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Assisted Heat Transfer and Shaft Work Targets for Increased Total Site Heat Integration

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Total Site Heat Integration (TSHI) provides a valuable framework for practical integration of multiple energy users. Previous studies have introduced the idea of utilising process heat recovery pockets to assist TSHI. However, these methods are shown to be effective for only some Total Site (TS) problems. As a result, this paper presents a new method for calculating assisted heat transfer and shaft work targets for an example TS problem. Analysis results show that assisted heat transfer increases TSHI only when a process heat recovery pocket spans the TS Pinch Region. The maximum assisted TSHI can be targeted by comparing each heat recovery pocket to the Site Utility Grand Composite Curve (SUGCC) using background/foreground analysis. Where heat recovery pockets span two steam pressure levels away from the TS Pinch Region (usually above), the example shows the potential for assisted shaft work production. In this case, the source segment of the heat recovery pocket generates steam (e.g. MPS), which replaces steam that would otherwise have been extracted from a steam turbine. The sink segment of the heat recovery pocket consumes lower pressure steam (e.g. LPS), which is extracted from the turbine. If a heat recovery pocket falls outside these two situations (assuming direct inter-process integration is disallowed), the entire pocket should be recovered internal to a process.

1. Introduction

Total Site Heat Integration (TSHI) provides a valuable framework for practical integration of industrial clusters (Dhole & Linnhoff 1993) and Locally Integrated Energy Systems (LIES) (Perry et al. 2008). In general, the method prioritises intra-process heat integration before searching for inter-process heat integration opportunities via the utility system (Klemeš et al. 1997) and/or dedicated indirect heat recovery systems (Walmsley et al. 2014). Recent advances in TSHI methodology include methods for minimising cost for Total Site recovery (Boldyryev et al. 2015), incorporation of district cooling into Total Sites (Liew et al. 2015), and consideration of safety aspect when proposing TS solutions (Liu et al. 2015). The Total Site (TS) method has five main steps: (1) process and stream data specification, (2) process level Pinch Analysis, (3) extraction of excess heating and cooling loads from process Grand Composite Curves (GCC), (4) Total Site Profile (TSP) composition, and (5) TS utility consumptions targeting. This paper focuses on step 4 and, specifically, on the removal internal heat recovery pockets that occurs before TSP composition, which may be exploited to assist TS heat recovery and shaft work generation.

Process heat recovery pockets can assist in increasing TS heat recovery. Bagajewicz and Rodera (2000) introduced the idea of assisted heat transfer for directly integrating two processes. Their analysis showed that heat integration between two (or more) processes should chiefly occur between the processes' Pinch Temperatures. However, in some presented cases, maximum heat recovery was only achieved by utilising a process heat recovery pockets, which are normally removed in conventional TSHI (Klemeš et al. 1997), for inter-process integration. For their two process case study, a tabular cascade analysis demonstrated that the Pinch of one plant could exchange heat with a heat recovery pocket of the other process, and thereby increase overall heat recovery. Later, Bandyopadhyay et al. (2010) revisited the idea of assisted heat transfer

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using a graphical TSHI approach. Their study recommended that GCCs are shifted to the utility temperature scale before segments of heat recovery pockets are removed. Segments of pockets on the right hand side of a new intersection point within the pocket were marked for intra-process heat recovery (i.e. removed), while the left hand segments continued to form part of the TSP. Bandyopadhyay et al. (2010) demonstrated that for one example case the modified TSHI method increased TSHI. However, as will be shown in this paper, such an increase in TSHI is not a generally applicable result.

Process heat recovery pockets can also assist in increasing TS shaft work generation. Cascading steam from high pressure to the demand using turbines for efficient power production is commonplace in TSHI (Sun et al. 2013). The concept of assisted shaft work is to utilise a pocket to, first, generate a higher quality steam, e.g. MPS, that is needed by another process and then, second, consume a lower quality steam, e.g. LPS, that is needed by the pocket. As a result, steam is cascaded from high to low pressure, providing an opportunity to assist TS shaft work by integrating with a Combined Heat and Power (CHP) system.

This study investigates how assisted heat transfer and assisted shaft work targets can be calculated for increasing TSHI. The conventional TSHI method of Klemeš et al. (1997) and the modified TSHI method of Bandyopadhyay et al. (2010), are compared against the proposed TSHI method, which begins with the conventional TSHI and improves the targets by including assisted heat transfer and shaft work.

2. Theory

The concepts of assisted heat transfer (A) and assisted shaft work generation (B) are illustrated in Figure 1. In conventional TSHI, process heat recovery pockets are preferentially recovered internally to processes. As shown for a two process example using background/foreground analysis (Figure 1A), removal of pockets can lower the target amount of TS heat recovery (Bagajewicz and Rodera 2000). The maximum amount of assisted heat transfer requires direct integration between the two processes, but this is often uneconomic for large sites. As a result, the steam utility levels may be used as an indirect heat recovery system, as shown in Figure 1A. Assisted heat transfer targets should, therefore, incorporate the normal TSHI constraint of integrating between processes using the utility system. Heat recovery pockets can also be used for assisted shaft work generation (Figure 1B). Where a pockets spans two steam pressure levels, there is opportunity to generate work. However, the amount of power generation for a single pocket is unlikely to economically warrant its own steam turbine. As a result, such opportunities must also fit into the wider Combine Heat and Power system to be useful.

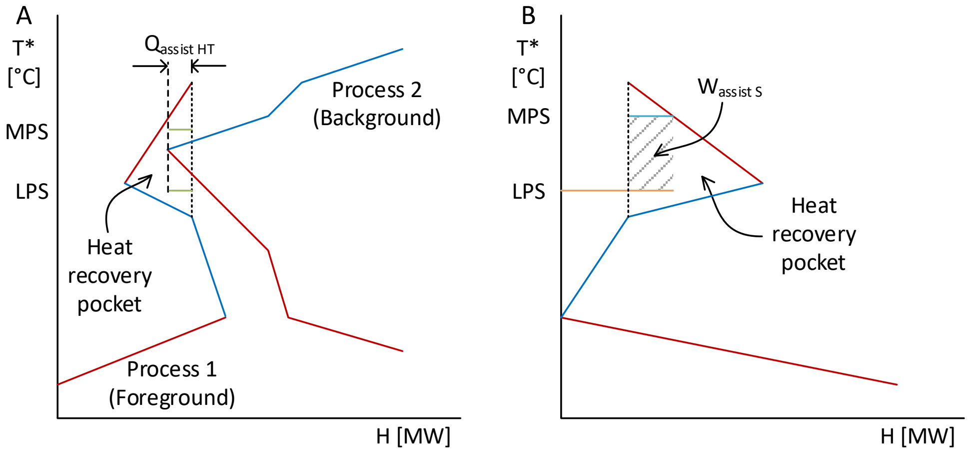

Figure 1: The concepts of an assisted heat transfer target for indirect integration of two processes (A) and an assisted shaft work target for a process (B)

3. Methods

Three methods have been used to determine the TSHI targets for an example TS problem, namely:

1. Conventional TSHI method of Klemeš et al. (1997)
2. Modified TSHI method with assisted heat transfer of Bandyopadhyay et al. (2010)
3. Conventional TSHI method with new assisted heat transfer and shaft work targets

The new assisted heat transfer and shaft work targets in Method 3 are the important contributions of this paper. New assisted heat transfer and shaft work targets are determined using a background/foreground analysis of process GCC heat recovery pockets compared to the conventional SUGCC.

New assisted heat transfer target

Where a single heat recovery pocket spans the TS Pinch Region, opportunity arises for assisted heat transfer in TSHI. The maximum assisted heat transfer may be determined by pinching the pocket against the SUGCC. Segments of the pocket that overlap the SUGCC should be used to increase TSHI, while non-over lapping segments should be recovered internal to the process.

New assisted shaft work target

Where a single heat recovery pocket spans two utility steam pressure levels (not crossing the Pinch Region), opportunity arises for assisted shaft work in TSHI. The maximum assisted shaft work may be determined by pinching the pocket against the steam utilities levels that the pocket spans, on the SUGCC. Segments of the pocket that overlap the two steam levels on the SUGCC should be used to increase TS shaft work, while non-over lapping segments should be recovered internal to the process.

4. A Total Site example with assisted heat transfer and shaft work

4.1 Stream and utility data

Table 1 presents the stream data for the example TS problem. Utilities for the TS include four steam levels: VHPS at 65 bar, HPS at 30 bar, MPS at 10 bar, LPS at 3 bar; and cooling water (CW) at 20 °C. The TS problem assumes a process ΔT_{min} of 20 °C and a process-to-utility ΔT_{min} of 10 °C.

Table 1: Steam data for example TS problem.

Steam	TS [°C]	TT [°C]	CP [kW/°C]
Process A			
A1 Hot	120	60	75
A2 Hot	150	100	100
A3 Cold	50	220	35
A4 Hot	250	230	150
Process B			
B1 Hot	200	90	30
B2 Hot	200	119	230
B3 Cold	30	200	40
B4 Cold	130	150	150
Process C			
C1 Hot	240	100	10
C2 Cold	50	250	15
C3 Cold	40	190	50
C4 Cold	140	210	100
Process D			
D1 Hot	220	170	60
D2 Cold	80	130	100
D3 Hot	110	80	75
D4 Hot	95	70	40

4.2 Process-level Pinch Analysis

The next step in TS analysis is process level Pinch Analysis. Figure 2 presents the GCCs for Processes A, B, C, and D, together with the respective heat recovery (Q_{rec}), hot utility (Q_{hot}), and cold utility (Q_{cold}) targets. Processes A, B and D each contain heat recovery pockets that may assist TS heat recovery and shaft work generation. The combined intra-process heat recovery is 19,950 kW, combined hot utility is 18,300 kW, and combined cold utility is 22,130 kW. The Pinch temperatures of the processes are 140 °C for Process A, 190 °C for Process B, Process C is a threshold problem, and 90 °C for Process D.

4.3 Conventional Total Site Heat Integration targets

Process GCCs have been shifted to T**, the utility temperature scale, and composited to form conventional TS Profiles (TSP), as presented in Figure 3A, using the method of Klemeš et al. (1997). Steam and cooling water utilities may be targeted using the TSP, from which the SUGCC is constructed and a shaft work target is calculated assuming 80% isentropic efficiency (Figure 3B). Inter-process heat recovery via the utility is 8,287 kW and the TS shaft work target is 1,062 kW_{ele}. The Pinch Region lies between the MPS and LPS utility levels. The original TSHI method does not include targets for assisted heat transfer or shaft work, whereas the modified TSHI method of Bandyopadhyay et al. (2010) does.

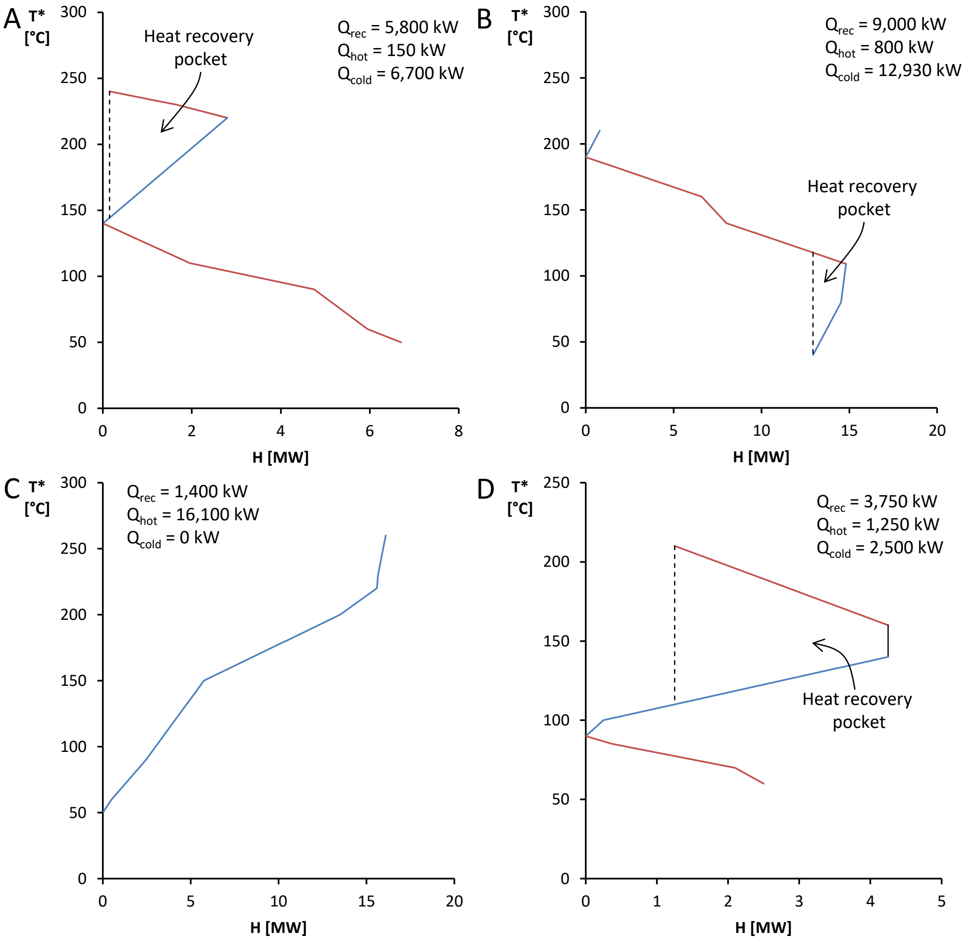

Figure 2: GCCs for Processes A, B, C, and D

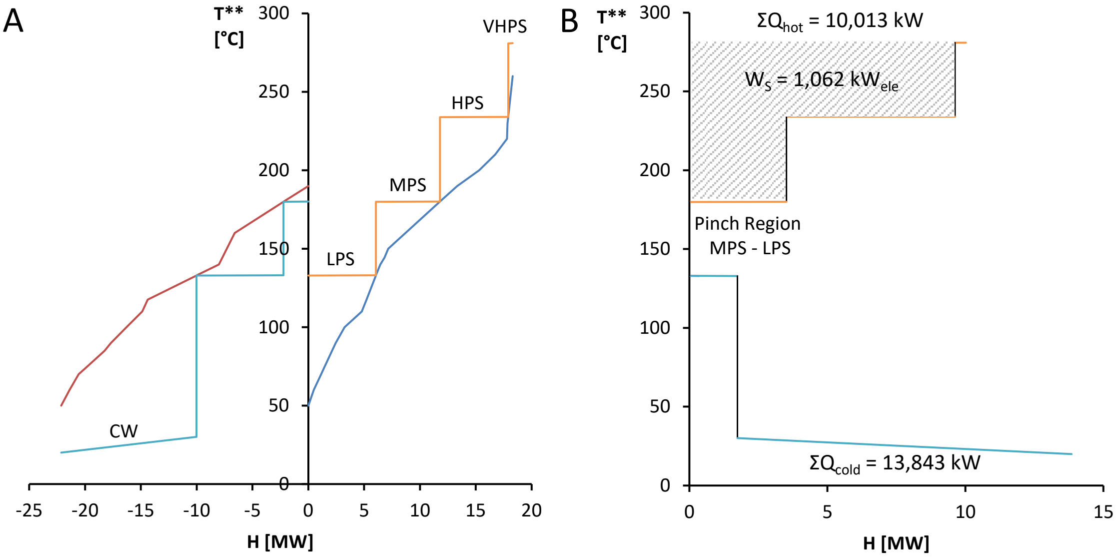

Figure 3: Conventional TSP (A) and SUGCC (B).

4.4 Modified Total Site Heat Integration targets

The method of Bandyopadhyay et al. (2010) may be applied to the same example TS problem. Their modified method carries over segments of most process GCC heat recovery pocket to form part of the TSP, as shown in Figure 4A. Modified targets for each utility and the corresponding SUGCC (Figure 4B) may be determined. As shown in Figure 4B, the Pinch Region shifts from between MPS-LPS levels in the conventional analysis to between LPS-CW levels. Hot and cold utility targets increase by 154 kW. The shaft work target also increases (69 kW_{ele}), due to the increase in total utility use and the lowering of the Pinch Region, which opens up more potential for power generation. Although the goal of the method of Bandyopadhyay et al. (2010) was to use GCC pockets to assist and increase TSHI, the method is clearly not universally advantageous. For the example TS problem, the modified method is detrimental to TSHI targets. As a result, there is a need to target assisted heat transfers and introduce the idea of assisted shaft work using a new method.

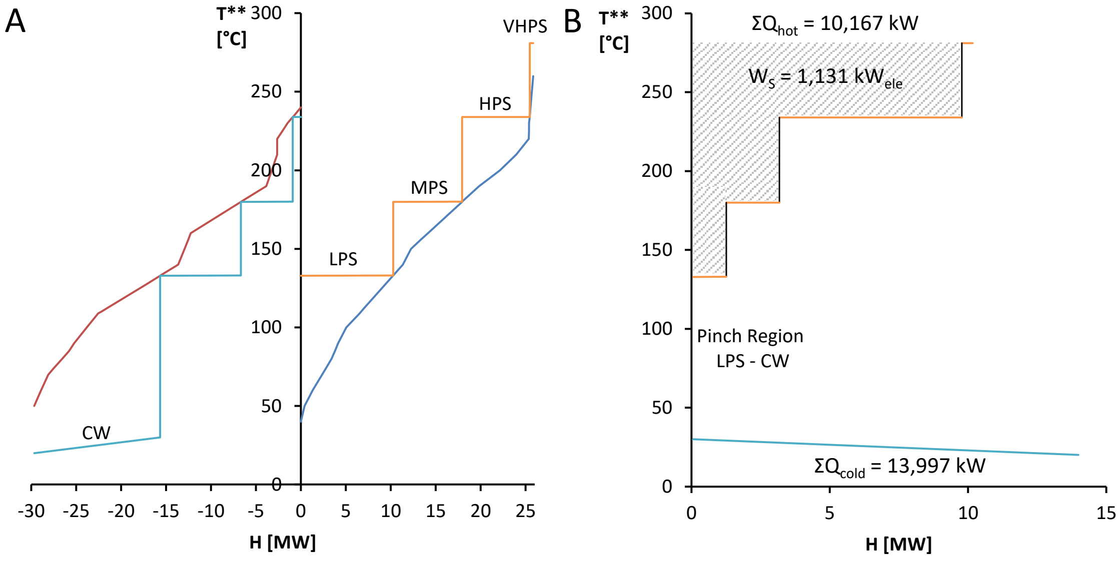

Figure 4: Modified TSP (A) and SUGCC (B) using the method of Bandyopadhyay et al. (2010)

4.5 New assisted heat transfer and assisted shaft work targets

The GCC pockets from Processes A, B, and D may be compared with the SUGCC using background/foreground analysis (Figure 5B) to identify effective assisted heat integration targets. The pockets have been inversed and positioned to target assisted heat transfer and shafted work, where possible. The segments that are used for assisted integration are then composited into the TSP in Figure 5A.

The pocket from Process D spans the Pinch Region MPS-LPS from Figure 3B, increasing MPS generation by 1,737 kW (above the Pinch) and LPS consumption by 1,737 kW (below the Pinch). As a result, TS heat recovery increases by 1,737 kW, which is a 21 % increase in inter-process heat recovery, to total 10,024 kW. The conventional SUGCC has been shifted to the left by 1,737 kW to show the overlap with the pocket from Process D. The segments not overlapping the shifted SUGCC are retained for internal integration within Process D.

The pocket from Process A sits above the Pinch Region and spans the HPS and MPS levels. This pocket can generate 915 kW of MPS but only needs to the equivalent in LPS. This difference in steam pressure requirements for heating and cooling within the pockets provides the opportunity for assisting shaft work generation. In such cases, MPS generated by the pocket is used to fulfil an MPS demand of another plant, while the demand for LPS by the pocket is satisfied using steam from the LP exit of the turbine. Extracting from the turbine an extra 915 kW of steam at the LPS level instead of the MPS results in assisted shaft work target of 80 kW_{ele}, as indicated by the horizontally shaded area in Figure 5B. The remainder of the pocket (i.e. the segments not required for assisted shaft work production) should be internally integrated within Process A. For the given utilities, the pocket from Process B has no potential for assisting TS integration and, therefore, is best left to be internally integrated within Process B.

It is important to note that the total shaft work target is a function of the amount of TS integration and the net consumption of HPS and MPS (and LPS, in other problems). The inclusion of assisted heat transfer from Process D in the TS problem reduces the opportunity for shaft work generation, while the assistance of Process A helps to increase the shaft work target. After including the assisted heat transfer and shaft work targets and the corresponding GCC segments into the TSP and SUGCC, the Pinch Region widens to be between the MPS and CW levels. Future work will focus on developing an improved TSHI method that incorporates targets for assisted heat transfer and shaft work generation.

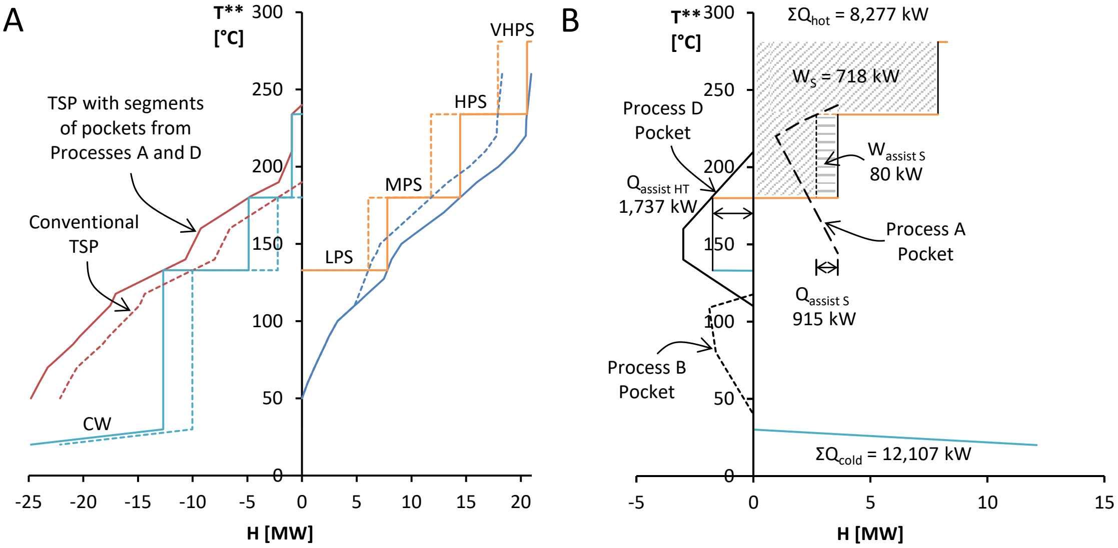

Figure 5: (A) New TSP including assisting segments of pockets from Process A and D compared to the conventional method. (B) Targets for assisted heat transfer and shaft work using the SUGCC and the GCC pockets from Process A, B, and D

5. Conclusions

Maximum utilisation of process heat recovery pockets for assisted heat transfer and shaft work in an example Total Site (TS) problem help increase heat recovery by 1,737 kW, which is a 21% increase in inter-process heat recovery, and shaft work by 80 kW_{ele}. This new level integration is significantly better than the Total Site heat recovery reduction of 154 kW that is targeted by a literature method, which includes assisted heat transfer in its modified TS method, compared to the conventional method. In general, it is concluded that process heat recovery pockets that span two or more utility levels are candidates for assisting TS heat recovery and shaft work production.

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