heat transfer, exchanger 1 (see Figure 45).

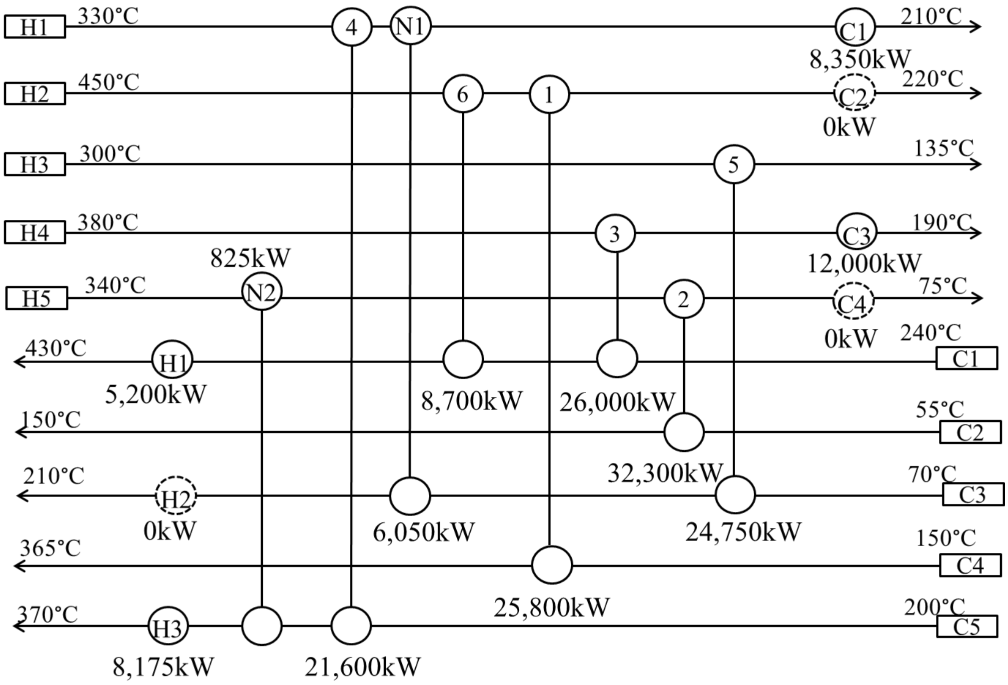


Figure 44: Alternative second modification for Case Study 3

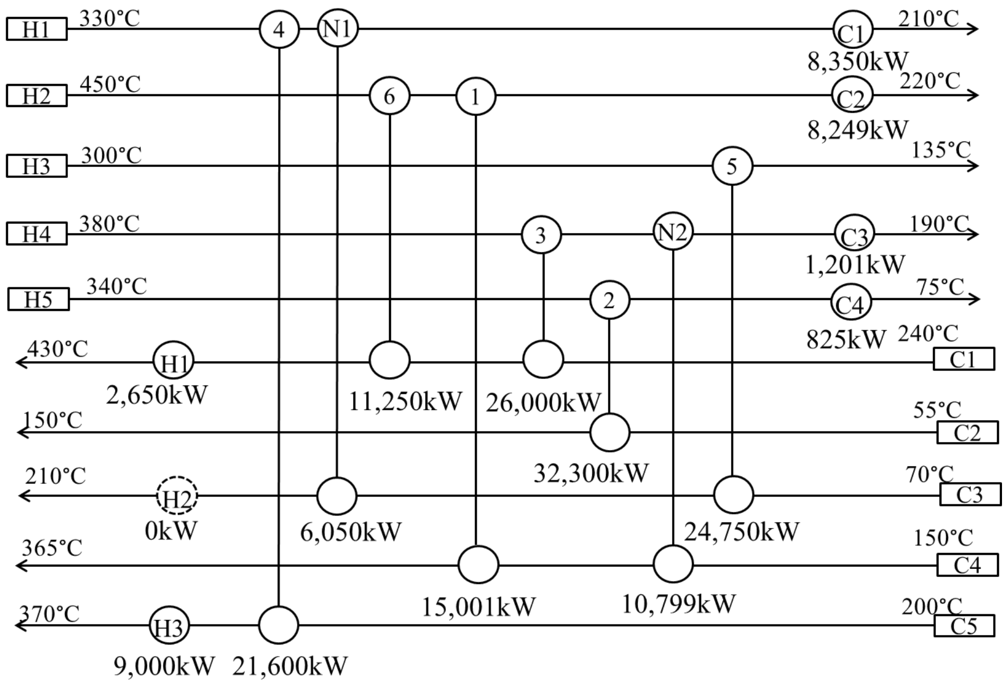


Figure 45: Best second modification for Case Study 3

The maximum energy saving is not achieved after the second modification. Therefore, the retrofit methodology is repeated until this is attained. The final network structure is given in Figure 46. The final result was obtained by carrying out a total of 9 modifications (4 new exchangers to create a loop and 5 new exchangers to create a utility path).

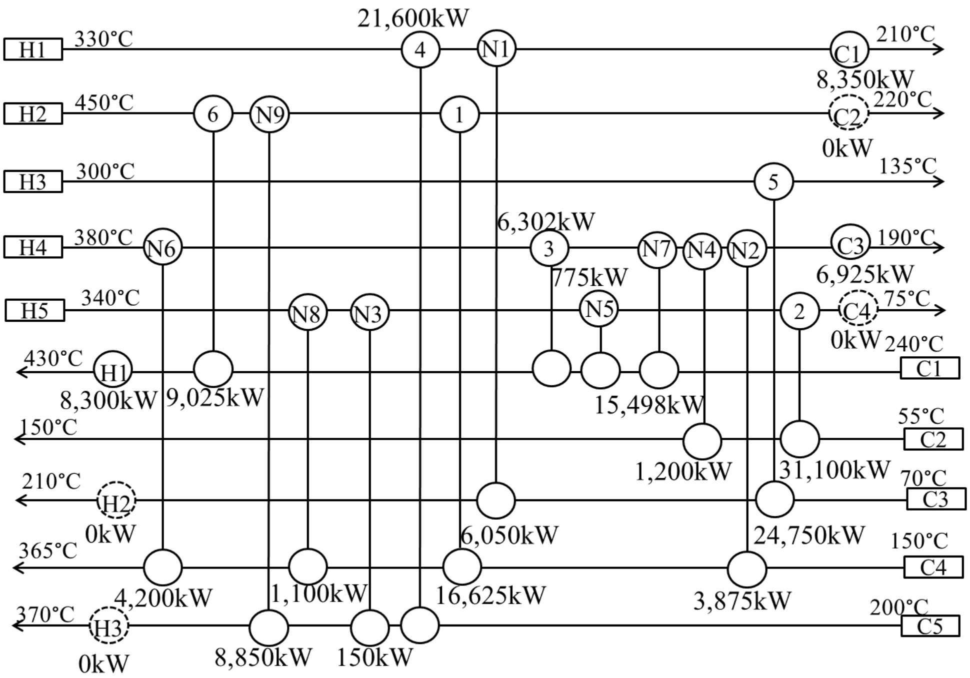


Figure 46: Best retrofit solution for Case Study 3

3.3.4 Case Study 4

The objective is to reduce the hot utility (H) consumption to a value of 13,906kW, which represents the minimum energy consumption at a ΔT_{min} of 10°C. The best single modification identified in this case was adding a new heat exchanger to create a path (see Figure 30). Pinching the network again identifies Exchangers 1, 2, 3 and N as pinched exchangers. Exchanger 1 is identified as a cross process pinch exchanger and utility exchangers H and C6 are identified as cross utility pinch exchangers. Analysing the network structure, stream splitting will be the most beneficial option (see Figure 47) because there are no upstream heat exchangers from pinched exchangers. Therefore, resequencing and adding a new heat exchanger to create a loop are eliminated. Also, the number of pinched exchangers is greater than 2. Although adding a new heat exchanger to create a utility path (see Figure 48) can provide a decrease in energy consumption, the degree of energy saving will be less than that of stream splitting. This is because the cold utility with the highest duty C1 is constrained by the presence of the pinched exchanger 4. Note that Exchanger 3, although a pinched exchanger, has not been included in the split streams. This is because exchanger 3 is neither on a viable loop or path. Including exchanger 3 will result in a violation of the network energy balance or network constraint.

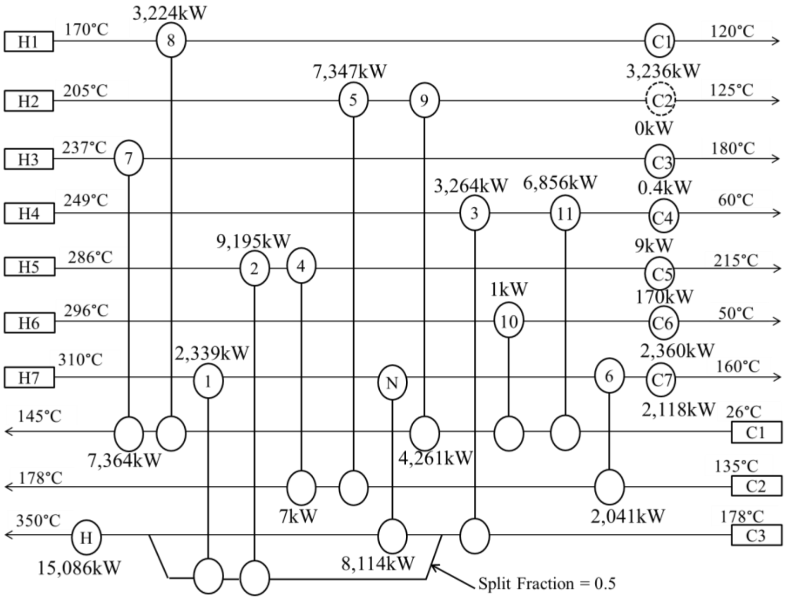


Figure 47: Best second modification for Case Study 4

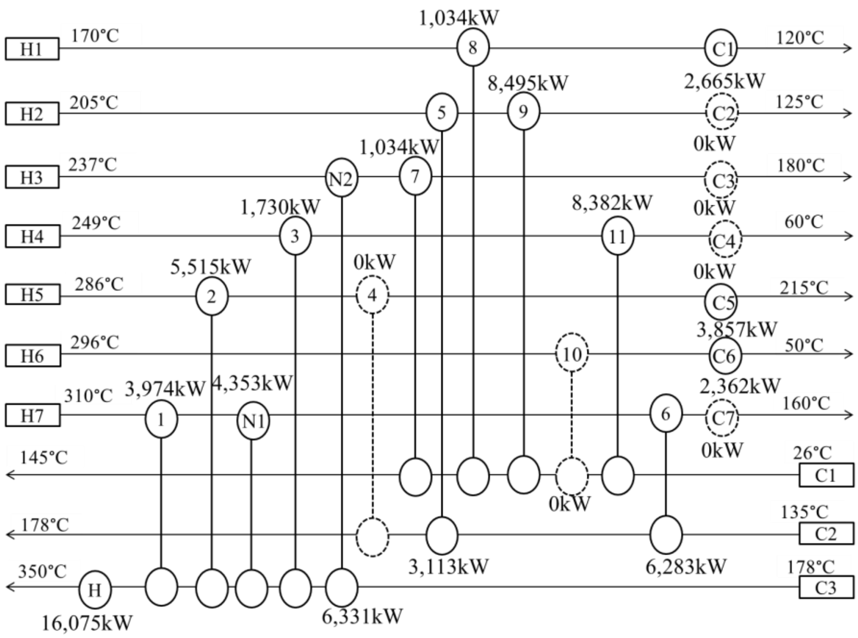


Figure 48: Alternative second modification for Case Study 4

The maximum energy saving is not achieved after the second modification. Therefore, the retrofit methodology is repeated until this is attained. The final network structure is given in Figure 49. The final result was obtained by carrying out a total of 7 modifications (1 stream split, 3 new exchangers and 3 resequencing moves).

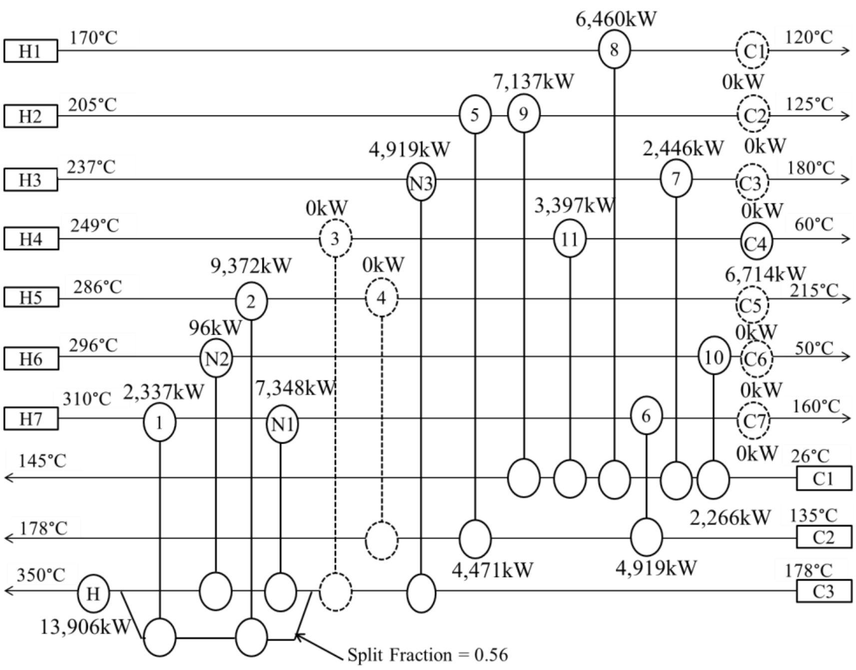


Figure 49: Best retrofit solution for Case Study 4

3.3.5 Case Study 5

The objective is to reduce the hot utility (H) consumption to a value of 11,568kW, which represents the minimum energy consumption at a ΔT_{min} of 10°C. The best single modification identified in this case was the application of stream splitting (see Figure 34). Pinching the network again identifies Exchangers 2, 3, 5 and 7 as pinched exchangers. Exchanger 1 and 7 are identified as a cross process pinch exchangers. Analysing the network structure, adding a new exchanger to create a loop will be the most beneficial option (see Figure 50) because there are no upstream heat exchangers from pinched exchangers. Therefore, resequencing is eliminated as a beneficial option. Also, although the number of pinched exchangers is greater than 2, all the pinched exchangers are not adjacent to each other. Therefore, stream splitting will not be a beneficial option. There are pinched exchanger on the streams with the highest utility therefore, adding a new exchanger to create a utility path will not be as beneficial as adding a new exchanger to create a loop

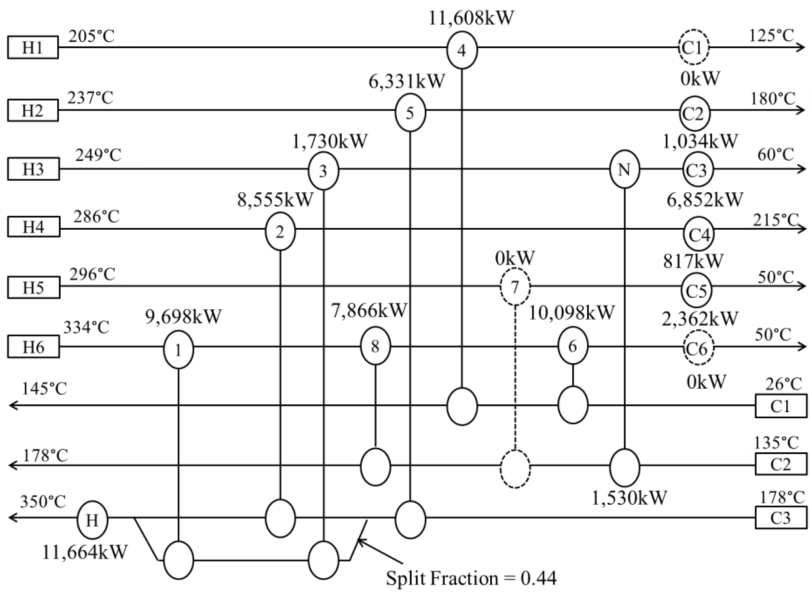


Figure 50: Best second modification for Case Study 5

The maximum energy saving is not achieved after the second modification. Therefore, the retrofit methodology is repeated. After the second modifications exchangers 1, 2, 3 and 5 are pinched. In addition, utility exchanger C5 transfers heat across the pinch. Based on the retrofit methodology, the best modification will be to add a new exchanger to create a utility path with the cross utility pinch exchanger. After doing this, the minimum energy consumption is obtained. The final network structure is given in Figure 51. The final result was obtained by carrying out a total of 3 modifications i.e.1 stream split and 2 new exchangers (1 loop and 1 path).

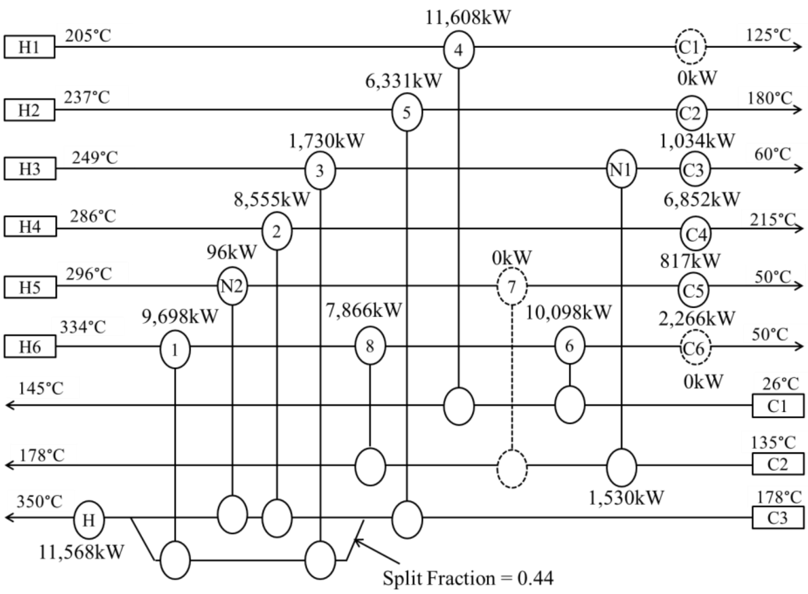


Figure 51: Best retrofit solution for Case Study 5

In conclusion, the step-by-step method is advantageous as it is able to provide simple and practical designs subject to a chosen ΔT_{min}. Also, it can be automated and encourages user interaction.

4 Optimisation-based Approach

Rather than use the step-by-step approach, the retrofit process can be carried using a single step optimisation approach. In this work, simulated annealing (SA) is used as the optimisation algorithm in validating the proposed retrofit methodology of step-by-step approach. This is because SA is widely used with benefits associated with its ability to avoid the local optima due to the random nature of its search.

The aim of the step-by-step approach was to provide insights based on key features of a given HEN to identify the best network modifications that can be applied. In the case of simulated annealing, the number of modifications required to meet a target can be set and the corresponding retrofit result obtained. Depending on the number of modifications, different retrofit designs can be obtained. With SA the following modifications considered are adding, deleting and resequencing heat exchangers; changing the heat loads of the heat exchangers; adding and/or deleting stream splitters; and modifying the splitting ratios.

To validate the results obtained by the step-by-step approach, SA has been applied to the five case studies studied in the previous section. The objective for all is the same as that used in the step-by-step approach, i.e. to maximise energy recovery subject to the network ΔT_{min} value, while ensuring the network energy balance is maintained. Initially, all modification options are assumed to have the same probability and no constraint on the maximum number of modifications.

4.1 SA Results

SA like the step-by-step approach was able to achieve the maximum energy recovery for all case studies as shown in Figures 52 – 56. It can be noted that there are slight variations between these results and that shown for the step-by-step approach (Figures 40, 42, 46, 49 and 51). The difference in continuous variables such as the duties and split fractions has an effect on the heat transfer area required. Also, the number of modifications required is different for both methods as shown in Table 5.

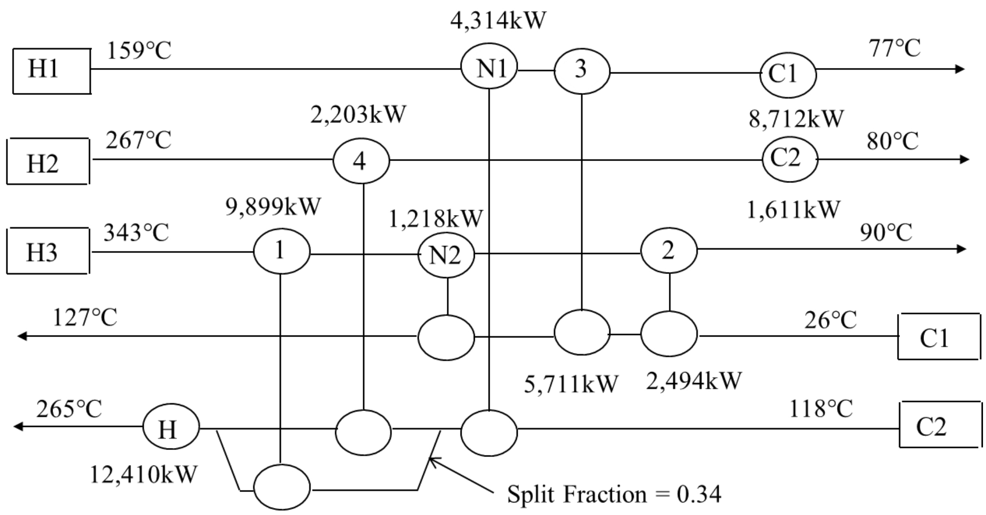


Figure 52: SA solution for Case Study 1

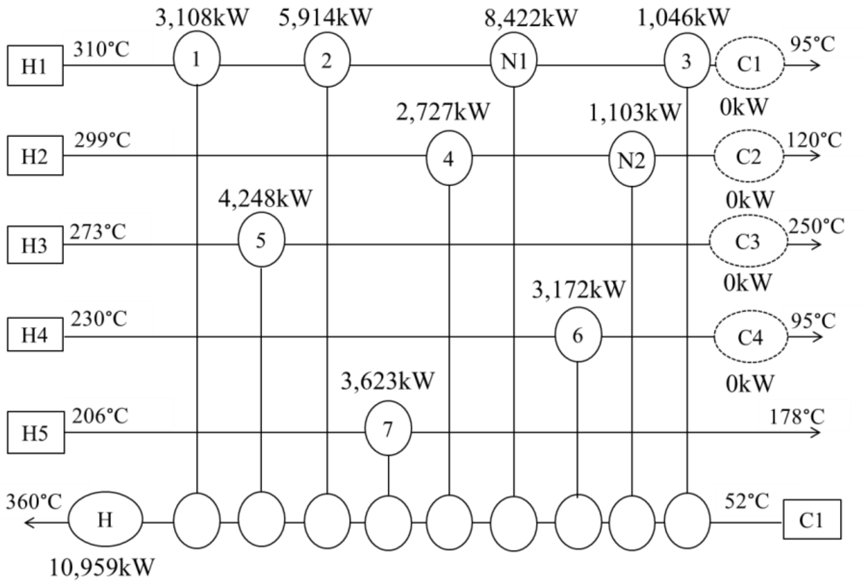


Figure 53: SA solution for Case Study 2

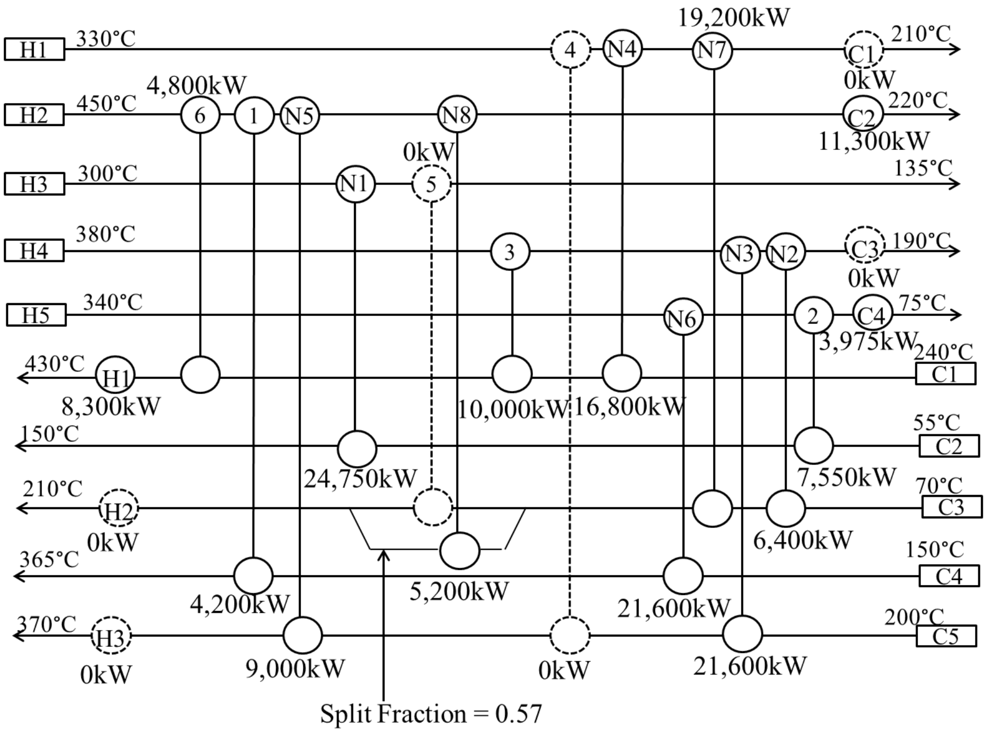


Figure 54: SA solution for Case Study 3

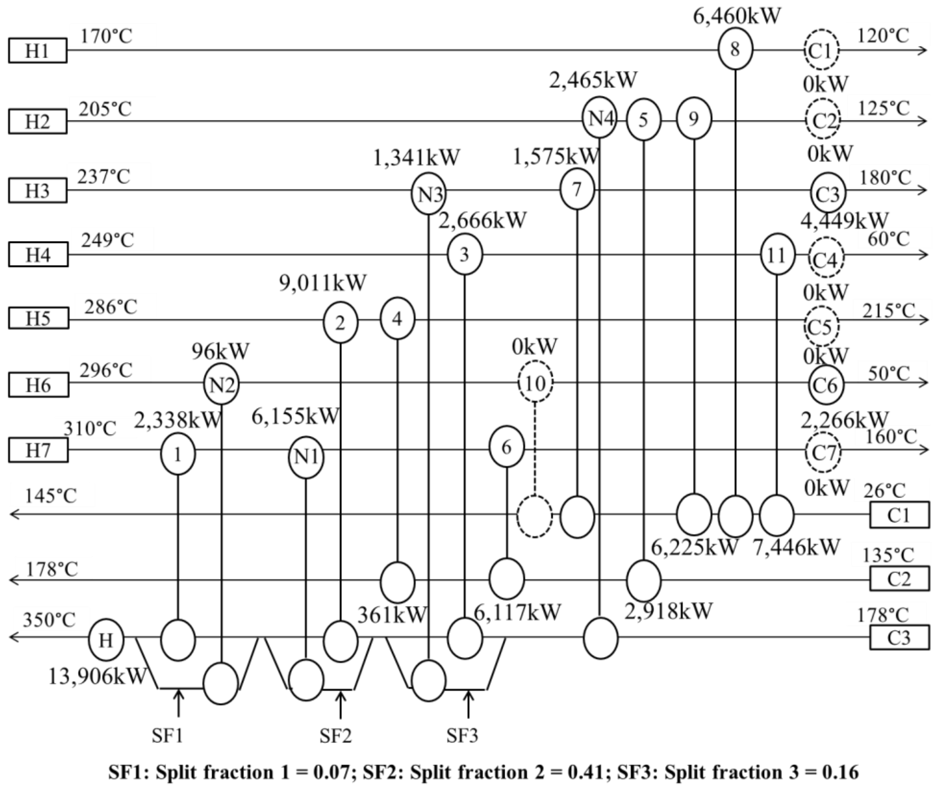


Figure 55: SA solution for Case Study 4

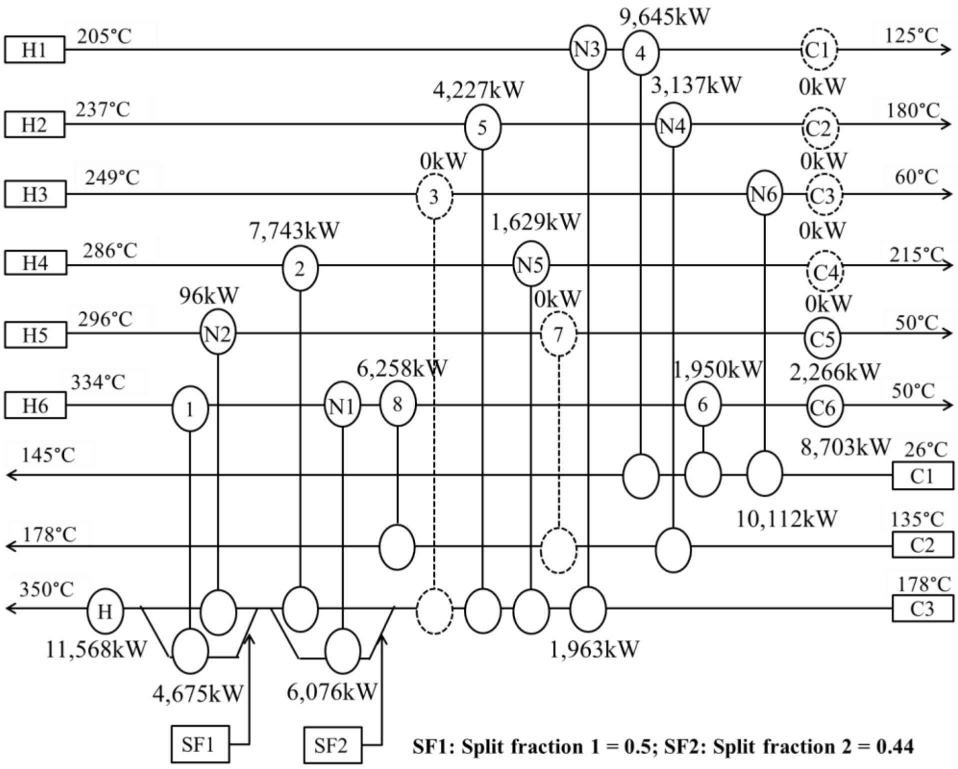


Figure 56: SA solution for Case Study 5

Table 6: Result Comparison

Case Studies	Methods	Number of modifications	Additional Area (m^2)
1	Step-by-Step	3 2 new exchangers (1 loop and 1 path) and 1 stream split	2,471.72
	SA	3 2 new exchangers (1 loop and 1 path) and 1 stream split	2,923.86
2	Step-by-Step	2 1 resequencing and 1 new exchanger to create a loop	2,778.83
	SA	3 1 resequencing and 2 new exchangers (1 loop and 1 path)	2,641.74
3	Step-by-Step	9 9 new exchangers (4 loops and 5 paths)	11,716.50
	SA	9 1 stream split and 8 new exchangers (2 loops and 6 paths)	20,315.90
4	Step-by-Step	7 1 stream split, 3 new exchangers (all paths) and 3 resequencing	4,116.31
	SA	9 3 stream splits, 4 new exchangers (all paths) and 2 resequencing	4,070.71
5	Step-by-Step	3 1 stream split and 2 new exchangers (1 loop and 1 path)	1,954.57
	SA	8 2 stream split and 6 new exchangers (3 loop and 3 path)	2,281.02

The results show that compared to the SA approach, the step-by-step approach identifies the modifications that can bring about maximum energy recovery with the fewest number of modifications. However, the result shown for SA is subject to there being no constraints on the number of modifications that can be made. If maximum numbers of modifications are set with SA for all case studies examined, SA identifies exactly the same network structures, heat loads, stream split fractions and heat transfer area requirement for all case studies.

5 Conclusions

A new step-by-step approach to HEN retrofit has been developed that can be used in identifying the best network modifications for a given HEN. Unlike the conventional methods used in retrofit, this method provides insights into the decision making process for the identification of the best network modifications. The new approach makes use of key features of a HEN to establish a retrofit design that is not only feasible, but guarantees the maximum energy recovery based on the network pinch approach. It also has the advantage over previous approaches by promoting user interaction.

However, analysis carried out in this work has solely been dependent on maximising energy recovery. As a result, capital cost associated with the suggested modifications and additional heat transfer area has not been considered in the decision making process. Future work will consider analysing the cost implication of the modifications and the additional heat transfer area required. In addition, future work will consider reducing the cost associated with performing structural modifications with the application of heat transfer enhancement in retrofit.

Nomenclature

Symbols	**Definitions**	**Units**
Q_{REC}	Energy recovery	MW
ΔT_{min}	Minimum temperature approach	°C
T	Temperature	°C
H	Enthalpy	MW
A_{exist}	Existing area	m^2

CP	Heat capacity flowrate	kW C^{-1}
E_{exist}	Existing energy requirement	MW
ΔT	Exchanger temperature difference	°C
NP	Number of pinching matches	-
T_S	Start temperature	°C
T_T	Target temperature	°C
Q	Duty	kW
Q_{cp}	Total cross pinch heat transfer	kW
H.T.C	Stream heat transfer coefficient	kW m^{-2} C^{-1}

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6.3 Summary

A new step-by-step approach was validated by comparing the results obtained with stochastic optimisation i.e. simulated annealing. The result shows that the new method is able to identify the least number of modifications required to achieve a set target compared to stochastic optimisation. In addition, as opposed to the optimisation-based approach, this method provides useful and new insights into the interaction between different components of the HEN. It also has an advantage over previous approaches by promoting user interaction. The method presented can be said to be a robust method for the identification for the best modifications to be applied to an existing HEN.

The objective of the new method is to identify the best modifications to obtain maximum energy recovery. However, the retrofit capital cost in terms of structural modifications and increasing the heat transfer area of existing exchangers has not been taken into account. The aim of this project is to present cost effective retrofit methods for HENs, thus the costs associated with performing structural modifications needs to be determined. In addition, ways of reducing the retrofit capital cost with structural modifications needs to be presented. This is tackled in the next section of this thesis.

Chapter 7 Structural Modifications with Heat Transfer Enhancement

7.1 Introduction to Publication 5

This section tackles the fourth research objective of this thesis given in Section 1.3. The ultimate goal in retrofit is to be able to present a cost effective design that achieves maximum energy recovery. Publication 5 develops the benefits of both structural modifications (high-energy recovery) and heat transfer enhancement (low retrofit capital cost). However, before achieving the ultimate goal set out in retrofit, the costs associated with the application of structural modifications are determined. This is based on literature cost data for performing structural modifications. Publication 5 is a combination of the methodologies for structural modifications and heat transfer enhancement with and without pressure drop considerations presented in previous chapters.

7.1.1 Development of Cost Effective Retrofit Methodology

This section addresses the question posed in “Objective 4, Questions ‘a’. To obtain maximum energy recovery structural modifications are applied to existing networks. A drawback of the application of structural modifications is the need for additional heat transfer area in existing exchangers. This work exploits the benefits of heat transfer enhancement i.e. an enhanced heat exchanger has a higher heat transfer coefficient to exchange the same duty under smaller heat transfer area requirements. Therefore, the energy saving obtained by applying structural modifications can be maintained and heat transfer enhancement used in eliminating or reducing the additional heat transfer area requirements after retrofit. The effects of heat transfer enhancement on pressure drop are also taken into consideration in Publication 5. A comparison is made between the use of only heat transfer enhancement in retrofit, the use of enhancement considering pressure drop constraints, the use of only structural modifications, and the use of structural modifications with heat transfer enhancement considering pressure drop in terms of energy recovery and retrofit profit.

7.2 Publication 5:

Akpomiemie, M. O., and Smith, R., (2016). Combined methods for heat exchanger network retrofit.

Combined Methods for Heat Exchanger Network Retrofit

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Abstract

In this work, structural modifications based on the network pinch approach have been combined with heat transfer enhancement to maximise energy recovery while maximising retrofit profit (i.e. difference between profit from energy savings subject to a specified payback time and capital cost of retrofit). The method presented is sequential in approach, where structural modifications are first considered to obtain maximum energy recovery. Heat exchangers requiring additional area are identified, and heat transfer enhancement is then used to reduce or eliminate the additional heat transfer area requirement. The reduced cost is as a result of it being generally cheaper to implement heat transfer enhancement than increasing the heat transfer area of existing heat exchangers in retrofit. With the application of enhancement, the added constraint of pressure drop restricts the maximum degree of enhancement of certain heat exchangers. As such, the retrofit profit is decreased. A comparative analysis is also presented in this work where the results obtained from four scenarios (the use of only heat transfer enhancement, the use of heat transfer enhancement considering pressure drop, the use of only structural modifications, the use of structural modifications and heat transfer enhancement considering pressure drop) are examined.

Highlights:

- Cost-effective retrofit by combining structural modifications and enhancement.
- Maximum energy recovery and reduced retrofit cost.
- Pressure drop considerations reduce retrofit profit.

Keywords: Heat exchanger network; Retrofit; Heat transfer enhancement; Structural Modifications; Pressure Drop

1 Introduction

Increasing concerns associated with greenhouse gas emissions have led to a rise in interest into the retrofit of heat exchanger networks (HENs). In the process industries, the retrofit of HENs can be a cost effective method to reduce the energy consumption. The retrofit of HENs is generally classified by three key methods, which are Pinch Analysis methods, Mathematical Programming methods and Hybrid methods. A detailed review of these methods has been presented in the work by Sreepathi and Rangaiah [1].

The pioneering work on Pinch Analysis was presented by Tjoe and Linnhoff [2]. Generally, Pinch Analysis makes use of a targeting stage for estimating the maximum energy recovery of a network, and a re-design stage to reconnect the cross-pinch exchangers to obey pinch decomposition. The drawback of Pinch Analysis is that it requires an expert user for its application and does not highlight the number of modifications required and the appropriate placement for the additional heat transfer area requirement.

In terms of mathematical programming, the retrofit problem is converted to an optimization model and solved. With mathematical programming, there are numerous network modifications that can be obtained either with the use of a superstructure [3] or through a matrix representation [4-6]. The HEN retrofit is a mixed integer non-linear programming (MINLP) problem [3]. The difficulty in solving a MINLP problem has led to authors simplifying the retrofit problem and to avoid a local optimum solution [7-9]. Drawbacks associated with the use of mathematical programming techniques include lack of guarantee of optimality, prolonged computational times required, the uncertainty in the optimality of the solution due to the assumptions and simplifications made to the model and that lack of user interaction.

Asante and Zhu [10] pioneered the hybrid method for retrofit that combines the features of Pinch Analysis and Mathematical Programming methods. The method proposed referred to as the network pinch approach, consists of a diagnosis and an optimisation stage. In the diagnosis stage, a mixed integer linear programming (MILP) model is used to identify the possible structural modifications that can provide maximum energy recovery subject to an assumed minimum temperature approach. The optimisation stage makes use of a non-linear programming (NLP) model to optimise the capital-energy trade-off of the structural modifications determined in the first stage. The sequential approach enables the automation of the design procedure while maintaining user interaction. The network pinch approach was modified by Smith et al. [11] by converting the process from sequential to simultaneous (structural modifications and capital-energy optimisation are considered in a single step). However, with the network pinch approach, there was still a lack of insights into the decision making process i.e. why a modification is favored above another. As such, there is a possibility of selecting a retrofit option early in the procedure that prevents obtaining the optimal solution in subsequent steps. To tackle this issue, Akpomiemie et al. [12] proposed a step-by-step approach based on the network pinch approach for retrofit of HENS. This work provides insights into the key interactions and key features of an existing HEN that aids in the selection of the best network modifications. This method provides the user with guidelines and selection criteria that aims to overcome the possibility of not being able to find the optimal solution.

Generally, retrofit methods for HENs involve performing structural modifications or the use of heat transfer enhancement. Mathematical programming methods with the application of heat transfer enhancement [13] are plagued with the same drawbacks as those mentioned for mathematical programming methods. To tackle the issues of mathematical programming methods with heat transfer enhancement, heuristic based methods have been developed. Wang et al. [14] presented a method based on sensitivity analysis. However, this method did not consider the impact of enhancement on the network, and assumptions of the degree of enhancement were made. Jiang et al. [15] extended the approach to consider accurate modelling of the chosen enhancement technique to ensure accurate representation of proposed energy saving. The work by Akpomiemie and Smith [16] extended both methodologies to account for the downstream effects on the network after the application of enhancement. The drawbacks with the use of sensitivity analysis for identifying the best heat exchanger to enhance were highlighted by Akpomiemie and Smith [17]. The authors presented an alternative method known as the area ratio approach for the identification of the best heat exchangers to enhance. With this method, the decision on the best heat exchanger is not dependent on a key utility exchanger, as in the case of sensitivity analysis, but on the degree of enhancement a heat exchanger can provide subject to its base case value. As such this method is more suited to large-scale problems. However, a drawback with the aforementioned methods is the lack of consideration of pressure drop resulting from heat transfer enhancement. A disadvantage with the use of enhancement in retrofit is its impact on pressure drop. Therefore, ignoring the effects of pressure drop in retrofit might present a retrofit result that cannot be replicated industrially.

The work by Akpomiemie and Smith [18] tackles this problem. The work makes use of pressure drop mitigation techniques proposed by Nie and Zhu [19] to tackle the pressure drop violations with heat transfer enhancement. Pressure drop mitigation techniques considered are reducing the number of tube passes or changing the shell arrangements of existing heat exchangers from series to parallel. Both methods have an impact of the tube-side velocity of the exchangers, which not only dictates the heat transfer coefficient, but also the pressure drop requirement.

In this work, a sequential method is presented for combining structural modifications and enhancement in retrofit. A case study is used to illustrate the proposed method and the benefits of this study are highlighted by a comparative analysis of the various retrofit options that can be applied to the retrofit of an existing HEN.

2 Retrofit Methodology

The proposed approach maximises the potential energy recovery with structural modifications for a given HEN, while reducing the retrofit cost with the application of heat transfer enhancement. The approach is shown in Figure 1.

Step 1: First, the step-by-step approach proposed by Akpomiemie et al. [12] is used to identify the best structural modifications that can achieve maximum energy savings. Heat exchangers that require additional area are then determined by evaluating the energy balance of the new network structure.

Step 2: The cost of performing structural modifications is evaluated to allow for a comparative study in terms of retrofit profit (RP). Equation 1 is used in determining the initial retrofit profit (RP_i) and is given by the difference between the utility cost before modifications (UC_B) and the utility cost after modifications (UC_{SM}) together with the retrofit capital cost (RC).

$$RP = UC_B - \left[UC_{SM} + \sum_{ex \in EX} RC_{ex}\right] \quad \text{Equation 1}$$

Equations 2 and 3 are used in calculating the utility cost before and after modifications. CCU and CHU are the annual cost parameters for cold and hot utility, Q_B and Q_{SM} are the duty before and after modifications and OT is the payback operating time.

$$UC_B = OT \times \left[CCU \times \sum_{ex \in EX_{CU}} Q_{B,ex} + CHU \times \sum_{ex \in EX_{HU}} Q_{B,ex}\right] \quad \text{Equation 2}$$

$$UC_{SM} = OT \times \left[CCU \times \sum_{ex \in EX_{CU}} Q_{SM,ex} + CHU \times \sum_{ex \in EX_{HU}} Q_{SM,ex}\right] \quad \text{Equation 3}$$

The initial retrofit cost RC_i is given in Equation 4. The retrofit capital cost is a function of the cost of structural modifications (SMC_{ex}), cost of additional area (AC_{ex}), and cost of installing a by-pass (BC_{ex}).

$$RC_{i,ex} = SMC_{ex} + AC_{ex} + BC_{ex} \qquad \forall_{ex} \in EX \quad \text{Equation 4}$$

Step 3: The enhancement sequence for all candidate heat exchangers (heat exchangers requiring additional area) can then be determined based on the area ratio approach [17]. The area ratio signifies the relationship between the degree of enhancement a heat exchanger can provide and its capability to accommodate for additional area as shown in Equation 5. Therefore, the best heat exchanger to enhance first is one with the smallest area ratio, as this signifies the heat exchanger that can provide the greatest degree of enhancement relative to its base case value. Detailed description on how the area ratio is determined is given in Akpomiemie and Smith [17].

$$A_R = \frac{A_{existing}}{\left(A_{existing} + \Delta A\right)} = \frac{U}{U_E} \quad \text{Equation 5}$$

Step 4: After each application of enhancement, the stream pressure drop is checked for pressure drop violations. If there are violations, pressure drop mitigation techniques such as those proposed by Nie and Zhu [19] and used in Akpomiemie and Smith [18] are applied. The application of these techniques will lead to a decrease in the degree of enhancement. The degree of enhancement that can be achieved is dependent on the heat exchanger modifications that are employed to reduce the pressure drop requirements. This decrease is as a result of the decrease in velocity when the pressure drop mitigation techniques are applied. Modifications considered in this work are reducing the number of tube passes and changing the shell arrangement from series to parallel. For each heat exchanger considered, the selection criterion defined in Equation 6 is used in determining the best modification to be applied to reduce pressure drop requirement [18]. The best option is one with the smallest selection factor, as this signifies the modification that can still provide a higher degree of enhancement with the lowest pressure drop penalty.

$$SF = \left(\frac{\Delta P_{N,E} - \Delta P_N}{\Delta P_{B,E} - \Delta P_B}\right)\left(\frac{U_{B,E} - U_B}{U_{N,E} - U_N}\right) \qquad \text{Equation 6}$$

Step 5: If there are no pressure drop violations, the new retrofit profit can then be determined. The difference between the new retrofit profit and those determined previously, is the addition of the cost of modifying the exchanger geometry to deal with pressure drop violations (MC_{ex}). The new retrofit cost is given in Equation 7. Note that Equation 1 is still used in determining the retrofit profit. The difference between the initial and new retrofit profit is due to the inclusion of modification costs to account for pressure drop mitigation shown in Equation 7.

$$RC_{n,ex} = SMC_{ex} + AC_{ex} + BC_{ex} + EC_{ex} + MC_{ex} \quad \forall_{ex} \in EX \qquad \text{Equation 7}$$

Step 6: If the new retrofit profit is less than the initial profit determined after the application of structural modifications, the procedure is stopped. This is to ensure that maximum retrofit profit is obtained with each modification. If not continue to Step 7.

Step 7: Finally, other viable heat exchangers requiring additional area are explored and the procedure is repeated until either the stream pressure drop requirement is violated or there are no other viable candidate heat exchangers for enhancement.

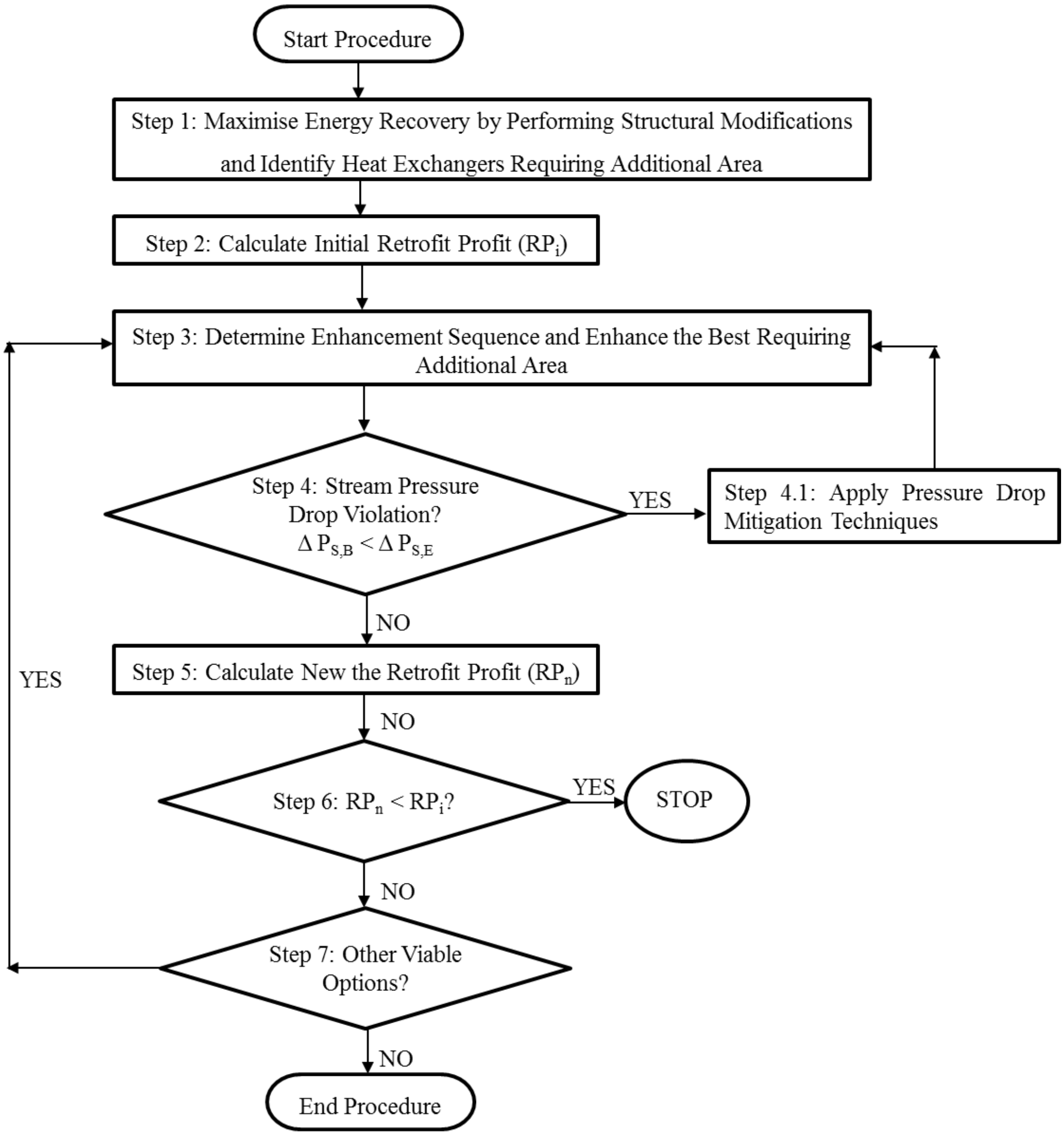

Figure 1: Retrofit Approach

3 Case Study

The proposed approach is applied to an existing HEN that has been studied by Akpomiemie and Smith [16] for the application of heat transfer enhancement in retrofit. The original network structure is given in Figures 2. The stream, exchanger details and the cost of modifications for this case study are given in Tables 1, 2 and 3 respectively. A payback time of one year has been assumed for the purpose of calculating the retrofit profit.

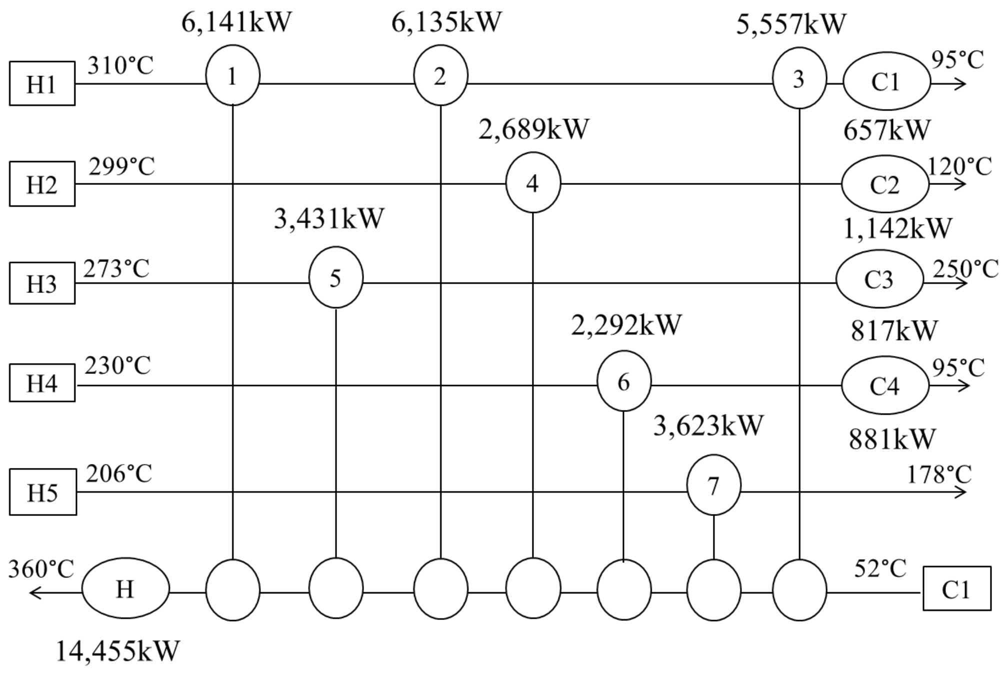

Figure 2: Simplified Pre-Heat Train

Table 1: Stream Data

Stream	CP [kW/°C]	TS [°C]	TT [°C]	Q [kW]	Maximum ΔP (kPa)
H1	86	310	95	18,490.0	400
H2	21.4	299	120	3,830.6	200
H3	184.7	273	250	4,248.1	200
H4	23.5	230	95	3,172.5	200
H5	129.4	206	178	3,623.2	100
C1	143.91	52	360	44,323.2	700

Table 2: Exchanger Data

Ex.	A (m^2)	h_s ($kW/m^2°C$)	ΔP_S (kPa)	h_T ($kW/m^2°C$)	ΔP_T (kPa)	U ($kW/m^2°C$)	Q (kW)
1	396.72	2.07	78.49	1.33	167.29	0.52	6141.33
2	545.45	2.31	100.80	1.40	131.40	0.48	6134.83
3	633.85	4.54	75.76	0.78	73.43	0.16	5556.61
4	354.64	1.27	4.27	0.62	45.38	0.10	2688.79
5	183.85	2.56	98.38	0.78	15.73	0.32	3431.16
6	843.73	0.96	14.66	0.49	146.74	0.06	2291.88
7	114.28	3.38	91.09	0.98	88.54	0.36	3623.20
C1	-	-		-		-	657.23
C2	-	-		-		-	1141.81
C3	-	-		-		-	816.94
C4	-	-		-		-	880.62
H	-	-		-		-	14455.41

Table 3: Cost Data

Utility Cost Data	Retrofit Cost Data
CHU: 400 ($/kW y)	EC: 500 + 10*A ($)
CCU: 5.5 ($/kW y)	BC: 500 ($)
	Cost of Increasing Heat Exchanger Area: 4,000 + 200*A ($)
	Cost of Resequencing: 30,000 ($)
	Cost of New Heat Exchanger: 6,000 + 200*A ($)
	Cost of Stream Splitting: 30,000 ($)

The best structural modifications are identified by applying the step-by-step approach. The objective was to maximise energy recovery, subject to a minimum temperature approach of 10° C. Analysis has been carried out using the SPRINT software [20]. The application of resequencing Exchanger 7 and adding a new heat exchanger N to create a loop with Exchanger 3 provided the greatest decrease in energy consumption as shown in Figure 3. Table 4 shows the exchanger data for this case study after applying structural modifications.

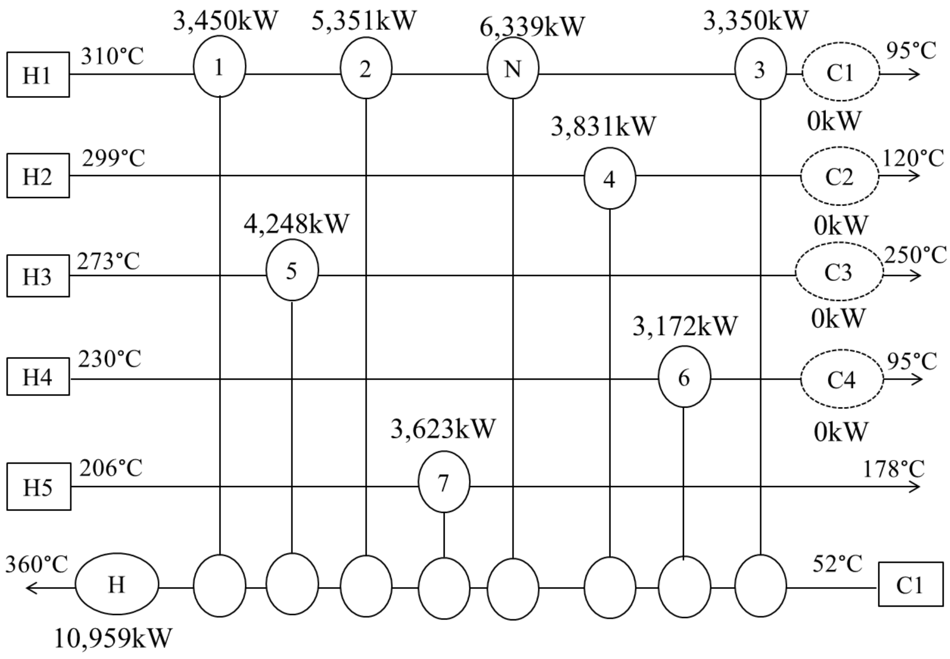

Figure 3: New Network Structure

Table 4: Exchanger Data after Structural Modifications

Ex.	$A_{existing}$ (m^2)	A_{SM} (m^2)	U_B ($kW/m^2°C$)	Q_B (kW)	Q_{SM} (kW)
1	396.72	451.96	0.52	6141.33	3449.98
2	545.45	550.45	0.48	6134.83	5351.40
3	633.85	475.44	0.16	5556.61	3449.94
4	354.64	569.73	0.10	2688.79	3830.60
5	183.85	826.71	0.32	3431.16	4248.10
6	843.73	906.89	0.06	2291.88	3172.50
7	114.28	892.97	0.36	3623.20	3623.20
N	-	1177.16	0.25	-	6338.68
C1	-	-	-	657.23	0
C2	-	-	-	114.81	0
C3	-	-	-	816.94	0
C4	-	-	-	880.62	0
H	-	-	-	14455.41	10958.81

The initial retrofit profit (RPi) after structural modifications is:

Profit from energy savings ($1, 417876)

–Cost of resequencing ($30,000)

– Cost of additional area ($863,741)

– Cost of new heat exchanger ($241, 433)

– Cost of by-pass ($1,500)

= $281, 203

To ensure that there are no stream pressure drop violations, enhancement is applied to heat exchangers requiring additional heat transfer area in a sequential manner. The maximum pressure drop in stream C1 is 700kPa and the existing total pressure drop is 668.51kPa (see Tables 1 and 2). The cost of modifying shell arrangements and the number of tube passes is assumed to be $10,000 and $5,000 respectively. From the study conducted by Akpomiemie and Smith [16] it was found that twisted tape inserts provided a greater degree of enhancement than wire coil inserts for this case study. Therefore, twisted tape inserts have been chosen as the enhancement device. Table 5 shows the twist ratio and tape thickness used to model each heat exchanger.

Table 5: Twisted Tape Insert Parameters

Ex.	Twist Ratio	Tape Thickness (m)
1	5.62	0.0022
2	2.83	0.0022
3	2.50	0.0084
4	2.44	0.0022
5	2.65	0.0022
6	2.65	0.0022
7	2.83	0.0022

The first step is determining the area ratio of all candidate heat exchangers for enhancement. From Table 4, all process heat exchangers required additional area with the exception of Exchanger 3. Therefore, Exchanger 3 has been left out from the next analysis. The area ratios of all candidate heat exchangers for enhancement are given in Table 6. Note that although Exchanger 7 is not on a utility path, it has been considered for enhancement because in this case, enhancement is carried out subject to maintaining the existing duty of all heat exchangers.

Table 6: Area Ratio Results

Ex	U_B (kW/m^2°C)	U_E(kW/m^2°C)	A_R
1	0.517	0.669	0.773
2	0.475	0.597	0.795
4	0.0963	0.108	0.891
5	0.325	0.448	0.725
6	0.610	0.674	0.905
7	0.363	0.487	0.745

First enhancement is applied to the heat exchanger with the smallest area ratio (i.e. Exchanger 5). By doing this, the tube-side pressure drop of Exchanger 5 increases from 15.73kPa to 37.67kPa. This brings the total pressure drop of the stream to 690.45kPa, which is below the maximum allowable enhancement. Therefore, the maximum degree of enhancement can be applied to Exchanger 5. The retrofit profit after enhancing Exchanger 5 is as follows:

Profit from energy savings ($1, 417,876)

–Cost of resequencing ($30,000)

– Cost of additional area ($818,332)

– Cost of new heat exchanger ($241, 433)

– Cost of by-pass ($1,500)

– Cost of enhancement ($6,497)

= $320,114

The new retrofit profit is higher than the initial retrofit profit. Therefore, the retrofit process is repeated with the heat exchanger with the next smallest area ratio (i.e. exchanger 7). Enhancing Exchanger 7 will result in an increase in the tube-side pressure drop from 88.54kPa to 131.95kPa. This brings the total pressure drop of the stream to 733.86kPa, which is above the maximum allowable. In this case, pressure drop mitigation techniques need to be applied.

Exchanger 7 has only one shell and two tube passes. In this case, there is only one option available i.e. reducing the number of tube passes from two to one. Decreasing the number of tube passes not only reduces the pressure drop with enhancement from 131.95kPa to 79.32kPa, but also the heat transfer coefficient from 0.487 kW/m^2°C to 0.4 kW/m^2°C. By doing this, the total stream pressure drop reduces from 733.86kPa to 681.23kPa, which is below the maximum allowable. The new retrofit profit obtained is:

Profit from energy savings ($1, 417,876)

–Cost of resequencing ($30,000)

– Cost of additional area ($801,458)

– Cost of new heat exchanger ($241, 433)

– Cost of by-pass ($1,500)

– Cost of enhancement ($15,083)

– Cost of modifying tube passes ($5,000)

= $323,403

The next best heat exchanger identified is Exchanger 1. Enhancing Exchanger 1 results in an increase of its tube-side pressure drop from 167.29kPa to 169.25kPa. This results in an increase in the total pressure drop to the value of 683.19kPa, which is below the total allowed. Therefore, Exchanger 1 is enhanced to the maximum degree of enhancement. The retrofit profit obtained is:

Profit from energy savings ($1, 417,876)

–Cost of resequencing ($30,000)

– Cost of additional area ($707,066)

– Cost of new heat exchanger ($241, 433)

– Cost of by-pass ($1,500)

– Cost of enhancement ($19,078)

– Cost of modifying tube passes ($5,000)

= $413,800

Again, this value is greater than the previous calculated. Therefore, the retrofit procedure is continued. Enhancing Exchanger 2 results in an increase of its tube-side pressure drop from 131.40kPa to 163.31kPa. This brings the stream total pressure drop to 715.10kPa, which is above the maximum allowable. Therefore, pressure drop mitigation techniques are applied. Exchanger 2 has two shells arranged in series and two tube passes. In this case, there are two options available i.e. reducing the number of tube passes from two to one and changing the shell arrangement from series to parallel. A split fraction of 0.5 is assumed for the case of changing shell arrangement. To determine the best option to select, the selection factor (SF) is used. From the result shown in Table 7, the modification of the shell arrangement is the best, as it has the lowest value for SF. This decreases the stream total pressure drop from 715.1kPa to 595.01kPa.

The retrofit profit obtained in this case is:

Profit from energy savings ($1, 417,876)

–Cost of resequencing ($30,000)

– Cost of additional area ($592,976)

– Cost of new heat exchanger ($241, 433)

– Cost of by-pass ($1,500)

– Cost of enhancement ($24,871)

– Cost of modifying tube passes ($5,000)

– Cost of modifying shell arrangement ($10,000)

= $512,097

Table 7: Modification for Exchanger 2

	Base Case				After Modification				SF
	U_B (kW/m^2°C)	$U_{B,E}$ (kW/m^2°C)	ΔP_B (kPa)	$\Delta P_{B,E}$ (kPa)	U_N (kW/m^2°C)	$U_{N,E}$ (kW/m^2°C)	ΔP_N (kPa)	$\Delta P_{N,E}$ (kPa)	
Original Design	0.475	0.597	131.40	163.31	-	-	-	-	-
Tube pass reduction (two to one)	0.475	0.597	131.40	163.31	0.356	0.490	113.80	125.48	0.33
Shell Modification (series to parallel)	0.475	0.597	131.40	163.31	0.361	0.494	33.77	43.22	0.27

Enhancing the next heat exchanger, Exchanger 4, results in an increase in its pressure drop from 45.38kPa to 60.53kPa, which increases the total pressure drop of the stream to 610.16kPa. The maximum pressure drop is not violated in this case. Therefore, Exchanger 4 is enhanced to its maximum capacity. The new retrofit profit obtained is:

Profit from energy savings ($1, 417,876)

–Cost of resequencing ($30,000)

– Cost of additional area ($580,525)

– Cost of new heat exchanger ($241, 433)

– Cost of by-pass ($1,500)

– Cost of enhancement ($30,445)

– Cost of modifying tube passes ($5,000)

– Cost of modifying shell arrangement ($10,000)

= $518,973

The final viable option, Exchanger 6 is enhanced. The tube-side pressure drop of exchanger 6 increases from 146.74kPa to 202.14kPa. This represents an increase in the total stream pressure drop from 610.16kPa to 665.56kPa, which is below the maximum allowable. Therefore Exchanger 6 is enhanced and the new retrofit profit is:

Profit from energy savings ($1, 417,876)

–Cost of resequencing ($30,000)

– Cost of additional area ($395,148)

– Cost of new heat exchanger ($241, 433)

– Cost of by-pass ($1,500)

– Cost of enhancement ($39,154)

– Cost of modifying tube passes ($5,000)

– Cost of modifying shell arrangement ($10,000)

= $695,642

The final exchanger details are given in Table 8.

Table 8: Final Exchanger Details

Ex.	$A_{existing}$ (m^2)	A_{SM} (m^2)	A_E (m^2)	U_B ($kW/m^2 °C$)	U_E ($kW/m^2 °C$)	Q_B (kW)	Q_{SM} (kW)
1	396.72	451.96	349.53	0.52	0.67	6141.33	3449.98
2	545.45	550.45	529.27	0.48	0.49	6134.83	5351.40
3	633.85	475.44	475.44	0.16	0.16	5556.61	3449.94
4	354.64	569.73	507.47	0.10	0.11	2688.79	3830.60
5	183.85	826.71	599.67	0.32	0.45	3431.16	4248.10
6	843.73	906.89	820.84	0.06	0.07	2291.88	3172.50
7	114.28	892.97	808.60	0.36	0.40	3623.20	3623.20
N	-	1177.16	-	0.25	-	-	6338.68
C1	-	-	-	-	-	657.23	0
C2	-	-	-	-	-	114.81	0
C3	-	-	-	-	-	816.94	0
C4	-	-	-	-	-	880.62	0
H	-	-	-	-	-	14455.41	10958.81

4 Comparative Analysis

The four scenarios studied are: (1) only heat transfer enhancement [16, 17], (2) heat transfer enhancement considering pressure drop [18], (3) only structural modifications [12], (4) structural modifications and heat transfer enhancement considering pressure drop (this work).

Figure 4 shows a comparative analysis of the results obtained for the case study in this work in terms of energy savings and retrofit profit. From Figure 4, the use of heat transfer enhancement alone provides a higher retrofit profit than the use of only structural modifications, but at a lower level of energy savings. However, when pressure drop is considered alongside the use of enhancement, both the retrofit profit and the energy savings are reduced. Considering pressure drop with enhancement provides a more realistic picture of the use of enhancement in retrofit as violating the maximum pressure drop in a HEN can be costly as either new pumps/compressors will need to be purchased or the existing pumps/compressors might need to be retrofitted to cope with the increase in pressure drop. This cost might not be justified in retrofit. Hence, it is advisable to always consider pressure drop alongside the use of heat transfer enhancement in retrofit.

Comparing the first three scenarios to scenario 4, there is a drastic increase in the retrofit profit obtained, while maintaining the energy savings of scenario 3. The increase in retrofit profit is due to the consideration of heat transfer enhancement, as it has been used to accommodate for the additional heat transfer area required after applying structural modifications. Therefore, scenario 4 is the best retrofit option as it maximises energy recovery and has a high retrofit profit, while making sure all the network constraints such as stream pressure drop are satisfied.

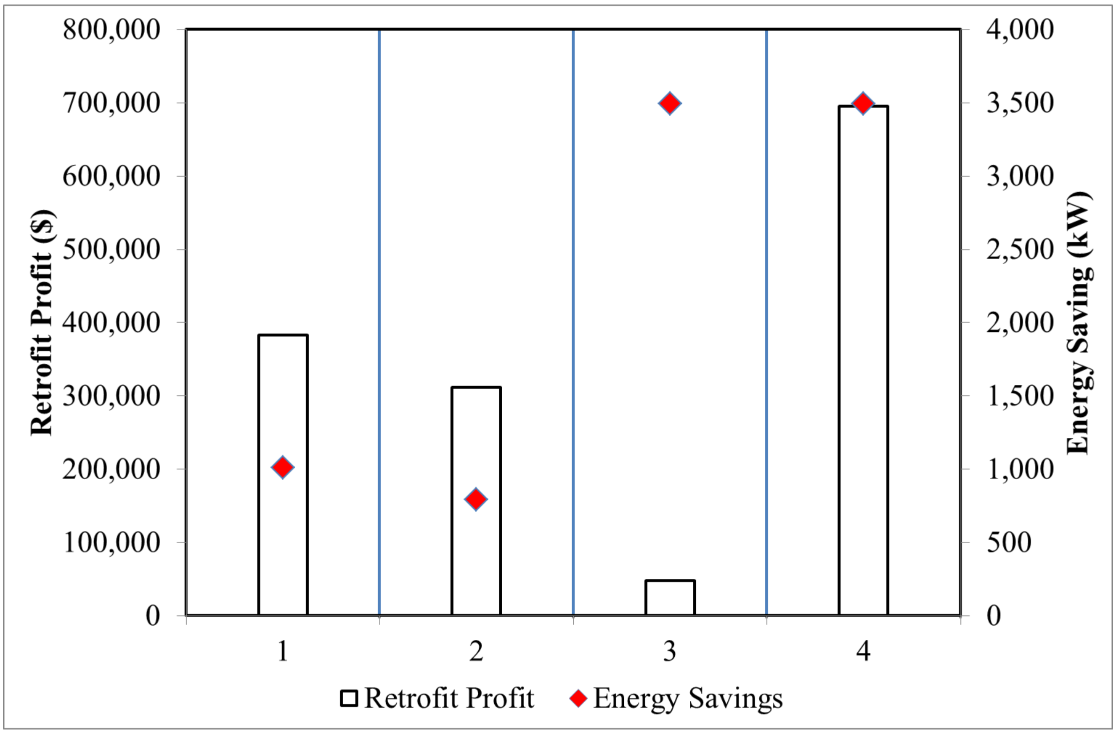

Figure 4: Comparative analysis of Different Retrofit Options

It is important to note that with structural modifications, other factors that can impact on the retrofit profit have not been considered, such as the downtime required in performing the proposed modifications.

5 Conclusions

A sequential method has been presented for the combination of structural modifications and heat transfer enhancement for HEN retrofit. The method capitalises on the benefits of structural modifications in retrofit and heat transfer enhancement. The method also accounts for the impact of the chosen heat transfer enhancement technique on pressure drop. Considering pressure drop constraint has an impact on the retrofit profit as the degree of enhancement that can be applied to a candidate heat exchanger might be reduced to prevent violating the network pressure drop constraint. Depending on the retrofit objective, this work shows the different methods that can be applied.

Nomenclature

Symbols	Definitions	Units
ΔP_T	Total tube-side pressure drop	kPa
h_T	Tube-side heat transfer coefficient	kW m^{-2} $°C^{-1}$
h_S	Shell-side heat transfer coefficient	kW m^{-2} $°C^{-1}$
ΔP_S	Total shell-side pressure drop	kPa
SF	Selection factor	-
$\Delta P_{N,E}$	New total pressure drop after enhancement	kPa
$\Delta P_{B,E}$	Base total pressure drop after enhancement	kPa
ΔP_N	New total pressure drop	kPa
ΔP_B	Base total pressure drop	kPa
$U_{B,E}$	Base overall heat transfer coefficient after enhancement	kW m^{-2} $°C^{-1}$
$U_{N,E}$	New overall heat transfer coefficient after enhancement	kW m^{-2} $°C^{-1}$
U_B	Base overall heat transfer coefficient	kW m^{-2} $°C^{-1}$

U_N	New overall heat transfer coefficient	kW m^{-2} $°C^{-1}$
RP	Retrofit Profit	$
RC	Retrofit cost	$
UC	Utility cost	$
EC	Enhancement cost	$
AC	Area cost	$
BC	Bypass cost	$
MC	Modification cost	$
SMC	Structural Modification cost	$
CCU	Cost parameter for cold utility	$/y
CHU	Cost parameter for hot utility	$/y
OT	Operating time	y
Q	Heat duty	kW
A	Heat transfer area	m^2
TT	Target temperature	°C
TS	Supply temperature	°C
ΔT_{LM}	Log Mean Temperature Difference	°C
F_T	Correction factor	-
AR	Area ratio	-
U_E	Enhanced overall heat transfer coefficient	kW m^{-2} $°C^{-1}$

Subscripts:

B	Base
E	Enhanced
T	Tube
S	Shell
SM	Structural Modification
ex, EX	Exchanger
HS	Hot stream
CS	Cold stream
CU	Cold utility
HU	Hot utility

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7.3 Summary

Publication 5 presents a sequential method for the application of structural modifications with heat transfer enhancement. Detailed models for determining the degree of enhancement and its effects on pressure drop have been used. The methodology in this paper presents a cost effective retrofit option for HENs. The comparison between the various retrofit options studied shows that heat transfer enhancement is an efficient method for reducing the additional area requirements in retrofit and as such, the retrofit capital cost.

Chapter 8 Conclusions and Future Work

8.1 Conclusions

The aim of this thesis was to present cost effective methods for the retrofit of heat exchanger networks (HENs). In this thesis, insights from the existing HEN structure and the identification of gaps from the literature survey were used to achieve this goal. From this, two retrofit methodologies have been proposed for the use of heat transfer enhancement in retrofit. However, a drawback with the use of heat transfer enhancement, pressure drop, needed to be addressed. Therefore, a retrofit methodology that considers pressure drop alongside heat transfer enhancement was proposed. Another aspect considered in this thesis was the use of structural modifications in retrofit. This thesis proposed guidelines and a retrofit methodology for the identification of the best structural modifications to achieve maximum energy recovery. However, a drawback with the application of structural modifications is the high capital investment required in retrofit. Therefore, this thesis investigated ways of combining the benefits of heat transfer enhancement and structural modifications to achieve maximum energy recovery but at low capital investment. It is important to point out that in this work, the cost functions used in determining the retrofit cost does not include the engineering costs that may be required with each modification option i.e. the use of enhancement and structural modifications.

Outlined below are the main contributions of this work that satisfied the four thesis objectives.

8.1.1 Retrofit Methodologies with Heat Transfer Enhancement for HEN Retrofit without Topology Modifications and Additional Area

From the literature survery conducted on the benefits of heat transfer enhancement, it was found that, if heat transfer enhancement is solely considered, the retrofit of HEN can be cost effective and easy to perform. However, given a HEN, it might not be beneficial to apply heat transfer enhancement on all process heat exchangers, as this might lead to the violation of the network constraint and/or the energy balance of the network. Therefore, before heat transfer enhancement can be applied, it is vital to identify a comprehensive method for the identification of the best heat exchangers to enhance. Also, in HENs, the change in one component can affect the performance of others within the network. An example of an effect that can occur is the need for additional heat transfer area in heat exchangers located downstream from an enhanced exchanger. This is due to the decrease in the driving force of these heat exchangers. Therefore, a method for dealing with this effect is required. To achieve these goals, two novel methodologies are proposed. This is based on a three-stage approach.

The first stage involves presenting a method for the identification of candidate heat exchangers. Candidate heat exchangers are referred to as heat exchangers that can provide energy savings without violating the energy balance of the network. In order to maintain the energy balance of the network, only heat exchangers on a utility path can be considered for enhancement. Therefore, a systematic method based on an incidence matrix, is used to identify heat exchangers on a utility path in a HEN. This method has been automated as part of a Centre for Process Integration (CPI) software, SPRINT. This method not only identifies utility paths, but can also identify other key network structural features such as loops.

In the second stage, the best candidate heat exchanger is identified. Two methods i.e. sensitivity analysis and area ratio approach are used. Sensitivity analysis identifies the best heat exchanger to enhance based on the passive response a heat exchanger has on a network. However, sensitivity analysis is not tailored for the application in large-scale networks due to its dependence on a key utility exchanger. Therefore, the area ratio approach is proposed for the identification of the best heat exchanger in large-scale networks. This is because the decision is not based on a key utility exchanger, but on the ability of candidate heat exchangers to accommodate for additional area , which still maintains a balanced network.

A non-linear optimisation model is used in the third stage. This is solely required to eliminate the need for additional heat transfer area on other process exchangers after the application of enhancement on the best candidate heat exchanger. The objective function used in this model is to maximise the retrofit profit i.e. the difference between the profit from energy savings subject to a payback time period and the total cost of retrofit. This is achieved by varying the duty of heat exchangers on a utility path and the overall heat transfer coefficient of heat exchangers not on a utility path.

The proposed methodologies used for solving objective one can be summarised to be a combination of heuristics and optimisation. This is beneficial as it not only has the benefit of encouraging user interaction and providing insights into retrofit with heat transfer enhancement, but also ensures that the optimal degree of of energy savings is attained while meeting set constraints such as no additional heat transfer area requirement and maintaining the energy balance of the network. The benefits of the methodologies proposed makes it applicable to large-scale retrofit problems.

8.1.2 Pressure Drop Considerations In HEN Retrofit with Heat Transfer Enhancement

Most enhancement techniques considerably increase pressure drop in existing heat exchangers. This is a key drawback with the use of heat transfer enhancement for industrial applications. In situations, where existing pumps/compressors cannot accommodate the required increase, this can have a negative financial implication in terms of the retrofit process. In addition, retrofit requiring the purchase of pumps/compressors might not be justified in retrofit.

Reducing the stream velocity in a heat exchanger not only reduces its heat transfer performance, but also the pressure drop. This can be achieved by performing structural modifications such as, reducing the number of tube passes and changing shell arrangement from series to parallel. The decrease in performance is compensated for by the use of heat transfer enhancement. As such, a degree of enhancement can still be obtained but at lower pressure drop requirement.

In different heat exchangers, there might be more than one beneficial option. Therefore, in this thesis, a selection factor is defined to ensure the best modification is chosen in terms of level of pressure drop reduction and low retrofit cost.

Analysis carried out considering pressure drop with enhancement showed that the degree of energy savings is reduced. This also reduces the retrofit profit obtained compared with the use of heat transfer enhancement without considering pressure drop. By doing this, the actual energy saving and retrofit profit with enhancement is presented that meets not only network constraints and energy balance of the network, but also ensures there are no pressure drop violations in the HEN.

8.1.3 Retrofit Guidelines and Methodology for Structural Modifications

The decision on the best structural modification has been based on obtaining a set objective. However, there are no insights into why a certain structural modification is suggested, as opposed to others in a given network. In addition, there is no guarantee that the recommended structural modification or number of modifications suggested is the best given a HEN. This work presents guidelines for identifying the best location to apply each type of structural modifications. This work makes use of the network pinch approach. Guidelines are formed by analysing the HEN structure and identifying key features such as: presence of utility paths and loops, presence of pinching matches, location of pinching matches in the network and with respect to one another. The insights obtained in this study help to provide insights to the designer to ensure modifications carried out for maximum energy recovery are placed appropriately in a HEN.

Retrofit methodologies for both single and multiple modifications have been presented in this work. The methodology makes use of the key features of a HEN to justify the best modification that guarantees minimum amount of modifications for maximum energy recovery. To validate the proposed approach, the results obtained by its application were compared with those of stochastic optimisation (i.e. simulated annealing). Results show that the new approach overall can identify either fewer or exactly the same number of modifications to achieve the set objective.

In general, the application of structural modifications is able to provide a greater decrease in energy consumption, as opposed to the use of enhancement. This is justified as with enhancement, the level of enhancement a heat exchanger can provide is restricted by the exchanger geometry and the type of enhancement technique used. With structural modifications, higher energy recovery is obtained as the network pinch, which restricts energy recovery, is overcome.

8.1.4 Structural Modifications with Heat Transfer Enhancement

From the analysis carried out in this work, it is clear that structural modifications as opposed to the use of heat transfer enhancement can provide higher decrease in energy consumption in existing HENs. However, the cost associated with carrying out such modifications is high. To reiterate, the best retrofit design is one with low retrofit cost. To achieve this, heat transfer enhancement has been used in eliminating or reducing the area requirement in existing heat exchangers. This is beneficial as additional area accounts for a large percentage of the retrofit costs when structural modifications are applied.

A sequential methodology that incorporates structural modifications and heat transfer enhancement with pressure drop considerations is presented in this work. From the results obtained, the use of heat transfer enhancement with structural modifications considerably reduces the retrofit cost, while maintaining the energy recovery when compared to the use of only structural modifications. The reduction in cost is because of heat transfer enhancement being generally cheaper than the increased area of existing exchangers. Heat transfer enhancement is also beneficial in this case, the issue of plant layout (i.e. evaluating if there is sufficient opportunity to apply the recommended additional area requirement after structural modifications) is addressed. However, with pressure drop considerations, the retrofit profit is reduced due to the decrease in the degree of enhancement that can be obtained in certain heat exchangers and the cost associated with the techniques used for pressure drop mitigation.

8.2 Future Work

Although the retrofit objectives set out in this thesis have been met, other areas are worth further research.

1. Retrofit methodologies included in this work have solely been focused on the application on shell and tube heat exchangers. It might be beneficial to consider extending the retrofit methodologies with heat transfer enhancement to other types of heat exchangers such as plate heat exchangers.

2. Retrofit methods for heat-integrated distillation systems usually involve performing structural modifications of the existing HEN. Future work can consider incorporating the retrofit methodologies with heat transfer enhancement and/or structural modifications with heat transfer enhancement presented in this work into heat–integrated distillation system as a retrofit strategy to reduce capital investment.

3. Other heat exchangers such as plate heat exchangers and twisted tube heat exchangers have been reported to be efficient methods for reducing annual CO2 emissions and energy consumption. Future work can consider replacing conventional shell and tube heat exchangers with welded plate heat exchangers or twisted tube heat exchangers as a retrofit strategy for existing HENs.

4. Although pressure drop has been tackled in this work, the approach used is sequential. A promising area will be to include the proposed methodology as part of a superstructure optimisation for performing exchanger modifications (i.e. modifying shell arrangements and tube passes) if there are violations in HEN pressure drop constraints in retrofit.

5. In this work, it has been assumed that the fouling factors in heat exchangers modelled are provided in retrofit and constant. In addition, the effect of heat transfer enhancement on fouling has not been considered. Modifications made to existing exchangers either by the application of enhancement alone, enhancement considering pressure drop or performing structural modifications will have an effect on temperature dependent properties and Reynolds number (in terms of change in velocity). This will have different impacts on fouling. It might be beneficial to consider presenting reliable models for predicting the fouling coefficients of heat exchangers in a given HEN that can accurately account for these changes.

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