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Cost-effective Strategy for Heat Exchanger Network Retrofit

Mary O. Akpomiemie*, Robin Smith

Centre for Process Integration, School of Chemical Engineering and Analytical

Science, The University of Manchester, Manchester, M13 9PL, UK.

*Corresponding authors' email address: mary.akpomiemie@processint.com

Abstract

Cost-effective retrofit of heat exchanger networks (HENs) remains a significant challenge. This paper explores different methods for achieving cost-effective retrofit. The first part of this article presents a novel methodology for the application of heat transfer enhancement in HEN retrofit with a fixed network structure considering pressure drop constraints. Heat transfer enhancement is a low-cost option. However, heat transfer enhancement on its own without changes to the network structure provides a limited scope for energy reduction. The second part of this paper presents a new pinch retrofit method that identifies network structural changes sequentially to meet the retrofit target. However, the high capital cost associated with installing new heat exchangers, relocating existing exchangers, and augmenting the heat transfer area of existing heat exchangers most often leads to uneconomic retrofits. Low-cost retrofit requires few modifications. Therefore, the third part of this paper combines the new pinch retrofit method with the use of heat transfer enhancement to provide low-cost retrofit by combining the merits of both approaches. A case study highlights the benefits of the new approach.

Keywords: Heat exchanger network; Retrofit; Heat transfer enhancement; Structural Modifications; Pinch retrofit method; 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. Maximising the use of existing equipment increases the profitability of the retrofit process [1]. In existing HENs, operating and physical constraints referred to as bottlenecks restrict the degree of energy savings.

Established techniques and methodologies for the retrofit of HENs focus on modifying the existing HENs to obtain energy savings and overcome network bottlenecks. Modifications to the existing HEN are primarily based on Pinch Analysis, Mathematical Programming, and Hybrid methods. There are several reports in literature dedicated to the retrofit of HENs based on these methods. Sreepathi and Rangaiah [2] presented a detailed review of the different methods for HEN retrofit. The book by Smith [3] has full chapters that introduce the fundamentals of energy targets, capital and total cost targets, and network design of HENs. Pinch Analysis for retrofit makes use of a targeting stage for estimating the maximum energy recovery of a network, and a re-design stage to disconnect and reconnect the cross-pinch exchangers to obey the pinch decomposition. The pioneering work on Pinch Analysis for retrofit was introduced by Tjoe and Linnhoff [4]. The objective of the work is to eliminate heat transfer across the pinch. This concept has since been extended to account for the cost required in HEN retrofit [5]. Most recently, the work by Gadalla [6] presented a new graphical method based on Pinch Analysis. The energy efficiency

is evaluated quantitatively in the existing HEN to identify the potential modifications for better energy recovery. The drawbacks of Pinch Analysis are 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. Also, Pinch Analysis requires too many changes in a single step, which makes it fundamentally not suited to retrofit, as it tries to convert the existing network into an ideal grass root design in a single step instead of accepting the features that already exist.

Mathematical programming methods convert the retrofit problem into an optimisation model and solved. However, the HEN retrofit is a mixed integer non-linear programming (MINLP) problem [7]. Ciric and Floudas [8] presented a superstructure approach for retrofit of HENs. The objective of the approach is to optimise the superstructure which contains all structural features of an existing HEN to remove all unnecessary features and minimise the cost. The difficulty in solving the MINLP problem has led to authors simplifying the retrofit problem to avoid obtaining a local optimum solution. Over the years, several authors developed ways of decomposing the retrofit problem. Ma et al. [9] developed the Constant Approach Temperature model used to linearise the area calculations. Other authors [10] presented a two-stage approach to retrofit. The first stage, the prescreening stage is solved as a mixed integer linear programming (MILP) problem. The second stage, the optimisation stage is solved as a nonlinear programming (NLP) problem. Another way to overcome the difficulty in solving the MINLP problem might be to apply stochastic optimisation [11]. A benefit of mathematical programming methods is that the total cost and environment impact of retrofit can be considered in the optimisation process [12]. Compared to the Pinch Analysis method, mathematical programming methods can

75 consider more variables and identify the optimal HEN. In general, the drawbacks
76 associated with the use of mathematical programming techniques include prolonged
77 computational times, uncertainty in the optimality of the solution due to the
78 assumptions and simplifications made to the model and the lack of user interaction.

79 Asante and Zhu [13] pioneered the hybrid method for the retrofit of HENs. The
80 method proposed, referred to as the Network Pinch Approach, consists of a diagnosis
81 and an optimisation stage. In the diagnosis stage, the MILP model is used to identify
82 the possible structural modifications that can provide maximum energy recovery
83 subject to an assumed minimum temperature approach. The optimisation stage makes
84 use of an NLP model to optimise the capital-energy trade-off of the structural
85 modifications determined in the first stage. The sequential approach enables the
86 automation of the design procedure while maintaining user interaction. Smith et al.
87 [14] modified the Network Pinch Approach by converting the process from sequential
88 to simultaneous (considering structural modifications and capital-energy optimisation
89 in a single step). The Network Pinch Approach by Asante and Zhu [13] was later
90 extended to handle more complex networks considering some practical features to
91 increase the possibility of identifying cost-effective design solutions [15]. The
92 Network Pinch Approach provides energy savings by manipulating the existing
93 degrees of freedom (utility paths, loops and stream splits) in an existing network [3].

94 However, the only way of overcoming the Network Pinch for energy savings is by
95 performing structural modifications. Examples of modifications considered to
96 overcome the Network Pinch are adding a new heat exchanger (new match),
97 relocating exchangers (resequencing), adding stream splits. The Network Pinch
98 Approach is an automated sequential method restricted to one change at a time. The
99 drawback with the Network Pinch Approach is the lack of insights into the decision-

making process of identifying the best series of modifications that can be applied to a given HEN. As such, there is a possibility of selecting a retrofit option early in the procedure that prevents obtaining the optimal solution in subsequent steps.

In recent years, there has been a rise in the research into the use of heat transfer enhancement in retrofit. Heat transfer enhancement not only increases energy recovery but can be a low-cost option for retrofit as existing network structure can be maintained. This makes the implementation of enhancement devices relatively simple and can be performed during the normal shutdown period. Optimisation methods presented by Pan et al. [16] applied detailed models of different heat transfer enhancement techniques for the application of heat transfer enhancement. The authors also provided a systematic design method for the application of conventional retrofit strategies [17]. Optimisation methods provide no insights into the identification of the best heat exchangers to enhance. Also, the simplifications in the retrofit method lead to uncertainty in the retrofit solution. Heuristic based methods have been developed to tackle the issues presented by optimisation methods for the application of heat transfer enhancement. Wang et al. [18] presented a method based on sensitivity analysis. However, this approach did not consider the impact of enhancement on the network. Also, the degree of enhancement is assumed. Jiang et al. [19] extended the approach to consider accurate modelling of the chosen enhancement technique to ensure accurate representation of proposed energy savings. The work by Akpomiemie and Smith [20] extended both methodologies to account for the downstream effects on the network after the application of heat transfer enhancement. The drawbacks with the use of sensitivity analysis for identifying the best heat exchanger to enhance were highlighted by Akpomiemie and Smith [21]. The authors [21] 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 that a heat exchanger can provide relative to its base case value. As such, this method is more suited to HENs with multiple utilities. A drawback of the heuristic based methods considering enhancement is the lack of pressure drop considerations with heat transfer enhancement. Ignoring the effects of pressure drop in retrofit might present a retrofit result that cannot be realised industrially as the existing pumps/compressors might not be able to cope with the increased pressure drop requirements.

Polley et al. [22] first considered the effects of pressure drop in retrofit. However, the work only considers a targeting stage based on area efficiency and does not present a systematic way of applying heat transfer enhancement in retrofit. Nie and Zhu [23] presented practical methods for mitigating the effects of pressure drop in a network after structural modifications are made. Techniques considered include decreasing the number of tube passes and modifying shell arrangements from series to parallel. Both methods have an impact on the tube-side velocity of the exchangers, which dictates not only the heat transfer coefficient but also the pressure drop requirement.

Recent methods used for the retrofit of HENs with pressure drop considerations have either been based on an iterative MILP optimisation approach [24] or a combination of a set of heuristic rules and NLP optimisation [25]. The drawbacks of the MILP optimisation approach are that there is a lack of insights into identifying the best exchangers to enhance and the use of the MILP model to solve the retrofit problem. To address these drawbacks, the work by Akpomiemie and Smith [25] present a novel sequential approach to retrofit with heat transfer enhancement considering pressure drop constraints. The new approach provides insights into identifying the best

exchangers to enhance. The new method also defines a ranking criterion for selecting the best pressure drop mitigation technique. An NLP model is used to ensure the feasibility of the retrofit solution based on a set of constraints. However, the energy savings that can be obtained for fixed network structure with heat transfer enhancement is limited [26]. To obtain high energy recovery, structural modifications to the existing HEN are required.

From the reviewed methods for performing structural modifications, the Network Pinch Approach presents the right balance between providing optimal solutions and user interaction. Studies based on the Network Pinch approach [14, 15] do not provide insights into the decision-making process for selecting the best series of structural modifications in retrofit. To overcome this drawback, this work presents a new pinch retrofit method that provides insights into the fundamental interactions and features of an existing HEN. The Network Pinch Approach identifies the bottleneck for heat recovery in an existing system. However, it provides no guidance as to how to overcome the Network Pinch. Overcoming Network Pinch is left to the use of NLP optimisation. This provides no insights into the solution and no insights as to whether other options might provide an equivalent answer. User intervention is particularly important in industrial retrofit. The problem is not the purchase of new equipment, but the many other issues of pipework and civil engineering requirements and in many situations simply the ability to accommodate new equipment. These issues cannot be included in optimisation, but require user insights. The paper presents an approach that allows the designer to include insights into the decision-making.

The main objective of this work focuses on providing low-cost retrofit methods for HENs. This work presents the benefits of combining the use of heat transfer enhancement and structural changes to existing HENs. The new method is applied

sequentially with an objective of maximising energy recovery with minimum investment. A case study is used to illustrate the proposed methods and highlight their benefits by making a comparative analysis of the various options considered in this work for HEN retrofit.

2 Heat Transfer Enhancement for a Fixed Network Structure

This section of the paper summarises the method presented by Akpomiemie and Smith [25] for the application of heat transfer enhancement for a fixed network structure with pressure drop considerations. The approach combines a set of heuristic rules and optimisation to meet the retrofit target. Figure 1 shows the retrofit methodology. Initially, the retrofit profit (RP) is 0.

2.1 Heuristic 1: Identify the best heat exchanger for enhancement

The two-step approach presented by Akpomiemie and Smith [20, 21] is used to determine the best sequence of enhanced exchangers.

2.1.1 Step 1: Identify exchangers on a utility path

A way of reducing the energy consumption in an existing HEN while maintaining the network structure is by shifting heat loads along a utility path. A utility path is a connection between two utilities through process exchangers. Therefore, for the application of heat transfer enhancement for a fixed network structure, only exchangers on a utility path are considered. For simple networks, heat exchangers on a utility path can be identified by inspection. However, for complex heat exchanger networks, the use of inspection is not reliable as key exchangers on a utility path in the network might be missed. Therefore, in the first step, a more systematic method, the Incidence Matrix Approach [26] is proposed. The identification of utility paths

based on the Incidence Matrix Approach is split into three steps, i.e. generation of the initial matrix, reducing the matrix, and utility path identification by linear combination.

2.1.1.1 Incidence matrix generation

The Incidence Matrix Approach is based on the fundamentals of graph theory for process modelling. A graph contains a set of nodes and edges. The Incidence Matrix depicts the relationship between the set of nodes and the corresponding edges, i.e. describes how the edges are incident on nodes [27]. The rows represent the nodes, and the columns represent the edges. In relation to HENs, the nodes are considered to be all streams in the network and the columns represent exchangers. The number of streams is denoted by S and the number of exchangers by E in this work. The Incidence Matrix A_{HEN} (size $S \times E$) describes how the streams are incident on exchangers. The rows represent streams, and the columns represent exchangers.

$$A_{\text{HEN}(ik)} = \begin{cases} +1 & \text{if exchanger } k \text{ removes heat from stream } i \\ -1 & \text{if exchanger } k \text{ supplies heat to stream } i \\ 0 & \text{if exchanger } k \text{ is not incident on stream } i \end{cases}$$

Each column of A_{HEN} will have exactly two non-zero entries, i.e. one +1 and one -1 entry. This is because a heat exchanger can only be matched between two streams. However, the difference between the new methodology based on Incidence Matrix and the standard Incidence Matrix is the addition of a column vector P to the matrix. The column vector P serves as a connection between two utilities, i.e. a utility path. As such, in the Incidence Matrix generated, a value of +1 is added to the hot utility stream and -1 to the cold utility stream. Explanation on how the column vector P is used in identifying exchangers on a utility path is provided in Section 2.1.1.3 of this paper.

Figure 2 shows an example network that will be used to generate the Incidence Matrix. Table 1 shows the Incidence Matrix for the example network. For example, Exchanger 1 removes heat from stream 3 and supplies heat to stream 5. Therefore, in Table 1, a value of +1 and -1 has been added in Column 1 (representing Exchanger 1). The procedure is repeated for all other process and utility exchangers in the network. From Table 1, it can also be noted that the column vector P is added to the Incidence Matrix. A value of +1 is added to signify the hot utility stream (HU) and -1 to signify the cold utility stream (CU).

2.1.1.2 Reducing the initial incidence matrix

As stated earlier, the column vector P signifies the link between two utilities and by definition, the utility path. However, the column vector P is given by a linear combination of the reduced Incidence Matrix. Therefore, the initial Incidence Matrix is reduced by performing row operations. This is to ensure that all entries below the first non-zero entry of each row in the matrix are zero.

From Table 1, the first non-zero entry in Row 1 is in Column 3. Column 3 is analysed to identify the non-zero entry below the first entry. From Table 1, the first non-zero entry is found in Row 4. Row 1 is added to Row 4 to eliminate this entry. Repeat the procedure for all other entries in the initial Incidence Matrix. Table 2 shows the reduced matrix. From Table 2 it can be noted that all entries below the first non-zero entry of each row are now zero and the matrix has been reduced. Row CU now only has zero entries.

2.1.1.3 Utility path identification by linear combination

Linear combination is performed based on an important feature of utility paths. Utility paths allow for heat loads to be shifted from one unit to another. The amount of heat load added to a heater must be subtracted from an exchanger in the path, added to the

245 next exchanger in the path, and so on, and finally added to a cooler in the path. This
 246 operation maintains the enthalpy balance and target temperatures of streams in the
 247 HEN.

248 In relation to the Incidence Matrix approach, the column profile identified by
 249 performing the plus-minus analysis must be equal to the column vector P i.e.

$$250 \quad \text{Column P} = \text{Column } H_{k=1 \rightarrow N} - \text{Column } X_{k=1 \rightarrow N} + \text{Column } C_{k=1 \rightarrow N}$$

$$251 \quad \text{Therefore, Column } X_{k=1 \rightarrow N} = \text{Column P} - \text{Column } H_{k=1 \rightarrow N} - \text{Column } C_{k=1 \rightarrow N}$$

252 Where the column profile of Column $X_{k=1 \rightarrow N}$ is obtained by performing random
 253 combinations of the columns in the reduced matrix except for the utility columns
 254 (Column $H_{k=1 \rightarrow N}$ and Column $C_{k=1 \rightarrow N}$). Note that $X_{k=1 \rightarrow N}$ can only be one column,
 255 representing one exchanger or a combination of an odd number of columns, i.e. 3, 5,
 256 7, etc. Also, the plus-minus rule applies when X is a representation of a combination
 257 of columns. This procedure has been automated as part of a Centre for Process
 258 Integration software, SPRINT [28]. For example, if three columns are considered, X
 259 will be obtained from performing $C1 - C2 + C3$ or a different combination of the
 260 three columns. For the example discussed here, the utility paths are given in Figures 3
 261 and 4.

262 2.1.2 Step 2: Determine the rank of identified exchangers

263 The second step involves evaluating the energy saving potential of candidate heat
 264 exchangers, i.e. exchangers on a utility path. For this, either sensitivity analysis [18,
 265 19, and 20] or area ratio approach [21] can be used. Sensitivity analysis is based on
 266 the well-known heat transfer equation:

$$267 \quad Q = UA\Delta T_{LM}F_T \quad \text{Equation 1}$$

Where Q , U , A , ΔT_{LM} , F_T are the heat duty, overall heat transfer coefficient, heat transfer area, logarithmic mean temperature difference and correction factor respectively. Sensitivity analysis is carried out by varying the product of the overall heat transfer coefficient, heat transfer area and correction factor against the inlet temperature of a key utility exchanger. This key utility exchanger is usually the most expensive utility. With sensitivity analysis, the best heat exchanger to enhance is one which brings about the greatest increase in the inlet temperature of the key utility exchanger. This identifies a heat exchanger that can provide the greatest decrease in the energy consumption of this key utility exchanger in order not to violate the target temperature of the stream on which it is located. The work by Wang et al. [18] identified reasons for high sensitivity in particular heat exchangers such as their proximity to the key utility, the heat capacity flowrate and the minimum temperature difference of the candidate heat exchangers. The benefit of sensitivity analysis is that it provides simple insights into the existing network. However, the decision is based on an unbalanced network. Also, its dependence on a key utility exchanger makes it difficult to be applied to networks with multiple utilities [21]. Therefore, Akpomiemie and Smith [21] presented a new method for identifying the best exchangers to enhance, i.e. the area ratio approach, where the area ratio is determined by Equation 2

$$A_R = \frac{A}{(A + \Delta A)} = \frac{U}{U_E} \quad \text{Equation 2}$$

Based on this equation, the best heat exchanger to enhance 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. The benefit of this method is that the best heat exchanger is identified based on the maximum allowable enhancement of each candidate heat exchanger that still maintains a balanced network. This makes it more

suited to networks with multiple utilities as the decision is not dependent on a key utility exchanger as in the case of sensitivity analysis.

2.2 Heuristic 2: Apply enhancement

The best exchanger for enhancement identified from Heuristic 1 is enhanced first. For a shell and tube heat exchanger, the decision on where to apply enhancement is based on the side with the highest percentage resistance, i.e. the side with the lower heat transfer coefficient. Jiang et al. [29] presented new models for heat exchangers enhanced with tube inserts for heat exchangers in retrofit. This model is used in our work to determine the maximum degree of enhancement for each candidate exchanger based on their geometry.

2.3 Heuristics 3 and 3.1: Check for stream pressure drop violation and identify the best pressure drop mitigation technique and apply.

Most enhancement devices have an adverse effect on pressure drop. In retrofit, replacing existing compressors/pumps to cope with the increase in pressure drop requirements might not be economic. In an existing HEN, maximum allowable pressure drop constrains each stream. Therefore, after each enhancement, the stream pressure drop should be checked for any violations, and if there are, corrected using pressure drop mitigation techniques (Heuristic 3.1). If not continue to Step 4 in the retrofit methodology. 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, a reduction in the number of tube passes or change in the shell arrangement could be considered. This work focuses on tube side enhancement, and as such, only mitigation techniques that can be applied to the tube side are discussed. Reducing the number of tube passes decreases the tube-side

316 velocity and as such, the pressure drop. However, the performance of the heat
 317 exchanger will also be affected, but performance can still be improved with
 318 enhancement but at a lower pressure drop penalty. The presence of more than one
 319 shell in a heat exchanger offers an opportunity for pressure drop mitigation. The total
 320 pressure drop of the heat exchanger is dependent on the shell arrangement. Different
 321 shell arrangements have different impacts on pressure drop. To reduce the pressure
 322 drop requirements, shells in series can be arranged in parallel. By doing so, the total
 323 pressure drop is no longer a sum of the pressure drop of each shell but the maximum
 324 pressure drop in either of the shells. With a parallel arrangement, the heat transfer
 325 coefficient and pressure drop are lower as the flow going through each shell is lower
 326 than that of series arrangement. Similar to modifying the number of tube passes, the
 327 performance can still be increased with enhancement but at a lower pressure drop
 328 penalty. Figure 5 shows the different shell arrangements that can be applied to a heat
 329 exchanger depending on the number of shells present. Equations for determining to
 330 total pressure drop in each scenario is provided.

331 For a given heat exchanger, there might be more than one mitigation technique that
 332 can be applied. Therefore, a ranking criterion is required. The work by Akpomimie
 333 and Smith [26] defines the selection factor (SF) as the relationship between the
 334 change in pressure drop relative to the change in the degree of enhancement before
 335 and after applying modifications (see Equation 3). The best option is one with the
 336 smallest SF, as this signifies the modification that can still provide a higher degree of
 337 enhancement with the lowest pressure drop penalty.

$$SF = \left(\frac{\Delta P_{N,E} - \Delta P_{N,ex}}{\Delta P_{B,E} - \Delta P_{B,ex}} \right) \left(\frac{U_{B,E} - U_B}{U_{N,E} - U_N} \right) \quad \text{Equation 3}$$

2.4 Heuristic 4 and Optimisation 1: Check for target temperature and additional heat transfer area violations and correct using non-linear optimisation model

The next step in the retrofit methodology is to check for stream target temperature and heat transfer area violations. The target temperature violation is as a result of the increase in the duty of the enhanced heat exchanger. This violation can easily be solved using the utility exchangers on the utility path as the enhanced exchanger. The heat transfer area violation is as a result of the decrease in the driving force of heat exchangers located downstream from the enhanced heat exchanger. Shifting a certain amount of heat load along the utility path corrects the additional heat transfer area requirement. By doing this, there is a trade-off between energy recovery and capital cost (i.e. cost of additional heat transfer area) as a certain amount of heat load needs to be added back to the utility exchangers and subtracted from the heat exchanger requiring additional area. However, if the exchanger requiring additional area is not on a utility path, heat transfer enhancement can still be exploited to reduce or eliminate the heat transfer area required. This is because 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. Therefore, these exchangers can be enhanced at constant duty to eliminate the heat transfer area required. To find the amount of heat load that should be shifted along the utility path and the degree of enhancement that should be applied the non-linear optimisation model proposed by Akpomiemie and Smith [20, 21] is used. However, the model presented has been extended to consider the cost associated with the application of pressure drop mitigation techniques. The objective function is to maximise the retrofit profit (RP) where:

$$RP = UC_B - \left[UC_E + \sum_{ex \in EX} RC_{ex} \right] \quad \text{Equation 4}$$

363 The retrofit cost (RC) includes the cost of all modifications and is given by:

$$RC_{ex} = EC_{ex} + AC_{ex} + BC_{ex} + MC_{ex} \quad \forall_{ex} \in EX \quad \text{Equation 5}$$

364 Where EC_{ex} is the cost of enhancement, AC_{ex} is the additional area cost, BC_{ex} is the
 365 cost of bypass, and MC_{ex} is the mitigation cost. Equations 6 and 7 are used in
 366 calculating the utility cost before (UC_B) and after enhancement (UC_E) where CCU and
 367 CHU are the yearly cost parameter for cold and hot utility, Q_B and Q_E are the duty
 368 before and after enhancement and OT is the payback operating time.

$$UC_B = OT \times \left[CCU \times \sum_{ex \in EX_{CU}} Q_{B, ex} + CHU \times \sum_{ex \in EX_{HU}} Q_{B, ex} \right] \quad \text{Equation 6}$$

$$UC_E = OT \times \left[CCU \times \sum_{ex \in EX_{CU}} Q_{E, ex} + CHU \times \sum_{ex \in EX_{HU}} Q_{E, ex} \right] \quad \text{Equation 7}$$

369 The aim of the optimisation model is to be able to apply heat transfer enhancement
 370 without the need for additional heat transfer area while maintaining the target
 371 temperatures of all streams. Equations 8 to 10 represent the constraints for heat
 372 transfer area requirements and temperature constraints for all cold and hot streams, CS
 373 and HS. A_{ex} and A_E represent the heat transfer area of all process heat exchangers
 374 before and after enhancement. TCOS and THOS represent the cold and hot outlet
 375 stream temperatures respectively. EX_E describes the set of all exchangers.

$$A_{ex} = A_E \quad \forall_{ex} \in EX_E \quad \text{Equation 8}$$

$$TCOS_i = TCOS_E \quad \forall_{CS} \quad \text{Equation 9}$$

$$THOS_i = THOS_E \quad \forall_{HS} \quad \text{Equation 10}$$

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, the heat exchanger duty is fixed. After correcting the violations continue to Heuristic 5.

2.5 Heuristic 5: Check for stopping criterion violation

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 cost of retrofit outweighs the profit from energy savings. As such, it is uneconomic. If the stopping criterion is not violated, continue to Heuristic 6.

2.6 Heuristic 6: Check for further retrofit options

Given that the retrofit methodology is sequential, there might be more than one heat exchanger that can improve energy recovery. Therefore Heuristics 1 to 5 of the retrofit methodology is repeated until all potential for energy recovery has been explored. The retrofit methodology is terminated when all options have been explored, or the stopping criterion is violated.

In summary, heuristic rules are first applied to identify the best exchangers for enhancement. The maximum degree of enhancement for a selected exchanger is restricted by the geometry of the exchanger and is determined before optimisation based on the chosen enhancement technique. Optimisation is used to maintain the energy balance of the network and ensure there is no additional heat transfer area required. The energy savings that can be obtained with enhancement is restricted by

the degree of enhancement that can be applied subject to no additional area requirement and pressure drop constraints. The non-linear optimisation employed has a 100% convergence rate.

3 Structural Modifications (The Pinch Retrofit Method)

The pinch retrofit method is based on the Network Pinch Approach presented by Smith et al. [14]. However, the primary purpose of the pinch retrofit method is to present guidelines for identifying the best location to apply a series of modifications based on fundamental insights in a step-by-step approach from the existing network. The aim is to identify the best series of modifications that can achieve maximum energy recovery with the minimum number of modifications to the existing network. The modifications considered in this work are resequencing, stream splitting, adding a new exchanger to create a loop and adding a new exchanger to create a path. Figure 6 shows the background of the pinch retrofit method. The retrofit target is subject to a selected temperature driving force ($\Delta T_{\min}$) value. The $\Delta T_{\min}$ value used for retrofit is selected by targeting using Pinch Analysis. With an objective of obtaining a cost-effective retrofit design, the effect of varying $\Delta T_{\min}$ is analysed against the utility consumption and costs of each value of $\Delta T_{\min}$. The $\Delta T_{\min}$ representing the best capital-energy trade-off is selected. For a selected $\Delta T_{\min}$, the first step is to pinch the original network by manipulating the existing degrees of freedom (i.e. stream splits, utility paths or loops). By doing this, the exchanger that constrains energy recovery is identified. This exchanger is referred to as the pinching match, and the location at which it occurs is referred to as the Network Pinch. The only way to overcome the Network Pinch is by performing structural modifications. With each structural modification, the temperature constraint on the pinching match is relaxed. The

network is pinched again for energy recovery and the process repeated until the Maximum Energy Recovery (MER) design is achieved for the specified $\Delta T_{\min}$ in retrofit.

To summarise, the pinch retrofit method evolves from the existing design. The Network Pinch constrains each structural change. The difference between the maximum energy recovery for a given temperature driving force and the existing energy consumption is the penalty associated with cross-pinch heat transfer. The cross-pinch heat transfer can be the inappropriate use of utilities (i.e., use of cold utility above the pinch or hot utility below the pinch) or process-to-process exchangers transferring heat across the process pinch. Therefore, the ultimate constraint to achieving maximum energy recovery is to eliminate all cross-pinch heat transfer in the network, but this might well be uneconomic.

Different networks have different features. The key features present in an existing network that govern the identification of the best structural modification are pinched exchangers and cross-pinch exchangers (either process-to-process or inappropriate use of utilities). The location of these features in the network and their proximity to other process exchangers and to one another also plays an important role in determining the best modification that should be applied to the network for energy recovery.

Guidelines and an algorithm have been developed for structural modifications based on the different network features and can be found in the work by Akpomiemie [30].

From the algorithm [30], before performing structural modifications, it is always advisable to pinch the HEN. Pinching the HEN not only provides a degree of energy saving while maintaining the network structure but also identifies the Network Pinch that restricts energy recovery. Heat exchangers that contribute to heat transfer across the pinch are also identified. However, this comes at an additional heat transfer area

penalty. Outlined below are the definitions of key terms used in the guidelines for the pinch retrofit method. Figure 7 shows a simple illustration of a HEN with the key terms highlighted.

Upstream exchanger: This refers to a heat exchanger located before the reference exchanger in the direction of the stream. For example, from Figure 7, selecting the pinched Exchanger 2 as the reference exchanger, Exchangers 1 and 4 are located upstream from the pinched exchanger on the hot and cold streams 1 and 5 respectively.

Downstream exchanger: This refers to a heat exchanger located after the reference exchanger in the direction of the stream. For example, from Figure 7, selecting the pinched Exchanger 2 as the reference exchanger, Exchanger 3 is located downstream from the pinched exchanger on the cold stream 5.

The exit of heat exchangers: This refers to the outlet of a heat exchanger on the streams which it is matched. For example, from Figure 7, the exits of Exchanger 3 on the hot and cold streams are highlighted.

Guidelines for modifications:

The decision on what modifications will be the most beneficial is dependent on the location of unconstrained (i.e. process exchanger with a ΔT greater than $\Delta T_{\min}$ of the network) upstream process exchangers relative to pinched exchangers in the network. In the first scenario, if there are upstream process exchangers from all pinched exchangers on either the hot or cold stream which the pinched exchangers are matched, resequencing or adding a new exchanger to create a loop will be the most beneficial options. The difference between adding a new heat exchanger to create a loop and resequencing when there are unconstrained upstream exchangers is the

possibility of moving all the heat load of the selected upstream exchanger (exchanger with the highest ΔT_{LM}) to a new exchanger further downstream without violating the network temperature constraint. If all the heat load of the upstream heat exchanger can be moved further downstream to a new exchanger, it will be a more economically viable option to apply resequencing. For both resequencing and adding a new exchanger to create a loop, the modifications are made relative to the upstream heat exchanger with the highest ΔT_{LM} . The heat exchanger with the highest ΔT_{LM} has the greatest potential to relax the temperature constraint of the pinched exchanger. Figure 8 shows an illustrative example. From Figure 8a, Exchangers 1 and 5 are upstream from the pinched exchanger (Exchanger 2). Exchanger 1 should be selected for analysis as it has the highest ΔT_{LM} . Figure 8b shows the appropriate placement for resequencing Exchanger 1. Moving Exchanger 1 downstream from the pinched exchanger relieves its temperature constraint as the inlet temperature of the pinched exchanger on the hot stream (1) increases. This allows for the pinched exchanger to take up more heat load thereby, reducing the energy consumption of the utilities.

On the other hand, if there is a temperature constraint violation when resequencing is performed, a new exchanger should be added to create a loop. Therefore, if it is assumed that moving all the heat load of Exchanger 1 downstream violates the temperature constraint of the network, a new exchanger N can be added to create a loop with Exchanger 1. A certain amount of heat load (H) can be transferred from Exchanger 1 to the new exchanger N (see Figure 8c). By doing this, the temperature constraint on the pinched exchanger is relaxed allowing for a reduction in energy consumption.

In the second scenario, if there are no upstream heat exchangers from pinched exchangers on either the hot or cold stream which the pinched exchangers are

matched, adding a new exchanger to create a path or stream splitting will be the most beneficial options. Adding a new exchanger to create a path is only possible if there are viable utility exchangers not constrained by pinched exchanger(s) on the stream with viable utility exchangers. To add a new exchanger to create a path, select the utility exchangers with the highest duty or the utility exchanger that contributes to the highest cross-pinch heat transfer. For stream splitting to be the most beneficial option, there must be more than two pinched exchangers located adjacent to one another. After identifying the first best option, the procedure is repeated sequentially until a specified stopping criterion is met. Examples of stopping criteria that can be imposed on the network are maximum energy recovery or a maximum number of modifications.

4 Combination of Structural Modifications with Enhancement

This section presents a methodology for considering structural modifications based on the pinch retrofit method alongside enhancement to achieve cost-effective energy savings. By combining structural modifications with enhancement, the level of energy savings obtained with structural modifications can be maintained but at a reduced retrofit cost. Increasing the heat transfer area of existing exchangers is capital intensive. However, 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 requirements. In addition, implementation of enhancement is less expensive as only minor modifications are required to the existing exchangers making the process less expensive. Therefore, the retrofit cost can be reduced by implementing heat transfer enhancement in place of increasing heat transfer area of existing exchangers. The proposed retrofit methodology given in Figure 9 aims to

provide maximum energy recovery, but at a reduced retrofit cost (increased retrofit profit).

Step 1: The pinch retrofit method is applied to the existing HEN to determine the best structural modifications to meet the retrofit target. A consequence of performing structural modifications is the additional heat transfer area requirement in existing exchangers. Heat exchangers requiring additional area are identified in this step.

Step 2: The initial retrofit profit is represented by the difference between the profit from energy savings and the total cost of retrofit as given in Equation 4. However, the retrofit cost, in this case, is given by:

$$RC_{ex} = SMC_{ex} + AC_{ex} + BC_{ex} \quad \forall_{ex} \in EX \quad \text{Equation 11}$$

Where SMC_{ex} is the cost of structural modifications, AC_{ex} is the additional area cost, and BC_{ex} is the cost of bypass. The determination of utility cost is the same as that given in Equations 6 and 7.

Step 3: Either sensitivity analysis or area ratio approach is used in identifying the best heat exchanger among the heat exchangers requiring additional area to enhance. The heat exchanger is enhanced by determining the maximum degree of enhancement based on the exchanger geometry.

Step 4 and 4.1: The stream pressure drop of the enhanced exchanger is checked to ensure that there are no violations. If the stream pressure drop after enhancement is higher than the maximum of the stream, pressure drop mitigation techniques are used to correct the violation. The best mitigation technique (for cases with more than one option) is determined using the procedure outlined in Step 3 and 3.1 in Section 3. If there is no stream pressure drop violation, continue to Step 5.

Step 5: Calculate the new retrofit profit. Again, the retrofit profit is determined using Equation 4, but the new retrofit cost is given by:

$$RC_{ex} = SMC_{ex} + AC_{ex} + BC_{ex} + EC_{ex} + MC_{ex} \quad \forall_{ex} \in EX \quad \text{Equation 12}$$

Where EC_{ex} is the cost of enhancement and MC_{ex} is the cost of pressure drop mitigation technique. The determination of utility cost is the same as that given in Equations 6 and 7.

Step 6: If the new retrofit profit determined in Step 5 is less than initial retrofit profit determined before applying heat transfer enhancement to a selected exchanger, the retrofit procedure is stopped. This means that it is not economical to consider enhancement alongside structural modifications. If the retrofit profit determined in Step 5 is greater than the retrofit profit determined before applying heat transfer enhancement to a selected exchanger, continue to Step 7.

Step 7: The network is analysed for other retrofit options by enhancing the next best heat exchanger requiring additional area to eliminate or reduce its heat transfer area requirements. The retrofit procedure is terminated when all exchangers requiring additional area has been enhanced, i.e. no more opportunities to reduce the retrofit cost.

5 Case Study

A simplified crude-oil preheat train is used to illustrate the application of the retrofit methodologies in this work. Figure 10 shows the existing HEN structure. Tables 3, 4 and 5 shows the stream, exchanger and cost data respectively.

5.1 Heat Transfer Enhancement for a Fixed Network Structure

Only tube-side enhancement techniques are considered in this case study, i.e. twisted tape inserts. Therefore, the focus is placed on stream C1. The first step is to identify the enhancement sequence. All process exchangers in the network are on a utility path except Exchanger 7 that has been left out in the next immediate analysis. The two methods (sensitivity analysis and area ratio approach) were used to identify the enhancement sequence. Figure 11 shows the result of sensitivity analysis. Table 6 shows the results from the area ratio approach.

From analysing the results from sensitivity analysis and area ratio approach, both methods identified the same enhancement sequence (see Figure 12). From Figure 12, Exchanger 5 is identified as the best heat exchanger to enhance as it has the smallest area ratio and brings about the greatest increase in the inlet temperature of the key utility exchanger. The stream pressure drop is analysed after enhancing Exchanger 5. The tube side pressure drop of Exchanger 5 has increased from 15.73kPa to 37.67kPa. This increase did not result in a stream pressure drop violation as the stream pressure drop increased from 668.51kPa to 690.45kPa, which is below the maximum allowable (700kPa). Target temperature and heat transfer area violations are then corrected using the non-linear optimisation model. The optimisation was carried out using the LINDO system What's Best global solver [31]. Enhancing only Exchanger 5, resulted in ~3% decrease in energy consumption of the hot utility H with an initial utility consumption of 14,455.41kW. The retrofit profit obtained was ~3% of the initial utility cost of \$5.8M.

Other opportunities for energy savings were explored by enhancing the next best heat exchanger (Exchanger 1). By doing this, the maximum stream pressure drop was not

violated as the pressure drop of Exchanger 1 only increased from an initial value of 167.29kPa to 169.25kPa. The energy savings after enhancing Exchanger 1 and correcting the target temperature and heat transfer area violations amounted to ~5.5% of the initial utility consumption and a retrofit profit of ~5.4% of the initial utility cost. The retrofit profit is higher than that obtained after enhancing exchanger 5. Therefore, the retrofit methodology is repeated. The next best exchanger for enhancement is Exchanger 2. However, after enhancing Exchanger 2, the stream pressure drop constraint was violated as the pressure drop of Exchanger 2 increased from 131.40kPa to 163.31kPa. The increase in the pressure drop of Exchanger 2 brought the total stream pressure drop to 724.32kPa, which is above the maximum allowable. The pressure drop violation is corrected using pressure drop mitigation techniques. Exchanger 2 has two shells arranged in series and two tube passes. Therefore, Equation 3 is used in determining the best mitigation technique by evaluating the value of SF as the arrangement of the shells can be changed from series to parallel and the number of tube passes can be reduced from two to one. A split fraction of 0.5 is assumed for the case of changing shell arrangement. Table 7 shows the results from applying both mitigation techniques. From Table 7, modifying the shell arrangement from series to parallel is the best as it has the lowest value of SF, which means that a higher degree of enhancement can still be obtained but at a lower pressure drop penalty.

Apply enhancement based on the modified degree of enhancement and correcting network violations, the retrofit profit is calculated. Figure 13 shows the retrofit result after enhancing Exchanger 2 compared to that after enhancing Exchanger 5 and Exchanger 5 and 1. From Figure 13, the retrofit profit after enhancing Exchanger 2 is less than that after enhancing Exchanger 5 and 1. Therefore based on the stopping

criterion (retrofit profit), the result obtained after enhancing Exchanger 2 is discarded, and the retrofit methodology is stopped. Table 8 shows the final exchanger details after enhancement.

Therefore, the final savings with only enhancement is ~5.5% of the initial energy consumption and ~5.4% of the initial utility cost. The analysis shows that heat transfer enhancement alone can bring about cost-effective energy saving. However, the energy recovery by enhancement alone for a fixed network structure is limited.

5.2 Structural Modifications (Pinch Retrofit Method)

The objective with the application of the pinch retrofit method is to minimise the energy consumption of the hot utility H subject to a $\Delta T_{\min}$ of 10°C. At this minimum temperature approach, the expected decrease in energy consumption is 3,497kW. The first step is to pinch the network by manipulating the existing degree of freedom. The network has 6 process streams (5 hot streams and 1 cold stream) and 2 utility streams (1 hot utility stream and 1 cold utility stream). The existing HEN shown in Figure 10 has 18 degrees of freedom (6 utility paths and 12 loops). Figure 14 shows the pinched network structure. The pinch temperatures for this HEN are 40°C (Hot) 30°C (Cold). Pinched exchangers identified are 2, 4 and 6. Cross pinch heat exchangers are C2 and C4 (cold utility exchangers used above the pinch). By pinching the network, a decrease in energy consumption of 13.9% is obtained, but this comes at additional heat transfer area penalty. The degrees of freedom decrease after pinching the network from 18 to 5 as the duties of the utility exchangers C1 and C3 goes to zero thereby eliminating 4 utility paths and 9 loops. Note that all analysis has been carried out using the SPRINT software [29].

The best modification is either the application of resequencing or adding a new exchanger to create a loop. This is because there is at least one upstream process heat exchanger upstream from all pinched exchangers on either the hot or cold stream on which the pinched exchangers are matched, i.e. Exchangers 1, 3 and 7.

The next step is to check the feasibility of moving the upstream exchanger with the highest ΔT_{LM} to the exit of the pinched exchanger most downstream and on a utility path. The ΔT_{LM} of the upstream exchangers 1, 3 and 7 are 20.47°C, 56.9°C and 82.1°C. Therefore; the analysis is carried out relative to Exchanger 7. To check the feasibility of moving all the heat load of Exchanger 7, a new heat exchanger is placed at the exit of Exchanger 4 (represents the pinched exchanger most downstream and on a utility path) to create a loop with Exchanger 7. The analysis found that all the heat load of exchanger 7 could be moved without violating the network feasibility.

Therefore, resequencing was identified as the best option. Figure 15 shows the result after the application of resequencing. Figures 16 – 18 shows the retrofit result for the other modification options. It can be noted that adding a new exchanger to create a loop provided the same decrease in energy consumption of the hot utility. However, the duty of the existing exchanger, 7, goes to zero as all the heat load is transferred to the new exchanger. Compared to resequencing, adding a new exchanger will not be the best option as the best retrofit option seeks to maximise the use of existing equipment as opposed to investing in new equipment to meet the same objective.

The decrease in energy consumption after resequencing is less than the targeted savings. The network data is updated and the retrofit procedure repeated. The second modification identified based on the retrofit algorithm was to add a new exchanger to create a loop. This is because there are still two upstream exchangers from all pinched exchangers, Exchangers 1 and 3. The new exchanger is added to create a loop as

shown in Figure 19 as Exchanger 3 has the higher ΔT_{LM} (59.01°C) compared to Exchanger 1 (18.72°C). After the second modification, the retrofit target is achieved. Therefore, the retrofit process is stopped.

Table 9 shows the final heat exchanger data after performing structural modifications. The total additional area required in existing exchangers after performing structural modifications is $\sim 1,760\text{m}^2$. The calculated retrofit profit after structural modifications is $\sim 3\%$ of the initial utility cost. However, this does not consider the cost associated with production losses due to the time required to carry out the modifications and civil engineering and piping work required to make the modifications. Also, these modifications might be difficult to implement due to topology, safety and downtime constraints imposed by the existing network.

5.3 Combination of Structural Modifications and Enhancement

The objective is to maximise energy recovery subject to a ΔT_{min} of 10°C while maximising retrofit profit. The final network structure for maximum energy recovery is given in Figure 19. From Table 9, all existing process heat exchangers require additional area except Exchanger 3. Therefore, Exchanger 3 has been left out from this analysis. Figure 20 shows the sequence for obtaining the retrofit target.

Enhancement is applied based on the enhancement sequence shown. Note that pressure drop mitigation techniques were only required when two exchangers (Exchangers 2 and 7) were enhanced. Also, there was no stopping criterion violation.

Therefore, all candidate heat exchangers were enhanced to meet the retrofit objective.

Table 10 shows the final exchanger data after the application of the combination of structural modifications with enhancement. Figure 21 shows a comparative analysis of the different retrofit options presented in this work. The result shows that by

combining structural modifications with enhancement, high energy recovery can be obtained with high retrofit profit unlike the use of only structural modifications or enhancement.

6 Conclusions

New retrofit methodologies for HENs based on the application of heat transfer enhancement considering pressure drop constraints, structural modifications and a combination of both methods have been presented in this work. The benefits of these methodologies have been demonstrated with a case study. The results show that the application of enhancement alone can bring about cost-effective energy savings, but the degree of energy savings is limited, i.e. achieving only 5.5% of the HEN initial utility consumption. This is because the energy savings by enhancement for a fixed network structure is constrained by the geometry of existing exchangers, which governs the maximum degree of enhancement that can be obtained. The potential for more energy recovery was exploited by considering the application of structural modifications based on the new pinch retrofit method. The new pinch retrofit method can identify the best location to apply a series of modifications and the best structural modifications for maximum energy recovery with the least number of modifications. Higher energy savings (24.2% of initial utility consumption) was obtained but at a higher capital investment penalty. Heat transfer enhancement is used to curb the high investment required for performing structural modifications while maintaining the energy savings at a reduced retrofit cost. As such, the energy savings of 24.2% is maintained with approximately 65% increase in retrofit profit compared to the retrofit profit after performing structural modifications. The new insights provided by the combination of the pinch retrofit method and the use of heat transfer enhancement is

710 believed to be a considerable contribution owing to its robustness, which lends itself
 711 to be applied to different HENs.

712

713 **Nomenclature**

Symbols	Definitions	Units
A	Heat transfer area	m ²
A _E	Area after enhancement	m ²
A _R	Area ratio	-
AC	Additional area cost	\$
BC	By-pass cost	\$
CCU	Cost parameter for cold utility	\$/y
CHU	Cost parameter for hot utility	\$/y
CP	Heat capacity flowrate	kW/°C
EC	Enhancement cost	\$
F _T	Correction factor	-
h _S	Shell-side heat transfer coefficient	kW m ⁻² °C ⁻¹
h _T	Tube-side heat transfer coefficient	kW m ⁻² °C ⁻¹
MC	Mitigation cost	\$
OT	Operating time	y
Q	Duty	kW
RC	Retrofit cost	\$
RP	Retrofit profit	\$
SF	Selection factor	-
SF	Selection factor	-
SMC	Structural modification cost	\$

TCOS	Target temperature of cold streams	°C
THOS	Target temperature of hot streams	°C
TS	Supply temperature	°C
TT	Target temperature	°C
U	Overall heat transfer coefficient	$\text{kW m}^{-2} \text{ }^{\circ}\text{C}^{-1}$
U_E	Enhanced overall heat transfer coefficient	$\text{kW m}^{-2} \text{ }^{\circ}\text{C}^{-1}$
ΔA	Additional area	m^2
ΔP	Pressure drop	kPa
ΔP_B	Stream total pressure drop	kPa
ΔP_S	Total shell-side pressure drop	kPa
ΔP_T	Total tube-side pressure drop	kPa
ΔT_{LM}	Log mean temperature difference	°C
$\Delta T_{\min}$	Minimum temperature approach	°C

714 **Subscripts:**

B	Base
B, E	Base and enhanced
CS	Cold stream
CU	Cold utility
E	Enhanced
ex, EX	Exchanger
f	Final
HS	Hot stream
HU	Hot utility

i	Initial
N	New
N, E	New and enhanced
S	Shell
SM	Structural modification
T	Tube

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Table 1: Initial Incidence Matrix

S/E	1	2	3	4	C1	C2	H	P
1	0	0	+1	0	+1	0	0	0
2	0	0	0	+1	0	+1	0	0
3	+1	+1	0	0	0	0	0	0
4	0	-1	-1	0	0	0	0	0
5	-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

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810

Table 2: Reduced Incidence Matrix

S/E	1	2	3	4	C1	C2	H	P
1	0	0	+1	0	+1	0	0	0
2	0	0	0	+1	0	+1	0	0
3	+1	+1	0	0	0	0	0	0
4	0	-1	0	0	+1	0	0	0
5	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

811

Table 3: 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
HU	72.3	500	300	14455.4	-
CU	349.7	20	30	3496.6	-

813 **Table 4:** 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

814 **Table 5:** Cost Data

Utility Cost Data	Retrofit Cost Data
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CHU: 400 (\$/kW y)	EC: $500 + 10 \cdot A$ (\$)
CCU: 5.5 (\$/kW y)	BC: 500 (\$)
Payback operating time: 1y	Cost of increasing heat exchanger area: $4,000 + 200 \cdot A$ (\$)
	Cost of resequencing: 10,000 (\$)
	Cost of new heat exchanger: $4,000 + 300 \cdot A$ (\$)
	Cost of stream splitting: 10,000 (\$)
	Cost of modifying shell arrangement: 10,000(\$)
	Cost of modifying tube passes: 5,000 (\$)

815

816 Table 6: Results from the Area Ratio Approach

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

817

818 Table 7: Application of pressure drop mitigation techniques for Exchanger 2

		Tube pass reduction (two to one)	Shell arrangement modification (series to parallel)
Base Case	U _B (kW/m ² °C)	0.475	
	U _{B, E} (kW/m ² °C)	0.597	
	ΔP _B (kPa)	131.40	

	$\Delta P_{B,E}$ (kPa)	163.31	
After Modifications	U_N (kW/m ² °C)	0.356	0.361
	$U_{N,E}$ (kW/m ² °C)	0.490	0.494
	ΔP_N (kPa)	113.80	33.77
	$\Delta P_{N,E}$ (kPa)	125.48	43.22
SF		0.33	0.27

Table 8: Final Heat Exchanger Data after Enhancement

Ex	A (m ²)	U (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
C1	-	-	-	-	661.04	-	-
C2	-	-	-	-	1142.28	-	-
C3	-	-	-	-	17.97	-	-
C4	-	-	-	-	881.29	-	-
H	-	-	-	-	13661.52	-	-

825 **Table 9:** Heat Exchanger Data after Structural Modifications

Ex.	A (m ²)	A _{SM} (m ²)	U (kW/m ² °C)	Q (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

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827 **Table 10:** Final Exchanger Details

Ex.	A (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

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Figure 1: Retrofit methodology with pressure drop and heat transfer enhancement

Figure 2: Example Network

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S/E	H		4		C2		P
1	0		0		0		0
2	0		+1		+1		0
3	0		0		0		0
4	0	-	0	+	0	=	0
5	-1		0		+1		0
HU	+1		0		0		+1
CU	0		0		0		0

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Figure 3: First Utility Path

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S/E	H		1		2		3		C1		P
1	0		0		0		+1		+1		0
2	0		0		0		0		0		0
3	0		+1		+1		0		0		0
4	0	-	0	+	-1	-	0	+	+1	=	0
5	-1		0		0		0		+1		0
HU	+1		0		0		0		0		+1
CU	0		0		0		0		0		0

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Figure 4: Second Utility Path

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Figure 5: Different shell arrangements and pressure drop calculation

Figure 6: Background of pinch retrofit method

Figure 7: Simple illustration for key terms

Figure 8: Illustrative example for upstream exchangers

Figure 9: Cost-effective retrofit methodology

Figure 10: Existing HEN

Figure 11: Sensitivity Analysis Result

Figure 12: Enhancement Sequence

Figure 13: Comparison of enhancement results

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Figure 14: Pinched HEN

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Figure 15: HEN after resequencing

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Figure 16: HEN after adding a new exchanger to create a loop

Figure 17: HEN after adding a new exchanger to create a utility path

Figure 18: HEN after stream splitting

Figure 19: Retrofitted HEN

Figure 20: Analysis Sequence

Figure 21: Comparative Analysis