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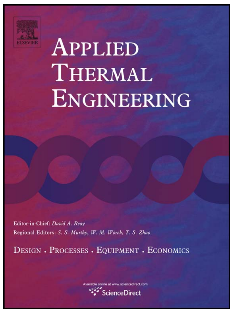

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Recent Development in the Retrofit of Heat Exchanger Networks

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Abstract

This work presents a methodology for heat exchanger network (HEN) retrofit, which is applicable to complex industrial revamps, considering existing networks and constraining the number of modifications. The network pinch approach [1] has been modified and extended to apply to the HEN design in which the thermal properties of streams are temperature-dependent. The modified network pinch approach combines structural modifications and cost optimisation in a single step to avoid missing cost-effective design solutions.

Keywords: Heat exchanger network; Network pinch approach; Mixed-integer non-linear optimisation; Retrofit design

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Nomenclature and abbreviation

A_{exit}	Total existing area of an existing network (m^2), in Figure 3
cu	Cold utility
DH_i	Accumulated enthalpy change from the start of the stream to the particular node i (kW), in Equations 2, defined by Equation 3
E_{exist}	Energy demand of an existing network (kW), in Figures 3
ff_{lj}	Flow ratio of the branch to the main stream j where the exchanger unit l is located on
HEN	Heat exchanger network
hu	Hot utility
LP	Linear programming
$MILP$	Mixed integer linear programming
$MINLP$	Mixed integer non-linear programming
mods	Modifications, in Figures 3
N_{BR}	Number of stream branches in a heat exchanger network
N_{HX}	Number of heat exchangers in a heat exchanger network
N_{ST}	Number of process streams in a heat exchanger network
N_{SUT}	Number of process streams on which there is a utility heat exchanger, in a heat exchanger network
$N_{\mathrm{var}y}$	Number of variables in the pinching problem
NLP	Non-linear programming
Q_l	Heat load of heat exchanger l (kW)
$R^i_{\max}$	Maximum heat recovery for the network with i modifications (kW) in Figures 3
SA	Simulated annealing
SQP	Successive quadratic programming
T_i	Temperature of node i (°C)
TC_l^{in}	Inlet temperature of cold stream in heat exchanger l (°C)
TC_l^{out}	Outlet temperature of cold stream in heat exchanger l (°C)
TH_l^{in}	Inlet temperature of hot stream in heat exchanger l (°C)
TH_l^{out}	Outlet temperature of hot stream in heat exchanger l (°C)
TS_j	Supply temperature of stream j (°C)
TT_j	Target temperature of stream j (°C)
$TT_{calc,j}$	Calculated target temperature of stream j, including transfer heat with utility (°C)
$TT_{ppcalc,j}$	Calculated temperature of stream j after process to process heat transfer in a heat exchanger network (°C)
y_{il}	Binary variable, denotes the existence of exchanger unit l on the section of the stream from node i to the start of stream

Greek letters

$\Delta T_{\min}$	Minimum difference temperature approach (°C)
γ	Penalty factor in equation 4.10
λ	Damping factor in Levenberg-Marquardt algorithm

1. Introduction and previous work

Numerous investigations have been carried out to improve the performance of HENs. The HEN design approaches can be grouped into three major categories: pinch analysis methods, mathematical programming methods and stochastic optimisation methods. Linnhoff and Hindmarsh [2] developed a method to design for the minimum hot and cold utility demand, for a set of hot and cold streams and a selected minimum temperature approach ($\Delta T_{\min}$), based on several heuristic rules. Because pinch analysis is difficult to apply to large scale problems, mathematical modelling methods were developed. Optimisation of HEN is generally formulated as a mixed-integer non-linear programming (MINLP). To avoid being trapped into local optimum, simplifications are made to convert the MINLP problem into Linear programming (LP) problem [3], or Non-linear programming (NLP) problem as in the work of Yee *et al*. [4]. Sorsak and Kravanja [5] and Ma *et al*. [6] have formulated MINLP models for the retrofit design of HEN. Compared to deterministic methods, using stochastic methods will give more chances to find the global optimum for MINLP problems, due to the random nature of the optimisation methods. Commonly used algorithms in the design of HENs are Genetic Algorithms [7] and Simulated Annealing [8].

Non-constant thermal properties often arise when multi-component streams are cooled down or heated up, such as in refining preheat trains. Only few methodologies considered the varying thermal property (e.g. heat capacity) issue of process streams [9-11]. These proposed methodologies have several limitations. In the work of Grossmann *et al*. [9], the network configuration has been fixed and not optimised. Castier and Queiroz [10] only estimated the minimum energy requirement, and detailed HEN designs were not considered. The MINLP model proposed in the work of Ponce-Ortega *et al*. [11] is for HEN synthesis only and not applicable to retrofit.

The network pinch approach [1] combines physical insights into retrofit problems and mathematical programming techniques. The bottleneck of the existing network configuration is first identified by redistributing the heat loads of existing exchangers, which is referred to as pinching the existing network. Then each candidate structural modification that may overcome the bottleneck of the HEN configuration is optimised at a time for maximum heat recovery. A list is generated after all suggested modifications are optimised, showing the corresponding maximum heat recovery for a given modified HEN topology. The difficult MINLP problem is then decomposed into Mixed-integer linear programming (MILP) problem and NLP problem. Although it is a sequential approach, it explores possible topology modifications in a systematic way and at the same time allows user interactions in the design procedure. This characteristic makes the network pinch approach to be a promising retrofit design methodology in industrial practice.

However, the existing network pinch approach assumed constant thermal properties (e.g. heat capacity) and stream split fractions are not considered in pinching existing networks. Moreover, the existing approach only carries out cost-optimisation after the diagnosis stage. The design with minimum cost cannot be guaranteed since the selection of the potential modifications is not based on costs but energy demands. In this paper, the network pinch design method [1] is modified to overcome these limitations.

2. Structure representation and modelling of heat exchanger network

There are some streams for which the thermal properties (e.g. heat capacity) are highly dependent on temperature. For those streams, multi-segment formulations are employed. The whole temperature range is broken into several intervals (the stream in each interval is referred to as a segment) in which the thermal properties are assumed constant.

The representation of HEN structure in this work employs the node-based representation. As shown in Figure 1, the links between every component in the heat exchanger network are represented by nodes. There are four nodes assigned to a heat exchanger unit (for example, process exchanger and utility exchanger): hot side inlet node, hot side outlet node, cold side inlet node and cold side outlet node. For unit operations, as they are only relative to one stream, two nodes associate with them, namely inlet and outlet nodes. Unit operations are devices designed to alter either the temperature or heat content of a stream. They represent the background process of the HEN without considering the actual details of the behaviour of the unit operation. For example, in preheat trains, the temperature of crude oil decreases after passing through a desalter. The desalter can be modelled as a unit operation. For a unit operation, temperature change of the stream is specified. Each node is associated with a unique temperature, which means that a new node is defined only if the temperature varies (e.g. the temperature of a stream branch after a splitting is the same as that before splitting). Therefore there is one node associated with supply temperature of each stream and also one node is associated with each stream splitter. The first node of each stream is always associated with the stream supply temperature; and the last node of each stream is always associated with the stream target temperature. Owing to the unique one-node-one-temperature data structure, redundant data are avoided and very complex networks are represented using moderate memory: stream splitting is considered in the HEN simulation and design; utility exchangers can be located at any places in the HEN; the number of exchangers on a given stream or branch thereof is not be inherently limited.

The HEN is modelled as an interconnected set of network elements, namely process heat exchangers, utility heat exchangers, stream splitters and mixers and unit operations. Because multi-segmented stream data are employed, the equations are not linear with respect to temperature. Therefore, with specified heat load of each exchanger unit, the node temperatures in the network are calculated sequentially. The calculation order of the node temperature is from the start of each stream to the end of that stream. After all the temperature nodes are calculated, the required heat transfer area is calculated for each exchanger. The needed area is then compared to the existing area of each exchanger. Capital cost will be incurred if the needed area is larger than the existing one.

3. Network pinch approach for HEN retrofit

In the first step of the modified network pinch method, the network pinch is identified by redistributing heat transfer loads between the existing matches and in the meantime varying stream split fractions for maximum heat recovery (minimum utility demand). Both heat loads and stream split fractions are adjusted to make sure that the network pinch is not caused by the heat transfer area limits but the topology of existing HEN. The redistribution of heat loads and variation of stream split fractions in the network for maximum heat recovery is of great importance due to its effect on determining the bottleneck of existing HEN topology and suggesting structural modifications that may overcome the bottleneck. Given a network having N_{HX} heat exchangers and N_{BR} stream branches, the objective in the pinching problem is to minimise utility demand of the network (*Utility*), by varying heat loads of existing exchangers ($Q_1, Q_2, \cdots Q_{N_{HX}}$) and stream split fractions ($ff_1, ff_2, \cdots ff_{N_{BR}}$), subjected to minimum temperature approach constraints and stream enthalpy constraints (Equation 1).

$$
\begin{aligned}
&\min Utility = f\left(Q_1, Q_2, \cdots Q_{N_{HX}}, ff_1, ff_2, \cdots ff_{N_{BR}}\right) \\
&st: TC_l^{out} - TH_l^{in} + \Delta T_{\min} \leq 0 \\
&\quad TC_l^{in} - TH_l^{out} + \Delta T_{\min} \leq 0 \\
&\quad TT_{calc,j} - TT_j = 0
\end{aligned}
\tag{1}
$$

where TH_l^{in} and TC_l^{in} are the hot inlet temperature and cold inlet temperatures of heat exchanger l; TH_l^{out} and TC_l^{out} are the hot outlet temperature and cold outlet temperatures of heat exchanger l; $TT_{calc,j}$ is the calculated target temperature of stream *j*, and TT_j is the specified target temperature of stream *j*.

The number of variables N_{VARY} in the pinching problem is the sum of N_{HX} (the number of heat exchangers) and N_{BR} (the number of branches). Considering the large number of optimisation variables and the non-linearity of the problem, the pinching problem is very complex. Normally N_{HX} is significantly larger than N_{BR}, since N_{BR} is limited for the reason of controllability. The relative importance of the heat exchangers suggests decomposing the pinching problem into two levels (Figure 2). In the outer loop the stream split fractions are optimised, and in the inner loop the heat loads of existing exchangers are redistributed. The minimum utility requirement obtained in the inner loop serves as the objective function value for the outer loop optimisation. By implementing the two-level pinching procedure, the size and complexity of the pinching problem are reduced. As will be explained in following sections, the inner loop optimisation is formulated as a least-squares problem, which has an easier convergence and less calculation iterations compared with other types of NLP problems [12]. Moreover, solving least-squares problems will less depend on the quality of the initial guess, which is not easy to be always sensible provided in a complex NLP problem. As the inner loop of the pinching problem contributes more than the outer loop, the penalties incurred by decomposing the pinching problem on the optimality are small. In a decomposed way, there are more chances to find a better solution, in terms of robustness of the optimisation method due to less dependence on the initial guess and easier convergence.

The successive quadratic programming (SQP) method is a popular approach for process optimisation, and are most efficient if the number of active constraints is nearly as large as the number of variables, that is, if the number of free variables is relatively small [12]. The SQP algorithm is selected as the optimisation solver for the outer loop where only the flow rates of stream branches are optimised. In particular, the optimisation subroutine E04UCF of the NAG FORTRAN library [13] is used to implement the Quasi-Newton method [14] in the solution. The details of the SQP algorithm are explained in Biegler *et al.* [15].

In the inner loop, the flow ratios of each branch respect to the main streams are fixed, thus the optimisation problem is related purely to heat loads, and subject to minimum temperature approach constraints and stream enthalpy balance constraints. The inner loop optimisation is a highly constrained non-linear programming problem, involving a large number of optimisation variables. The commonly used SQP algorithm, which is normally suit optimisation problems with small number of variables, is not applied in the inner loop, where a large number of variables, N_{HX}, are involved. This work presents a novel approach for solving the inner loop optimisation problem.

As in this work, the limitation of assuming constant heat capacity with temperature is overcome. In the inner loop, the heat loads of existing exchangers are optimised toward minimum energy requirement. In order to solve this optimisation problem, first of all, a correlation needs to develop to associate the node temperature (T_i) with heat loads of exchangers ($\mathbf{Q}$) and the supply temperature (TS_j) of the stream where the node *i* is located. A polynomial correlation is proposed to represent each node temperature in terms of enthalpy change (Equation 2).

$$T_i = A_j \times DH_i^4 + B_j \times DH_i^3 + C_j \times DH_i^2 + D_j \times DH_i + E_j \quad (2)$$

where DH_i is the accumulated enthalpy change from the start of the stream (TS_j) to the particular node *i*, as shown in Equation 3:

$$DH_i = \sum_{l=1}^{N_{HX}} y_{il} Q_l \big/ ff_{lj} \quad (3)$$

where $y_{il} = 0 \text{ or } 1$, denotes the existence of exchanger unit *l* on the section of the stream from node *i* to the start of stream *j*; Q_l represents the heat load of exchanger unit *l*; ff_{lj} represents the flow ratio of the branch to the main stream *j* where the exchanger unit *l* is located.

Although there are other types of correlations that are commonly used (e.g. exponential, moving average), the polynomial correlation is proposed based on the following considerations:

- The formulation of polynomial correlation is flexible. The order of the formation can be adjusted to best suit the set of data. In this work, fourth order is proposed based on experiments, which gives the best fitting.
- The formulation of the polynomial correlation is simple. The analytical form of the first and second order derivatives can be attained easily. This allows employment of deterministic methods, which require detailed formulation and derivatives of the problem, in solving the inner loop optimisation problem.
- In the simulation of HEN, no formulation between the temperature and thermal properties are required since the stream data with varying thermal properties are input as multiple linear segments. It is simple to attain the coefficients in Equation 2 from the multi-segmented stream data due to the popularity of the polynomial correlation and availability of the regression in many commercial tools.

The proposed polynomial correlation is implemented to optimise the heat loads in the inner loop. If there are utility heat exchanger units located on stream *j*, the overall cumulative enthalpy change applied in Equation 2 excludes heat loads of those utility heat exchanger units. Then the calculated temperature of stream before utility exchangers ($TT_{ppcalc,j}$) is equivalent to the temperature after process-to-process heat recovery. It is clear that the smaller the difference between $TT_{ppcalc,j}$ and the target temperature TT_j, the lower the utility demand. Therefore, the utility consumption in terms of heat loads of process exchangers can be formulated by Equation 4. In the equation, the minimum temperature approach constraints and stream enthalpy balance constraints are considered by associating penalty functions in the objective.

$$Objective = \min\{ \sum_{j=1}^{N_{SUT}} \left(TT_{ppcalc,j} - TT_j\right)^2 + \gamma \times \left[\sum_{l=1}^{N_{HX}} \min\left(TC_l^{out} - TH_l^{in} + \Delta T_{\min}, TC_l^{in} - TH_l^{out} + \Delta T_{\min}, 0\right)^2 + \sum_{j=1}^{N_{ST}-N_{SUT}} \left(TT_{calc,j} - TT_j\right)^2 \right] \}$$

(4)

where each of TH_l^{in}, TC_l^{in}, TH_l^{out}, TC_l^{out}, TT_j and $TT_{ppcalc,j}$ is calculated by Equations 2, so each of the term in Equation 4 is a function of heat loads of all the process exchangers; γ is the penalty factor for violated constraints.

It can be seen that by employing the polynomial correlation, the optimisation in the inner loop of the decomposed network pinching is formulated as a least-squares problem (Equation 4), which has an easier convergence and less calculation iterations compared with other types of NLP problems [12]. Levenberg-Marquardt algorithm [16] is used to solve the inner loop optimisation where heat loads of existing matches are distributed for maximum heat recovery.

The Levenberg-Marquardt algorithm is explained here in short. The searching process starts with an initial guess of $\mathbf{x}^0$, then $\mathbf{F}\left(\mathbf{x}^0\right)$ is calculated by Equation 4. The Jacobian matrix $\mathbf{J}\left(\mathbf{x}^0\right)$ is then calculated. The searching direction and length of the step $\Delta\mathbf{x}$ is determined by solving $\left(\mathbf{J}^T\mathbf{J} + \lambda\mathbf{I}\right)\Delta\mathbf{x} = -\mathbf{J}^T\mathbf{F}$. The searching process stops until the final solution is found. The setting of initial damping factor λ^0 and μ are more or less experimental and problem specific [17]. In this work, these values are taken as 0.001 and 10.0 respectively based on trial and error.

After the bottleneck of the HEN configuration is diagnosed by pinching the network, different types of modifications are suggested to overcome the pinch. The modifications fall into four groups: re-piping existing matches, re-sequencing existing matches, adding new matches and introducing stream splitting.

In the work of Asante and Zhu [1], each modification is modelled and optimised for maximum energy recovery and ranked according to the utility consumption. Up to this step, the diagnosis stage is accomplished, and followed by the optimisation stage which optimises the selected candidate modifications for minimum total annualised cost. However, in the diagnosis stage, capital cost is not considered, the heat loads may be redistributed such that additional area is needed in many existing heat exchanger units. In practice, adding additional heat transfer area to one heat exchanger unit is not only about installing new area. The associated pipe work also requires modifications, which is normally more expensive than the installed area [18]. For example, adding 500 m^2 to 5 existing units is much more expensive and less favourable in industry than adding same amount of 500 m^2 to a single unit.

To take into consideration retrofit costs, in the current study, the network pinch approach of Asante and Zhu [1] is modified as shown in Figure 3. In the new network pinch approach, the structure searches in the diagnosis stage and the cost-optimisation are combined into one stage. The design problem then becomes a search for the most cost-effective structural changes in only one step, rather than sequential steps of a search for structural changes followed by a capital-energy optimisation, as employed in the original network pinch approach of Asante and Zhu [1]. The one-step design approach avoids missing potentially cost-effective designs in the diagnosis stage, by ranking the alternative designs based on costs, rather than heat recoveries.

In the proposed one-step approach, each candidate modification is optimised for minimum total cost directly. The minimum total cost found in the optimisation of each modification is used later as the criterion for ranking potential modifications. The design problem thus becomes a non-linear programming (NLP) problem. The simulated annealing algorithm with a feasibility solver [19] is employed to solve this NLP problem because of the following considerations:

- In the SA algorithm, the simulation and the optimisation algorithm are decoupled. No derivatives are required. The NLP optimisation problem is treated as a black-box; only objective function values of trial solutions are needed. That is, no simplifications to the simulation models are required for the sake of optimisation. The calculation of capital cost and operating cost can also be as complex as is required.
- Compared with using deterministic methods, using stochastic methods will give more chances of finding global optimum for non-linear problems due to their random characteristics. The non-linearity of the problem is increased greatly by the implementation of more accurate non-constant thermal properties for process streams.
- The network feasibility may be violated when simulating candidate solutions. It is not suitable to use deterministic methods, where a feasible initial design is normally required. The SA algorithm proposed in the work of Chen *et al*. [19] is capable of dealing with an infeasible initial design facilitated by the feasibility solver.

There are many advantages to employ the SA algorithm as the optimisation method, such as solutions of better quality, more constraints that can be handled, and fewer simplifications to the models of HENs to ensure convergence. However, relative longer computation times are the cost of these benefits. Compared to the original sequential order of structure searches in the diagnosis stage and the cost optimisation stage where a deterministic method is employed to solve the optimisation problem, more time is needed (at least 102 more time is required, the length of calculation time depends on the setting of SA parameters, see Appendix B.2) using the SA algorithm in minimising the total annualised cost of modifications that may overcome the bottleneck of the exiting network.

In order to reduce the calculation time, the SA algorithm [19] is modified such that only one run is needed in searching one type of structural modification. In retrofit design of HEN, there are four types of structural modifications to overcome the network pinch by moving heat from below the pinch to above the pinch of the existing network. The four possible types of changes are: re-piping existing matches, re-sequencing existing matches, inserting a new match and introducing additional stream splitting to the existing network. In the optimisation, both continuous variables and structural options of a particular type are optimised. If the SA algorithm makes a structural move, the structural modification is selected from those suggested after pinching the existing network. In the SA optimisation procedure, the best design of each potential modification is stored and reported at the end of the structure searching process. Note that the best design for each structural change from the modified SA algorithm is slightly worse than those gained from running the SA algorithm hundreds of times to optimise each potential modification and identify the most cost-effective design with the particular modification. However, given N candidates in a type of structural modifications, the calculation time is reduced to only 1/N of that required in running the SA algorithm each time in optimising each single candidate.

Normally, the objective in HEN design is to design a practical cost-effective network. Therefore, In SA algorithm, total annualised costs, comprising utility costs and annualised capital costs, is taken as the objective function in current work.

The modified network pinch approach takes into account different levels of complexity in the HEN retrofit. The complexities addressed include non-constant thermal properties, the effects of stream split fractions on determining the network pinch and the combination of the diagnosis stage and the cost optimisation stage to avoid missing cost-effective designs. In order to reduce the computational time, different methods are used to solve different types of design problems. For instance, if the constant heat capacity assumption stands, and initially there are no stream splits in the existing network, the pinching problem is solved by a linear solver (e.g. E04MBE of the NAG FORTRAN library) rather than the SQP method which is particularly suitable for non-linear system; Figure 4 shows the overall structure of the modified network pinch approach together with Figure 5 showing the sub-section of the overall network pinch approach.

4. Case study

The application of the modified network pinch is illustrated through adding a new exchanger unit in an existing preheat train. The crude oil preheat train is the heat exchanger network that is associated with an existing atmospheric crude unit [20]. The multi-segmented stream data considering varying heat capacities (target temperature, supply temperature, enthalpy change) are shown in Table 1. The existing HEN structure is shown in Figure 6, while the existing heat transfer areas for exchanger units are presented in Table 2. The utility costs are calculated using unit cost data (annual cost per unit of energy, \$/kW·y) and the calculated demand for each utility. The unit cost of hot utility is calculated from fuel cost, fuel net calorific value and efficiency of the atmospheric furnace. The unit cost of cold utility is taken from Gadalla [20]. The capital cost of heat exchanger modifications are calculated from simple correlations, which link a cost per unit area [18]. Unit cost of utilities and correlations to calculate heat exchanger capital cost from areas are shown in Table 3. The structural bottleneck of the existing network for $\Delta T_{\min}$ of 30 °C is identified using the developed two-level pinching method. The identified heat exchanger units at pinch location of the original network are shown in Figure 7. The change in flow fractions of braches, relative to the main stream, and redistribution of heat loads of existing matches for the pinched network are presented in Tables 5 and 6, respectively. The existing crude oil preheat train is also pinched using the SQP algorithm to optimise the heat loads and stream split fractions in a single step. In addition, the network is pinched by using the method of Asante and Zhu [1], in which only heat loads are redistributed for maximum heat recovery.

The minimum utility demands attained using the three methods are compared in Table 4. Table 7 shows the performance of the optimised design with a new match using the developed approach. The performance of the best design without any topology modifications is also shown in Table 7, and compared with the results of adding a new exchanger.

Table 4 shows that the developed two-level approach gives pinched HEN with most heat recovery, indicating that it is more capable of exploring the scope for recovering heat with the existing HEN configuration and determining the network topology bottleneck. It can be seen from Table 7 that by adding a new exchanger, the cost-effective retrofit design saves 20,358 kW hot and cold utilities, around 23% of the base case energy consumption. Table 7 also shows that a further 4,376 kW hot utility can be saved by adding a new exchanger, compared with no structural changes. These results indicate that in some cases, cost-effective retrofit does not always require topology modifications. Figure 8 presents the most cost-effective design with a new exchanger.

5. Conclusions

A retrofit design methodology is proposed for HENs of process streams with temperature-dependent thermal properties. The two-level pinching approach is developed for the optimisation of all continuous variables so that the heat recovery of the existing HEN is exploited to make sure that the bottleneck is the network topology rather than heat transfer areas. Moreover, the search for structural changes and capital-energy optimisation are combined into a single step for the first time, in order not to miss cost-effective designs. The new HEN retrofit design approach enables identifying the most critical HEN configuration changes, and provides access to designers, which makes sure the retrofit designs are mathematically optimum and industrially applicable.

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Figure 1 HEN structure representation

Figure 2 Optimisation approach for pinching a network

Figure 3 Modified network pinch approach design strategy

(mods: modifications; $R^{i}_{\max}$: maximum heat recovery with i modifications, kW; E_{exist}: Energy demand of the existing network, kW; Solid black curve represents the current search procedure of structural modifications; Dotted curve stands for the search procedure of original network pinch approach of Asante and Zhu [1]

Figure 4 The overall modified network pinch procedure

Figure 5 Pinch network for maximum heat recovery

Figure 6 Grid diagram of the existing heat exchanger network [20]

Figure7 Pinch locations of the existing heat exchanger network

Figure 8 Suggested location of adding a match

Table 1

Segmented stream data of illustrative example 4.1

Stream	Name	Supply temperature °C	Target temperature °C	Enthalpy change MW
1	Pump-Ar 1	298	268	12.828
2	Bott Cool 1	339	299	9.604
		299	259	9.164
		259	219	8.705
		219	179	8.228
		179	139	7.735
		139	100	7.024
3	Pump-Ar 2	250	210	14.416
		210	200	3.467
4	Bott Cool 2	257	217	1.142
		217	177	1.077
		177	137	1.011
		137	97	0.943
		97	57	0.874
		57	50	0.148

5	Pump-Ar 3	170	150	11.175
6	Bott Cool 3	282	242	3.949
		242	202	3.705
		202	162	3.471
		162	122	3.238
		122	82	3.004
		82	42	2.768
		42	40	0.164
7	Cond Duty 4	100	77	47.865
8	Dist Cool 4	77	40	1.321
9	Bott Cool 4	189	149	1.852
		149	109	1.707
		109	69	1.568
		69	40	1.059
10	Flue gas	1500	800	68.593
11	Feed PreH 1	25	65	12.465
		65	105	13.572
		105	145	14.660
		145	166	8.044
		166	185	9.197
		185	225	20.107
		225	265	21.076
		265	305	21.782
		305	345	22.310
		345	365	11.282
12	Reb Duty 3	271	282	8.783
13	Reb Duty 4	182	189	6.625
14	CW	10	40	71.908

Table 2

Existing heat exchangers

Heat exchanger ID	Area (m^2)	Overall heat transfer coefficient (kW/°C·m^2)
1	292	0.5
2	280	0.5
3	20	0.5
4	2	0.5
5	156	0.5

6	161	0.5
7	285	0.5
8	278	0.5
9	16	0.5
10	37	0.5
11	19	0.5
12	14	0.5
13	273	0.5
14hu	135	0.667
15cu	24	0.714
16hu	16	0.667
17hu	11	0.667
18cu	20	0.714
23cu	55	0.714
24cu	1054	0.714
25cu	61	0.714
26cu	116	0.714
27cu	258	0.714
28cu	85	0.714
Total	3669	-

Table 3

Utility and exchanger modification costs

Parameter	Unit cost	
Flue gas (1500 – 800 °C)	306.8	\$/kW·y

Cold water (10 – 40 °C)	5.25	\$/kW·y
Exchanger additional area	$9665 \times (\text{additional area})^{0.68}$	\$
New exchanger unit	$94093 + 1127 \times (\text{exchanger area})^{0.9887}$	\$

Table 4

Energy demand of pinched HEN

	Existing HEN	Pinched HEN		
		Approach 1	Approach 2	Approach 3
Coil Inlet Temperature (°C)	231	258	243	261
Hot Utility (kW)	88,951	74,171	82,417	72,969
Cold Utility (kW)	92,300	77,478	85,772	76,288

Approach 1: Network pinch: only heat loads varied; Approach 2: SQP algorithm: heat loads and split fractions varied in a single step; Approach 3: Two-level approach: network pinch varying both heat loads and split fractions

Table 5

Split fraction of branches for pinched HEN by the new two-level approach (with respect to main streams)

Branch No	15 (Str 10)	18 (Str 1)	21 (Str 9)	24 (Str 2)	27 (Str 3)
Split fraction	0.472	0.850	0.682	0.534	0.452

Table 6

Redistributed heat loads for pinched HEN by the new two-level approach

Hx no	Redistributed heat loads (MW)	Existing heat loads (MW)
1	11.87	13.25
2	14.12	13.19
3	0.93	0.86

4	10.10	0.11
5	16.29	7.47
6	1.63	7.33
7	13.74	11.42
8	10.76	11.52
9	1.70	0.89
10	2.91	2.05
11	1.32	2.37
12	3.87	1.74
13	7.64	8.76
14hu	57.61	73.54
15cu	0.00	3.08
16hu	8.78	8.78
17hu	6.63	6.63
18cu	0.00	1.09
23cu	1.32	1.32
24cu	47.86	47.87
25cu	4.26	4.33
26cu	11.18	11.18
27cu	10.20	20.19
28cu	1.58	32.44

Table 7

Energy and cost reduction after adding a new match

	Existing network	No modification	Adding a new match

Hot Utility (kW)	88,951	72,969 (18%*)	68,593 (23%*)
Cold Utility (kW)	92,300	76,288 (17%*)	71,908 (22%*)
Operating cost ($/y)	27,770,300	22,783,800 (18%*)	21,418,400 (23%*)
Additional area (m^2)	-	1334	1655
Capital investment ($)	-	2,392,760	2,730,390
Payback (year)	-	0.31	0.30

*: percentage of saving with respect to base case

Figure1 HEN structure representation

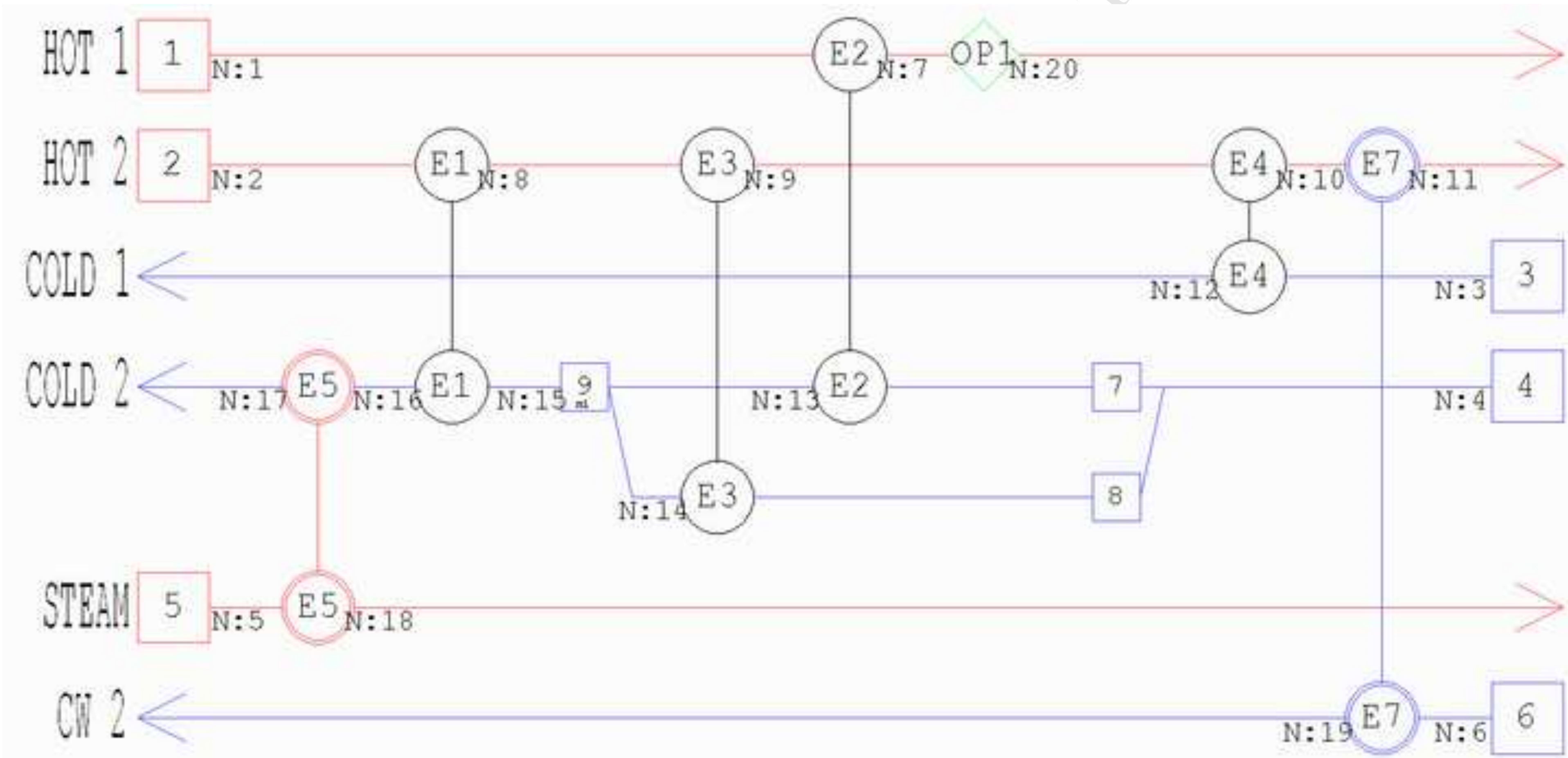

Figure2 Optimisation approach for pinching a network

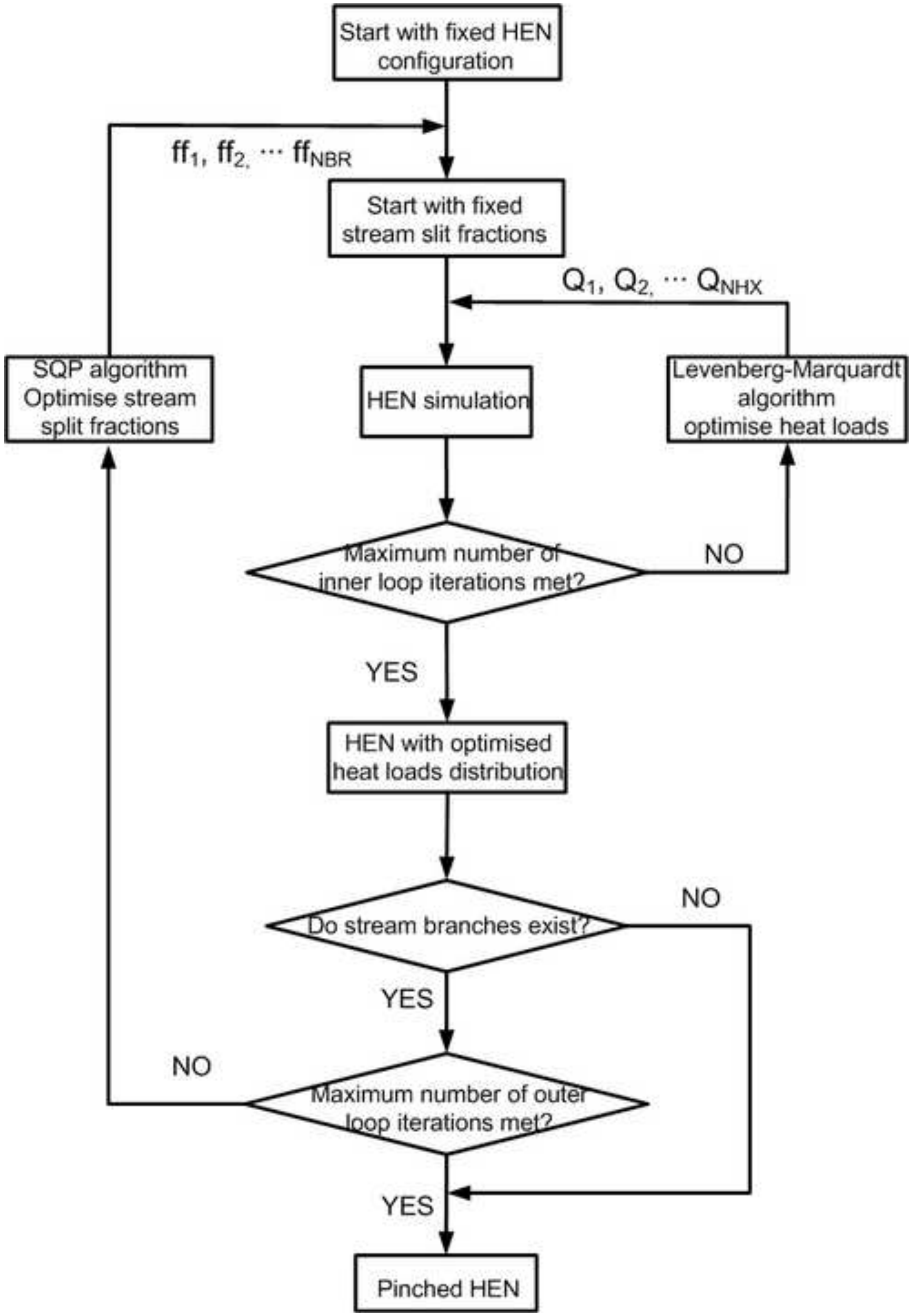

Figure3 Modified network pinch approach design strategy

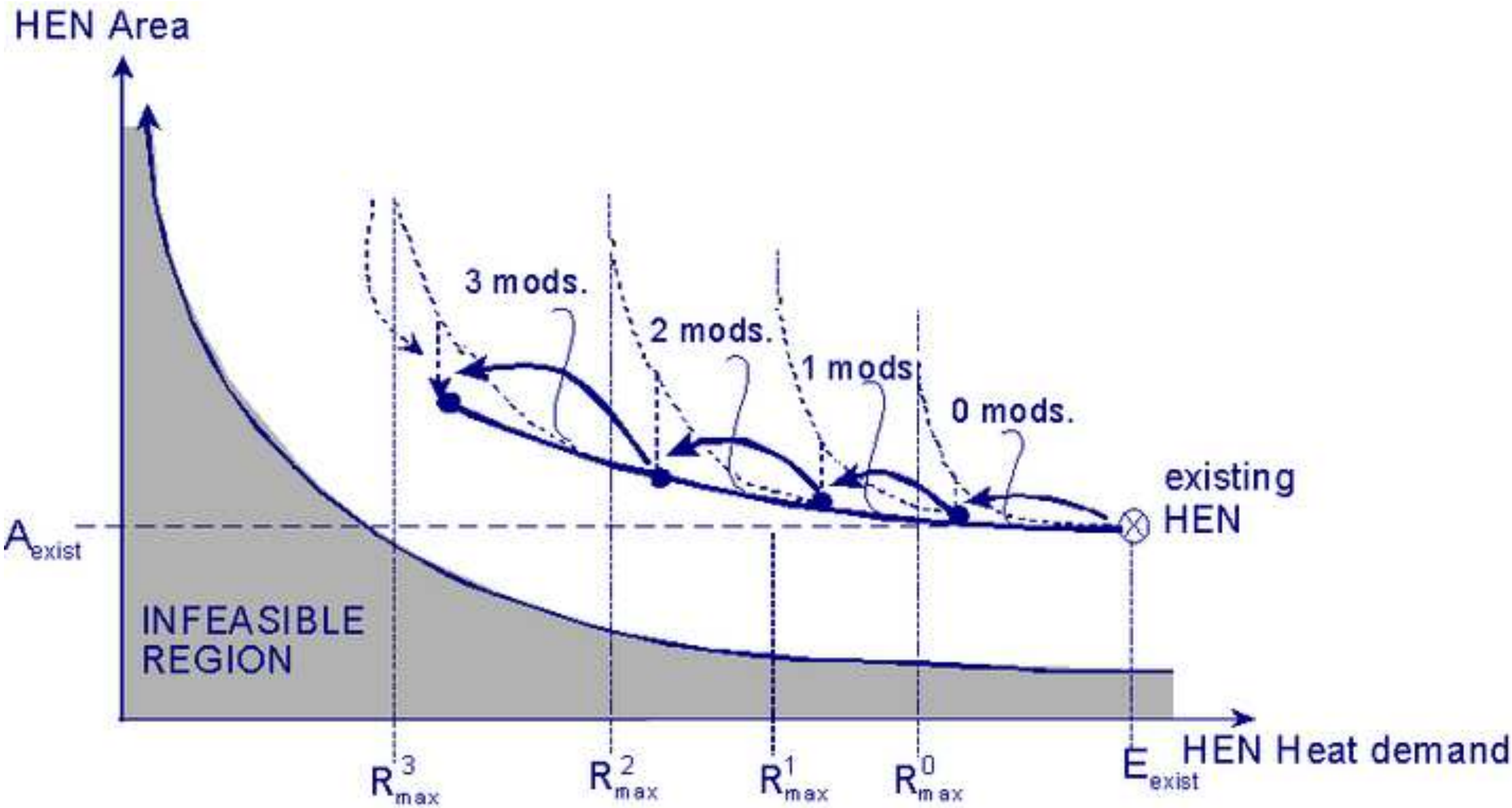

Figure4 The overall modified network pinch procedure

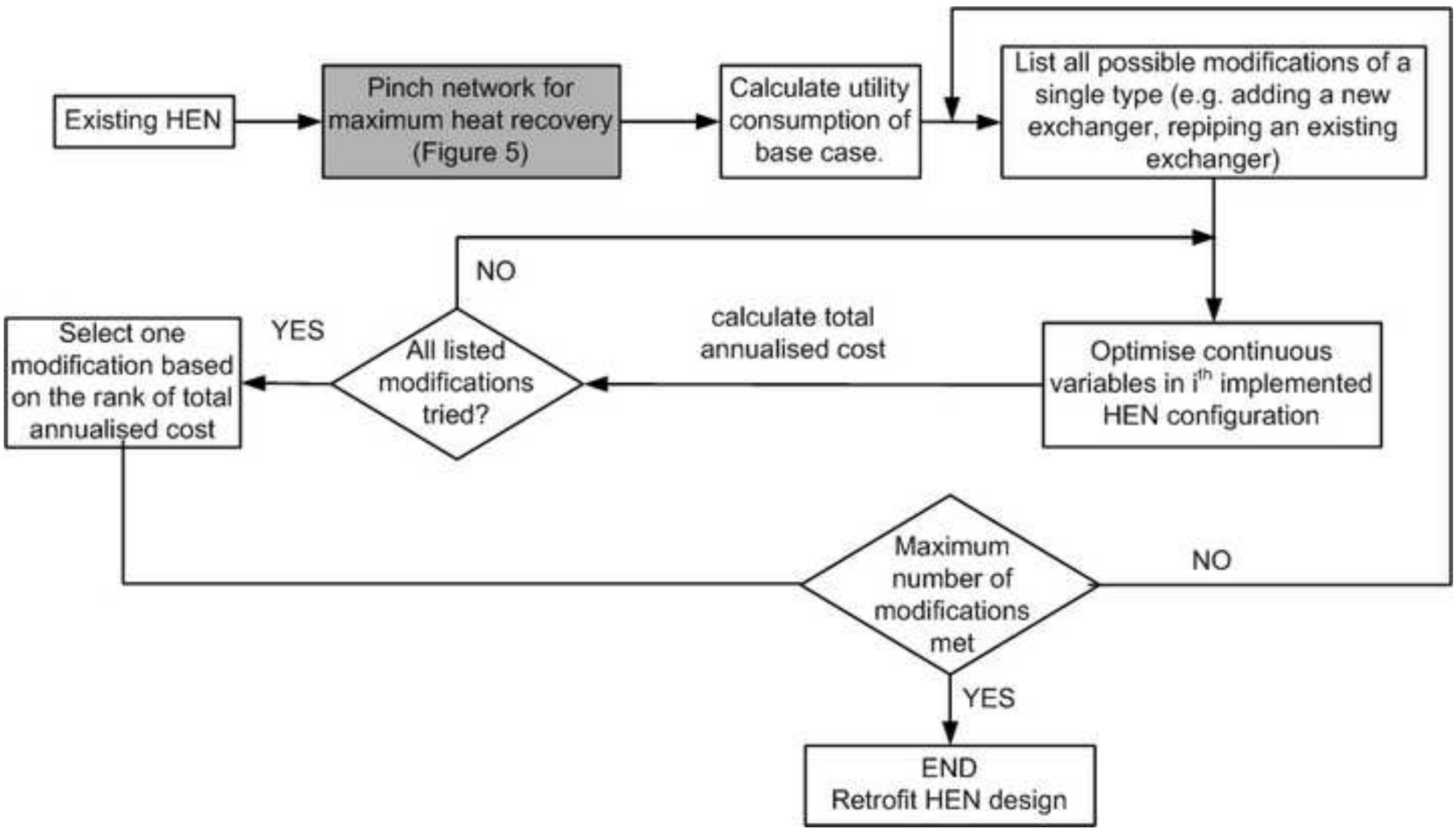

Figure5 Pinch network for maximum heat recovery

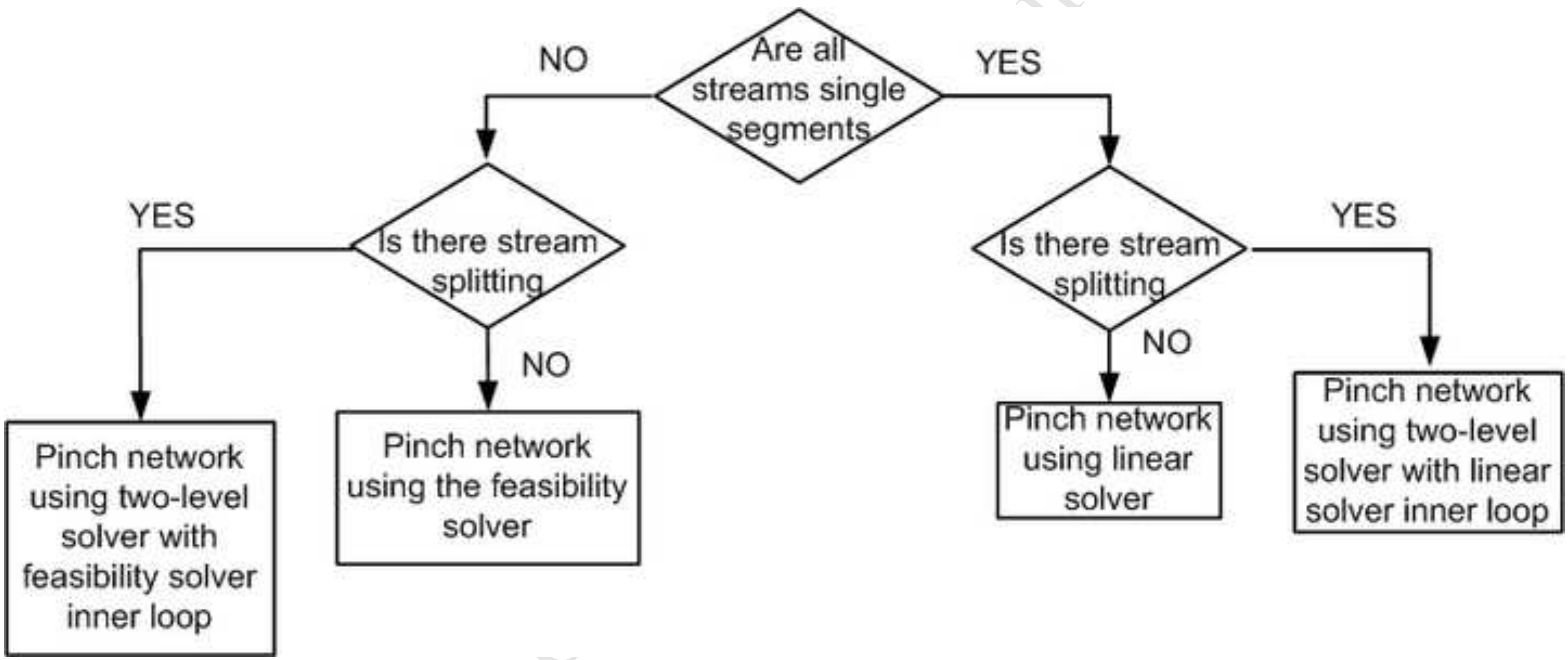

Figure6 Grid diagram of the existing heat exchanger network

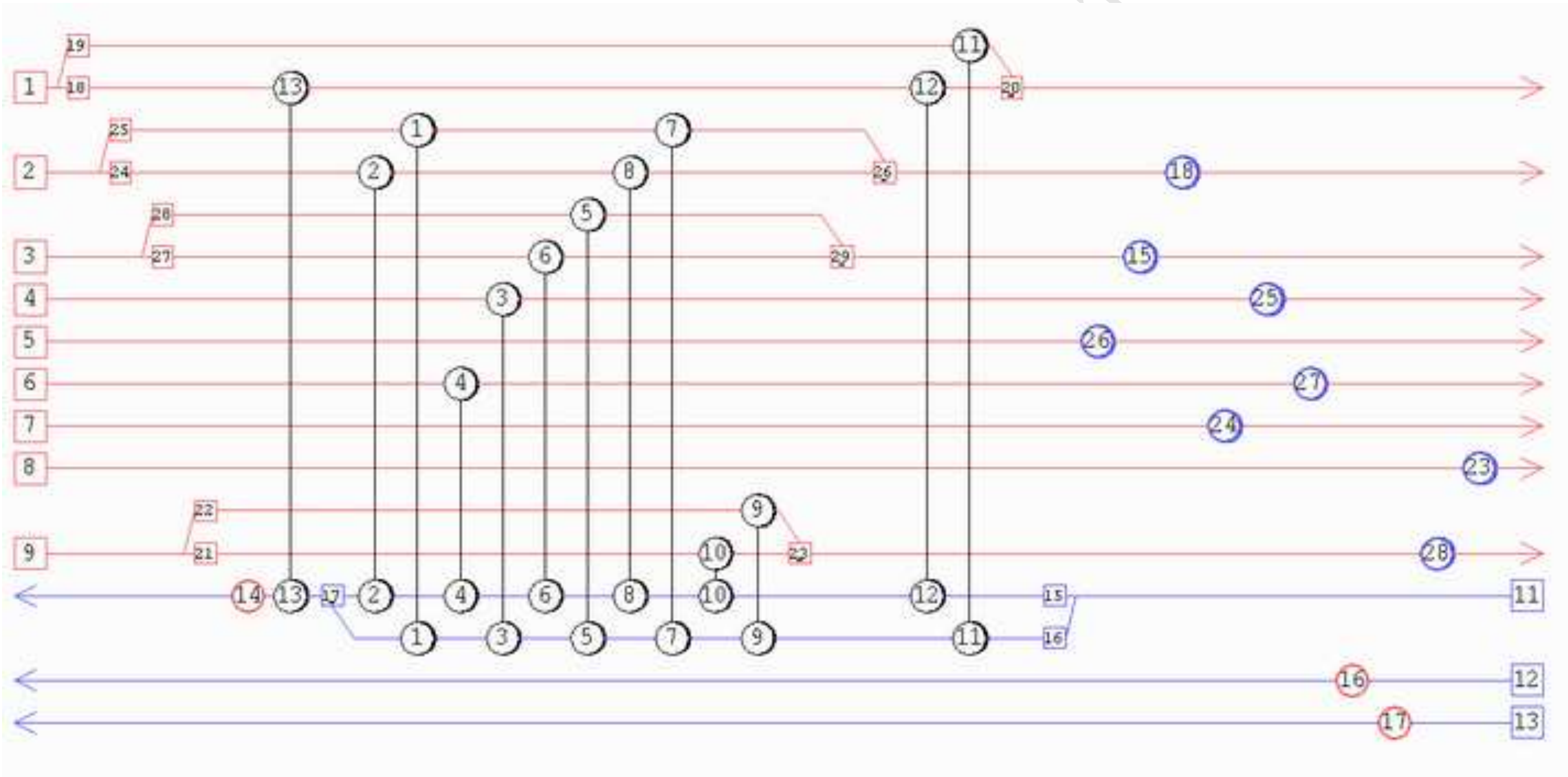

Figure7 Pinch locations of the existing heat exchanger network

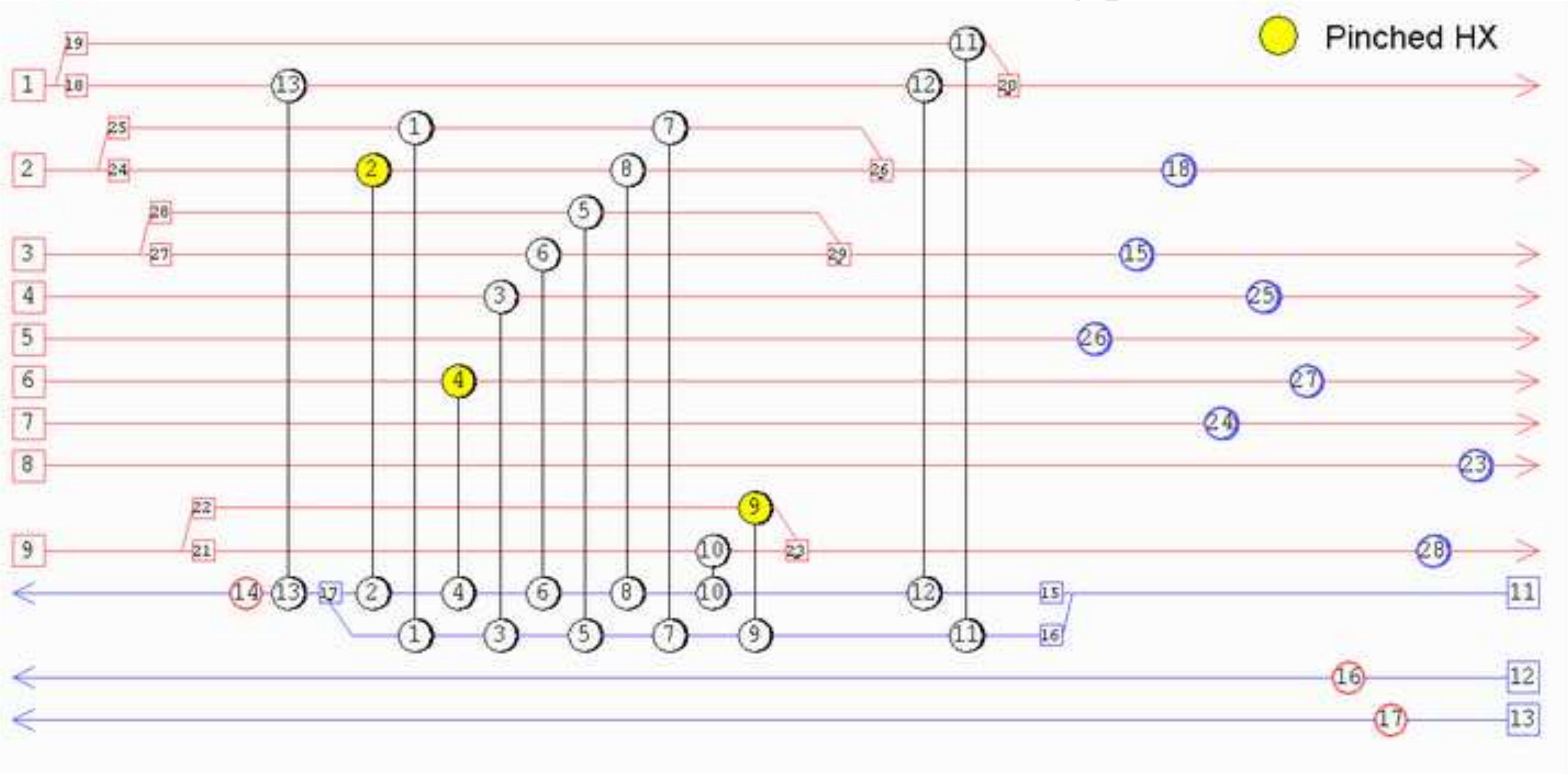

Figure8 Suggested location of adding a match