# Application of Supply and Target Based Superstructures for the Optimal Placement of Multiple Utilities in Heat Exchanger Networks

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***Abstract*****—**Process synthesis techniques have been applied to reduce energy consumption on processing plants (thereby reducing their environmental impact), as well as the mass load of contaminants released into the environment. In this paper we explore the use of a particular set of mathematical programming techniques for the reduction of the energy requirement in a heat exchange network (HEN) by optimizing the use of utilities at different levels. The Supply Based Superstructure (SBS), the Supply and Target Based Superstructure (S&TBS) and the Target and Supply Based Superstructure (T&SBS) are applied to the optimal placement of multiple utilities for the minimization of total annual cost (TAC) in HENs. The superstructures presented in this study place multiple utilities along the superstructures. The results compare well with those of other researchers in terms of TACs and the solutions utilize minimum number of utilities which is friendlier to the environment.

***Keywords*****—** Heat exchanger networks; multiple utilities; total annual cost.

## I. Introduction

HEAT exchanger network synthesis (HENS) has been broadly studied with the pinch technology and mathematical programming techniques (Linnhoff and Flower [7] ; Yee and Grossmann [11]; Isafiade and Fraser [4]; Azeez, *et al*., [1], [2]). The pinch technology approach initially considered the use of single utility in HEN after the optimal heat exchange between the process streams as observed in the pinch based optimization process (Linnhoff and Flower [7] ; Umeda, *et al*., [10]). This pinch approach was achieved by the use of composite curve where the composite of the hot process streams is plotted against the cold process streams on the same temperature versus enthalpy axes (Linnhoff *et al*., [8]). The region of maximum heat recovery between the two composite curves was identified as the area of vertical overlap between the two composite curves. This process leads to the targeting for the hot utility and the cold utility to satisfy the energy need of cold streams and hot streams that fall in the area of overshoot. This constitutes part of the optimization process in pinch technique. However, the pinch based optimization process is more tedious to apply when the process involves the use of multiple utilities in HENS.

The problems associated with the use of multiple utilities in HENS have therefore compelled researchers to evolve different techniques for the efficient use of such utilities when the need for their use arises. Linnhoff *et al*. [8] developed the grand composite curve (GCC), where interval temperatures (adjusted by $\frac{1}{2}\Delta T_{min}$) is plotted against the cumulative heat on temperature-enthalpy axes. This GCC presents the multiple utilities at different optimum temperature levels in their utilization process. This GCC is the basis for subsequent research carried out by other workers in this regard (Jezowski & Friedler[5]; Sachdeva [9]). In all these pinch based studies involving multiple utilities, the utilities were sequentially considered and the TAC was not considered.

Shenoy, *et al*.,.[12] also presented a pinch based optimization technique called the cheapest utility principle (CUP) for the optimization of HENs involving multiple utilities. This technique involved TAC targeting. The authors kept the temperature driving forces constant at the utility pinches and varied the minimum approach temperature $\Delta T_{min}$ at the process pinch in the utility optimization process represented on the optimum load distribution (OLD) diagram. This was followed by energy-capital trade off using the supertargeting technique to determine the minimum TAC.

The gap observed with the CUP of Shenoy, *et al*., [12] is that the technique of utility optimization was done sequentially. This is because only the most expensive utility was used to determine the total utility needed for the process before successive replacement of this most expensive utility with cheaper utilities. Another problem with this technique is that the energy-capital trade-off was done on the balanced composite curve, where true TAC is only possible if the heat transfer coefficients of all the streams are equal. However, problems involving multiple utilities often have different heat transfer coefficients. Also, the technique of Shenoy, *et al*. [12], becomes difficult when a large number of utilities are involved since the method of successive replacements of the utilities becomes cumbersome as the numbers of utilities increases. For these reasons, the CUP of Shenoy, *et al*.,[12] cannot always produce the global optimum solution for HENS involving multiple utilities.

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This shortcoming observed in pinch technique has prompted other workers (Isafiade and Fraser, [4], and Jose, *et al*., [6] to optimize HEN involving multiple utilities with the mathematical programming approach. Isafiade and Fraser [4] used the interval based mixed integer non linear programming (IBMS) where the superstructure intervals was defined using the supply and target temperatures of either the hot streams or the cold streams to define the superstructure intervals.

Also, Jose, *et al*., [6] used the concept of SWS to develop MINLP model where heat exchange between process streams and utilities is possible in the stages of the superstructure in contrast to the SWS of Yee and Grossman where the utilities can only exchange heat at the ends of the superstructure. The approach is to determine the optimal location of hot and cold utilities at any stage of the superstructure using the disjunctive programming. The SWS of Jose, *et al*.,[6] is however similar to that of Yee and Grossmann [11] in terms of isothermal mixing assumption at the stage borders to be able to do away with the nonlinear heat balances.

Recently, Azeez, *et al*., [1], [2] and [3] presented various superstructures where the superstructure intervals are defined using one or the combinations of all the key variables in HENS to be able to obtain more number of stages in the superstructures. This was done to achieve more combinations of stream matches than in the SWS and obtain features that are much more similar to the spaghetti design structures of the pinch approach. The first superstructure known as supply based superstructure (SBS) was developed using the supply temperatures of all the streams and utilities in HENS to define the superstructure intervals. The second superstructure called the supply and target based superstructure (S&TBS) was developed using the supply temperatures of hot streams including hot utilities and target temperatures of cold streams including cold utilities to define the intervals of superstructure. The third superstructure developed used the target temperatures of hot streams including hot utilities and supply temperatures of cold streams and utilities in the definition of the intervals This superstructure was called the T&SBS.

These superstructures have now been applied to problems involving multiple utilities presented by Shenoy, *et al*.,[12]. Those problems have been previously solved by other workers (Isafiade and Fraser [4]; Jose, *et al*.,[6]. In this paper, it is shown that the SBS, S&TBS and T&SBS can be of great benefit when determining the placement of multiple utilities for optimum TAC. It can also reduce the environmental impact through the reduction of the use of these utilities. This is because the release of hot water, oil or any other fluid used as utility will carry along the treatment chemicals into the environment. The temperature of such fluid will also normally be higher than the temperature of the ambient. Two examples will be presented to demonstrate the application of these superstructures.

<u>Example 1</u>

This problem was solved by Shenoy, *et al*.,[12] to demonstrate the notion of the cheapest utility principle (CUP). It involves a system of two hot streams and one cold stream. The system uses three hot utilities (steam) at low pressure, medium pressure and high pressure (LP, MP and HP) as well as cooling water (CW). The authors solved this problem using the CUP. In the solution, they started with the hottest hot utility (HP) and gradually replaced it with less expensive MP and LP in order to minimize the TAC. The stream and cost data for the problem are presented in Table 1 while their CUP optimisation results are shown in the appendix. This problem was solved by Isafiade and Fraser [4] using the IBMS technique. Also, Jose, *et al*.,[6] has solved it using a stagewise superstructure (SWS) MINLP based approach employing a disjunctive formulation. The IBMS solution and that of SWS based approach of Jose *et al*. are also presented in the appendix. The SBS, S&TBS and T&SBS techniques have been applied to this problem and the results are also shown in the appendix. The optimal networks of SBS, S&TBS and T&SBS are about 4.95% higher than that of Jose et al. that gives the lowest TAC for this example. The CUP and IBMS optimal network structures are also higher than that of the lowest TAC by about 1.2% and 0.14% respectively as shown in Table 2. The CUP technique of [12] uses the combinations of the three hot utilities together with the one cold utility to obtain the minimum TAC network. If there is the possibility that the load of 1 kW in the solutions of interval based techniques can be removed, then, the combinations of two hot utilities jointly with the one cold utility produced the minimum TAC in IBMS, SWS, SBS, S&TBS and T&SBS. This can therefore reduce the utility load that will eventually be released to the environment.

TABLE 1

STREAM AND COST DATA FOR EXAMPLE 1.

| Stream | $T^{in}$ ($^oC$) | $T^{out}$ ($^oC$) | Heat capacity flowrate (kW/$^oC$) | Heat transfer coefficient (kW/m$^2$/$^oC$) | Cost (£/kW/yr) |
|---|---|---|---|---|---|
| H1 | 105 | 25 | 10 | 0.5 | |
| H2 | 185 | 35 | 5 | 0.5 | |
| C1 | 25 | 185 | 7.5 | 0.5 | |
| HP Steam | 210 | 209 | | 5.0 | 160 |
| MP Steam | 160 | 159 | | 5.0 | 110 |
| LP Steam | 130 | 129 | | 5.0 | 50 |
| CW | 5 | 6 | | 2.6 | 10 |

Heat Exchanger Capital cost (£) = 800 x area (m). Annualization factor = 0.298 (/yr).

TABLE II

SUMMARY AND COMPARISON OF RESULTS OF LOWEST TAC FOR EACH METHOD FOR EXAMPLE 1

| Method | No. of Units | TAC ($/year) | Percentage Difference (%) |
|---|---|---|---|
| T&SBS | 7 | 101,893 | 4.96 |
| S&TBS | 6 | 101,889 | 4.95 |
| SBS | 6 | 101,889 | 4.95 |
| CUP of Shenoy *et al.* ,[12] | 9 | 98,263 | 1.22 |
| IBMS of Isafiade and Fraser,[4] | 9 | 97,211 | 0.14 |
| SWS of Jose *etal.* ,[6]. | 7 | 97,079 | 0.00 |

Example 2

This problem is also from Shenoy *et al*..,[12] It involves two hot streams and three cold streams. There are three hot utilities (steam) at different levels: low pressure, medium pressure and high pressure steam (LP, MP and HP). There are also two cold utilities, cooling water (CW) and air cooling (AC). Shenoy *et al*. employed the CUP technique the way they did in Example 1 for minimization of TAC for this example. The stream and cost data for this example are shown in Table 3. This problem was also solved with the IBMS and the SWS based model of Jose, *et al*.,[6]. The SBS, S&TBS and the T&SBS have also been applied to this problem and all the results including those of researchers that solved previously are shown in the appendix. The SBS TAC is just about 0.3% higher than the network structure of Jose *et al.,* but lower than the CUP of Shenoy, *et al,*.[12] and the IBMS of Isafiade and Fraser [4] by about 3% and 2.2% respectively as shown in Table 4. In a similar manner to the CUP and the approach of Jose et al, the present techniques use combinations of two hot utilities (HPS and MPS) to obtain their lowest TAC network. The IBMS used 1kW of LPS along with the HPS and MPS in its network [3]. It is thus evident that less pollutant will be released to the environment using the present technique. The S&TBS also return a TAC that is lower than those of CUP and the IBMS in this example as shown in Table 4.

TABLE III

STREAM AND COST DATA FOR EXAMPLE 2.

| Stream | $T^{in}$ ($^oC$) | $T^{out}$ ($^oC$) | Heat capacity flowrate (Kw/$^oC$) | Heat transfer coefficient (kW/m$^2$/$^oC$) | Cost (£/kW/yr) |
|---|---|---|---|---|---|
| H1 | 155 | 85 | 150 | 0.5 | |
| H2 | 230 | 40 | 85 | 0.5 | |
| C3 | 115 | 210 | 140 | 0.5 | |
| C4 | 50 | 180 | 55 | 0.5 | |
| C5 | 60 | 175 | 60 | 0.5 | |
| HP Steam | 255 | 254 | | 0.5 | 70 |
| MP Steam | 205 | 204 | | 0.5 | 50 |
| LP Steam | 150 | 149 | | 0.5 | 20 |
| CW | 30 | 40 | | 0.5 | 10 |
| AC | 40 | 65 | | 0.5 | 5 |

Exchanger Capital cost (£) = 13000 + 1000 (area) $^{0.83}$ (m$^2$), Annualization factor = 0.322(/yr).

TABLE IV

SUMMARY AND COMPARISON OF RESULTS OF LOWEST TAC OF EACH METHOD FOR EXAMPLE 2

| Method | No. of Units | TAC ($/year) | Percentage Difference (%) |
|---|---|---|---|
| T&SBS | 8 | 1,226,806 | 9.42 |
| CUP of Shenoy et al. ,[12] | 9 | 1,158,500 | 3.33 |
| IBMS of Isafiade and Fraser ,[4] | 7 | 1,150,460 | 2.61 |
| S&TBS | 7 | 1,150,303 | 2.60 |
| SBS | 8 | 1,125,417 | 0.38 |
| SWS of Jose et *al.* ,[6]. | 8 | 1,121,175 | 0.00 |

## II. CONCLUSION

This study demonstrates that the SBS, S&TBS and the T&SBS are able to solve HENS problems involving multiple utilities. The TACs obtained by the three techniques although marginally higher than those of modified SWS, some are much lower than the CUP and the IBMS techniques. In the second example, the SBS obtained the second lowest TAC which is just 0.38% higher than the lowest. These superstructures presented thus produce TACs that are in the same range as those of previous workers. They also utilize minimum number of utilities to produce their minimum TACs as demonstrated in Example 2.. This shows that the solutions return by the present superstructures are cost effective and more environmentally friendly than some of the techniques presented by previous workers..

## APPENDIX

The following tables in the appendix show the utility load distribution for different combinations of hot utilities as presented by various researches in the two examples.

Example 1: CUP of Shenoy *et al*.,[12]

| Options | Cold utility load (KW) | HPS Load KW | MPS Load KW | LPS Load K | N | TAC design (£/yr) |
|---|---|---|---|---|---|---|
| 1 (3HU) | 725.5 | 203 | 53 | 119.5 | 9 | 98,263 |
| 2 (2HU) | 725.5 | 240 | - | 135.5 | 7 | 98,699 |
| 3 (1HU) | 664 | 314 | - | - | 5 | 105,027 |

Example 1: Isafiade and Fraser ,[4]

| Options | Cold Utility Load (KW) | HPS Load (KW) | MPS Load (KW) | LPS Load (KW) | N | TAC design (£/yr) |
|---|---|---|---|---|---|---|
| 1 (3HU) | 694.27 | 256.56 | 86.71 | 1 | 7 | 100,954 |
| 2 (3HU) | 739.34 | 244.61 | 1 | 143.72 | 9 | 97,211 |
| 3 (2HU) | 693.65 | 256.55 | 87.10 | - | 6 | 100,942 |
| 4 (2HU) | 743.70 | 252.71 | - | 140.99 | 7 | 98,845 |
| 5 (1HU) | 675.45 | 325.45 | - | | 5 | 102,396 |

Example: 1 SWS of Jose *et al.* (2010)

| Option | Cold Utility Load (KW) | HPS Load (KW) | MPS Load (KW) | LPS Load (KW) | N | TAC design (£/yr) |
|---|---|---|---|---|---|---|
| 1( 2HU) | 740 | 238.7 | 0 | 151.3 | 7 | 97,079 |

Example 1: SBS

| Options | Cold Utility Load (KW) | HPS Load (KW) | MPS Load (KW) | LPS Load (KW) | N | TAC design (£/yr) |
|---|---|---|---|---|---|---|
| 1 (3HU) | 690.76 | 267.96 | 71.79 | 1 | 7 | 101,897 |
| 2 (2HU) | 676.20 | 325.10 | - | 1 | 6 | 102,403 |
| 3 (2HU) | 690.15 | 268.06 | 72.09 | - | 6 | 101,889 |
| 4 (1HU) | 675.50 | 325.50 | - | - | 5 | 102,403 |

Example 1: S&TBS

| Options | Cold Utility Load (KW) | HPS Load (KW) | MPS Load (KW) | LPS Load (KW) | N | TAC design (£/yr) |
|---|---|---|---|---|---|---|
| 1 (3HU) | 676.79 | 324.79 | 1 | 1 | 7 | 102,462 |
| 2 (2HU) | 690.15 | 268.06 | 72.1 | - | 6 | 101,889 |
| 3 (2HU) | 676.34 | 325.34 | - | 1 | 6 | 102,431 |
| 4 (1HU) | 675.49 | 325.49 | - | - | 5 | 102,402 |

Example 1: T&SBS

| Options | Cold Utility Load (KW) | HPS Load (KW) | MPS Load (KW) | LPS Load (KW) | N | TAC design (£/yr) |
|---|---|---|---|---|---|---|
| 1 (3HU) | 690.71 | 267.93 | 71.78 | 1 | 7 | 101,893 |
| 2 (2HU) | 710.98 | 240.29 | 120.61 | - | 6 | 110,451 |
| 3 (2HU) | 800 | 429.67 | - | 20.33 | 5 | 119,557 |
| 4 (1HU) | 800 | 450 | - | - | 3 | 120,078 |

Example 2: Shenoy *et al.* ,[12]

| Options | HPS load (KW) | MPS Load (KW) | LPS Load (KW) | CW Load (KW) | Air C Load (KW) |
|---|---|---|---|---|---|
| 1(3HU,1CU) | 1600 | 6860 | - | 7760 | - |
| 2 (2HU,1CU) | 1600 | 6860 | - | 7760 | - |
| 3 (2HU,2CU) | 4885 | 3575 | - | 3600 | 4160 |
| 4(2HU,2CU) | 2730 | 5730 | - | 3600 | 4160 |

Option 3 of CUP gives the lowest TAC for this example.

Example 2: Isafiade and Fraser [4]

| Options | HPS Load (KW) | MPS Load (KW) | LPS Load (KW) | CW Load (KW) | AC Load (KW) |
|---|---|---|---|---|---|
| 1(3HU,2CU) | 4298.5 | 4033.4 | 1 | 714.85 | 19.38 |
| 2(3HU,2CU) | 6096.74 | 2089.1 | 1 | 707.87 | 16.32 |
| 3(2HU,2CU) | 6027.75 | 1977.6 | - | 707.33 | 9.28 |
| 4(2HU,1CU) | 5928.5 | 1852 | - | 708.7 | - |

Option 1 of IBMS gives the lowest TAC for this example.

Example 2: Jose *et al.* ,[6]

| Option | HPS Load (KW) | MPS Load (KW) | LPS Load (KW) | CW Load (KW) | AC Load |
|---|---|---|---|---|---|
| 1( 2HU) | 4290 | 4075.3 | - | 7665.3 | - |

Option presented here of SWS gives the lowest TAC for this example.

Example 2: SBS

| Options | HPS Load (KW) | MPS Load (KW) | LPS Load (KW) | CW Load (KW) | AC Load (KW) |
|---|---|---|---|---|---|
| 1(3HU,2CU) | 9302 | 75.96 | 1 | 2177 | 6503 |
| 2(3HU,2CU) | 7787.3 | - | 1 | 7063.3 | 25 |
| 3(2HU,2CU) | 4228.71 | 4098 | - | 7078.7 | 548.03 |
| 4(2HU,1CU) | 6007.77 | 1770.9 | - | 7078.7 | - |

Option 3 of SBS gives the lowest TAC for this example.

Example 2: S&TBS

| Options | HPS Load (KW) | MPS Load (KW) | LPS Load (KW) | CW Load (KW) | AC Load (KW) |
|---|---|---|---|---|---|
| 1(3HU,2CU) | 4566.35 | 4098.21 | 1 | 7416.35 | 549.21 |
| 2(3HU,2CU) | 1 | 11319.57 | - | 5427.6 | 5192.96 |
| 3(2HU,2CU) | 9327.72 | - | 3972 | 6586.56 | 6013.44 |
| 4(2HU,1CU) | 5926.2 | 1852 | - | 7078.65 | - |

Option 4 of S&TBS gives the lowest TAC for this example.

Example 2: T&SBS

| Options | HPS Load (KW) | MPS Load (KW) | LPS Load (KW) | CW Load (KW) | AC Load (KW) |
|---|---|---|---|---|---|
| 1(3HU,2CU) | 2547.7 | 9167.5 | 1 | 5709 | 5306.68 |
| 2(2HU,2CU) | 6264.35 | 1852 | - | 7391.83 | 25 |
| 3(2HU,2CU) | 9302.6 | - | 284 | 2384 | 6502 |
| 4(2HU,1CU) | 3300 | 10000 | - | 12600 | - |

Option 2 of T&SBS gives the lowest TAC for this example.

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