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Optimisation of Non-Isothermal Utilities using the Unified Total Site Heat Integration Method

Amir H. Tarighaleslami*, Timothy G. Walmsley, Martin J. Atkins,
Michael R. W. Walmsley, James R. Neale

Energy Research Centre, School of Engineering, University of Waikato, Private Bag 3105, Hamilton 3240, New Zealand
aht5@students.waikato.ac.nz

Total Site Heat Integration is an effective method for design of large scale utility systems that serve large chemical processes, such as refineries, petrochemicals or even lower temperature chemical and process plants. Total Site Heat Integration of different chemical plants might confront batch, semi-continuous or continuous plants which are clustered into one large site. Excess heat produced from one plant could be transferred to other plants using an intermediate fluid. In this paper, Total Site optimisation of targeting utility generation and consumption for lower temperature processes, which mainly use non-isothermal utilities, is presented. The utility temperature selection optimisation applies to the recently developed Unified Total Site Heat Integration Targeting (UTST) method. The new method shows that, for low temperature processes where non-isothermal utilities are used, the supply and target temperatures of a utility is an important constraint, while for higher temperature processes, where isothermal utilities are applied, no significant change in targets from conventional Total Site are obtained. New heuristics based on UTST method with respect to non-isothermal utility temperature selection are proposed. A Kraft Pulp Mill case study has been investigated in this research, using optimised non-isothermal utilities, showing a 3.6 MW increase in heat recovery, 0.87 MW decrease in shaft work generation, and $ 330,000 /y utility cost saving in the system applying the new UTST method compared to the conventional Total Site method.

1. Introduction

Total Site Heat Integration (TSHI) is a useful tool for engineers to plan and make strategic decisions regarding energy optimisation of entire processing sites. TSHI is a graphical method based on the concept of the site's heat source and heat sink profiles, i.e. Total Site Profiles (TSP). Total Site (TS) integrates a number of individual processes to recover heat indirectly via a common utility system, which offers additional inter-process heat recovery (HR) through consumption and generation of utilities (Klemeš, 2013).

One of the targeting issues with most TSHI methods is they generate overly optimistic HR targets for non-isothermal utilities such as hot water loops (Tarighaleslami et al., 2016a). TSHI has been developed based on using isothermal utilities such as steam at different pressure levels as the main utility. This is one contributing factor as to why TSHI has found the most success with high temperature processes that require steam, rather than low temperature processes that use hot water. In Conventional TSHI methods non-isothermal utilities are treated in the same way as isothermal utilities where the utility supply temperature is the primary constraint. As a result Conventional TSHI methods inherently allows the a utility's target temperature to be achieved using a single heat exchanger match or using heat exchanger matches in series from any of the serviced processes. To realistically achieve the TSHI target, such an allowance for series utility matches from different processes presents a challenge for non-continuous processes and can result in very high piping costs due to a required complex utility network. For non-isothermal utilities, the utility target temperature is normally an additional fixed constraint when TSHI is desired. This is a second important difference compared to isothermal steam utilities when the target temperature is not of concern.

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To improve the targeting of inter-plant heat recovery, Walmsley et al. (2014) developed a Heat Recovery Loop (HRL) method using a dedicated hot water heat recovery system. The method has been optimised for area targeting and storage temperature selection (Walmsley et al., 2012), application of nanofluids as heat transfer fluid in HRLs (Tarighaleslami et al., 2015) and in site level heat recovery systems (Tarighaleslami et al., 2016b), optimisation of HRLs by using MINLP model with economy is objectives (Chang et al., 2015), and using solar thermal sources to optimise HRLs energy level (Walmsley et al., 2015). However, inherent to the method is the constraint that the utility target temperature must be achieved with each heat exchanger match, which lowers the inter-process HR potential compared to conventional TSHI. Furthermore it requires information about the process heat exchanger network designs prior to targeting inter-process Heat Integration.

Recently Tarighaleslami et al. (2016a) developed the Unified TSHI Targeting (UTST) method, which relaxes the HRL constraint to allow for the utility target temperature to be achieved by heat exchangers in series, if and only if they are in series within the same process. The new method initially targets utility use at the individual process level, which targets are then carried over to the TS level; whereas conventional TSHI re-targets utility use at the TS level. As a result the fidelity of individual process heat demand profiles is not lost in the targeting of utilities for the Unified TSHI method. The HR targets for non-isothermal utilities established using the Unified TSHI method are therefore more achievable and realistic than those using the HRL and conventional TSHI methods.

Selection of the number of utility levels and the associated temperatures are important degrees of freedom for the maximisation of TSHI. The earliest optimisation based on TSHI is presented by Mavromatis and Kokossos (1998) who present a model to optimise utility networks for operational variations. Zhu and Vaideeswaran (2000) developed a systematic method for operational optimisation, retrofits, grassroots design and debottlenecking of TS energy systems. Prashant and Perry (2012) used a MINLP model to determine the cost optimal location and number of steam levels to meet the process heating and cooling demands. Sun et al. (2013) showed no shaft work generation potential at the Site Pinch region. They showed that by adding new steam mains within or away from the Site Pinch has significant improvement on boiler steam saving, high temperature utility targets, and shaft work generation target. As discussed, TSHI literature has various methods for optimising the number and temperature of utility levels for steam (i.e. isothermal) utility systems. However, there is a gap in the literature with regards to an optimisation method for non-isothermal utility temperatures in TSHI.

The aim of this paper is to investigate the selection of utility temperatures (both supply and target) on fuel consumption, power generation, and energy cost using the UTST method. A Kraft Pulp Mill has been investigated as the illustrative case study.

2. Methods

2.1 Unified Total Site Heat Integration

The new Unified TSHI method, recently developed by Tarighaleslami et al. (2016a), has been applied in this study. It performs utility targeting at the process level using the Grand Composite Curve (GCC). This gives the opportunity for the engineer to consider more constraints around meeting supply and target temperatures of non-isothermal utilities within individual processes. The new method restricts any inter-dependency of utility use between processes, which is important for non-isothermal utilities as well as non-continuous processing clusters that often operate with different schedules and independently. By adding this new constraint the calculated targets become more achievable and realistic. The new method has been implemented into an Excel^{TM} spreadsheet.

2.2 Utility temperature selection and optimisation method

The selection and optimisation of non-isothermal (e.g. hot water) utility temperatures has been investigated using the new Unified TSHI method. For each utility a range of supply and target temperatures has been chosen and targeted using the Unified TSHI method. TS targets including TS heat recovery, shaft work generation, energy cost, and generation and consumption for each utility in the system have been calculated using the spreadsheet tool. The temperature ranges for two hot water utilities in the case study were divided into 2.5 °C intervals and the spreadsheet cycled through every logical combination of utility temperatures. In total, the targeting method was repeated 31,200 times to analyse the case study. Shaft work targets are based on the Site Utility Grand Composite Curve (SUGCC) in conjunction with the Medina-Flores and Picón-Núñez (2010) turbine model.

Eq(1) and (2) present constraints that are needed in the optimisation of temperature selection for non-isothermal utility.

$$T_{h(i)}^{ut} > T_{c(i)}^{ut} \quad (1)$$

$$T_{c(i)}^{ut} \geq T_{h(i+1)}^{ut} \quad (2)$$

Where T is the temperature and superscript ut refers to utility, either hot or cold utility, and subscripts c is the cold temperature of the utility and h is the hot temperature of the utility, with i referring to a utility level. Depending on the location of the utility and whether it is assumed as a hot or cold utility, these hot and cold temperatures for the utility might be either supply or target temperatures.

3. Illustrative case study

A Kraft Pulp Mill plant has been chosen as the case study. The stream data including minimum approach temperatures are taken from Bood and Nilsson (2013), which has 10 different processes with a total of 64 streams. Utilities include Very High Pressure Steam (VHPS), High Pressure Steam (HPS), Low Pressure Steam (LPS), High Temperature Hot Water (HTHW) and Low Temperature Hot Water (LTHW), which cover the required temperature ranges in the TSHI, and details are given in Table 1. Energy costs are estimated to be $ 30 /MWh for heating utilities, $5 /MWh for cooling utilities, and $ 100 /MWh for power generation. The site operates an estimated 8,500 h/y.

Table 1: Initial required utilities for Kraft Pulp Mill.

Utility Name	Utility Type	T_s (°C)	T_t (°C)	P (bar g)
Very High Pressure Steam (VHPS)	Hot	450.0	449.9	90
High Pressure Steam (HPS)	Hot	210.0	209.9	15
Low Pressure Steam (LPS)	Hot	160.0	159.9	9
High Temperature Hot Water (HTHW)	Hot	85.0	60.0	
Low Temperature Hot Water (LTHW)	Cold	25.0	45.0	

4. Results and discussion

Figure 1 presents the TSP and SUGCC for the Kraft Mill case study given the initial utility selection. These plots show 100.78 MW of HR, 37.84 MW of shaft work, 21.22 MW of HTWT net generation, and 52.48 MW of LTHW net consumption.

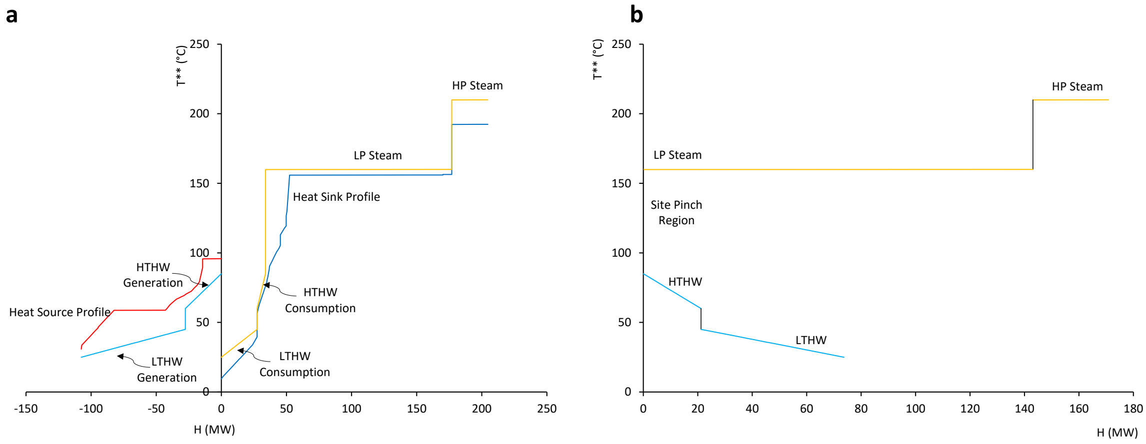

Figure 1: UTST method analysis based on initial utility selection for case study; a) TSP, and b) SUGCC

4.1 HTHW supply and target temperature selection

An important consideration is the selection of the supply and target temperatures for the HTHW and the LTHW. Figure 2 presents Total Site heat recovery for different ranges of supply (T_s) and target (T_t) temperatures for the HTHW utility, given a LTHW utility of T_s=30 °C, T_t= 45 °C, Option A (Figure 2(a)) and T_s=15 °C, T_t= 30 °C, Option B (Figure 2(b)).

It can be seen in both LTHW options HR increases for higher T_t values until it peaks when T_t is 95 °C, which is a process Pinch in the TS heat source profiles, and then HR decreases. On the other hand, as the result of increase in T_s, HR increases and remains approximately constant in a region for Option A. However, increases in T_s shows a decrease for Option B beyond 67.5 °C. When the utility target temperature passes the Site Pinch temperature, utility consumption and generation balance may change. Therefore, due to lack of heat sources the amount of heat recovery will decrease. If HTHW target temperature is adjusted above the Site Pinch temperature, no cold utility will be generated and next cold utility (i.e. LTHW in this case) must tolerate all the heat which is rejected to the utility system. The consequence is a significant decrease in amount of heat recovery. Therefore, 95 °C is chosen as target temperature for this case study.

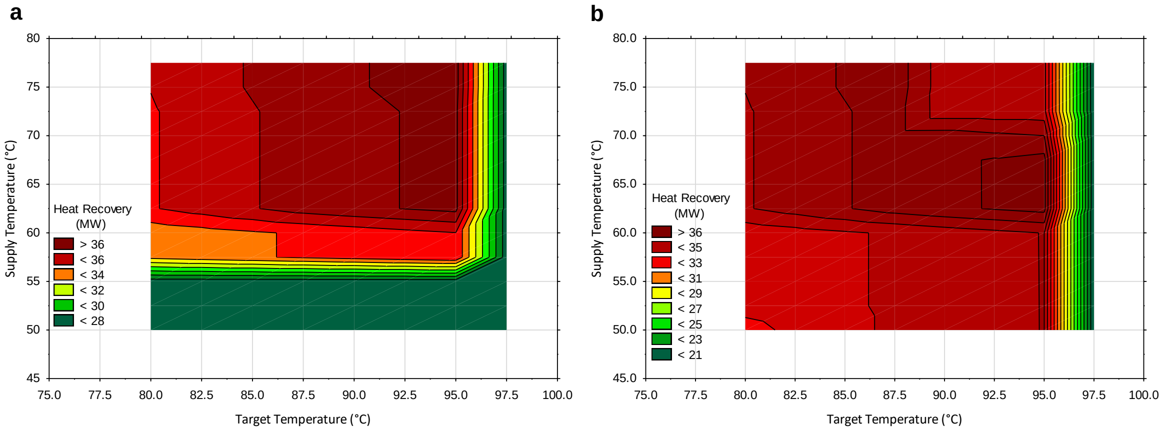

Figure 2: HR vs. variation of supply and target temperatures for HTHW utility; a) option A, b) option B

Figure 3 depicts the relation between the net HTHW consumption, HR, shaft work generation, and utility cost in a range of different supply temperatures. Net utility consumption above the Pinch (i.e. heat source) has been assigned as positive values; below the pinch (i.e. heat sinks) as negative values. Optimum T_s might be somewhere in the flat region which is formed as the result of maximum HR. This point represents the maximum HR and the minimum amount of utility cost as well as decrease in shaft work generation. In this region balance between utility generation and consumption should be considered.

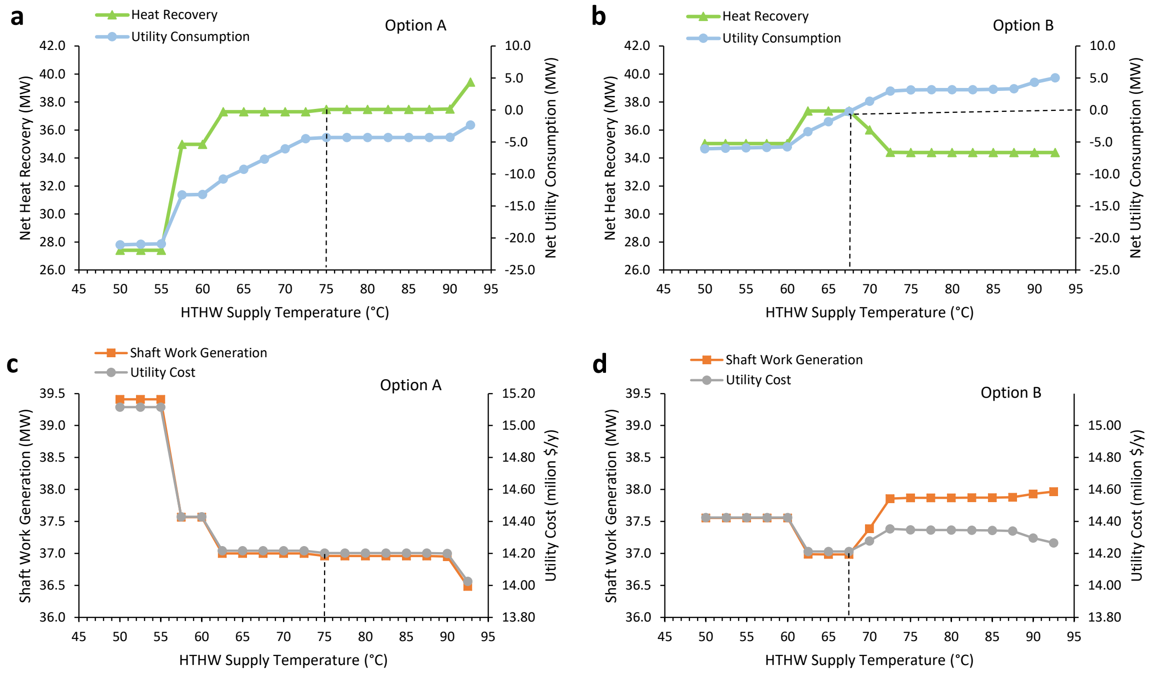

Figure 3: Heat Recovery, HTHW consumption, shaft work generation, and utility cost vs. supply temperature

Figure 3(a) (option A) shows that HR increases as the T_s is increased with a constant region between 62.5 to 90 °C. To keep high heat transfer driving force in each utility loop and prevent significant increase in the amount of utility requirement, it is suggested to consider at least 10 °C temperature difference between T_s and T_t in non-isothermal utility loops. Therefore, any temperature between 62.5 to 85 °C could be used for maximum HR; however, by considering temperature driving force and a small HR increase at 75 °C, this temperature will be the chosen as the optimum temperature. For option B (Figure 3(b)) a peak in HR occurred, with the optimum T_s range located between 62.5 and 67.5 °C (i.e. constant HR). HTHW consumption balance changes as T_s increases, prior to 67.5 °C utility consumption transferred to positive values which means there is no more utility generation and a decrease in HR. Therefore, 67.5 °C is optimum HTHW supply temperature. Figure 3(c) and 3(d) show that in both cases the region with the highest HR presents the lowest utility cost and shaft work generation potential, which can be interpreted as an acceptable trade-off between shaft work decrease and increased HR. In summary, 75 °C as supply temperature and 95 °C as target temperature has been chosen for HTHW utility.

4.2 LTHW supply and target temperature selection

To set supply and target temperatures of the last utility, which in this case study is LTHW, additional constraints must be considered. Supply temperature of LTHW must be equal or lower than any temperature of process segments in the GCC in each individual process to prevent additional cold utility requirement; thus, T_s has been set in 30 °C. As shown in Figure 4(a), HR increases and remains approximately constant for T_t higher than 35 °C. The maximum possible target temperature is 45 °C. Beyond this point, a process Pinch occurs; therefore, additional utility is required. To keep heat recovery driving force within the highest range and minimise the amount of cold utility, T_t equal to 45 °C has been chosen as the optimum temperature. In this point steady rate of utility cost and shaft work is shown in Figure 4(a). Therefore, 30 °C as supply temperature and 45 °C as target temperature have been chosen for LTHW utility.

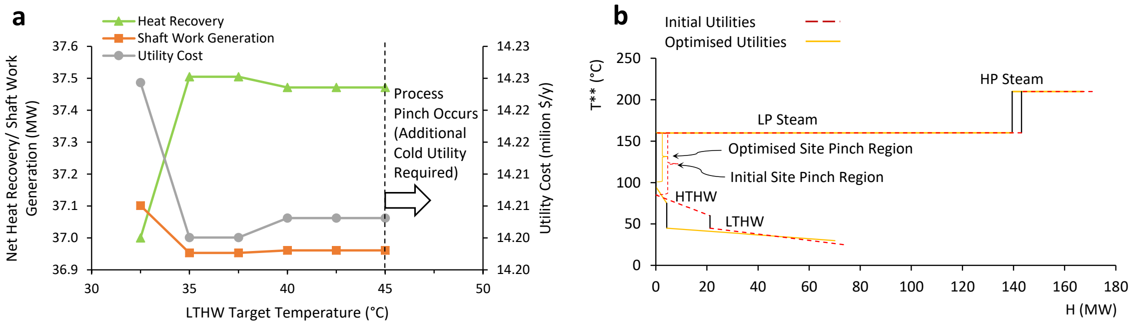

Figure 4: (a) Optimum target temperature selection for LTHW utility, and (b) Optimised UGCC for the case study

Figure 4(b) shows the initial UGCC in dashed lines and optimised UGCC in solid lines. As illustrated in Figure 4(b) by using optimised temperature ranges for HTWH and LTHW utilities, net HR increases up to 3.6 MW with an equal decrease in LP Steam requirement. Generally, shaft work generation drops only 0.87 MW compared to 3.6 MW increase in HR. consequently, total utility savings of $ 330,000 /y is achieved.

4.3 Suggested additional constraints and heuristics for non-isothermal utility temperature selection

Understanding gained from the case study can be summarised into a set of additional constraints and new heuristics that narrows the search space for the TS utility temperature optimisation problem.

Required additional constraints for supply and target temperature selection of non-isothermal utilities are:

- Select a minimum temperature difference for each non-isothermal utility loop, e.g. 10 °C, to prevent excessive piping, pumping and thermal storage costs.
- The maximum target temperature for cold utility consumption is constrained by the process with the highest cold Pinch Temperature.
- The minimum target temperature for hot utility consumption is constrained by the process with the lowest hot Pinch Temperature.
- The supply temperature of the coldest cold utility must be equal to or lower than the minimum temperature of process GCC segments that need cold utility.
- The supply temperature of the hottest hot utility must be equal to or higher than the maximum temperature of process GCC segments that need hot utility.

Heuristics for supply and target temperature selection of non-isothermal utilities are:

- Select allowable utility supply and target temperature ranges for each utility with consideration for limitations such as pipe pressure ratings, pumping costs, and product quality requirements.
- Optimise utility supply and target temperatures of each utility for a given objective, e.g. maximise HR or minimise utility cost, starting with the hot and cold utilities forming the TS utility Pinch region and then working away from the Pinch.
- The optimum combination of utility supply and target temperatures often occurs for a utility when its net consumption/generation is zero, if at all feasible.
- Increasing a utility's supply or target temperature, generally shifts the balance of utility use in the direction of generating more cold utility (which is the same as consuming more hot utility). Decreasing a utility's supply or target temperature has the opposite effect.
- If multiple combinations of supply and target temperatures for an individual utility are equally optimal, select the combination with the greatest temperature difference between the utility supply and target temperatures, so that piping and pumping costs are minimised and thermal storage is maximised.

5. Conclusions

Non-isothermal utility supply and target temperature selection has been studied in this paper as part of the new Unified Total Site Targeting method for isothermal and non-isothermal utilities. More realistic targets are achievable if new constraints are applied. Based on the method and case study several heuristics are proposed for the selection of the supply and target temperatures for non-isothermal utilities. For the closest non-isothermal to the TS Pinch region, the Pinch point is the target temperature constraint. UTST method targets utility in GCC level; therefore, supply temperature must be chosen by considering the balance between net utility generation and consumption, and the Process Pinches in each GCC. This process can be repeated for non-isothermal utilities in series. For the last utility, supply temperature must be adjusted considering the lowest process stream in the TS to avoid extra cooling utility requirement. Target temperatures must be selected considering utility and process Pinches. Results show that for the Kraft Pulp Mill case study compared to the original case HR increases up to 3.6 MW, $ 330,000 /y utility cost saving occurred; however, shaft work generation decreased by 0.87 MW.

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