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STEP—A new graphical tool for simultaneous targeting and design of a heat exchanger network

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ABSTRACT

For 40 years, composite curves (CCs) and grid diagram (GD) have been among the most popular graphical tools for designing optimal heat exchanger networks (HEN). However, since CCs represent the temperature versus enthalpy plot of composites rather than individual streams, they have some significant limitations. Among others, CCs cannot completely map individual hot and cold process streams, as well as process and utility streams, and cannot be used for HEN design. In addition, CCs cannot be conveniently and effectively used to predict minimum network area and the optimum ΔT_{min} that should strictly be based on parameters and properties of individual as opposed to composite streams. Grid diagram on the other hand requires designers to provide or calculate stream temperatures as well as enthalpies, to do heat balance and to check temperature feasibility during HEN design as the diagram does not follow any temperature or enthalpy scale. This paper presents STEP (Stream Temperature vs. Enthalpy Plot) as a new graphical tool for simultaneous targeting and design of a HEN that overcomes the key limitations of CCs and the GD. The new STEPs are profiles of continuous individual hot and cold streams being mapped on a shifted temperature versus enthalpy diagram that simultaneously show the pinch points, energy targets and the maximum heat allocation (MHA). The MHA is graphically converted to an MER network and represented on a Heat Allocation and Targeting (HEAT) diagram in terms of STEP temperature and enthalpy. This paper also demonstrates that STEP can provide more realistic solutions for targeting multiple utilities and the minimum network area. STEP application on a palm oil refinery, and finally, its limitations, are also highlighted. With capabilities to overcome the limitations of CCs and GD, STEP can become a vital alternative graphical tool for optimal HEN design.

1. Introduction

The majority of energy consumed in industrial processes is typically used mainly for heating and cooling purposes. A statistics compiled by Renewables Academy (RENAC) of Germany indicates that the total heat energy usage in German industry can be up to three times higher than electrical energy usage [1]. Efficient design of heating and cooling systems in industry is therefore vital, and can be accomplished through design optimal heat recovery network using tools such as pinch analysis. Heat pinch analysis is a systematic technique for the design of thermally efficient systems. It allows a designer to identify the minimum heating and cooling requirements and maximum heat recovery (MHR) potential by identifying a thermodynamic bottleneck, or the pinch point for heat recovery. Graphical pinch analysis approach typically involves two key stages, i.e. setting the minimum energy targets (energy targeting) and heat exchanger network (HEN) design.

The *composite curves* which are temperature versus stream composite enthalpy plots were introduced by Hohmann [2] for setting the minimum utility targets. Until now, the composite curves have been most widely used for energy targeting [2–12]. The popular and efficient alternative for composite curve is a numerical technique known as *problem table algorithm* (PTA) [3,5,9,11,12]. Other refinements of the PTA technique include *simple problem table algorithm* [13], *geometry-based approach* [14], *enthalpy flowrate and temperature technique* [15]. For HEN design, the grid diagram and pinch design rules which include FCp inequality, stream splitting, loops breaking and energy relaxation have been used [5,12,16–19].

For 40 years, the popularity of the composite curves as a graphical tool to determine the minimum energy targets as well as the pinch points and the grid diagram as a template to design optimal heat exchanger network (HEN) have been virtually unrivalled. However, since the composite curves principally represent the temperature and enthalpy of composite, as opposed to individual streams, they naturally have the limitations listed below. The composite curves:

- do not entirely represent individual hot and cold streams heat transfer profile.

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Nomenclature

C	Cold stream
q	Heat duty (kW)
ΔH	Enthalpy change (kW)
ΔT_{min}	Minimum temperature difference (°C)
FCp	Heat capacity flowrate (kW/°C)
h	Heat transfer coefficient (kW/(m K))
H	Hot stream
HE	Heat exchanger
Q	Heat duty (kW)
Q_C	Cooler
$Q_{C,min}$	Minimum cold utility (kW)
Q_H	Heater
$Q_{H,min}$	Minimum hot utility (kW)
T_{pinch}	Pinch temperature (°C)
T_s	Supply temperature (°C)
T'_s	Shifted supply temperature (°C)
T_t	Target temperature (°C)
T'_t	Shifted target temperature (°C)
T_c	Cold composite temperature (°C)
ΔT_{LMk}	Limited temperature difference

- offer little guidance on individual stream matching.
- cannot be used for HEN design.
- cannot completely represent the integration between individual process streams and utilities, heat pump and combined heat and power.
- cannot be conveniently and effectively used to determine the minimum HEN area and the optimum ΔT_{min}. Note that the minimum HEN area and the optimum ΔT_{min} determination should strictly be based on parameters and properties of individual as opposed to composite streams.

On the other hand, the grid diagram, which has been extensively used as an interface for HEN design, is merely a qualitative template for hot and cold streams mapping in a process. As the grid diagram is not represented in any temperature or enthalpy scale, it requires a user to provide or calculate critical parameters including streams' temperatures as well as enthalpies, to do heat balance and to check temperature feasibility during HEN design.

This paper presents STEP (Stream Temperature vs. Enthalpy Plot) as a new graphical tool for simultaneous targeting and design of a HEN that overcomes all the perennial and critical limitations of composite curves and the grid diagram listed previously. The new STEPs are profiles of continuous individual (as opposed to composite) hot and cold streams being mapped on a shifted temperature versus enthalpy diagram that simultaneously show the pinch points, the energy targets and the maximum heat allocation (MHA). The MHA is graphically converted to a MER network and represented on a Heat Allocation and Targeting (HEAT) diagram in terms of STEPs' temperature and enthalpy.

The graphical approach for energy targeting and network design using STEP is presented next. Section 2 describes the STEP techniques for simultaneous setting of the minimum utility targets and streams heat allocation. Section 3 deals with complex systems involving threshold and multiple pinch problems. Sections 4 and 5 describe the procedure for MER network design and network evolution using STEP and Heat Allocation and Targeting (HEAT) diagram. This paper also demonstrates that STEP can provide more realistic solutions for targeting multiple utilities (Section 6) and the minimum network area (Section 7) based on individual as opposed to composite hot and cold streams matching. With the capabilities to overcome the limitations of composite curves and grid diagram, STEP can become an alternative visualization tool for the targeting and design of an MER network. It reduces the routine HEN design tasks such as streams enthalpy balances, and temperature feasibility checking associated with the composite curves and the grid diagram, and offers more reasonable solutions for multiple utility placement and area targeting.

2. *STEP* for setting the minimum utility targets and for streams heat allocation

The procedure to determine the minimum utility targets and to perform heat allocation using STEP is described next using Example 1 (see Table 1).

2.1. Step 1: convert stream temperatures into shifted temperatures

The first step is to convert the hot and cold stream temperatures (T_h and T_c) into shifted temperatures (T'_h and T'_c) using Eqs. (1) and (2), as is done for Problem Table Algorithm [3,5,9,11,12]. Using shifted temperatures effectively builds ΔT_{min} into the hot and cold STEPs and allows them to intersect at zero shifted ΔT_{min} and facilitates pinch point search during the curves construction and streams allocation.

$$T'_h = T_h - \frac{\Delta T_{min}}{2} \quad (1)$$

$$T'_c = T_c + \frac{\Delta T_{min}}{2} \quad (2)$$

Assuming a ΔT_{min} of 20 °C, the last two columns of Table 1 shows the streams shifted temperatures for Example 1. The hot and cold temperature intervals are shown in dotted lines in Fig. 1. Note that the temperature interval values can be read directly from the T axis of the T–H diagram in Fig. 1.

2.2. Step 2: construct the continuous hot and cold STEPS

The step-wise construction of the continuous hot STEPs followed by the continuous cold STEPS is described next using Fig. 1 and Example 1.

Table 1
Stream data for Example 1.

Stream	Description	Supply temp., T_s (°C)	Target temp., T_t (°C)	Heat capacity flowrate, FCp (kW/°C)	Enthalpy, ΔH (kW)	Shifted supply temp., T'_s (°C)	Shifted target temp., T'_t (°C)
Hot 1 (H1)	Reactor 1 product	300	160	3	–420	290	150
Hot 2 (H2)	Reactor 2 product	230	120	7	–770	220	110
Hot 3 (H3)	Distillate product	160	60	2	–200	150	50
Cold 1 (C1)	Reactor 2 feed-1	40	230	2	380	50	240
Cold 2 (C2)	Reactor 2 feed-2	100	230	4	520	110	240
Cold 3 (C3)	Reactor 1 feed	230	300	3	210	240	310

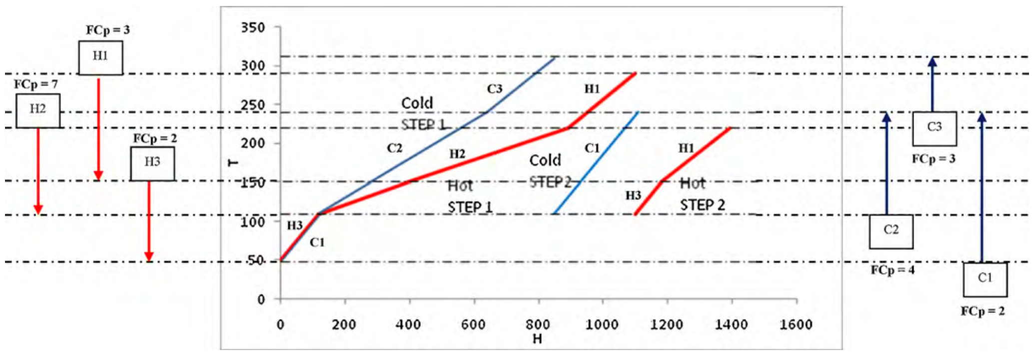

Fig. 1. The hot and cold STEPS for Example 1.

1. Draw the hot streams as arrows according to the temperature intervals where they exist, and sort them from left to right starting with the largest FCp stream, to the smallest FCp stream (i.e., H2 followed by H1 and H3). Repeating this step for the cold streams yields the arrangement shown on the right hand side of the *T*–*H* graph in Fig. 1 (i.e., C2 followed by C3 and C1).
2. Plot the first continuous hot STEP segment by segment, from the lowest to the highest hot temperature interval by choosing the largest FCp hot stream from each temperature interval region. In order to fix the hot stream location on the left of the *T*–*H* graph, begin by plotting the largest FCp hot stream in the lowest temperature interval region from its supply temperature to its target temperature at $\Delta H = 0$. Fig. 1 shows H3, which is the only stream available, being plotted from 110 °C to 50 °C (@ $H = 0$).
3. Link the tail-end of the previous hot stream segment to the largest FCp hot stream in the next temperature interval region. Note that H2 and H3 exist between 110 °C and 150 °C. H2 with the larger FCp is linked to the tail-end of the previous H3 segment.
4. Repeat step 3 for the remaining temperature intervals to build a continuous hot STEP. The first continuous hot STEP (hot STEP 1 in Fig. 1) is completed by connecting H2 between 150 °C and 220 °C to the previous H2 tail-end; followed by connecting H1 between 220 °C and 290 °C to the last H2 tail-end.
5. For the remaining hot streams in all the intervals with multiple streams, repeat steps 2 and 3 to construct the next continuous hot STEP that begins from the cumulative ΔH of the first continuous hot STEP. The continuous hot STEP 2 in Fig. 1 is then constructed, beginning from cumulative value of hot STEP 1 ($H = 1100$).
6. Repeat steps 1–5 to construct the continuous cold STEPs. Fig. 1 shows the completed hot and cold STEPs.

2.3. Step 3: determine the pinch temperature and the minimum utility targets

Step 3 involves getting the pinch point temperature and the minimum utility targets. Referring to Fig. 2, this is done by shifting the first cold STEP (cold STEP 1) to the right hand side of the first hot STEP (hot STEP 1) and the second cold STEP (cold STEP 2) to the right hand side of the second hot STEP (hot STEP 2) and so on, until the hot and cold STEP pairs are pinched as shown in Fig. 3. The point where the hot and cold STEP pairs touch at exactly the same temperature is the shifted pinch point temperature, T_{pinch}. Note that no trial-an-error is required during the cold STEP shifting since the use of shifted temperatures allows hot and cold STEPs to touch during the pinch point search. Sometimes there may either be more hot STEPs, or more cold STEPs. In such a case, the excess hot or cold STEPs can be used to satisfy any excess enthalpy of other STEPs, or be matched with the relevant utilities. Fig. 3 shows an example

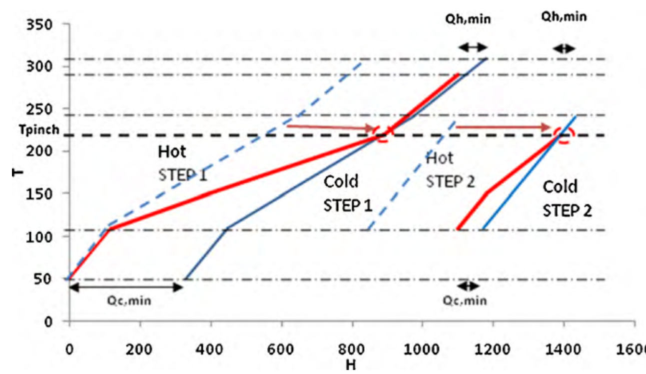

Fig. 2. Shifted hot and cold STEPs showing the $Q_{H,min}$, $Q_{C,min}$ and T_{pinch}.

where cold STEP 3 and excess cold STEP 2 are without a pair, and are used to satisfy the excess heat of hot STEP 1.

For Example 1, the shifted T_{pinch} is found at 220 °C as shown in Fig. 2. The sum of enthalpy overlaps between hot and cold STEPs represents the maximum process heat recovery. The $Q_{C,min}$ is the sum of the enthalpy from the overshoots of the hot STEPs, whereas the $Q_{H,min}$ is the sum of the enthalpy from the overshoots of the cold STEPs. Referring to Fig. 2, the $Q_{H,min}$ is 120 kW and the $Q_{C,min}$ is 400 kW. The maximum process heat recovery (the sum of enthalpy overlaps between hot and cold STEPs) is 990 kW. The $Q_{H,min}$, $Q_{C,min}$ and T_{pinch} obtained using STEPs match those obtained using the composite curves. However, STEP clearly shows the exact heat allocation between individual hot and cold streams. This graphical allocation is vital for the MER network design and for performing network evolution as demonstrated in Sections 4 and 5.

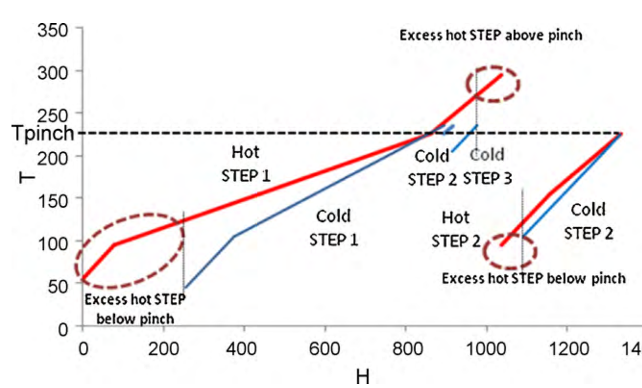

Fig. 3. Example 2 with excess hot stream above and below the pinch (a threshold problem).

Table 2
Stream data for Example 2.

Stream	Description	Supply temp., T_s (°C)	Target temp., T_t (°C)	Heat capacity flowrate, FCp (kW/°C)	Enthalpy, ΔH (kW)	Shifted supply temp., T_s' (°C)	Shifted target temp., T_t' (°C)
H1	Reactor 1 product	300	160	2.5	−350	295	155
H2	Reactor 2 product	230	100	6	−780	225	95
H3	Distillate product	160	60	2	−200	155	55
C1	Reactor 2 feed-1	40	230	2	380	45	235
C2	Reactor 2 feed-2	100	230	4	520	105	235
C3	Reactor 1 feed	200	230	2	60	205	235

Table 3
Stream data for Example 3.

Stream	Supply temp., T_s (°C)	Target temp., T_t (°C)	Heat capacity flowrate, FCp (kW/°C)	Enthalpy, ΔH (kW)	Shifted supply temp., T_s' (°C)	Shifted target temp., T_t' (°C)
H1	170	60	2.5	−275	165	55
H2	150	30	4	−480	145	25
C1	80	135	5	275	85	140
C2	50	100	3	150	55	105
C3	20	135	3.5	402.5	25	140

3. Threshold and multiple pinch problems

For special cases like the threshold problem (where either the hot or the cold utility is zero [12]) and the multiple pinch problem, a few additional rules are needed in order to achieve MER design with the minimum utility targets. Guidelines to handle these cases to achieve the MER design are described next.

3.1. Guide for threshold problems

Once hot and cold STEPs have been constructed and the pinch point found, cases exist where there are still excess hot STEP enthalpy above the pinch or excess cold STEP enthalpy below the pinch. This case is known as the threshold problem. To achieve the minimum utility targets and ultimately the MER design, if hot stream is in excess above the pinch, continue to shift the cold STEPs to the right in order to satisfy all excess hot STEPs enthalpy above the pinch. For this case, only cold utility will finally exist below the pinch.

On the other hand, if cold STEP is in excess below the pinch, continue to shift the cold STEPs to the left in order to satisfy all excess cold STEPs enthalpy below the pinch. For this case, only hot utility will finally exist above the pinch.

Example 2 illustrates the targeting procedure for a threshold problem. For a ΔT_{min} of 10 °C, the stream data in Table 2 yields the STEPs shown in Fig. 3 with excess hot STEP above the pinch point (shifted T_{pinch} of 225 °C), even after cold STEP 3 and part of the cold STEP 2 have been used to satisfy hot STEP 1 above the pinch. To achieve the minimum utility targets and ultimately the MER design, the cold STEP is shifted further to the right until all excess hot STEP enthalpy above the pinch is satisfied. Only cold utility is required for this case. Fig. 4 shows the hot utility ($Q_{H,min}$) is 0 kW and the cold utility ($Q_{C,min}$) is 370 kW.

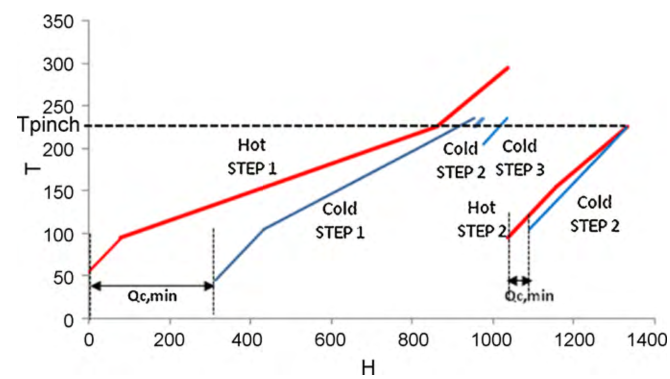

Fig. 4. Example 2 showing all excess hot STEP is satisfied above the pinch.

3.2. Guide for problems with multiple pinches

3.2.1. Type-1 and Type-2 multiple pinch problems

The previous sections apply to the single pinch problem where all pairs of hot and cold STEPs have only one common pinch temperature (see Fig. 2). Cases exist where all pairs of hot and cold STEPs may demonstrate either *global* multiple pinch points which means that each hot and cold STEPs pair pinch at exactly the same temperatures as do other pairs (Type-1, Fig. 6) or, several *local* pinch points which means that hot and cold STEPs pairs pinch at a unique temperature for each pair (Type-2, Fig. 5). These cases are known as the multiple pinch problems. To guarantee the minimum utility targets and an optimal overall heat allocation for a multiple pinch problem, each pair of hot and cold STEPs must be designed to pinch at exactly the same temperatures as do other pairs, i.e. to approach the Type-1 multiple pinch problem. For the Type-2 multiple pinch problem where each pair hot and cold STEPs have a unique pinch point (at different temperatures), stream splitting is necessary to achieve the minimum utility targets and the optimal heat allocation.

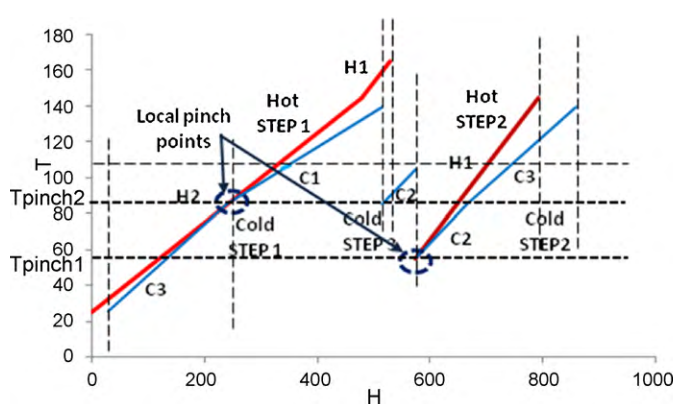

Fig. 5. STEPs for Example 3 demonstrating the Type-2 multiple pinch problem.

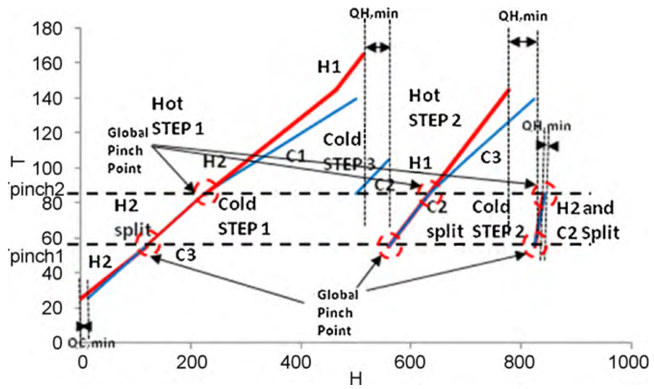

Fig. 6. STEPs for Example 3 demonstrating the global (Type-1) multiple pinch points after stream splitting.

The stream data in Table 3 for Example 3 is used to illustrate the Type-2 multiple pinch problem. The ΔT_{min} for this case is set at 10 °C. Fig. 5 shows the STEPs for the Type-2 multiple pinch problem. Note that for this case, hot STEP 1 and cold STEP 1 are pinched at 85 °C while hot STEP 2 and cold STEP 2 are pinched at 55 °C. The minimum utility targets and the optimal heat allocation have not been achieved for this case since the pinched temperatures are not the same for both pairs of hot and cold steps. It is therefore necessary to split both the hot and the cold streams between the two interval pinch temperatures in order to achieve the minimum utility targets and the optimal heat allocation.

3.2.1.1. *Procedure for stream splitting.* Stream splitting for the Type-2 multiple pinch problem involves dividing the bigger FCp stream (of the hot and cold STEP pairs) into two stream portions, with one split portion of the bigger stream matching the FCp of the smaller stream. For this case, between the interval temperatures of 55 °C and 85 °C, H2 from hot STEP 1 (FCp = 4) has a bigger FCp than C3 from cold STEP 1 (FCp = 3.5). Hence, H2 is split into two stream portions at an FCp ratio of 3.5:0.5 in order to match the FCp (and hence, the gradient) of C3. On the other hand, C2 from cold STEP 2 (FCp = 3) has a bigger FCp than H1 from hot STEP 2 (FCp = 2.4). Hence, C2 is split into two stream portions at an FCp ratio of 2.4:0.6 in order to match the FCp of H1. The remaining H2 from hot STEP 1 (FCp = 0.5) and C2 from cold STEP 2 (FCp = 0.6) splits are finally matched with one another. Fig. 6 shows the final STEP after stream splitting. The final $Q_{H,min}$ is 98.5 kW and the $Q_{C,min}$ is 15 kW, which are the same as those obtained using the composite curves.

Note that the graphical STEP simultaneous targeting and stream splitting procedures not only guarantees the minimum utility targets, but also the optimal heat allocation throughout a heat exchanger network. The traditional composite curves targeting approach however does not guarantee a feasible and optimal heat allocation, and must be followed by detailed heat exchanger network (HEN) design that involves enthalpy balance calculations, stream splitting and temperature feasibility calculations, using the grid diagram as a design interface.

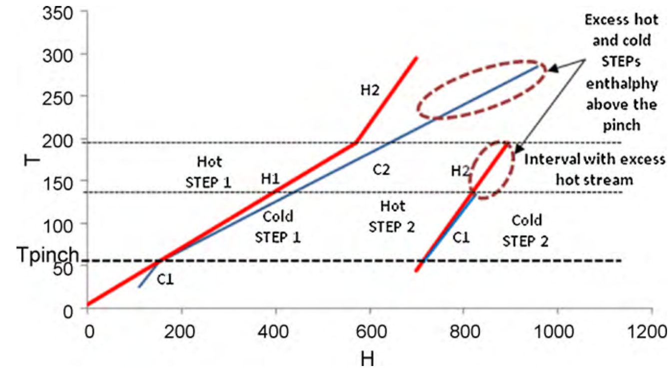

Fig. 7. Example 4 demonstrating the Type-3 multiple pinch problem.

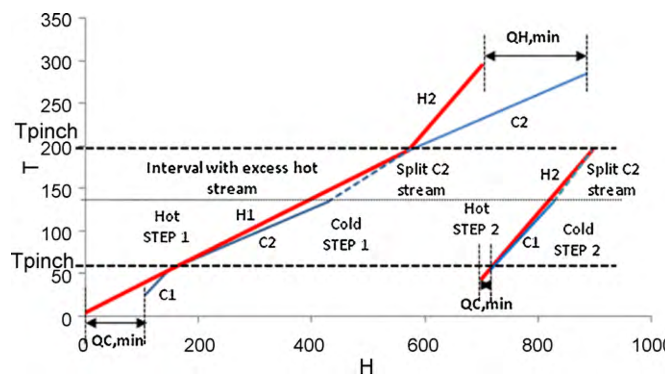

Fig. 8. Example 4 demonstrating multiple pinches after stream splitting.

3.2.2. *Type-3 multiple pinch problem*

The Type-3 multiple pinch problem involves cases where both excess hot and cold STEP enthalpies exist on one side of the pinch region. The stream data in Table 4 for Example 4 is used to illustrate the Type-3 multiple pinch problem. For this case, ΔT_{min} is set at 10 °C. Fig. 7 shows the STEPs for Example 4. Even though only one T_{pinch} apparently exist at 55 °C, the STEPs in this case demonstrate Type-3 multiple pinch problem where both excess hot and cold STEP enthalpies exist above the pinch. Referring to Fig. 7, the excess hot stream between 135 °C and 195 °C temperature interval should be fully utilized so that only excess cold STEP enthalpy exists above the pinch, in line with the basic pinch rules, and ultimately the minimum utility targets and the optimal heat allocation are achieved.

The minimum utility targets and the optimal heat allocation can be achieved through streams splitting and re-matching until only excess hot STEPs exist below the pinch, and excess cold STEPs above the pinch. For Example 4 in Fig. 7, the interval between 135 °C and 195 °C where the excess hot stream H2 exists, is clearly the best starting point to maximize heat allocation by performing stream splitting and re-matching. Note that there are 2 hot streams (H1 and H2) and only 1 cold stream (C2) in this interval. C2 which has the biggest FCp (FCp = 3.5) is split into a ratio of 2.37:1.13 in order

Table 4
Stream data for Example 4.

Stream	Supply temp., T_s (°C)	Target temp., T_t (°C)	Heat capacity flowrate, FCp (kW/°C)	Enthalpy, ΔH (kW)	Shifted supply temp., T'_s (°C)	Shifted target temp., T'_t (°C)
H1	200	10	3	−570	195	5
H2	300	50	1.3	−325	295	45
C1	20	130	1.4	154	25	135
C2	50	280	3.5	805	55	285

Table 5
Stream data for Example 5, ΔT_{min} = 10 °C [4].

Stream	Supply temp., T_s (°C)	Target temp., T_t (°C)	Heat capacity flowrate, FCp (kW/°C)	Enthalpy, ΔH (kW)	Shifted supply temp., T_s' (°C)	Shifted target temp., T_t' (°C)
H1	170	60	3	−330	165	55
H2	150	30	1.5	−180	145	25
C1	20	135	2	230	25	140
C2	80	140	4	240	85	145

to fully satisfy the enthalpy of both H1 and H2 within the interval in question. Matching C2 splits with H1 and H2 leaves only excess cold STEP enthalpy above the pinch, and ultimately yields $Q_{H,min}$ of 185 kW and $Q_{C,min}$ of 121 kW as shown in Fig. 8. This STEP allocation procedure not only allows the minimum utility targets to be achieved like those obtained using composite curves, but also enables the optimal heat allocation to be attained in a way that cannot be realized just by using the composite curves.

4. Network design for maximum energy recovery (MER) using the *heat* diagram

The STEP not only yields utility targets and pinch temperatures, but also shows how the individual hot and cold streams are mapped in terms of temperature as well as enthalpy to achieve these targets. The individual hot and cold streams allocation from the STEPs can now be graphically translated into an MER network design and represented on a HEat Allocation and Targeting (HEAT) diagram proposed in this work. The graphical allocation using STEP and HEAT diagram completely eliminates the need for enthalpy balance calculations and temperature feasibility checking that are essential for the MER network design using the conventional grid diagram. The procedure to construct a HEAT diagram is described below using Example 1 and the STEP in Fig. 9:

i. Below the STEP, draw all hot streams (running from right to left) above, and countercurrent to the cold streams.
ii. Draw vertical lines from the STEP to the HEAT diagram to represent the enthalpy segments for every pair of hot and cold stream allocation (including utility allocation).

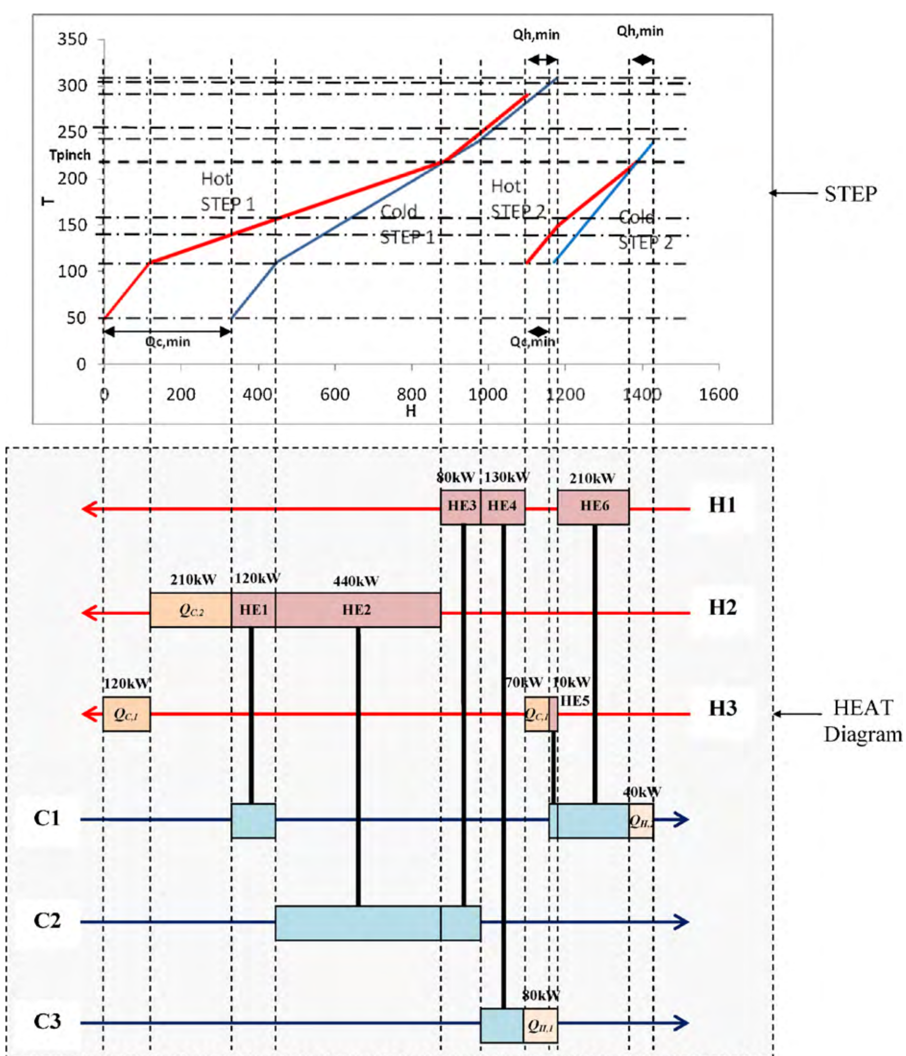

Fig. 9. Example 1 HEAT diagram.

iii. On a HEAT diagram such as the one shown below the STEP in Fig. 9, a heat exchange allocation between a hot and a cold stream is represented by a pair of rectangular boxes with a line linking the hot and the cold stream. The width of the box, which can be read directly from STEP enthalpy axis, indicates the amount of heat exchange between a hot and a cold stream. In addition, the shifted inlet and outlet heat exchanger temperatures on a HEAT diagram can be read directly from the temperature axis of the corresponding hot and cold stream pairs shown in STEP. For Example 1 in Fig. 9, the hot stream enters HE1 at 157.14 °C and leaves at 140 °C (shifted temperature). The cold stream enters HE1 at 50 °C and exits at 110 °C (shifted temperature). The heat exchange between these two streams is 120 kW (corresponding to the width of HE1 box).
iv. The MER network design on the HEAT diagram can be completed by drawing all remaining heat allocation boxes, using the vertical lines (enthalpy segments) as a guide as shown in Fig. 9.

The HEAT diagram can be converted to the conventional heat exchanger network (HEN) flow diagram as follows:

i. Convert the shifted temperatures back to normal temperature.
ii. Draw either the hot or cold streams first. In this case, the cold streams are drawn first horizontally.
iii. Next, draw the heat exchangers on the cold streams in increasing temperature order. For example, for stream C1, HE1 (from 40 °C to 100 °C) is drawn first followed by HE5 (from 40 °C to 100 °C), HE6 (temperature from 105 °C to 210 °C) and $Q_{H,2}$ (from 210 °C to 230 °C).
iv. Finally, connect all the hot streams to the heat exchangers in decreasing temperature order. For example, for stream H1, the stream is connected to HE4 (from 300 °C to 256.7 °C) followed by HE3 (from 256.7 °C to 230 °C) and HE6 (from 230 °C to 160 °C).

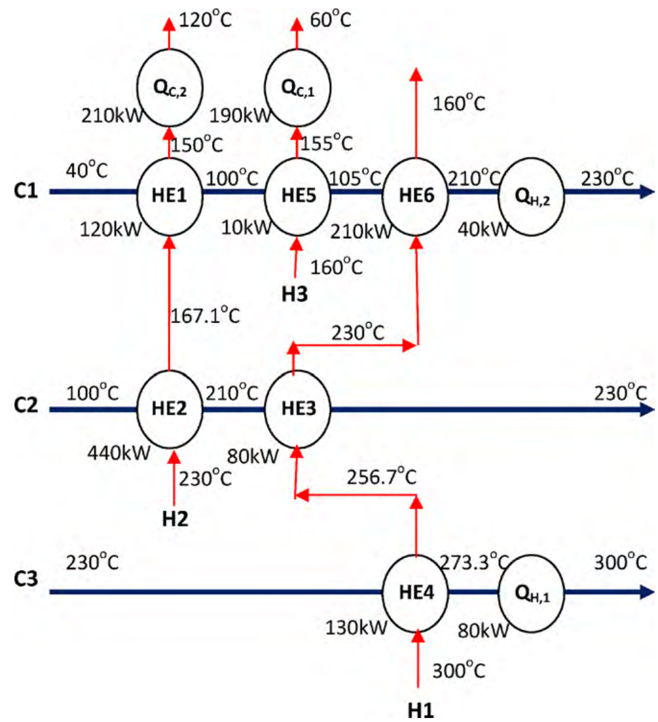

Fig. 10. Final network design for Example 1 based on HEAT diagram.

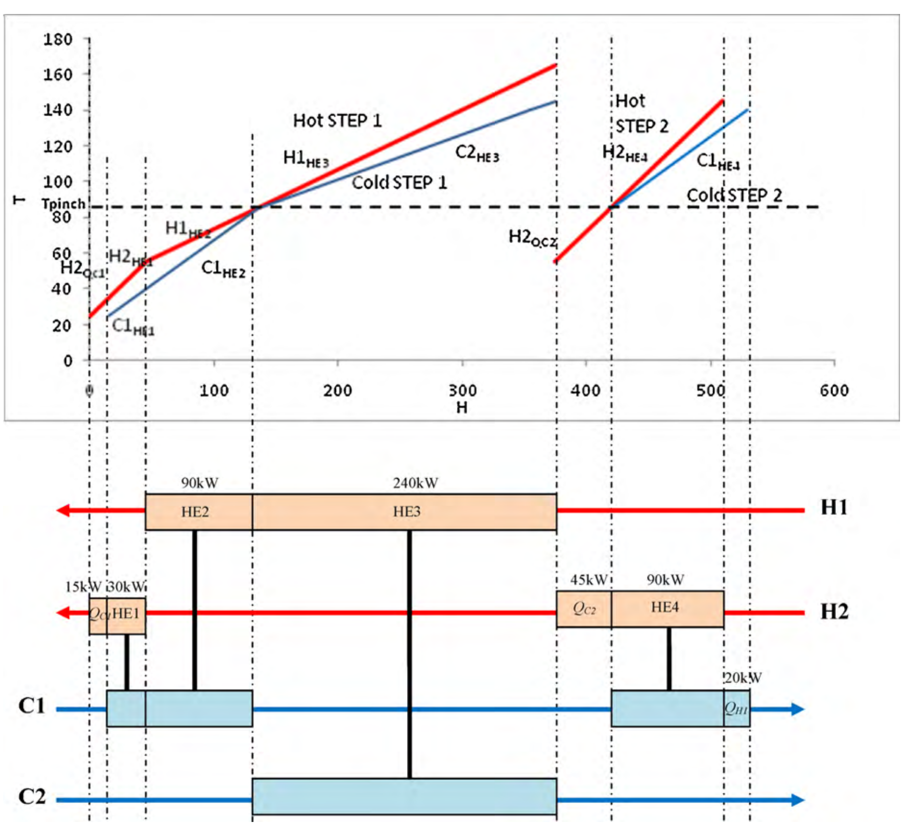

Fig. 11. Initial STEP and HEAT diagram for Example 5.

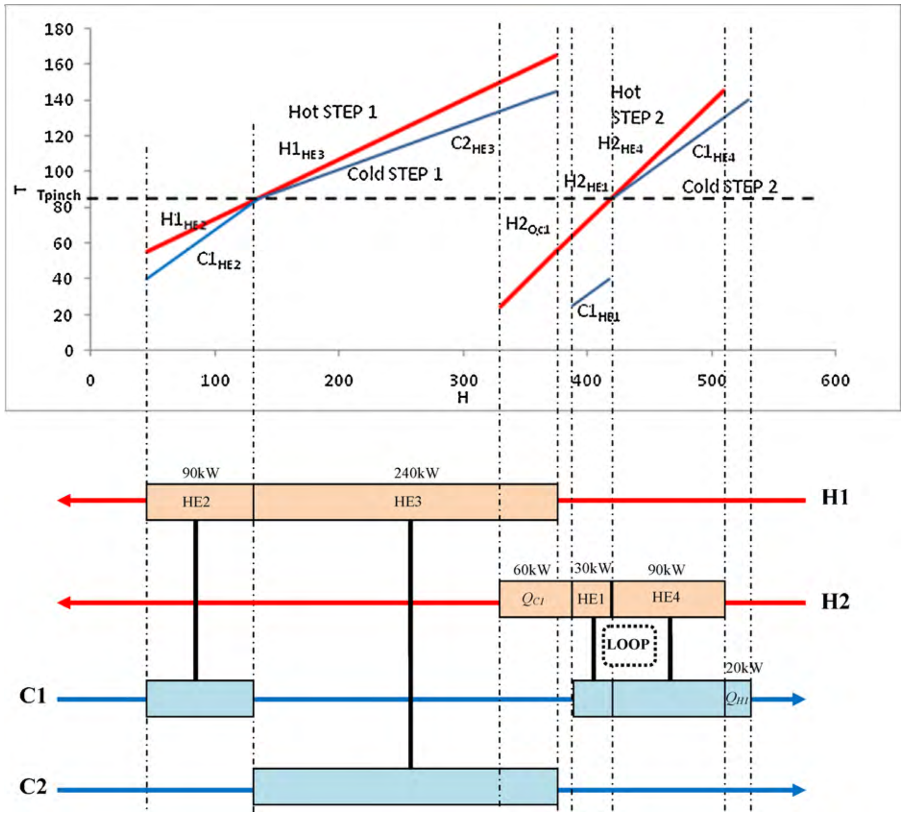

Fig. 12. STEP and HEAT diagram for Example 5 after simplification.

Fig. 10 shows the conventional maximum heat recovery (MHR) network flow diagram for Example 1.

5. Network evolution using the *heat* diagram

In pinch analysis, heat exchanger network evolution (HEN) is an established technique for simplifying an MER network aimed at reducing the number of heat exchanger units, and hence, the HEN capital cost, at the expense of some energy penalty. Network evolution is typically done in four steps:

1. Identify heat exchanger loops in the HEN. A loop is a cyclic path in a HEN that allows heat load shift among exchangers forming the cyclic path, while maintaining an overall stream's enthalpy balance.
2. Break the loops by eliminating one exchanger for each loop, and by shifting heat load through the exchangers located in the loop;
3. Search for any ΔT_{min} violation within the loop.
4. Perform energy relaxation to restore any violated ΔT_{min}, by shifting heat load through a heat exchanger "path" that is connected to a heater and cooler, and affects the temperature of the heat exchanger involved in ΔT_{min} violation in the loop.

Steps 2–4 involves formulating an algebraic solution to search for the right amount of heat load to enable loop breaking; the search for ΔT_{min} violation, and energy relaxation to restore ΔT_{min}.

STEP and HEAT diagram provides an alternative approach that is completely based on graphical visualisation, as described next. The stream data in Table 5 for Example 5 is used to illustate the steps to simultaneously perform loop breaking and energy relaxation using STEP and HEAT diagram. Fig. 11 represents the completed STEP and

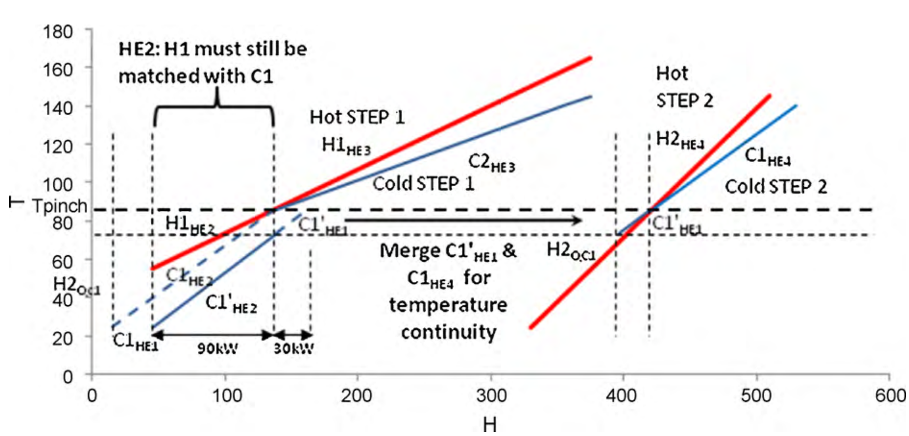

Fig. 13. STEP for Example 5 showing $C1'_{HE1}$ combined with $C1_{HE4}$, and $H1_{HE2}$ matched with $C1'_{HE2}$.

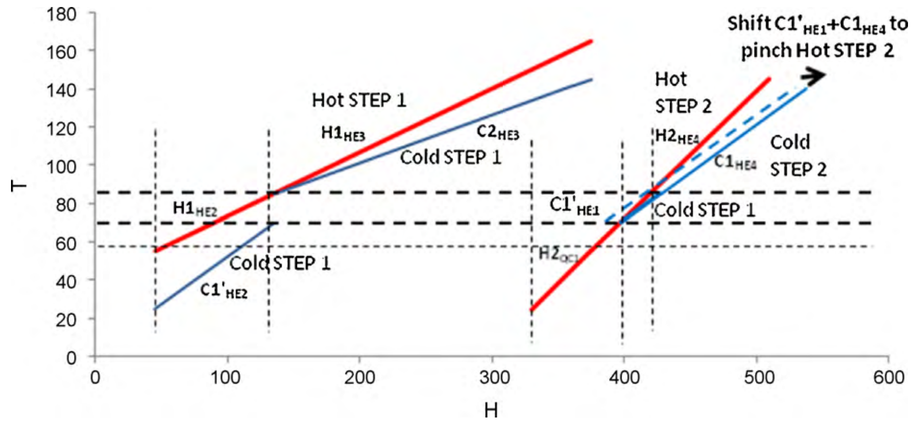

Fig. 14. STEP for Example 5 showing $C1'_{HE1}$ and $C2_{HE4}$ shifted to restore ΔT_{min}, and $H2'_{HE1}$ merged with $H2_{HE4}$ after temperature exchange with $H2'_{QC2}$.

HEAT diagram for Example 5. ΔT_{min} is assumed as 10 °C. The shifted T_{pinch} is at 85 °C, $Q_{H,min}$ = 20 kW and $Q_{C,min}$ = 60 kW.

Fig. 11 shows that the MHR and minimum utility design have been achieved for Example 5, just like in the case of conventional pinch design method (PDM). However, unlike in the conventional PDM, the MHR network design has been accomplished through graphical matching of hot and cold streams temperature (using STEP) as well as enthalpy (using STEP and HEAT diagram) separately for regions above and below the pinch points. A close observation of the HEAT diagram reveals a slight difference in the network design generated by STEP–HEAT diagram as compared to the network generated by conventional PDM. While the base case STEP approach yields two coolers (i.e., Q_{C1} = 15 kW and Q_{C2} = 45 kW), PDM yields only one cooler (Q_C = 60 kW). This difference arises

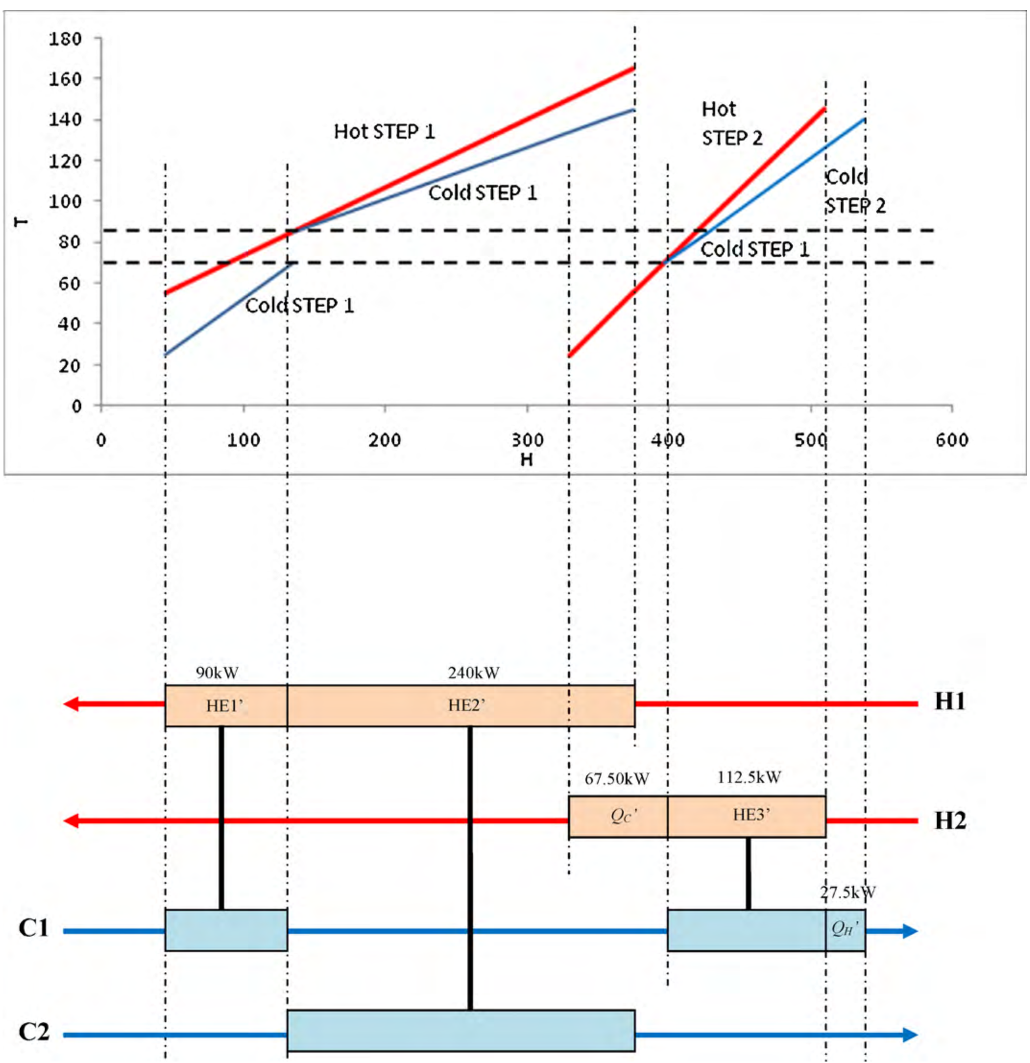

Fig. 15. The final HEAT diagram for Example 5 after loop breaking.

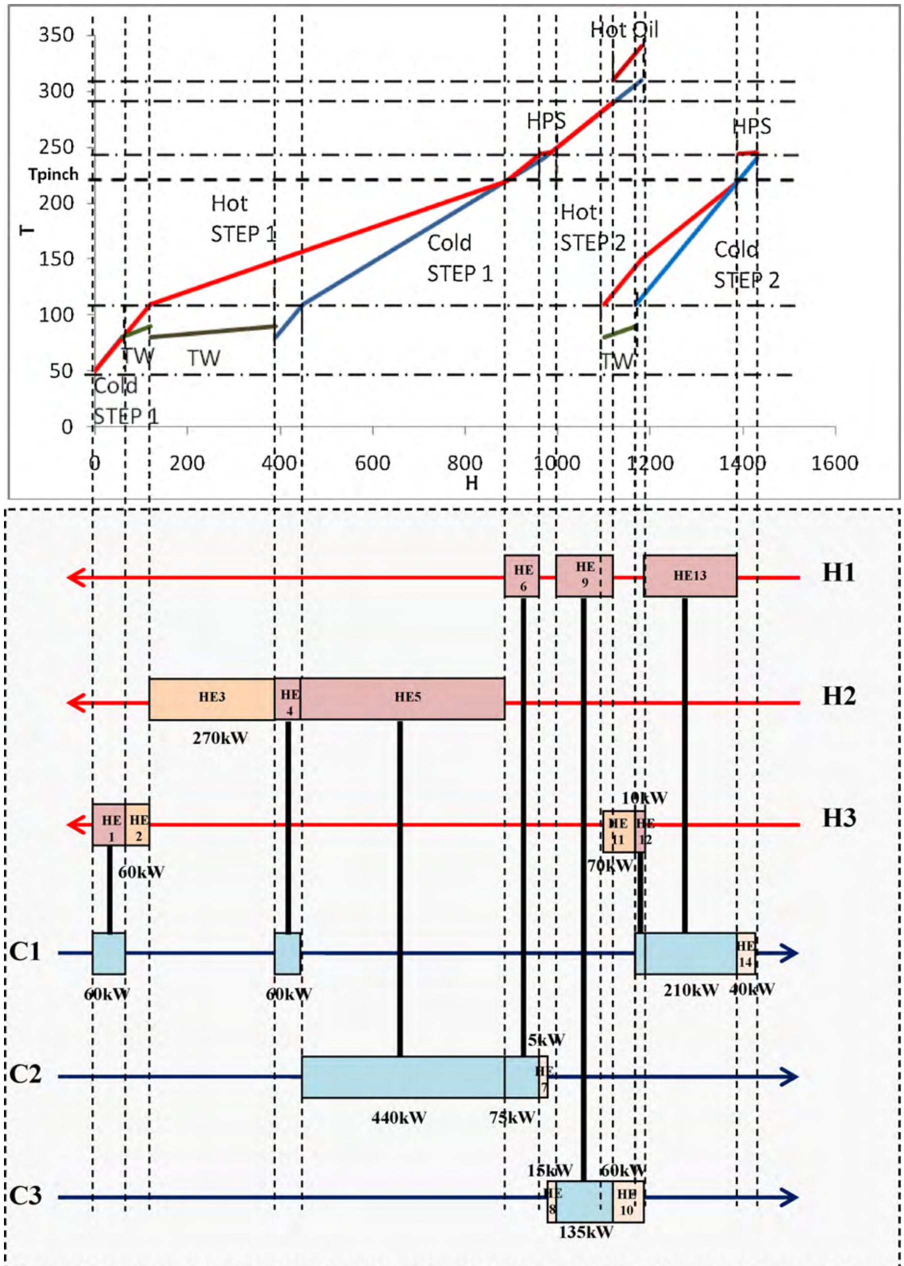

Fig. 16. STEP and HEAT diagram with multiple utilities.

since STEP procedure involves the matching between hot and cold streams with the closest approach temperature in order to maximize heat exchange efficiency. Fig. 11 shows that, even though Q_{C1} and Q_{C2} exist on the same stream, there is a temperature break between the two coolers. Note that this case provides an additional option for designers to consider supplying cold utilities from different sources that may exist at different temperature levels. For example, cooling water and recycled tempered water may be used as different sources of cold utilities from different parts of a plant.

Alternatively, a designer may choose to use one cooler instead of two in order to reduce the number of units, and hence, the capital investment. For this latter option, the two coolers can be merged by shifting HE1 next to HE4. Note that this is possible since $H2_{Q_{C1}}$, $H2_{HE1}$ and $H2_{Q_{C2}}$ lie on the same stream, and since there is no temperature violation from the heat exchanger shifting (see Fig. 12). $C1_{HE1}$ is now used to satisfy the newly shifted $H2_{HE1}$ enthalpy segment. Note that STEP provides designers with the advantage and flexibility to visually manipulate the

Table 6
Utilities data.

Utilities	T_s (°C)	T_t (°C)	T'_s (°C)	T'_t (°C)	Cost (USD/kW)
Hot oil	350	320	340	310	0.150
High pressure steam (HPS)	255	254	245	244	0.120
Tempered water (TW)	70	80	80	90	0.015
Cooling water (CW)	25	30	35	40	0.020

Table 7
Example 1 heat exchanger area based on Fig. 15 HEAT diagram.

	Q (kW)	T_{h1} (°C)	T_{h2} (°C)	T_{c1} (°C)	T_{c2} (°C)	ΔT_{LMk} (°C)	$h_{h,k}$ (kW/(°C m²))	$h_{c,k}$ (kW/(°C m²))	Area (m²)
HE1	60	90	60	40	70	20.00	1	1	2400
HE2	60	120	90	70	80	28.84	1.1	1.4	2810
HE3	270	159	120	70	80	63.21	1.3	1.4	25319
HE4	60	167	159	70	100	77.36	1.1	1.2	8088
HE5	440	230	167	100	210	38.82	1.1	1.2	29763
HE6	75	255	230	210	228.75	22.98	1.1	1.2	3004
HE7	5	255	254	228.75	230	25.12	4.4	1.2	133
HE8	15	255	254	230	235	21.94	4.4	1.2	349
HE9	135	300	255	235	280	20.00	1.3	1.2	4327
HE10	60	350	320	280	300	44.81	4.4	1.2	2852
HE11	70	155	120	70	80	61.66	1.3	1.4	6403
HE12	10	160	155	100	105	55.00	1.2	1.2	917
HE13	210	230	160	105	210	34.55	1.1	1.2	12643
HE14	40	255	254	210	230	33.61	1	1.2	2464
Total									86,363

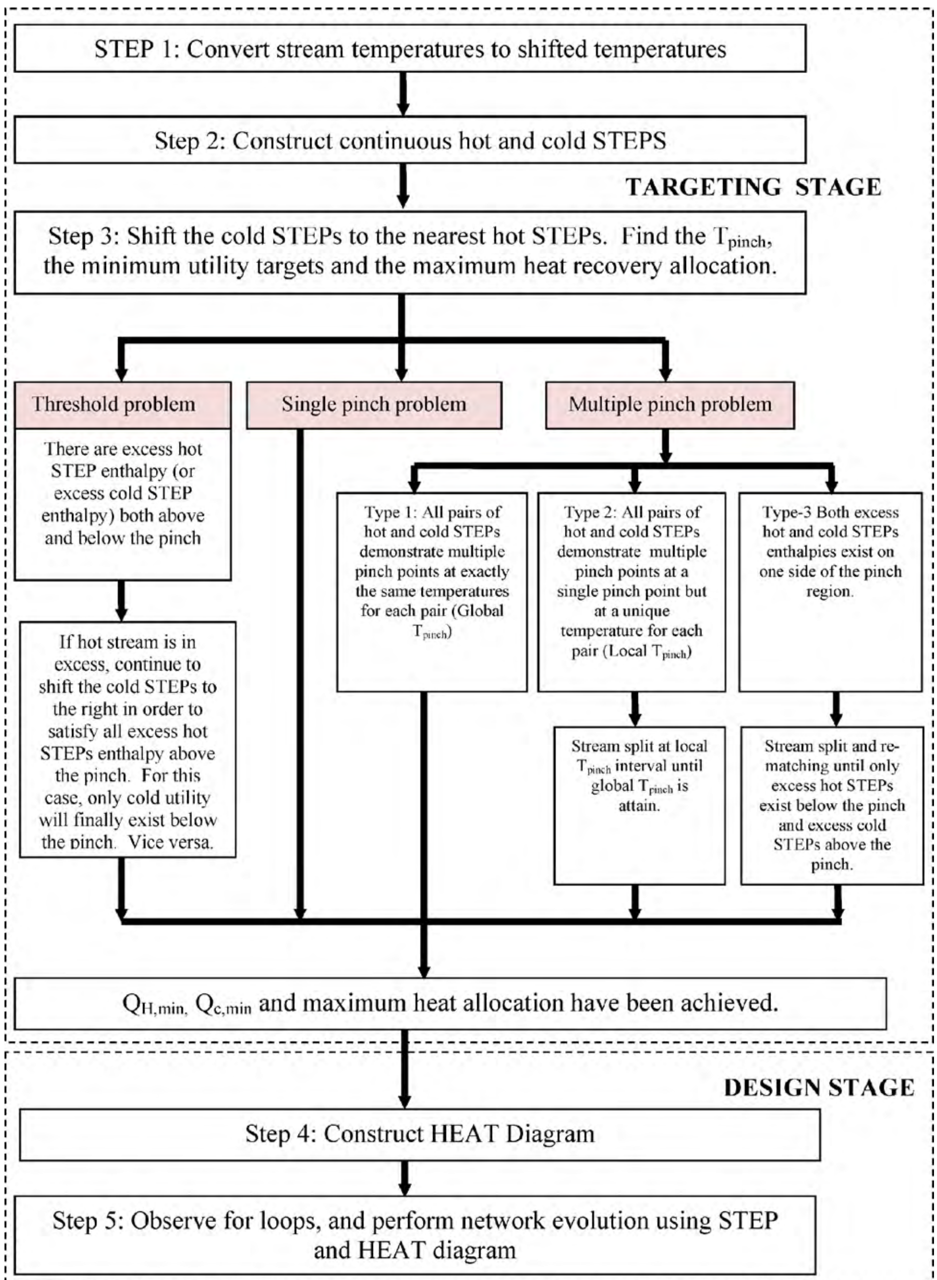

Fig. 17. Summary of methodology for simultaneous targeting and design using STEP.

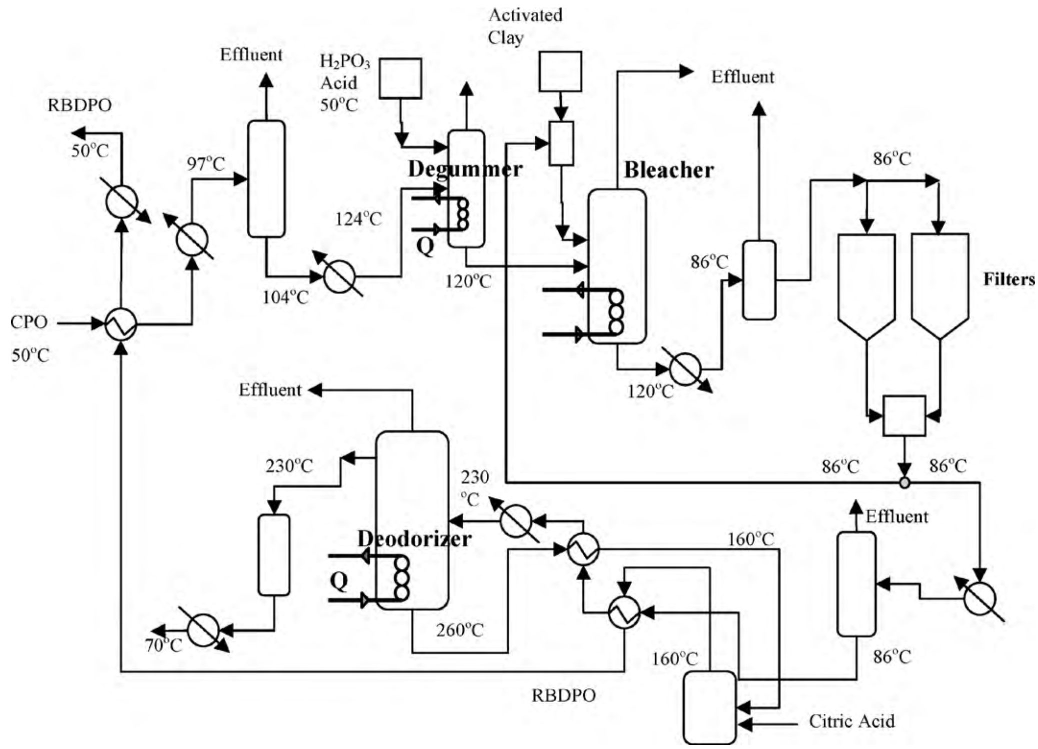

Fig. 18. Process flow diagram for a palm oil refinery [19].

stream matches and graphically assess the implications of these changes.

Fig. 12 shows that there is one loop linking exchangers HE1 and HE4. In principle, the loop can be broken by merging HE1 and HE4 into a single heat exchanger. However, this cannot be readily done due to C1 temperature break (discontinuity) between HE1 and HE4. Note that $C1_{HE1}$ temperature runs from 25 °C to 40 °C while $C1_{HE4}$ temperature runs from 85 °C to 140 °C. C1 segment from 40 °C to 85 °C is used to satisfy $H1_{HE2}$. Loop breaking should therefore include steps to swop heat exchanger locations on the cold as well as the hot sides of the loop as described next.

To have temperature continuity and enable loop breaking, it is possible to susbtitute the equivalent of $C1_{HE1}$ heat load with part of $C1_{HE2}$ heat load (labeled as $C1'_{HE1}$) as shown in Fig. 13. $C1'_{HE1}$ is then shifted to the right to be continuously linked to $C1_{HE4}$. To compensate for the shifted heat load of $C1'_{HE1}$, the combination of $C1_{HE1}$ and the remainder $C1_{HE2}$ (labelled as $C1'_{HE1}$) must also be shifted to the right until the heat load of $H1_{HE2}$ is fully satisfied. Note, however, that the combination of $C1'_{HE1}$ and $C1_{HE4}$ streams crosses the hot STEP 2 and causes a ΔT_{min} violation. To have a feasible match, the combined $C1'_{HE1}$ and $C1_{HE4}$ streams are shifted to the right until it pinches hot STEP 2 as shown in Fig. 14. This however leads to an increment of 7.5 kW for both Q_H and Q_C.

Fig. 15 shows the final HEAT diagram after loop breaking. Note that the total number of heat exchangers has been reduced from 7 units (see Fig. 10) to 5 units. The entire procedure involving loop breaking, search for temperature cross and ΔT_{min} violation, and finally, energy relaxation to restore ΔT_{min} was accomplished using STEP–HEAT diagram graphical visualisation tool. The final results of the alternative STEP–HEAT graphical approach match those obtained using the conventional pinch approach that uses the grid diagram to break heat exchanger loops, to locate ΔT_{min} violation, and to determine the optimal heat load to be shifted during energy relaxation.

6. Multiple utility targeting

Multiple utility targeting, or searching for the optimum combination of utilities from a selection of available hot utilities like steam, flue gas, hot oil as well as cold utilities like cooling water, chilled water and refrigerant is traditionally performed using the grand composite curves (GCC) which is a plot of the problem table heat flow profile at different temperature intervals [12]. The balanced composite curves (BCC), which are composite curves that include various types of utilities, can also be used as an alternative for multiple utility targeting [12,21]. Even though the BCC can

Table 8
Stream data for palm oil refinery case study, ΔT_{min} = 10 °C [19].

Stream	Supply temp., T_s (°C)	Target temp., T_t (°C)	Heat capacity flowrate, FCp (kW/°C)	Enthalpy, ΔH (kW)	Shifted supply temp., T'_s (°C)	Shifted target temp., T'_t (°C)
H1	120	86	10.99	−373.66	115	81
H2	260	160	6.04	−604	255	155
H3	230	70	13.13	−2100.8	235	75
H4	160	50	6.56	−721.6	165	55
C1	50	97	11.83	556.01	55	102
C2	104	124	14.89	297.8	99	119
C3	86	230	5.69	819.36	81	225

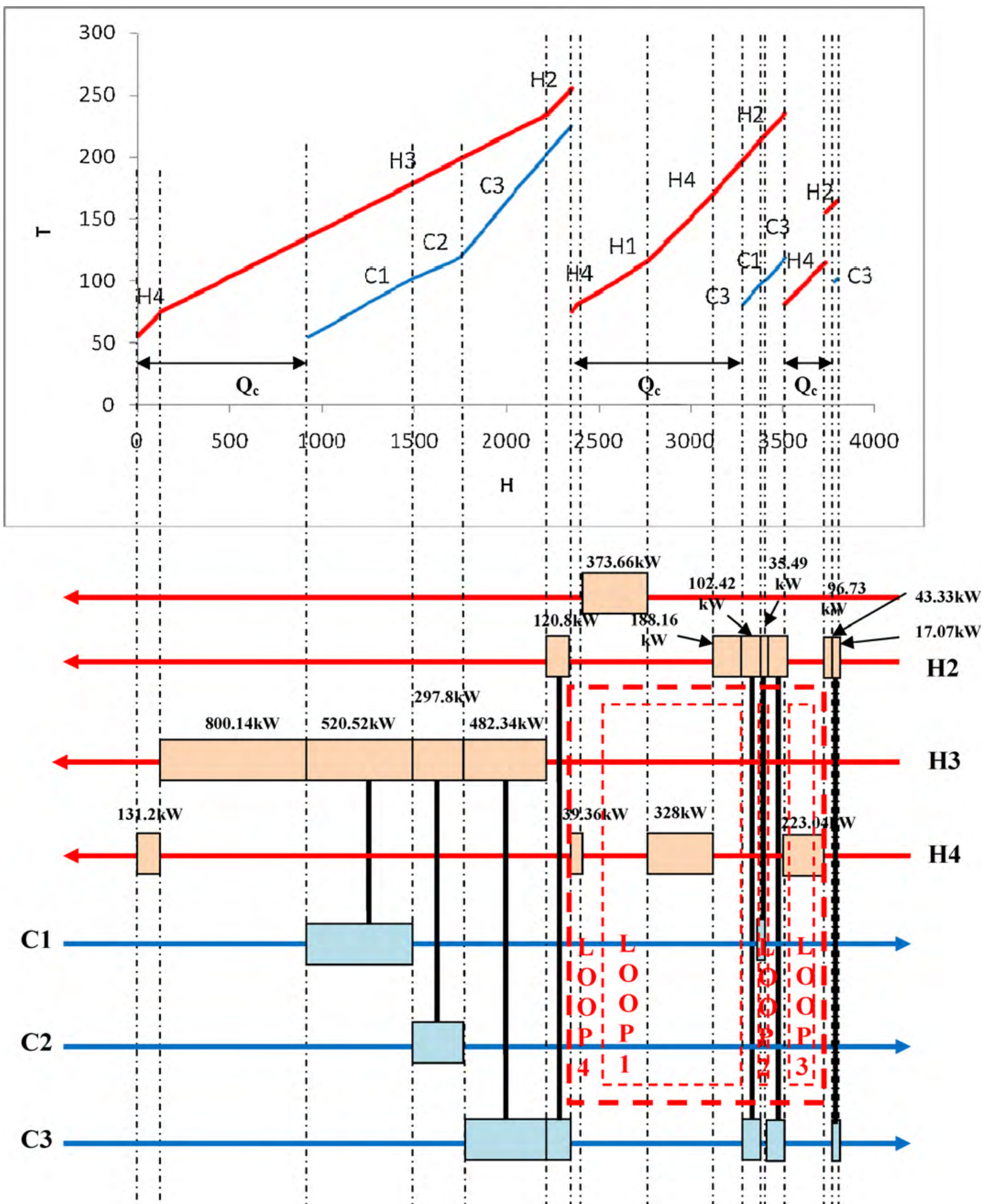

Fig. 19. STEP and HEAT diagram for palm oil refinery case study (before loop breaking).

additionally show the driving forces between the various process sources and sinks, they are however less popular than the GCC for utility targeting since, like the composite curves, the BCC are more tedious to draw as compared to the GCC. Both the GCC and the BCC however cannot clearly map the integration between individual process streams and utility streams as these curves typically comprise of composites as opposed to individual streams. Currently, designers have to resort to the grid diagram to show the process and utility streams integration.

Using Example 1 and the utility data in Table 6, we now demonstrate how STEP overcomes the limitations of the BCC and GCC during multiple utility targeting. Recall that Fig. 9 shows the STEP and HEAT diagram for a single level of hot as well as cold utilities. For this problem, the available hot utilities include high pressure steam (HPS) at 245 °C at and hot oil with a supply temperature (T_s) of 350 °C. The cold utilities include tempered water (TW) between 80 °C and 90 °C and cooling water between 30 °C and 40 °C. To be economical, the general rule is to maximize the use of lower temperature hot utilities as well as higher temperature cold utilities.

Referring to Fig. 16, above the pinch, HPS at 245 °C which is the cheapest hot utility is maximized first by heating cold STEP 2. Note also from Fig. 16 that shifting the hot STEP 1 above 245 °C to the right until it pinches the cold stream allows the unmatched part of cold STEP 1 below 245 °C to be also matched with HPS. Altogether, the total amount of HPS needed is 60 kW. Next, the remaining 60 kW hot utility requirement for this process is satisfied with hot oil which is the only utility available above 300 °C.

Below the pinch, tempered water (TW) between 80 °C and 90 °C is the cheapest cold utility available, and is maximized first. Any cold process stream below 80 °C is shifted to the left until it pinches the hot stream. The unmatched hot stream at temperature above 80 °C is satisfied using TW. A total of 400 kW of TW, and no cooling water is needed to satisfy the excess hot streams for this process. Fig. 16 shows the final STEP and HEAT diagram with multiple

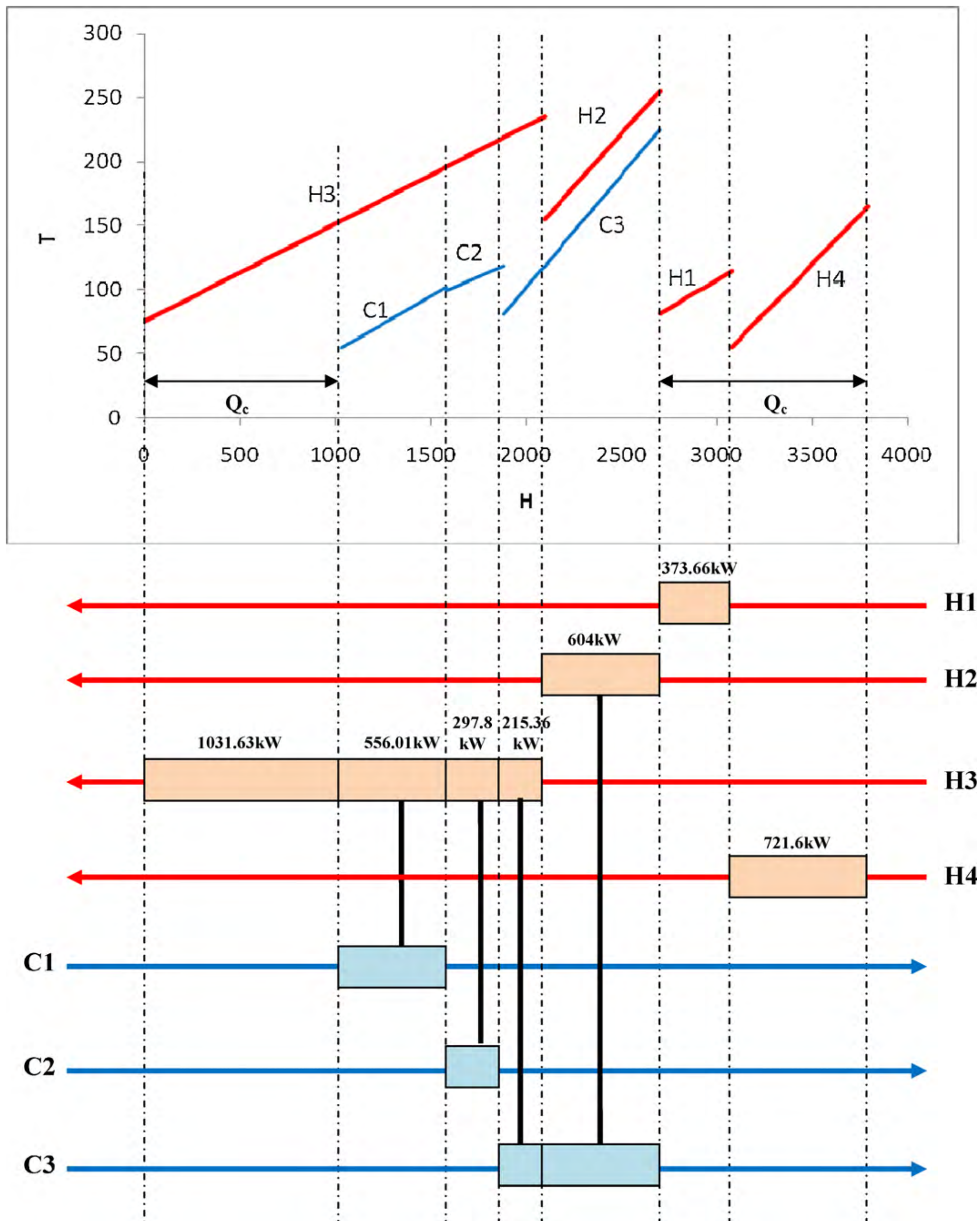

Fig. 20. STEP and HEAT diagram for palm oil refinery case study (after loop breaking).

utilities that match the results obtained by the GCC. Note that, in addition, STEP can simultaneously map all the hot and cold utilities with the individual process streams on the *T* versus *H* plot. This process-utility streams mapping is graphically translated into the HEN on the HEAT diagram representation without any calculations.

7. Minimum network area targeting

One of the most established methods to design a HEN to achieve the minimum total area target is by using the technique proposed by Linnhoff and Ahmad [8]. The overall technique involves four steps. The first step is to compute the minimum network area target (A_{min}) by summing up the heat transfer areas for all enthalpy intervals of composite curves. The area of an enthalpy interval is the sum of areas for "vertical heat exchange" among hypothetical hot and cold split stream branches within the enthalpy interval, calculated using the ΔT_{LMk} of *composite* hot and cold streams. Next, the actual network area (A_{actual}) is obtained by adding the individual heat exchanger areas once a heat exchanger network is designed on a grid diagram. The actual network area is then compared with the minimum network area target. Finally, designers are recommended to consult the driving force plot (i.e., the plot of temperature difference (ΔT) between the hot and cold composite curves versus the cold composite temperature (T_c); i.e., the $\Delta T - T_c$ plot) if the A_{actual} is greater than $1.2A_{min}$. Adjustments to HEN design are then made as required [8].

Practically, the minimum total area of a HEN should be derived from the sum of areas due to heat exchange between real individual hot and cold streams, and not between imaginary split streams from *composite* hot and cold curves. Algorithms to obtain minimum network area based on composite curves and driving force

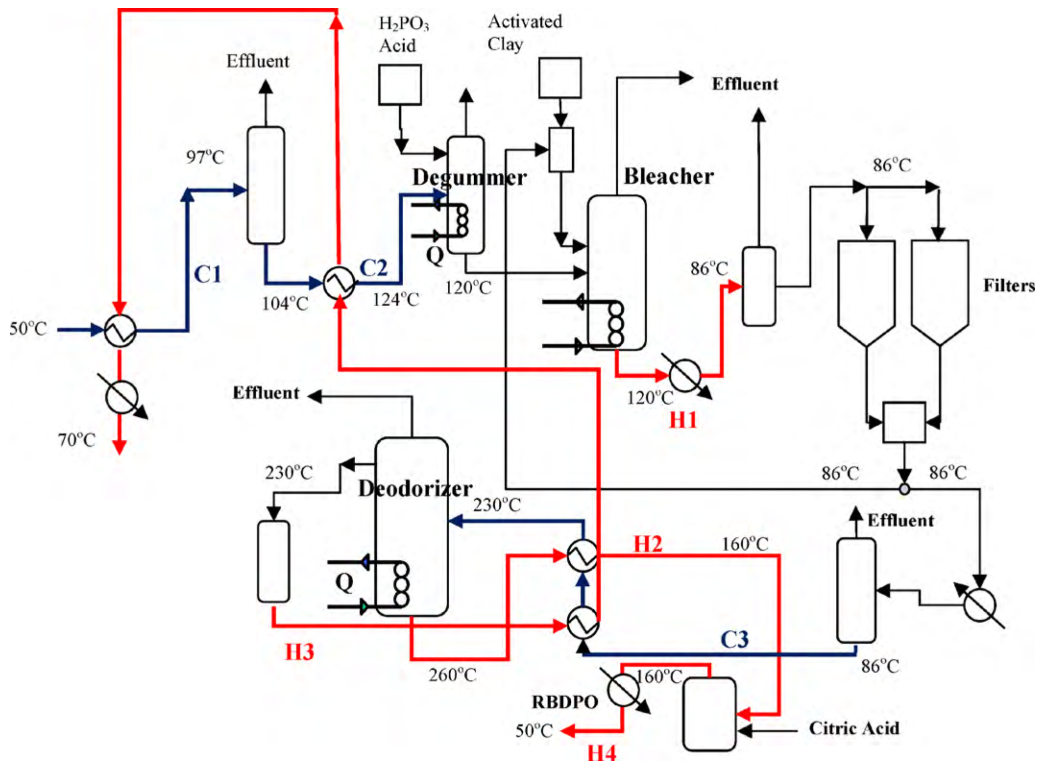

Fig. 21. Process flow diagram for a palm oil refinery after pinch analysis.

plot, including the popular one proposed by Linnhoff and Ahmad [8] may be limited by the fact that the areas for some of the hypothetical "heat transfer units" in certain enthalpy intervals maybe calculated from, and benchmarked against, properties of composited streams as opposed to individual streams (e.g., ΔT_{LMk} and $\Delta T - T_c$). This approach may lead to significant deviations from the actual network area.

The preceding limitations do not arise when STEP procedure is used since it is based on heat exchange between individual streams. STEP allows the total minimum network area to be calculated in just a single step, i.e. by summing up the individual areas for all heat exchangers that exist within the STEP diagram enthalpy intervals. Note that, since the STEP diagram also represents the maximum heat allocation/recovery network, the need to recalculate the "actual area" and to compare the actual with the "targeted area" do not arise.

Referring to the STEP and HEAT diagram in Fig. 16 as an example, the area of an individual heat exchanger (e.g., HE5) is calculated using the established heat exchanger design equation (Eq. (3)). The heat exchanger duty is obtained from the enthalpy axis ($Q = 440$ kW for HE5). The log-mean temperature difference ($\Delta T_{\mathrm{LMk}} = 38.82\,^\circ$C for HE5) is calculated using Eq. (4) after converting the shifted supply and target temperatures of the hot and cold streams obtained from the STEP temperature axis to the actual temperatures. Note that Eq. (4) [22] is used to calculate ΔT_{LMk} instead of the more popular Eq. (5) [11] to avoid the difficulties when the temperature difference on both sides of the heat exchanger are equal. The individual heat exchanger areas for the network in Fig. 16 are given in Table 7. The sum of the individual areas in Table 7 gives the total minimum network area.

$$A_k = \frac{Q_k}{\Delta T_{\mathrm{LMk}}}\left(\frac{1}{h_{\mathrm{h},k}} + \frac{1}{h_{\mathrm{c},k}}\right) \tag{3}$$

$$\Delta T_{\mathrm{LMk}} \cong \left((T_{\mathrm{h1}} - T_{\mathrm{c2}})(T_{\mathrm{h2}} - T_{\mathrm{c1}})\left(\frac{(T_{\mathrm{h1}} - T_{\mathrm{c2}}) + (T_{\mathrm{h2}} - T_{\mathrm{c1}})}{2}\right)\right)^{1/3} \tag{4}$$

$$\Delta T_{\mathrm{LMk}} = \frac{\Delta T_{\mathrm{h}} - \Delta T_{\mathrm{c}}}{\ln \frac{\Delta T_{\mathrm{h}}}{\Delta T_{\mathrm{c}}}} = \frac{(T_{\mathrm{h1}} - T_{\mathrm{c2}}) - (T_{\mathrm{h2}} - T_{\mathrm{c1}})}{\ln\left(\frac{T_{\mathrm{h1}} - T_{\mathrm{c2}}}{T_{\mathrm{h2}} - T_{\mathrm{c1}}}\right)} \tag{5}$$

8. Methodology summary and limitations of step

Fig. 17 is a summary of the overall procedure for utility targeting and heat recovery network design using STEP and HEAT diagram.

Even though STEP is a useful visualization tool that can provide important insights for simultaneous targeting and design of HEN, it may not be effective to manually use STEP to handle complex problems involving more than 10 streams. Beyond 10 streams, typically, there will be a large number of hot and cold STEP pairs to be translated into a heat recovery network that must be drawn according to the STEP's and HEAT diagram's temperature as well as enthalpy scale. For a large number of streams, these diagrams can be tedious to draw manually.

Note however that industrial problems having less than 10 streams can be quite common after all. This is because process integration problems are practically solved and managed by decomposing a plant into sub-areas or sub-units, and seldom done by integrating processes and streams throughout an entire plant site. The latter approach can result in a very rigid process system that can be prone to operability problems. Hence, STEP can still be a useful tool for a wide range of industrial problems.

Finally, one must bear in mind that the limitation in STEP construction also applies to other graphical techniques like the composite curves for energy targeting and to the source and demand curves for water targeting. This limitation can be overcome by building computer programs and spreadsheets to handle the graphical procedure either automatically or semi-automatically (with some user insights). The procedure in this work can be used as a guide for the algorithm development.

9. Case study: application of step technique for MER network design of a palm oil refinery

The present technology for palm oil refining applied commercially involves energy and capital-intensive operations. Crude palm oil (CPO) is currently refined via physical or chemical refining. Physical refining, which is the more popular and cheaper technique, consists of three major processes (see Fig. 18). The first is the degumming step to remove undesired gum, that is, phosphatides; the second is the decolorization or bleaching step to extract color pigment in crude palm oil; and the final step is the deodorization process to get rid of unpleasant odor and taste due to the presence of aldehyde and ketone. Deodorization removes free fatty acids (FFA) by vacuum steam-distillation at 270 °C to produce refined, bleached, deodorized palm oil (RBDPO) at the deodorizer bottoms' stream as the final product with less than 0.1% FFA content. During the removal of FFA, valuable nutrients such as tocopherol and carotenes present in palm oil are also destroyed.

Table 8 [20] shows the extracted stream data (assuming ΔT_{min} = 10 °C) having potential for process integration for the palm oil refinery in Fig. 18 [20]. Following the methodology shown in Fig. 17, for the first step is to convert the stream temperatures into shifted temperatures as shown in columns 6 and 7 of Table 8. Steps 2 and 3 involve constructing the STEP (Fig. 19). This case is a threshold problem since there is only hot stream below the pinch region even though ΔT_{min} has not been achieved. The minimum hot and cold utility targets are 0 kW and 2126.89 kW, respectively, which matches the targets obtained from traditional composite curves.

Step 4 is to construct the HEAT diagram below STEP as shown also in Fig. 19. Note from Fig. 19, a few loops are observed. Step 5 involves network evolution through loops breaking and load shifting to simplify the network and achieve the minimum number of units. Fig. 20 shows the STEP and HEAT diagram for the palm oil refinery that achieves the minimum number of units of six after loops breaking and network evolution. The final maximum heat recovery network design for the palm oil refinery is shown on a conventional process flow diagram in Fig. 21.

10. Conclusion

A new versatile graphical tool for simultaneous utility targeting and design of a maximum energy recovery (MER) network known as the *Stream Temperature versus Enthalpy Plot* (STEP) has been introduced to overcome the key limitations of composite curves for utility targeting and the grid diagram for heat exchanger network (HEN) design. The STEPs are profiles of continuous individual hot and cold streams being mapped on a shifted temperature versus enthalpy diagram that simultaneously show not only the pinch points and energy targets, but also the maximum heat allocation (MHA). The MHA is graphically converted to a maximum energy recovery (MER) network and represented in terms of STEP's temperature and enthalpy, on a Heat Allocation and Targeting (HEAT) diagram. This paper has also demonstrated how STEP can be conveniently used even for systems involving threshold problems and multiple pinches, and how STEP can provide more realistic solutions for targeting multiple utilities and the minimum network area based on individual as opposed to composite hot and cold streams matching. With the capabilities to overcome the limitations of composite curves and grid diagram, STEP can become an alternative visualization tool for the targeting and design of an MER network. It reduces the routine HEN design tasks such as streams enthalpy balances, and temperature feasibility checking associated with the composite curves and the grid diagram. Apart from its advantages, the limitations of STEP have also been highlighted. Work is underway to extend STEP into an ultimate process integration graphical multi-tasking tool not only for heat, but also for mass recovery network. Currently, the key features under development at Process Systems Engineering Centre (PROSPECT), Universiti Teknologi Malaysia include the Segregated Problem Table Algorithm (SePTA), process–utility interface, process modifications, combined heat and power, trigeneration, total site profiles as well as mass-exchange network targeting and design techniques.

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