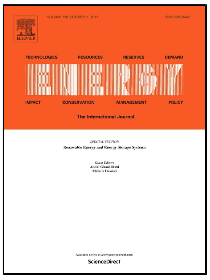

Total Site Heat Integration: Utility Selection and Optimisation Using Cost and Exergy Derivative Analysis

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Highlights

- A new Total Site Heat Integration utility optimisation method is developed
- The new method is based on iterative derivative analysis of the objective functions
- Objective functions are Utility Cost, Exergy Destruction, and Total Cost
- A new Total Site targeting and optimisation software spreadsheet tool is introduced
- Three industrial case studies achieve between 0.6 to 4.6 % reduction in Total Cost

Total Site Heat Integration: Utility Selection and Optimisation Using Cost and Exergy Derivative Analysis

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Abstract

This paper presents a new Total Site Heat Integration utility temperature selection and optimisation method that can optimise both non-isothermal (e.g. hot water) and isothermal (e.g. steam) utilities. None of the existing methods addresses both non-isothermal and isothermal utility selection and optimisation incorporated in a single procedure. The optimisation affects heat recovery, the number of heat exchangers in Total Site Heat Exchanger Network, heat transfer area, exergy destruction (ED), Utility Cost (UC), Annualised Capital Cost (CC), and Total Annualised Cost (TC). Three optimisation parameters, UC, ED, and TC have been incorporated into a derivative based optimisation procedure where derivatives are minimised sequentially and iteratively based on the specified approach. The new optimisation procedure has been carried out for three different approaches as the combinations of optimisation parameters based on the created derivative map. The merits of the new method have been illustrated using three case studies. These case studies represent a diverse range of processing types and temperatures. Results for the case studies suggest the best derivative optimisation approach is to first optimise UC in combination with ED and then optimise TC. For this approach, TC reductions between 0.6 to 4.6 % for different case studies and scenarios are achieved.

Keywords: Total Site Heat Integration, Optimisation, Utility Temperature, Exergy Destruction, Total Annualised Cost, Utility Cost.

Nomenclature

Roman

A	heat transfer area (m^2)
a	cost coefficient
b	cost coefficient
c	cost coefficient
C_p	specific heat capacity (kJ/kg°C)
H	enthalpy (MW)
j	interest rate (%)
$\dot{m}$	mass flow rate (kg/s)
n	investment return duration (y)
OP	operating period (h/y)
PP	power price (NZD/MWh)
Q	utility target (MW)
S	entropy (MW/°C)
T	temperature (°C)
T^*	shifted temperature (°C)
T^{**}	double shifted temperature (°C)
UP	utility price (NZD/MWh)
W	power target (MW)
X	exergy (MW)

Greek

Δ	difference between two states
$\sum$	summation of parameters

Subscripts

0	reference
c,ut(i)	cold utility for utility (i)
Cold	cold
d	destruction
gen	generation
h,ut(i)	hot utility for utility (i)
Hot	hot
i	counter
min	minimum
s	step
Sink	sink
Source	source
x	exergy

Abbreviations

BCC	Balanced Composite Curve

CC	Annualised Capital Cost
CHP	Combined Heat and Power
ChW	chilled water
CW	cooling water
ED	exergy destruction
GCC	Grand Composite Curve
HEN	heat exchanger network
HOL	hot oil loop
HW	hot water
HPS	high pressure steam
HR	Heat Recovery
HTHW	high temperature hot water
ISCC	Interplant Shifted Composite Curves
LPS	low pressure steam
LTHW	low temperature hot water
MINLP	mixed integer non-linear programing
MP	Mathematical Programing
MPS	medium pressure steam
SUGCC	Site Utility Grand Composite Curve
SWG	Shaft Work Generation
TC	Total Annualised Cost
TS	Total Site
TSHI	Total Site Heat Integration
TSHR	Total Site Heat Recovery
TSP	Total Site Profile
TW	tempered water
UC	Utility Cost
UTSI	Unified Total Site Integration
UTST	Unified Total Site Targeting
VHPS	very high pressure steam

1 Introduction

Total Site Heat Integration (TSHI) is a proven tool for engineers to plan and make strategic decisions regarding energy optimisation for entire processing sites [1]. TSHI integrates several 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. Dhole and Linnhoff [2] introduced a TSHI graphical targeting method based on the concept of a site’s heat source and heat sink profiles. Klemeš et al. [3] developed a systematic method to apply TSHI to large industrial sites. HR options may be illustrated using the Total Site Profiles (TSP) [4]. Improvements have been proposed to these conventional TSHI methods to obtain more realistic utility and HR targets such as process specific minimum temperature difference [5], stream specific minimum temperature difference [6], and integration and management of renewable energy into TS [7].

Selection of the number of utility levels and the associated temperatures are important degrees of freedom to maximise HR. The earliest optimisation based on TSHI is presented by Makwana et al. [8] for retrofit and operations management of existing Total Site (TS), and Mavromatis and Kokossis [9] who present a model to modify targeting procedure and optimise utility networks for operational variations. Zhu and Vaideeswaran [10] developed a systematic method for operational optimisation, retrofits, grassroots design and debottlenecking of TS energy systems. Since these early studies, researchers have applied both Mathematical Programming (MP) and graphical methods to attempt to optimise the selection of utility temperatures.

Minimising Total Annualised Cost (TC) as the main objective function presents an acute trade-off between investment (capital cost) and operational (mostly utility) costs. Several studies have applied MP based methods to optimise the utility temperatures. Shang and Kokossis [11] proposed a methodology to optimise steam levels under different operational scenarios using a boiler and turbine hardware model. The study developed a transhipment model to represent a TS system and used the location of steam levels, the overall fuel requirement, the cogeneration potential and the cooling utility demand as major decision variables to minimise Utility Cost (UC) by applying a multi-period MILP model. Prashant and Perry [12] used an MINLP model to determine the cost optimal location and number of steam levels to meet the process heating and cooling demands. Sun et al. [13] showed that at the Site Pinch region there is no Shaft Work Generation (SWG) potential. They also showed that by adding new steam mains within or away from the Site Pinch can significantly improve boiler steam saving, high temperature utility targets (>120 °C), and SWG. Later they proposed a practical approach based on extended site composite curves to provide realistic utility targets [14]. The method only allows for boiler feedwater preheating, steam superheating in steam generation, steam desuperheating for process heating, and condensate HR from steam consumption. However, the method doesn’t take other non-isothermal utilise into account. Nemet et al. [15] proposed a new TS optimisation model including the selection of utility pressure levels for intermediate utilities to optimise TC considering future energy prices. The model also included thermal and hydraulic parameters, such as pipeline layout design, pipe design, and insulation thickness and heat losses, when synthesising the MINLP problem through the trade-off between capital and operating cost.

Another approach to utility temperature optimisation is graphical based methods. Song et al. [16] developed a new graphical method called Interplant Shifted Composite Curves (ISCC) to target the maximum HR for indirect HI between two plants without basic changes, such as infrastructure improvements, in the existing Heat Exchanger Network (HEN). The ISCC method selects streams with the potential to participate in the TS, and determines maximum feasible HR as well as minimises the flow rate of the heat transfer medium. However, the method has not been applied to industrial clusters with different level of utilities. Boldyryev et al. [17] developed a method to decrease capital cost by minimising heat transfer area for HR on TS using different utility levels. In their method, heat transfer area is reduced by selection of the appropriate temperature of intermediate utilities. Minimum heat transfer area depends on slopes of TSP in each enthalpy interval.

TSHI has various methods in the literature for optimising the number and temperatures of utility levels for steam (i.e. isothermal) utility systems, and new methods based on optimisation of non-isothermal (i.e. hot water or hot oil) utilities. Tarighaleslami et al. [18] proposed heuristics to optimise selection of non-isothermal utilities based on the Unified Total Site Targeting (UTST) method [19] to maximise the amount of HR and SWG, which was followed by a detailed synthesis and analysis of HEN with focus on the utility heat exchanger network [20]. Recently, Song et al. [21] presented a modified MINLP model with an objective of TC to determine the final inter-plant HEN configurations.

Exergy analysis has often been proposed by many researchers for optimisation of process HI. Parker [22] introduces a fast and easy algorithm for the energy-capital trade-off in a HEN, but in this method the effect of the capital trade-off on the utility system was not taken into an account. Dhole [23] combines PA and exergy analysis to for a multiple utility optimisation problems. The method showed reducing the exergy destruction (ED) in a HEN will ultimately benefit the power generation in the utility plant. An Exergy Grand Composite Curve was used to minimise the exergy losses in the HEN and can be constructed from the GCC by converting the temperature axis into Carnot factor. Linnhoff and Dhole [24] presented a method that combines PA and exergy analysis to optimise low temperature processes. The method allows the engineer to specify a refrigeration system while increasing its exergy efficiency. Dhole and Linnhoff [2] manipulated utility temperatures to assess ED in TS cogeneration targets. Hui and Ahmad [25] proposed a four steps heuristic based method for multiple utility optimisation of TSs. They used exergy analysis for steam costing that can act as interface between the utility plant and the processes energy-capital trade-off. Khoshgoftar Manesh et al. [26] performed exergo-economic and exergo-environmental evaluation of the coupling of a gas-fired steam power plant with a TS utility system. Hackl and Harvey [27] expanded the use of exergy analysis in the TS to target shaft work in sub-ambient and cryogenic processes. Farhat et al. [28] attempted to increase HR between plants by combining TS and exergy analysis. They performed classical HR optimisation via HENs. However, they did not consider optimisation regarding UCs.

There is a gap in the literature with regards to simultaneous optimisation of both isothermal and non-isothermal utility that considers the trade-off between UC and Annualised Capital Cost (CC). Exergy has been discussed as an option for optimisation assessments but, in the case of utility temperature optimisation beyond turbines, it has not been applied as a tool for utility optimisation. Cost and exergy analysis may also be combined with derivative analysis, as demonstrated by Walmsley et al. [29], to create a new method for optimising utility temperature selection.

The aim of this paper is to develop a new derivative method to optimise the selection of both isothermal and non-isothermal utility supply and target temperatures in TSHI. The main goal is a reduction in TC, which comprises CCs and UCs, which is proportional to fuel consumption in the TS as indicated by utility targets. Depending on the approach, minimization of the UC and/or ED targets may be considered as the initial objective functions in the optimisation procedure while TC is the ultimate objective function, as is discussed in Section 3. The method is primarily for grassroots design, but may also be beneficial for retrofit design studies as an initial step. A new software tool has been developed based on the new Unified TSHI method [19], which covers both isothermal (e.g. steam) and non-isothermal utility (e.g. hot water). Case studies of a Kraft Pulp Mill, a Petrochemical Complex and a Dairy Factory have been investigated to illustrate the method and demonstrate its merits.

2 The Opportunity of Total Site Utility Temperature Optimisation for Maximising Heat Integration Targets

2.1 Total Site Utility Temperature Optimisation

In PI techniques, the most important objective is to minimise TC by balancing the trade-off between fuel consumption utility demand and capital investments. The appropriate utility temperature selection can lead to lower UCs using the less expensive utility, increased HR at the TS level, increased cogeneration, and/or decreased refrigeration work consumption. Each utility generally has a different unit price. Typically, the lowest temperature cold utility and the highest temperature hot UC have a higher unit price than those with temperatures closer to Total Site Pinch Temperature range. Another approach for utility optimisation is to maximise the use of less expensive utilities in place of more expensive ones. HR may also be optimised to minimise TC. In this regard, exergy analysis in terms of ED has potential to be applied for utility temperature selection, although utility pricing does not always follow exergy changes.

To minimise TC, those utilities that have the potential to optimise Total Site Heat Recovery (TSHR), power generation/consumption, and fuel consumption must be identified. At the first stage, the designer should recognise whether any utility is optimisable in the TS. An optimisable utility refers to any utility that has the capacity to be generated and consumed within the TS, or a utility that has potential to generate shaft work through a turbine in the utility system. In this context, two categories may be defined for utility target temperatures, i.e. fixed (hard) temperatures and soft temperatures. Soft utility target temperatures refer to target temperatures that are non-essential to be achieved that may be changed by varying utility heat capacity flow rates. With a soft target temperature, it becomes difficult to use a utility for TSHR because as it is generated and consumed, the final temperature of the utility is uncertain. Return utility flows from multiple processes may then be mixed together resulting in an unknown average temperature. A higher quality utility is needed to heat or cool the return utility flow to the intended supply temperature of the reverse utility (e.g. a hot utility loses heat to become a cold utility). Hard utility target temperatures refer to temperature constraints that must be met. These utility temperatures have an opportunity to be optimised to increase HR.

TSP in Figure 1 can be divided into three different regions. The process heat deficit region sits above the hottest TSP source temperature, which is derived from the Grand Composite Curves (GCC) in each process (or plant) before the TSP is constructed. The process heat surplus region is below the coldest TSP sink temperature and is again derived from the GCCs. The region in between may be in process heat deficit or surplus depending on the balance between utility generation and consumption. Those utilities that occur within this middle region, which may be generated and consumed, are optimisable to maximise TSHR, Utility C and D in Figure 1.

When Combined Heat and Power (CHP) generation is exploited, more complex utility options are available. Rejected heat from gas turbines and/or boilers with steam turbines may be used to generate or supply hot utility, e.g. steam. In such systems, the utilities that are in the upper region of Figure 1 may provide the potential for SWG through a turbine. These hot utilities can also be considered as optimisable to maximise shaft work, e.g. Utility B. Similarly, for processes which require sub-ambient utility in the lower region of Figure 1, the cold utility requires compressors in refrigeration cycles to generate the needed cooling, Utility F. As a result, the appropriate utility temperature selection, which is considered as optimisable, may lead to minimum work consumption.

In short, any utility that is either connected to a turbine, linked to a refrigeration cycle, or both generated/consumed, is a candidate for temperature optimisation.

UC can be calculated considering hot utility, cold utility, and power generation/consumption prices and targets. Equation 1 presents the UC calculation method.

$$UC = \left(\sum \left(UP_{h,ut(i)} \times Q_{h,ut(i)} \right) + \sum \left(UP_{c,ut(i)} \times Q_{c,ut(i)} \right) - (PP_{gen} \times W_{gen}) \right) \times OP \tag{1}$$

Where *UP* is utility price, *Q* is utility target, *PP* is power price, *W* is power target, and *OP* is operating period of the plant. Subscripts *h,ut* is hot utility, *c,ut* is cold utility, and *gen* is generation. The final term is an offset but not total power cost.

Total Annualised Cost (TC) is calculated using UC and CC as presented in Equation 2.

$$TC = UC + CC \tag{2}$$

Where CC only includes heat exchangers area and infrastructure costs are not considered in this paper.

2.2 The Role of Exergy Analysis in the Total Site Utility Temperature Optimisation

To help select utility temperature levels in the TS, exergy and ED may be analysed. Since there is no chemical reaction, separation or mixing in the utility mains, only physical exergy needs consideration [30].

Exergy is defined as maximum theoretical useful work potential, i.e. shaft work or electrical work, obtainable as two systems interact to equilibrium [31]. Exergy analysis can, therefore, provide insights to process optimisation evaluations. Heat transfer through finite temperature difference always generates entropy and any process that generates entropy always destroys exergy. As a result, ED (X_d) is proportional to the entropy generated (S_{gen}) as in Equation 3.

$$X_d = T_0 S_{gen} \geq 0 \tag{3}$$

Where T_0 is the reference temperature. As it can be seen ED is a positive quantity for any actual process and becomes zero for a reversible process.

Marmoleji-Correa and Gundersen [32] summarised a simple method to determine the temperature based physical exergy of a process flow, as shown in Equation 4.

$$X = \dot{m}c_p \left[T_0 \left(\frac{T}{T_0} - \ln \frac{T}{T_0} - 1 \right) \right] = \dot{m}c_p T_X \tag{4}$$

Exergy can be calculated using Equation 4 when the specific heat capacity has been assumed constant with respect to temperature in the range from *T* to reference T_0. The factor in the square bracket is called exergetic temperature (T_x) and has units of Kelvin. Exergetic temperature is a function of stream temperature in K and the selected zero state temperature, T_0, in K. This equation determines the change in exergy as a process flow heats or cools from its supply to its target temperature.

Figure 2 shows the exergy potential of a single heat exchanger where the hot stream as a heat source has an exergy relative to the T_0, and the cold stream as a heat sink has a lower exergy relative to the T_0. For the ED, it can be said that:

$$X_d = X_{Source} - X_{Sink} \tag{5}$$

The same concept applies to a process plant. Figure 3 illustrates utility-process and process-process EDs on a Balanced Composite Curve (BCC). BCCs are particularly useful to demonstrate the effects of multiple utilities, multiple Pinch Temperatures and the driving force in the HEN of a process. Non-isothermal utilities are normally shown as a diagonal segment in enthalpy-temperature plots while isothermal utilities are shown as a horizontal segment. It is not always easy to distinguish non-isothermal utilities, such as hot water, on a BCC because it often composites with the process streams [33]. However, BCC is still a useful tool to provide a clear visualisation for ED of heat transfer within a processing system.

In Figure 3, three different regions can be recognised: (a) utility source-process sink ED, (b) process source-process sink ED, and (c) process source-utility sink ED. Each of these regions presents exergy transfer and destruction within the process based on the available exergy sources and sinks. As a result, total exergy destruction of the plant can be demonstrated by Equation 6.

$$X_d = \sum X_{Source} - \sum X_{Sink} \tag{6}$$

Figure 4 shows how ED applies to a TS. Figure 4a illustrates the ED region in the TSP. Figure 4b shows that by shifting utility temperatures, ED has been increased for small regions on both sides of TSP while it has decreased for most other regions. In Figure 4b, shifted utility temperature levels are illustrated in solid lines and original utility temperature levels from Figure 4a are illustrated in dashed lines. In summation, total exergy destruction has been reduced because of the utility temperature change. Equation 3 can be applied to analyse TS which determines utility-process ED for entire TS due to heat transfer.

Figure 4c shows the work generation potential using the Site Utility Grand Composite Curve (SUGCC). When the HR increases (solid utility lines), power generation often decreases. While in the Figure 4d, the same concepts of ED reduction apply. Shifting utility temperatures towards the Total Site Pinch region shows an effect on ED resulting in increased HR across the TS and slightly higher power generation for this example. There is a complex trade-off between power generation, HR, and ED that must be considered when analysing the selection of utility temperatures.

The smaller temperature difference between the hot and cold available utilities in the TS may offer lower ED and a reduction in UCs through improved HR. Improved temperature selection in the TS may provide the opportunity to reduce energy consumption within the TS as the result of a decrease in ED (i.e. shifting utility temperatures towards the Total Site Pinch will cause a reduction in ED). There is a trade-off between hot and cold utility temperature difference in the TS and total heat transfer area, which affects CC and finally TC. TC is normally the final objective function in the optimisation of TS targets. To select utility temperatures, a temperature range may be considered for each required utility.

3 Method

3.1 Overview

Utility supply and target temperatures can be selected by using the derivative of the objective function. Derivatives provide a direction to change utility temperatures and improve the key TS metrics. Three different approaches are investigated to find the best sequential combination of derivative objective functions in the optimisation procedure.

- Approach 1: Minimise the derivative of the TC function with respect to temperature, which may be approximated numerically using Equation 7.

$$\frac{dTC}{dT} \cong \frac{TC(T_i \pm \Delta T) - TC(T_i)}{\Delta T} \quad (7)$$

Where subscript, *i* is representing each individual utility temperature for either supply or target temperature (hot or cold sides of the utility) and ΔT is a small change in temperature (step change).

In this approach, the TC derivative is minimised given the initial utility temperature selection. One of the challenges with this method is, TC functions are discontinuous functions due to changes of the number of utility and number of heat exchangers. This means the function contains numerous local minima.

- Approach 2: Minimise the derivative of the UC, then sequentially minimise the derivative of the TC (UC+TC). UC derivative may be presented as:

$$\frac{dUC}{dT} \cong \frac{UC(T_i \pm \Delta T) - UC(T_i)}{\Delta T} \tag{8}$$

This approach includes a two-step process: first, minimise the derivative of UC iteratively, then, second, minimise the derivative of TC. But the UC function tends to be more continuous but still can have local minima in the form of flat regions. This was demonstrated recently by Tarighaleslami et al. [18].

- Approach 3: Minimise the derivative of the UC iteratively with the derivative of ED, then sequentially minimise the derivative of the TC (UC+ED+TC). Where ED derivative can be presented as:

$$\frac{dX_d}{dT} \cong \frac{X_d(T_i \pm \Delta T) - X_d(T_i)}{\Delta T} \tag{9}$$

The third approach, similar to the second approach, includes a two-step process: first, minimise the derivative of UC iteratively and, when constant (flat), minimise the derivative of ED, then, second, minimise the derivative of TC. It is important to understand that UC functions tend to be continuous with many flat sections where a change in temperature has no impact on UC. In this region, it becomes necessary to apply the derivative of ED as the objective, which is not flat. The logic for initially minimising UC with ED is to help select temperatures that are more likely in the proximity of the global optimum, from which starting point a TC minima may be located. The TC local minimum is not guaranteed to be the global optimum.

3.2 Detailed Method and Software Tool Development

An Excel^{TM} spreadsheet software tool has been developed over the past several years based on conventional and new Unified Total Site Integration (UTSI) approaches. The UTSI software was recently extended to include the improved TSHI method of Tarighaleslami et al. [19] as well as the new utility optimisation procedure. Figure 5 presents the detailed utility optimisation procedure. New steps have been added to the TSHI targeting procedure to complete utility selection and optimisation procedure for any available TSHI method.

There are a few important reasons why the new Unified Total Site Targeting (UTST) method of Tarighaleslami et al. [19] is applied in this study as opposed to conventional TSHI. UTST performs utility targeting at the process level using the GCC. This method considers more constraints around meeting supply and target temperatures of utilities, especially for non-isothermal utilities, within individual processes. As a result, the UTST 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 independently with different schedules. By adding this new constraint, the calculated targets become more achievable and realistic.

Step 1: Objective function derivatives calculation

A derivative map can be constructed using the framework presented in Table 1 for each utility. The first column presents the temperature ranges for hot and cold sides of each utility while optimising utility temperatures. Eight different options can be considered as either hot, cold or both hot and cold sides of the utility may change. The temperature step ΔT_s represents the amount of change in the utility temperature for each iteration in the procedure. The smaller temperature step, the less convergence time and the more accurate temperature selection. However, it may be trapped in local optimum as opposed to converging in an overall optimum in the HR function. Therefore, for each of the main objective functions, eight different subset rows have been defined, as it is shown in Table 1. In other words, supply and target temperatures of each utility are monitored separately. However, according to temperature ranges and the nature of the utility, the temperature step may vary.

The next three columns represent one of the objective function derivatives as presented in section 3.1, where subscript *i* is representing each individual temperature point at either supply or target temperatures of the utility.

Step 2: Objective function selection

In this step, initially, the objective function can be selected then in each iteration, the selected objective function (or the objective function which is in the iteration) goes to the related direction A or B in Figure 5. This step can lead optimisation procedure for a different combination of objective functions. Two question boxes can lead the procedure back to Step 2 or Step 5 if the iteration is not the first iteration.

Step 3: Selection of appropriate value from the derivative map

The most negative value, i.e. a reduction in cost, utility, or ED, for the objective function is located on the derivative map, which shows the highest potential for improvement, and identifies the utility, its temperature and the direction that it should be changed. The utility corresponding to this value must be selected in this step.

Step 4: Utility temperature re-selection

After identifying the best utility temperature to change, whether utility generation turns to utility consumption or vice versa, ΔT_s must be divided by half and the shift backwards or forwards to converge to the optimum; i.e. new ΔT_s can be added or subtracted to the utility temperature. After changing the utility temperature, the process is re-targeted according to the TSHI targeting method which is used, and the derivative map is re-calculated. This procedure may be repeated unless the result converges.

After the first iteration, the optimisation procedure may lead to step 5:

Step 5: Objective function check

The value obtained for the objective function (UC or ED) from the derivative map should be checked. If the value is negative it means there is a potential to improve the objective function by increasing or decreasing its supply/target temperature by ΔT_S. Therefore, the procedure goes back to Step 3; otherwise, it should be checked that if ED is the optimised objective function and/ or if it is targeted that ED be an objective function. The answer may lead the procedure either to Step 6 or Step 7.

Step 6: ED derivative check

In this step, ED is to be checked. The ED negative values represent the potential of further improvement. Therefore, if the corresponding value to the most negative ED value in the other objective function, i.e. UC, is equal to zero or negative, then the utility temperature still can be improved.

Step 7: TC objective function check

This step is similar to step 5 and 6, but this time the value obtained for the TC column from the derivative map should be checked. The negative value means there is a potential to improve the objective function by increasing or decreasing its supply/target temperature by ΔT_s. For negative values go to Step 3, otherwise, there will not be any more potential to improve selected utility temperature, which means all the utility temperatures are optimal.

There are several advantages of this new method compared to the other methods. The exergy analysis is based on exergetic temperatures, which have a linear relationship to exergy flow. Previous TSHI exergy targeting methods were based on converting temperature to Carnot factor and plotting an efficiency-enthalpy diagram. The new method is a derivative based technique that can be programmed while conventional methods are heuristic based [25], which are difficult to automate. In the specific case of Hui and Ahmed [25], only some GCC segments are collected for TSHI, which can lead to significantly reduced HR. Hui and Ahmed [25] also based the pricing of utility on exergy as opposed to actual prices as done in this paper. Furthermore, the TSHI targeting method [19] used as part of the optimisation is improved from conventional approaches [3]. Finally, none of the other methods considers non-isothermal utility optimisation within the same procedure as isothermal utilities.

4 Utility Temperature Optimisation Results for Three Industrial Case Studies

Three case studies have been considered to illustrate the derivative optimisation procedure, namely: the Södra Cell Värö Kraft Pulp Mill plant [34], a Petrochemical Complex [19] and a large Dairy Factory in New Zealand [19].

Table 2 presents TS characteristics of each case study considered.

Capital and energy costs are estimated in New Zealand dollars (NZD). Energy cost for utilities is estimated to be NZD 5 /MWh for cooling utilities, NZD 30 /MWh for heating utilities, NZD 40 /MWh for chilled water (ChW), and NZD 100 /MWh for power generation. To calculate the CC for all case studies, investment return duration (*n*) has been set to 10 years with 7 % interest rate (*j*). It has been assumed that plate and frame heat exchangers are chiefly required in the dairy factory and shell and tube heat exchangers for the pulp mill and petrochemical case studies. Heat exchanger cost can be calculated based on required heat exchanger area according to Equation 10 [35] and cost parameters are taken from Statistics New Zealand Infoshare [36] data as is shown in Table 3. Note that to calculate the total CC, infrastructure cost such as civil, steel structure, and piping costs are not considered.

$$CC = \left(a + (b \times A^{c})\right) \times \left(\frac{j \times (1+j)^{n}}{(1+j)^{n} - 1}\right) \tag{10}$$

Where A is the heat transfer area in m^2, and a, b, and c are cost coefficients and exponent relating to the heat exchanger type, as given in Table 3.

4.1 Case Study I: Södra Cell Värö Kraft Pulp Mill plant

Södra Cell Värö Kraft Pulp Mill plant in southern Sweden [34] has been chosen as the first case study. Initial utility streams as a base case for the optimisation procedure, are taken from Tarighaleslami et al. [19] to cover the required temperature ranges in TSHI as shown in Table 4. The Very High Pressure Steam (VHPS) which enters to the turbine is taken at 450 °C and 90 bar$_g$ [18]. Shaft work targets are based on the SUGCC in conjunction with the Medina-Flores and Picón-Núñez turbine model [37]. All utilities presented in Table 4 except cooling water have been considered as an optimisable utility according to the described definition in the method section as it is clear in Table 4.

Figure 6 illustrates a comparison of utility targets of the base case, in dashed lines, compared to the optimised case in solid lines using original utility temperatures as a starting point in both TSP and SUGCC.

Targeting has been repeated considering three different approaches. Table 5 compares the optimised temperatures obtained by applying optimisation procedure. Table 6 demonstrates targeting results for three different optimisation criteria for the case study. It shows 43.1 MW of TSHR, 37.1 MW of SWG, NZD 14,618,951 /y UC, 77 heat exchanger units, and NZD 16,408,482 /y TC.

The optimised case, UC+ED+TC criteria, shows a 4.1 % increase in TSHR, 1.0 % increase in SWG, reduction of one heat exchanger unit, and a 4.51 % decrease in TC compared to other two criteria which have lower TC reduction. As can be seen in Table 6 for all three different cases, SWG and UC are identical. However, ED increases in the third case while TC has been reduced. This is due to LTHW optimal temperature (57 °C) that increases temperature driving force that led the total required heat transfer area to be decreased while total heat exchangers reduced by one unit. TC decreases up to 4.5 %.

4.2 Case Study II: Petrochemical Complex

This case study demonstrates the advantages of the implementation of the new optimisation method to plants that typically operate at high temperature ranges. The plant utilities are presented in Table 7. SWG is not considered in this case study.

As can be seen in Figure 7a, Medium Pressure Steam (MPS) and LPS are considered as an optimisable utility. In the Figure 7 base case utility targets, in dashed lines, has been compared with optimised targets in solid lines using original utility temperatures as a starting point for both TSP and SUGCC.

The case study has been targeted and repeated for all three different criteria. The initial utilities used as starting point and the result optimised utilities in each criterion are presented in Table 8. Targeting results are presented in Table 9. In this case, optimisation based on TC as an individual objective function has a lower reduction in TC (-2.52 %) while other two criteria show identical TC reduction (-3.36 %). This means that when the TS is optimised considering UC as the objective function, the optimal temperatures are used as the starting point for the next optimisation step where TC is the objective function. The dual optimisation function approach requires fewer iterations and enables an improved target to be achieved. However, in this case, the benefit of including ED in the procedure is negligible since the UC+TC approach and UC+ED+TC approach achieve the same final results.

4.3 Case study III: New Zealand Dairy Processing Factory

A large dairy factory in New Zealand has been chosen for the last case study and details are illustrated in Table 2. All processes in the factory, which is considered as TS, have recently been investigated and integrated to industry best practice. However, further improvements have been achieved by using UTST method [19]. Table 10 presents initial utilities which are used in the plant. As it is illustrated in Table 10 only LTHW has the conditions to be optimisable utility.

Figure 8a shows TSP comparison between the Base Case targets using original utility temperatures as a starting point, in dashed lines, and optimised targets in solid lines using the same starting points. As can be seen hot utility targets, utility heat surplus, are identical before and after optimisation but in cold utility side, utility heat deficit, LTHW has been slightly improved. The similar comparison is illustrated for SUGCCs in Figure 8b which shows TSHR has been increased about 100 kW.

Surprisingly, Tables 11 and 12 show that the optimisation results of all three criteria are identical in this case study. This might be due to a couple of reasons, first, the LTHW is a non-isothermal utility that has only 9.5 % of total heat load in both heat surplus and heat deficit sides of TS which after optimisation is fully balanced. This means the utility has the exact amount of generation and consumption as shown in Figure 8. Second, as mentioned above the plant is highly efficient as a consequence of recent optimisation planning and also TS targets are now more realistic and accurate based on UTST method [19]. However, the optimisation targets could still decrease TC by 0.62 % and increase TSHR by 5.0 % while increasing number of heat exchangers units by one.

5 Additional Analysis of the Södra Cell Värö Kraft Pulp Mill

5.1 The Effect of the Utility Price on Optimal Utility Temperature Selection

The utility price plays a significant role in the TC. It may vary site to site and/or location to location. In this section, the effect of the utility price on the optimisation procedure has been studied. The optimisation procedure has been repeated for 5 different hot utility prices (25, 30, 35, 40, and NZD 45 /MWh) in the Kraft Pulp Mill case study. In all cases of different hot utility prices, identical utility optimal temperatures were achieved for all optimisable utilities in the TS as shown in Figure 9. This means the optimal utility temperatures are weakly dependent on the utility price for the utility price range that has been studied.

Figure 10 illustrates the changes of the UC and TC based on the optimisation results, and the TC saving in each case with the different hot utility unit price. For each unit price, the optimisation result has been compared to its original unit price based on the case study's targets. As it can be seen in Figure 10, by increasing the hot utility price in the plant, the reduction in the UC and TC may decrease based on the initial results. However, the net annual cost saving increases from NZD 664,574 /y, which is a 7.1 % cost reduction for NZD 25 /MWh to NZD 960,804 /y, which is 2.6 % cost reduction for NZD 45 /MWh.

5.2 The Effect of the Number of Utility Mains on Optimal Utility Temperature Selection

The number of utility mains can greatly affect TSHR, utility and CCs as well as TC. In this additional analysis, only four utility mains have been chosen for the Kraft Pulp Mill plant compared to the previous five utility mains to quantify the impact on TC. HTHW and LTHW have merged together as a single Hot Water (HW) utility. Optimised utility temperatures for the new scenario are presented in Table 13.

The new scenario of four utility mains has been targeted with and without optimisation. Results are presented in Table 14. After optimisation for the four utility mains case, TC has decreased by 4.59 %, which offers NZD 773,406 /y of TC savings. As a percentage, this reduction is not significantly higher than the previous analysis using five utility mains including HTHW and LTHW. In terms of absolute TC, the optimised four utility mains case is 2.6 % higher than the optimised five utility mains case, NZD 406,031 /y (Table 6) In future work, the TC trade-off will include other capital costs, such as piping and civil works infrastructure, to correct choose between four or five utility mains.

5.3 Sensitivity Analysis of Optimisation Method

A sensitivity analysis has been carrying out for the Kraft Pulp Mill case study to determine how parameters such as the temperature starting point and the temperature step size may affect optimisation procedure and its results. At the first stage, two sets of different starting utility temperatures, Cases 1 and 2 in Table 15, have been selected to be applied to the presented procedure. Results have been compared with the optimised results from Section 4.1 based on the original utility temperature as a Base Case.

Table 16 presents the TS targets for the all three optimised cases from Table 15. The optimisation procedure converges to similar optimal temperatures for the three cases with a couple of exceptions. The optimised hot side temperature of the LTHW in Case 1 differs from the Base Case, which very slightly lowers the TC target. In Case 2, HPS does not converge to the same temperature as the other cases, which affects its TS target. SWG decreases by 2.7 % and TC increases by 14 % compared to the Base Case.

Appropriate selection of the initial utility temperatures is important. Utility temperatures may be selected by experience and in conjunction with viewing the TSP where the shape provides valuable information about potential utility mains temperatures. As can be seen in Figure 6, the heat sink profile has a flat region around 157 °C and a steep slope in temperature range immediately below 157 °C. If an isothermal utility, i.e. LPS, temperature is chosen below 157 °C, the optimal temperature may not converge above the region's higher boundary. As a result, a logical initial temperature for LPS is >157 °C, as selected in the Base Case.

Different step sizes have been considered to study the sensitivity of the presented optimisation procedure. The procedure has been carried out using initial 16 °C step size. It has been repeated for 0.1, 1.0, 8.0, and 24.0 °C. Table 17 shows the optimal temperatures for different step sizes. The original temperatures are considered as the utility temperature starting points and targets are repeated for each step size. As it can be seen in Table 17, for 8.0 °C and 24.0 °C step size, the same optimal temperature can be achieved. For the 1.0 °C, only cold side of HTHW converged 1.8 °C lower than the optimal case. For the very small step size (0.1 °C) final temperatures did not converge as it may be due to the local optimums of the optimisation function.

Table 18 presents TS targets deviation from the initial 16 °C optimal temperature results after optimisation carried out using different step sizes. Only the deviation of the 0.1 °C step size can be taken into an account as it is not converging the optimal utility temperature. It means, it is not easy to adjust utility temperatures by very small amounts due to operational uncertainties such as heat loss and hydraulic difficulties. Therefore, from both Table 17 and

18 it can be said that step size does not have a direct effect on optimisation procedure; however, smaller step sizes may not present accurate results due to unpredicted optimums in objective functions. On the other hand, larger step sizes can cover a wide range of objective function in the mathematical procedure; thus, larger step sizes may present more accurate results.

6 Conclusions

A new improved Total Site Heat Integration utility temperature selection and optimisation procedure has been demonstrated using three industrial case studies. None of the existing optimisation and utility temperature procedures addressed non-isothermal utility selection and optimisation incorporated isothermal utilities in the same procedure. The concept of the optimisable utility and three optimisation parameters such as Utility Cost (UC), Exergy Destruction (ED), and Total Annualised Cost (TC) have been included in the procedure. Results show that TC slightly improves when UC derivatives are considered in the optimisation compared to the case with considering only TC derivatives. However, the best optimal results are based on minimising the derivative of the UC iteratively with the derivative of ED, then sequentially minimise the derivative of the TC where TC decreases for three case studies in the range of 0.5 to 4.6 %.

Variation of utility prices in different plants may affect the TC. Results show that hot utility prices from 25 to NZD 45 /MWh had many minimal effect optimal utility temperature section. However, the optimal temperature may not be affected by utility prices. Changing the number of the utility mains can affect the TS targets as well as UC, CC and TC. Kraft Pulp Mill case study results revealed that lower hot utility price shows a higher proportion of TC reduction, while quantitatively, it has lower TC savings per annum. However, all options must be studied to find the best combination of the utilities. The optimisation procedure has a very low objective function deviation from optimal results as only very small temperature step sizes may show about 1 % deviation from optimal results. Presented optimisation method converges any chosen starting points to an identical optimal temperature. However, due to the temperature function of each case, the arrangement of Total Site Profiles must be considered. Smaller temperature step size may accelerate the optimisation procedure when it halves at any iteration while optimisation procedure is in progress. Also, larger step sizes may cover a wider range of temperature function; therefore, the chances to converge on lower optimums may be reduced.

The optimisation procedure has been examined via developed software tool based on Unified Total Site targeting method presented in authors' previous work. The procedure can be applied for both retrofit and grassroots design in an industrial plant as all temperatures converge to an identical optimal temperature in each utility.

Acknowledgements

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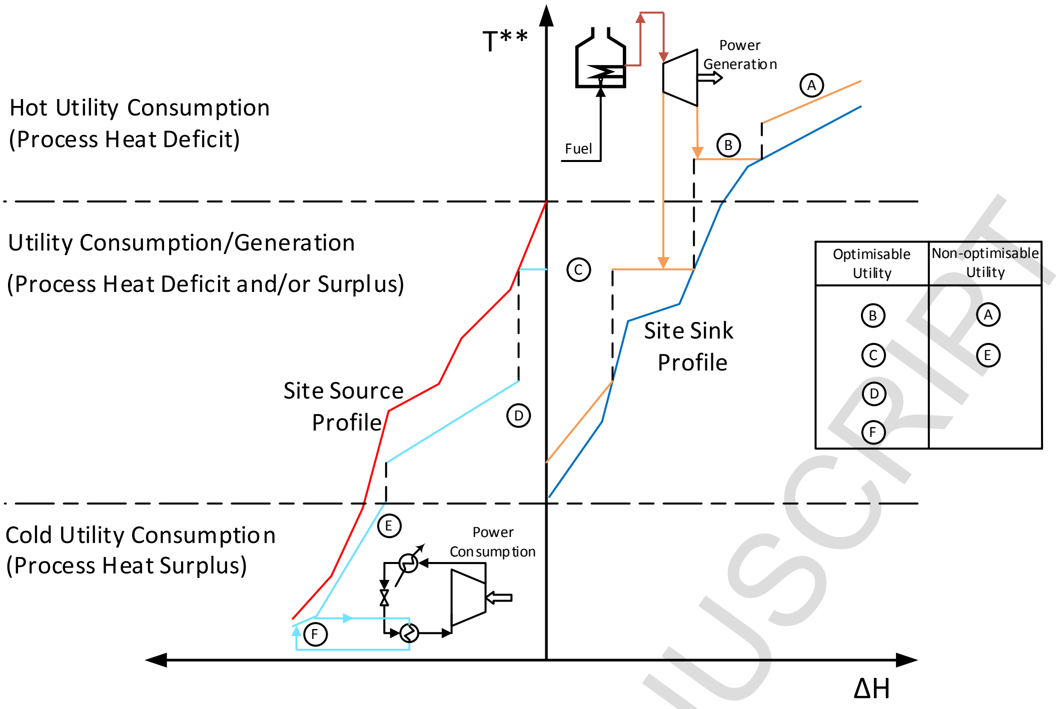


Figure 1: Possibility of utility to be optimised in a typical TSP.

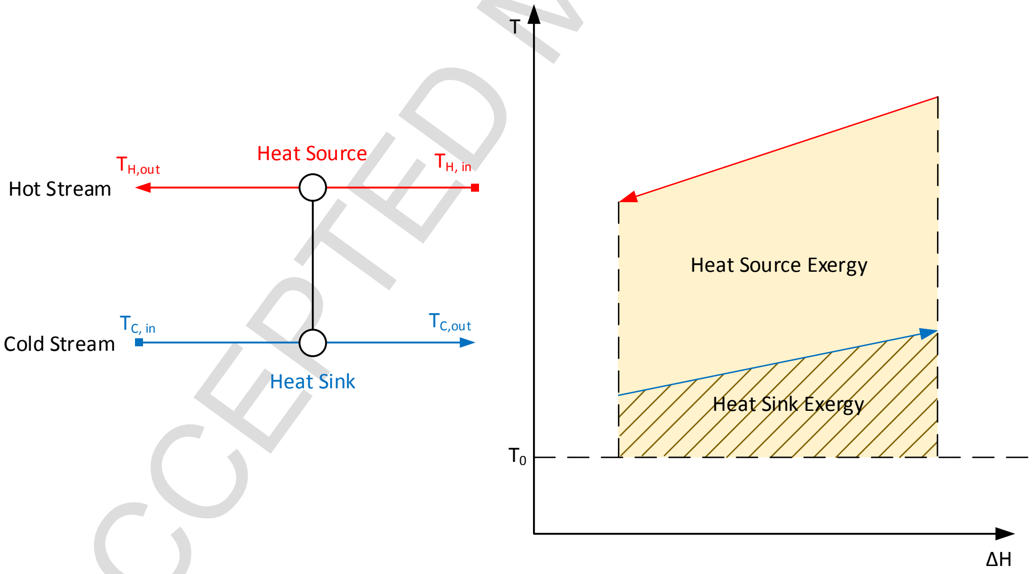


Figure 2: Exergy analysis of a single heat exchanger

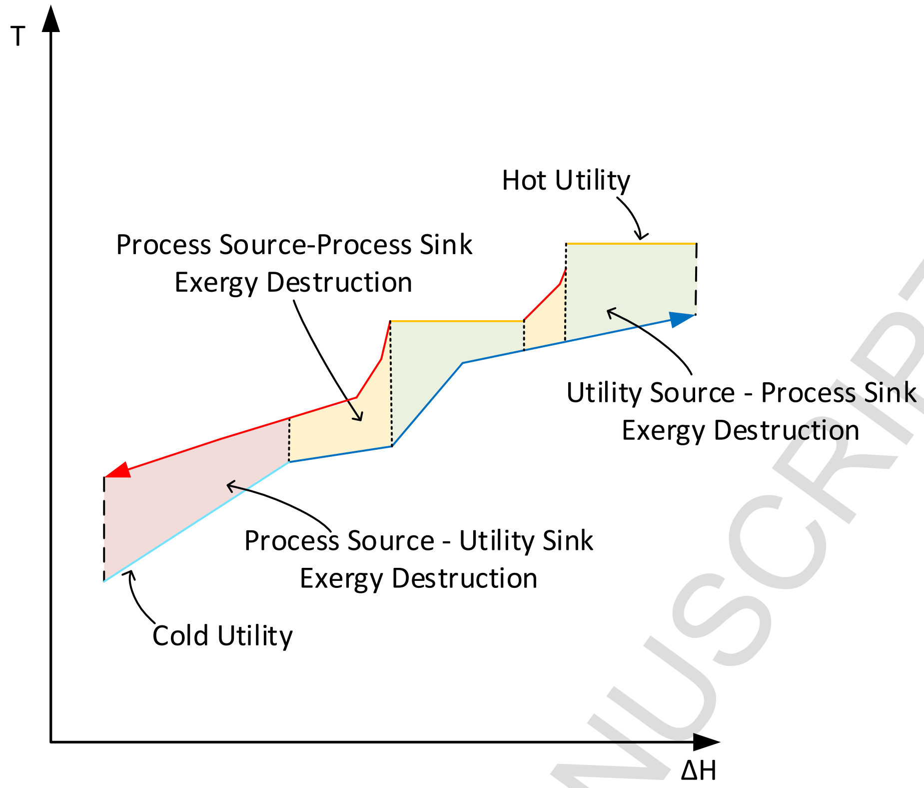


Figure 3: Utility-Process and Process-Process ED in a single process BCC.

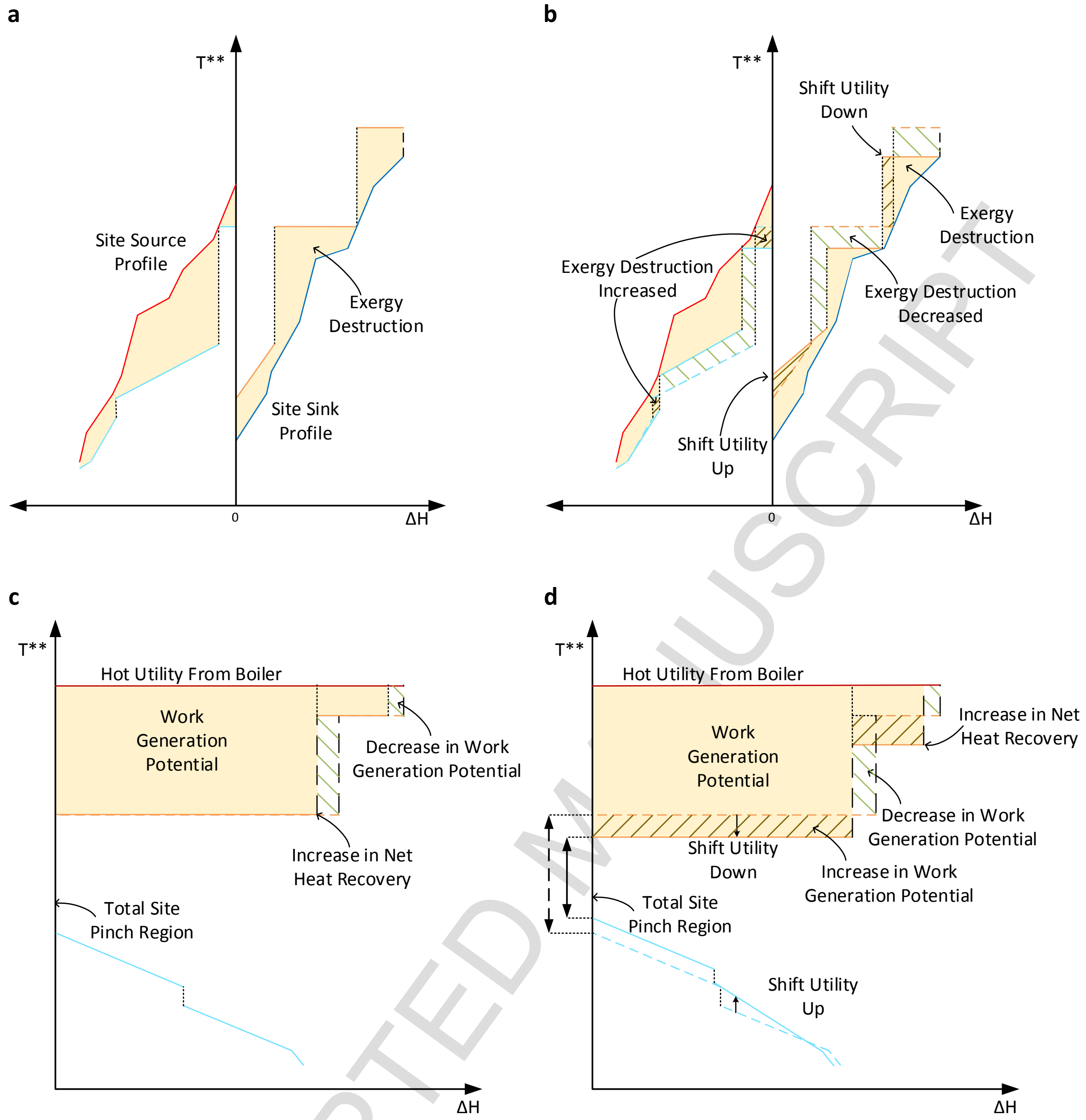
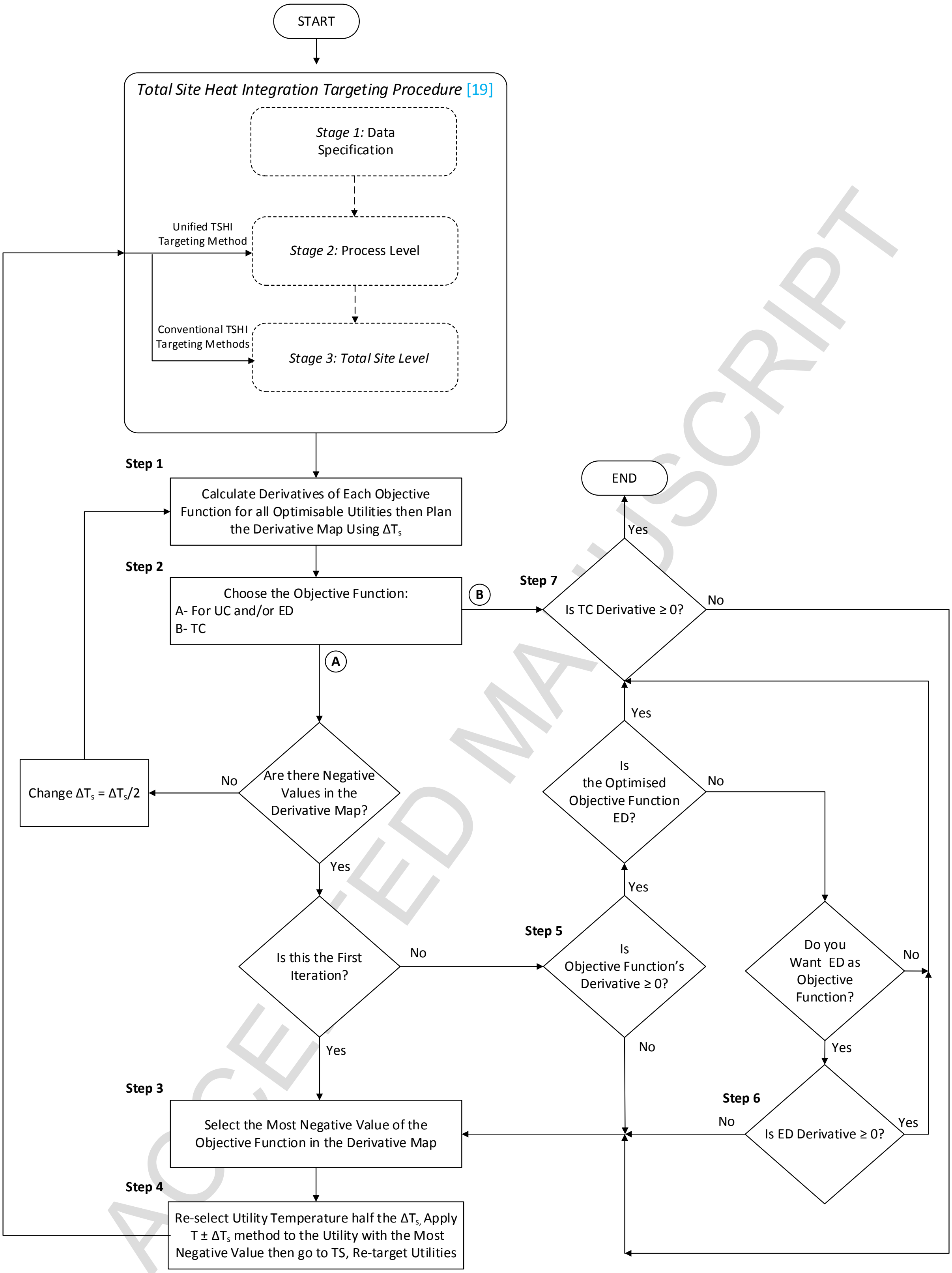


Figure 4: a) Total ED in a typical TSP; b) Total exergy destruction as results of utility shifts; c) Typical SUGCC HR and power generation trade-off; d) Complex trade-off between power generation, HR, and ED after utility shifts



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761 Figure 5: Optimisation procedure for Unified TSHI method.

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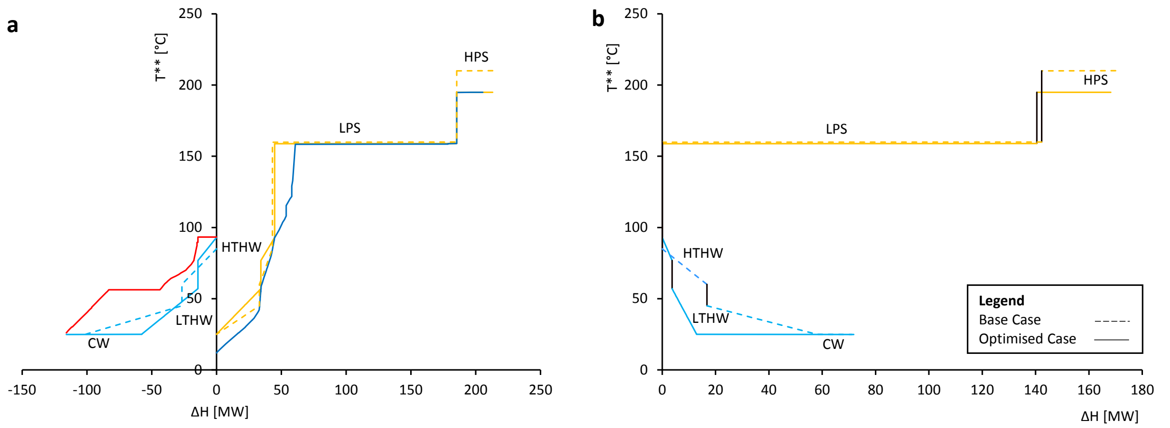


Figure 6: Comparison of the base case and optimised case a) TSP and; b) SUGCC, for Kraft Pulp Mill case study.

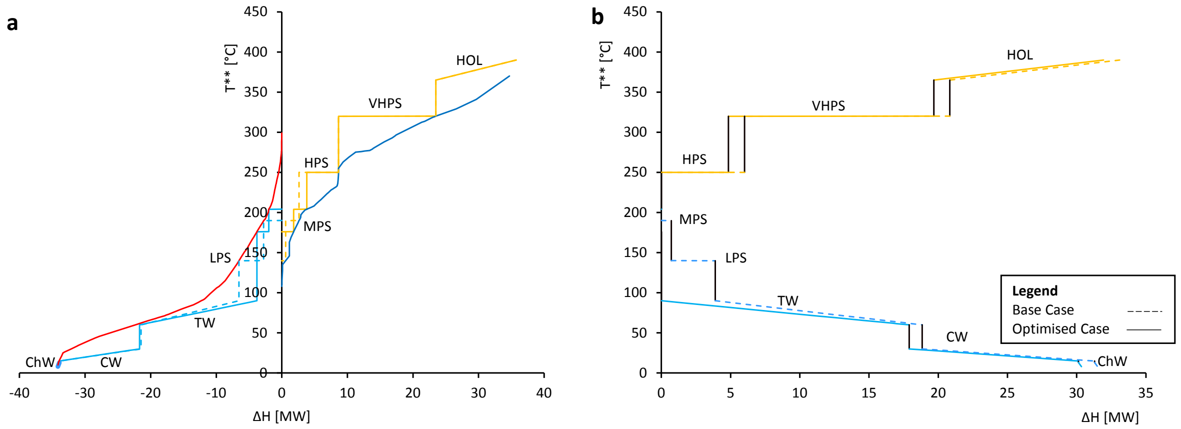


Figure 7: Comparison of the base case and optimised case a) TSP and; b) SUGCC, for Petrochemical Complex case study.

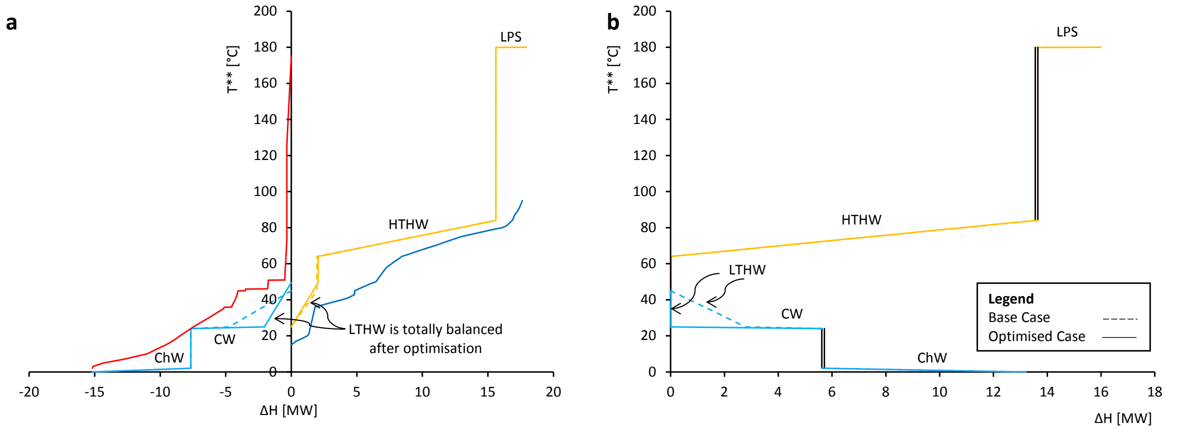
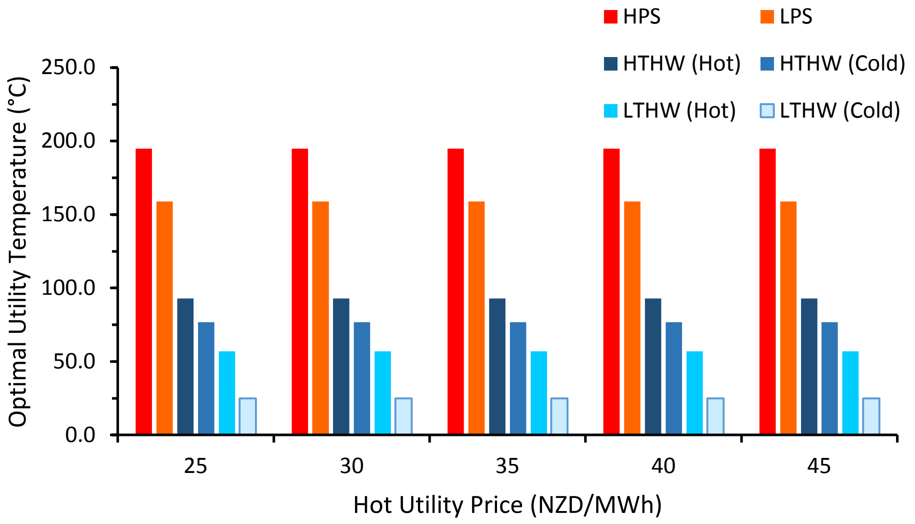


Figure 8: Comparison of the base case and optimised case a) TSP and; b) SUGCC, Dairy Factory case study.



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774 Figure 9: The effect of hot utility price on optimal utility temperatures for optimisable utilities in the Kraft Pulp
775 Mill Case study.

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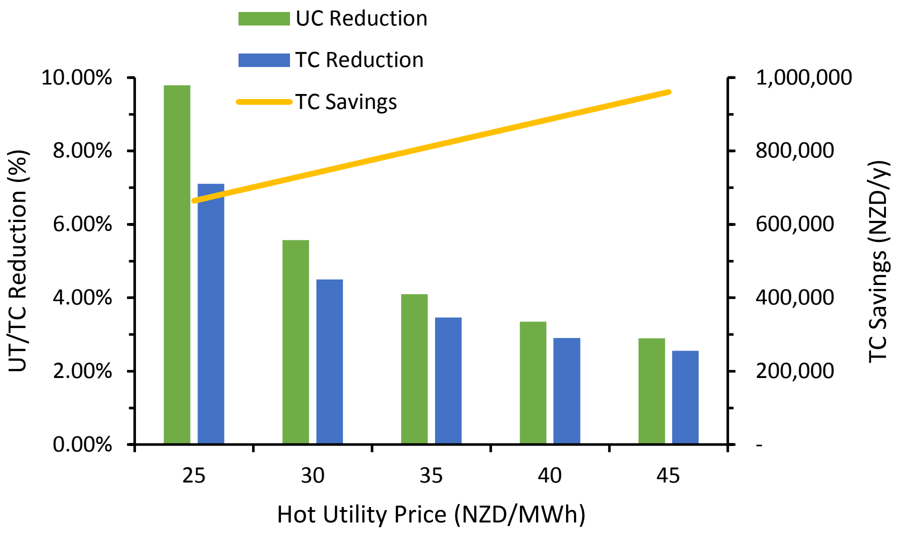

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778 Figure 10: Changes in the percentage of UC and TC reduction, and TC savings for different hot utility prices in
779 the Kraft Pulp Mill Case study.

Table 1: A general framework to construct a derivative map for a utility.

Temperature Ranges	Objective Function Derivative		
T_{Cold}, T_{Hot} (°C)	Utility Cost $\frac{dUC}{dT}$ (NZD/°C)	Exergy Destruction $\frac{dX_d}{dT}$ (kW/°C)	Total Annualised Cost $\frac{dTC}{dT}$ (NZD/°C)
$T_{c,i}$, $T_{h,i}+\Delta T_s$	$\frac{UC(T_{c,i},T_{h,i}+\Delta T_s)-UC(T_{c,i},T_{h,i})}{\Delta T_s}$	$\frac{X_d(T_{c,i},T_{h,i}+\Delta T_s)-X_d(T_{c,i},T_{h,i})}{\Delta T_s}$	$\frac{TC(T_{c,i},T_{h,i}+\Delta T_s)-TC(T_{c,i},T_{h,i})}{\Delta T_s}$
$T_{c,i}$, $T_{h,i}$-ΔT_s	$\frac{UC(T_{c,i},T_{h,i}-\Delta T_s)-UC(T_{c,i},T_{h,i})}{\Delta T_s}$	$\frac{X_d(T_{c,i},T_{h,i}-\Delta T_s)-X_d(T_{c,i},T_{h,i})}{\Delta T_s}$	$\frac{TC(T_{c,i},T_{h,i}-\Delta T_s)-TC(T_{c,i},T_{h,i})}{\Delta T_s}$
$T_{c,i}+\Delta T_s$, $T_{h,i}$	$\frac{UC(T_{c,i}+\Delta T_s,T_{h,i})-UC(T_{c,i},T_{h,i})}{\Delta T_s}$	$\frac{X_d(T_{c,i}+\Delta T_s,T_{h,i})-X_d(T_{c,i},T_{h,i})}{\Delta T_s}$	$\frac{TC(T_{c,i}+\Delta T_s,T_{h,i})-TC(T_{c,i},T_{h,i})}{\Delta T_s}$
$T_{c,i}$-ΔT_s , $T_{h,i}$	$\frac{UC(T_{c,i}-\Delta T_s,T_{h,i})-UC(T_{c,i},T_{h,i})}{\Delta T_s}$	$\frac{X_d(T_{c,i}-\Delta T_s,T_{h,i})-X_d(T_{c,i},T_{h,i})}{\Delta T_s}$	$\frac{TC(T_{c,i}-\Delta T_s,T_{h,i})-TC(T_{c,i},T_{h,i})}{\Delta T_s}$
$T_{c,i}+\Delta T_s$, $T_{h,i}+\Delta T_s$	$\frac{UC(T_{c,i}+\Delta T_s,T_{h,i}+\Delta T_s)-UC(T_{c,i},T_{h,i})}{\Delta T_s}$	$\frac{X_d(T_{c,i}+\Delta T_s,T_{h,i}+\Delta T_s)-X_d(T_{c,i},T_{h,i})}{\Delta T_s}$	$\frac{TC(T_{c,i}+\Delta T_s,T_{h,i}+\Delta T_s)-TC(T_{c,i},T_{h,i})}{\Delta T_s}$
$T_{c,i}+\Delta T_s$, $T_{h,i}$-ΔT_s	$\frac{UC(T_{c,i}+\Delta T_s,T_{h,i}-\Delta T_s)-UC(T_{c,i},T_{h,i})}{\Delta T_s}$	$\frac{X_d(T_{c,i}+\Delta T_s,T_{h,i}-\Delta T_s)-X_d(T_{c,i},T_{h,i})}{\Delta T_s}$	$\frac{TC(T_{c,i}+\Delta T_s,T_{h,i}-\Delta T_s)-TC(T_{c,i},T_{h,i})}{\Delta T_s}$
$T_{c,i}$-ΔT_s , $T_{h,i}+\Delta T_s$	$\frac{UC(T_{c,i}-\Delta T_s,T_{h,i}+\Delta T_s)-UC(T_{c,i},T_{h,i})}{\Delta T_s}$	$\frac{X_d(T_{c,i}-\Delta T_s,T_{h,i}+\Delta T_s)-X_d(T_{c,i},T_{h,i})}{\Delta T_s}$	$\frac{TC(T_{c,i}-\Delta T_s,T_{h,i}+\Delta T_s)-TC(T_{c,i},T_{h,i})}{\Delta T_s}$
$T_{c,i}$-ΔT_s , $T_{h,i}$-ΔT_s	$\frac{UC(T_{c,i}-\Delta T_s,T_{h,i}-\Delta T_s)-UC(T_{c,i},T_{h,i})}{\Delta T_s}$	$\frac{X_d(T_{c,i}-\Delta T_s,T_{h,i}-\Delta T_s)-X_d(T_{c,i},T_{h,i})}{\Delta T_s}$	$\frac{TC(T_{c,i}-\Delta T_s,T_{h,i}-\Delta T_s)-TC(T_{c,i},T_{h,i})}{\Delta T_s}$

Table 2: Total Site characteristics for each case study.

Case study	No. of processes	No. streams available in TS	ΔT_{min} (°C)	Operating Period (h/y)
Kraft Pulp Mill Plant	10	64	10	8,300
Petrochemical Complex	8	60	20	8,600
Dairy Factory	15	79	5	5,500

Table 3: CC parameters for Shell and Tube, and Plate and Frame heat exchangers.

Heat Exchanger Type	a	b	c
Shell and Tube	0	5,870	0.57
Plate and Frame	4,265	649	1.00

Table 4: Initially required utilities for Kraft Pulp Mill case study.

Utility Name	Utility Type	T_{Cold} (°C)	T_{Hot} (°C)	Pressure Range (bar_g)
HPS	Hot		210.0	15
LPS	Hot		160.0	9
HTHW	Hot	85.0	60.0	
LTHW	Cold	25.0	45.0	
CW	Cold	25.0	*	

*Soft utility temperature

Table 5: Optimised utility temperatures comparison for different three criteria in Kraft Pulp Mill case study.

Optimisation Criteria	Isothermal Utility		Non-Isothermal Utility				
	HPS	LPS	HTHW		LTHW		CW
	T_{Hot} (°C)	T_{Hot} (°C)	T_{Hot} (°C)	T_{Cold} (°C)	T_{Hot} (°C)	T_{Cold} (°C)	T_{Cold*} (°C)
Original Utilities	210.0	160.0	85.0	60.0	45.0	25.0	25.0
TC	194.9	158.9	93.0	76.8	46.0	25.0	25.0
UC+TC	194.9	158.9	93.0	76.8	46.0	25.0	25.0
UC+ED+TC	194.9	158.9	93.0	76.8	57.0	25.0	25.0

*Soft utility target temperature (T_{Hot})

Table 6: Utility targets comparison for different three criteria in Kraft Pulp Mill case study.

Optimisation Criteria	Heat Exchanger Unit Target	TSHR Target	SWG	ED	UC	TC	Change
	#	kW	kW	kW	NZD/y	NZD/y	%
Original Utilities	77	43,061	37,027	19,095	14,618,951	16,408,482	-
TC	76	44,845	37,384	19,107	13,804,364	15,675,136	-4.47
UC+TC	76	44,845	37,384	19,107	13,804,364	15,675,136	-4.47
UC+ED+TC	76	44,845	37,384	20,242	13,804,364	15,669,850	-4.51

Table 7: Initially required utilities for Petrochemical Complex case study.

Utility Name	Utility Type	T_{Cold} (°C)	T_{Hot} (°C)	Pressure Range (bar_g)
HOL	Hot	390.0	365.0	
VHPS	Hot		320.0	65
HPS	Hot		250.0	15
MPS	Hot		190.0	9
LPS	Hot		140.0	5
TW	Cold	60.0	90.0	
CW	Cold	15.0	30.0	
ChW	Cold	8.0	13.0	

Table 8: Optimised utility temperatures comparison for different three criteria in Petrochemical Complex case study.

Optimisation Criteria	Isothermal Utility				Non-Isothermal Utility							
	VHPS	HPS	MPS	LPS	HOL		TW		CW		ChW	
	T_{Hot} (°C)	T_{Hot} (°C)	T_{Hot} (°C)	T_{Hot} (°C)	T_{Hot} (°C)	T_{Cold} (°C)	T_{Hot} (°C)	T_{Cold} (°C)	T_{Hot} (°C)	T_{Cold} (°C)	T_{Hot} (°C)	T_{Cold} (°C)
Original Utilities	320	250	190	140	390	365	90	60	30	15	13	8
TC	320	250	214	180	390	365	90	60	30	15	13	8
UC+TC	320	250	204	176	390	365	90	60	30	15	13	8
UC+ED+TC	320	250	204	176	390	365	90	60	30	15	13	8

Table 9: Utility targets comparison for different three criteria in Petrochemical Complex case study.

Optimisation Criteria	Heat Exchanger Unit Target	TSHR Target	ED	UC	TC	Change
	#	kW	kW	NZD/y	NZD/y	%
Original Utilities	139	2,633	5,759	9,895,506	10,751,421	-
TC	131	3,488	5,964	9,638,319	10,480,799	-2.52
UC+TC	134	3,796	5,967	9,545,481	10,390,653	-3.36
UC+ED+TC	134	3,796	5,967	9,545,481	10,390,653	-3.36

Table 10: Initially required utilities for Dairy Factory case study.

Utility Name	Utility Type	T_{Cold} (°C)	T_{Hot} (°C)	Pressure Range (bar_g)
LPS	Hot		180.0	10
HTHW	Hot	84.0	64.0	
LTHW	Hot	45.0	25.0	
CW	Cold	24.0	*	
ChW	Cold	0.0	2.0	

*Soft utility temperature

Table 11: Optimised utility temperatures comparison for different three criteria in Dairy Factory case study.

Optimisation Criteria	Isothermal Utility	Non-Isothermal Utility						
	LPS	HTHW		LTHW		CW	ChW	
	T_{Hot} (°C)	T_{Hot} (°C)	T_{Cold} (°C)	T_{Hot} (°C)	T_{Cold} (°C)	T_{Cold*} (°C)	T_{Hot} (°C)	T_{Cold} (°C)
Original Utilities	180	84	64	45	25	24	2	0
TC	180	84	64	49.5	25	24	2	0
UC+TC	180	84	64	49.5	25	24	2	0
UC+ED+ TC	180	84	64	49.5	25	24	2	0

*Soft utility target temperature (T_{Hot})

Table 12: Utility targets comparison for different three criteria in Dairy Factory case study.

Optimisation Criteria	Heat Exchanger Unit Target	TSHR Target	ED	UC	TC	Change
	#	kW	kW	NZD/y	NZD/y	%
Original Utilities	97	1,952	2,125	4,454,612	4,873,609	-
TC	98	2,501	2,201	4,435,662	4,843,602	-0.62
UC+TC	98	2,501	2,203	4,435,662	4,843,602	-0.62
UC+ED+ TC	98	2,501	2,203	4,435,662	4,843,602	-0.62

Table 13: New required utility set for Kraft Pulp Mill case study.

Utility	Isothermal Utility		Non-Isothermal Utility		
	HPS	LPS	HW		CW
	T_{Hot} (°C)	T_{Hot} (°C)	T_{Hot} (°C)	T_{Cold} (°C)	T_{Cold*} (°C)
New Utilities	210.0	160.0	75.0	25.0	25.0
New Utility Optimal Temperatures	194.9	158.9	72.3	25.0	25.0

*Soft utility temperature

Table 14: Utility targets comparison for four utility mains case and its optimised targets based on UC+ED+TC criteria in Kraft Pulp Mill case study.

Optimisation Criteria	Heat Exchanger Unit Target	TSHR Target	SWG	ED	UC	TC	Change
	#	kW	kW	kW	NZD/y	NZD/y	%
New Utilities	73	39,135	37,703	23,536	15,198,152	16,849,345	-
UC+ED+TC	72	39,354	38,705	22,931	14,303,060	16,075,881	-4.59

Table 15: Optimised utility temperatures comparison for different cases in Kraft Pulp Mill case study.

Start Point Temperatures	Isothermal Utility			Non-Isothermal Utility			
	HPS	LPS	CW	HTHW		LTHW	
	T_{Hot} (°C)	T_{Hot} (°C)	T_{Cold} (°C)	T_{Hot} (°C)	T_{Cold} (°C)	T_{Hot} (°C)	T_{Cold} (°C)
Base Case	210.0	160.0	25.0	85.0	60.0	45.0	25.0
Case 1	230.0	160.0	25.0	90.0	70.0	40.0	25.0
Case 2	210.0	140.0	25.0	90.0	70.0	35.0	25.0
Base Case Optimised	194.9	158.9	25.0	93.0	76.8	57.0	25.0
Case 1 Optimised	194.9	158.9	25.0	93.0	76.8	49.0	25.0
Case 2 Optimised	162.0	138.9	25.0	93.0	76.8	49.0	25.0

Table 16: Comparison of optimised objective functions with the base case in Kraft Pulp Mill case study.

Start Point Temperatures	TSHR	SWG	ED	UC	TC	Change
	kW	kW	kW	NZD/y	NZD/y	%
Base case	44,845	37,384	20,242	13,804,364	15,669,850	-4.51
Case 1	44,845	37,384	20,196	13,804,364	15,672,299	-4.48
Case 2	44,845	36,399	21,064	16,923,756	18,688,636	13.90

Table 17: Optimised utility temperatures for different step sizes.

Step Size (°C)	Isothermal Utility			Non-Isothermal Utility			
	HPS	LPS	CW	HTHW		LTHW	
	T_{Hot} (°C)	T_{Hot} (°C)	T_{Cold} (°C)	T_{Hot} (°C)	T_{Hot} (°C)	T_{Hot} (°C)	T_{Cold} (°C)
0.1	201.3	158.9	25.0	90.9	60.5	45.0	25.0
1.0	194.9	158.9	25.0	93.0	74.6	57.0	25.0
8.0	194.9	158.9	25.0	93.0	76.9	57.0	25.0
16.0*	194.9	158.9	25.0	93.0	76.9	57.0	25.0
24.0	194.9	158.9	25.0	93.0	76.9	57.0	25.0

*Step applied in initial case study analysis

Table 18: Deviation from TS targets for different step sizes compared to initial 16 °C step.

Step Size (°C)	TSHR Deviation %	SWG Deviation %	ED Deviation %	UC Deviation %	TC Deviation %
0.1	-1.3	0.0	0.0	0.8	0.8
1.0	-0.4	0.1	0.2	0.1	0.1
8.0	0.0	0.0	0.0	0.0	0.0
24.0	0.0	0.0	0.0	0.0	0.0