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The design of the total site exchanger network with intermediate heat carriers: Theoretical insights and practical application

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ABSTRACT

The present work is focused on finding a cost-effective solution to the synthesis of Heat Exchanger Networks (HEN) for Total Site Integration (TSI). The possible solutions for minimum-investment retrofit of the Total Site HEN are also discussed. The feasibility of intermediate heat carriers number is also analysed for better plants interconnection considering the optimal amount of the recovered heat.

The presented case studies illustrate the pathway selection of site recovery system synthesis with a certain number of heat exchangers, heat transfer area, intermediate utilities, and interconnection between production processes, heat consumers, heat generation facilities and other members of an integrated regional network. Case studies demonstrate that the use of two proposed approaches allows minimising unit numbers and heat transfer area. The first one provides 18% less heat transfer area and the second one suggest network with 41% less unit. The economic results are compared and discussed. The results of this work can be used for site recovery network development as well as a decision-making tool during interplant heat integration and improvement of side-wide heat recovery. The results of this paper are potentially interesting for both research and engineering staff. The current work provides the methodological improvement when designing the Total Site Heat Recovery and better estimation of the HEN capital cost.

1. Introduction

The energy efficiency in reprocessing industries is one of the main objectives in the coming future. It relates to strategic issues for energy system transition to ensure a sustainable future [1]. Achieving higher energy efficiency is of prime importance if the supply from renewable energy sources would be sufficient – considering that world-wide nearly 2/3 of the overall energy sourced is lost and only 1/3 used to deliver energy services. On the one hand, more efficient process plants have low energy targets and produce fewer emissions. On the other hand, it guarantees additional employment to operate a smart industrial cluster [2]. Industrial sites are becoming more and more attractive as potential sources of heat for district heating systems, municipal heat needs, interplant heat usage, heat to power generation [3]. The reduction of energy prices decreases the investment attractiveness of the retrofit; this fact forces finding solutions with the minimised investment to get an appropriate financial payback.

There has been much research published solving the problem of the energy efficiency of industrial systems. A variety of methodologies has been used to solve and, in some cases, reduce the problem. One of the most effective methods that provide the solutions in a systematic way for industrial systems engineering, energy efficiency and regional sustainability is a Total Site Analysis (TSA) [4], applied to analyse the heat recovery options for entire sites. This methodology is still has been developed to improve the quality of the solutions – e.g. improved targeting accounting for process-specific heat transfer properties [5]. It has achieved a wide-spread application in various industrial sectors – such as refinery [6], petrochemical [7], cement [8], sponge iron [9] and others. The basics of the Total Site methodology was well described by Perry [10] as an extension of the Pinch Technology Targeting methodologies. The Total Site Targeting methodology includes data extraction methods, the formation of Total Site Profiles, Total Site Composite Curves and the Site Utility Grand Composite Curve. The process modification principles of Pinch Analysis were extended for the

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Total Site to improve energy saving [11].

Some approaches cover locally integrated energy sector, which incorporates the energy systems (heat and power) of the industrial cluster with commercial and residential buildings, energy storage and batteries [12]. The cascade energy targeting methodology was also updated for total site heat integration incorporating long- and short-term heat energy supply and demand variation problem [13].

Ghannadzadeh et al. [14] introduced a new shaft work targeting model, termed the Iterative Bottom-to-Top Model (IBTM), to facilitate the targeting stage and also eliminate the need for simulation of the steam turbine networks. The refinery was analysed to show the importance of the reliable shaft work targeting model to identify the areas in which heat recovery projects should be focused on. Approach tor estimating the capital cost of Total Site Power Cogeneration based on steam turbines was later proposed [3]. However, the heat recovery part was not considered in that work. The application of sustainable energy may provide an innovative and high-efficient biomass-driven cogeneration system for the real need of the utility systems by considering a suitable Total Site heat recovery and distribution mechanism [15].

Total Site methodology provides the target of the cogeneration potential of utility systems of industrial clusters. Targeting for cogeneration potential of Total Site utility systems can be made by the commercial software [16]. Optimisation approach provides the model for simultaneous cogeneration and utility levels optimisation [17].

A method to combine Mass, Heat and Power Integration for Total Sites was proposed that used P-graph as the modelling tool [18]. The visualisation tool during the construction and optimisation of the problem was considered, and a biorefinery case study was used. While this points to the need to consider jointly multiple utilities in industrial sites, the use of P-graph implementation based only on a proportional model, and the low suitability of using P-graph as a visualisation tool, limit the applicability of the proposed model. The heat recovery and utility level optimisation are not considered.

Tarighaleslami et al. [19] dealt with Utility Exchanger Network (UEN) design to provide the required process heating and cooling while also facilitating inter-process heat recovery, i.e. TSHI. They developed a new UEN design procedure based on a customised TSHI targeting method, allowing series utility exchanger matches for a non-isothermal utility if the exchangers in series are from the same process. They concluded that the number of exchangers reduces compared to the Conventional methods' design procedure. However, the influence of heat transfer area was not additionally considered. Total Site Exchanger Network utilise excess heat from one process to another one by intermediate heat carriers. Utility exchanger network can be designed by a procedure based on a targeting method [19]. Derivative based optimisation procedure, where results are minimised sequentially and iteratively based on the specified approach, is presented in Ref. [20]. This approach provides utility temperature selection and optimisation method for non-isothermal and isothermal utilities.

The authors in Ref. [21] presented a useful retrofit framework for a TS system to determine the most cost-effective retrofit options and maximise the potential savings. The approach determines the baseline total site consumption and benchmark targets, identifying retrofit options from the TS context. The results of the analysis have shown significant energy savings for both direct and indirect heat recovery. The Particle Swarm Optimisation model for the synthesis of HEN is proposed in Ref. [22] to minimises the total annualized cost. It is based on a simultaneous superstructure optimisation for the HEN synthesis, including stream splitting. However, solving such models may be difficult, and Isafiade et al. [23] proposed a modified superstructure of HEN having multiple periods of operations. Inter-plant integration may be solved using such multiperiod optimisation minimising environmental impact [24]. Nano-fluids may also be used as intermediate for interplant integration, and it may be a cost-saving, in case of low electricity price [25]. Besides, interplant integration with non-isothermal utility loop may be represented with the use of transhipment type HEN model to avoid non-linear terms and simplify the model formulation [26]. But, in some cases, it is challenging to solve such model due to heat transfer restrictions between subsystems and problem is converted to Mixed-Integer Linear Programming (MILP) [27]. It was proved in Ref. [28] that the piping and pumping cost is defining for interplant integration, and this is an objective for further optimisation. The optimisation of intermediate carriers temperature was not focused due to consideration of maximum possible heat integration.

In [29], the authors performed the synthesis of Total Site Heat Exchanger Networks, which simultaneously considers integration within and between plants. The superstructure optimisation approach is used. The process streams and the intermediate utility streams were considered as heat carriers. The proposed two-step procedure yields the result simultaneously at both the process and the Total Site levels, while also accounting for important properties such as heat losses, pipeline design and cost, temperature/pressure drop during transport between processes, and different types of heat exchangers. However, there are severe nonlinearities and numerous options for heat recovery; the model is difficult to implement even for small-scale problems.

In [30] a systematic methodology for the simultaneous synthesis and design of a utility system and HEN was proposed. The energy from the steam condensate and boiler feed water preheating were integrated into the HEN coupling with the design optimisation of a Rankine cycle-based utility system. It provided additional economic benefits of additional heat recovery.

In a recent review of HEN retrofit [31], it has been established that there are many methods applicable to Total Site exchanger network retrofit. In tropical countries like ASEAN, residential and service buildings consumed 59% of the total energy consumption [32]. The authors extended Locally Integrated Energy Sector model to utilise the low-grade industrial heat for the district heating system. A new methodology, which incorporates absorption chillers in TSHI to reduce the site cooling requirements, was introduced. Another work [33] optimised the structural design of a central utility system for a Local Integrated Energy Sector, considering its environmental performance. The environmental performance was captured by Greenhouse Gas emissions, Water, and Particulate Matter Footprints.

On the other hand, a comprehensive planning and design framework is crucial at the development of Site-wide energy system, and it should estimate supply and demand sides. The environmental footprints may be assessed by objective dimensionality reduction method that was proved by the regional supply chain case study [34]. In Ref. [35] discussed key factors for integration of industrial, residential, commercial, and other systems, maximising the integration and reuse of waste and low potential heat, including renewables to boost sustainability aspects. The economic efficiency is ignored that makes the feasibility of such integration is doubtful.

Estimation of cogeneration potential prior to the design of the central utility system for Total Sites is necessary to set targets onsite fuel demand as well as heat and power production. The approach was updated in Ref. [36] and a methodology for minimisation of heat transfer area of steam boilers and condensers.

However, despite the many successful industrial retrofit studies, several issues remain unresolved and are of vital importance for the industry, as stated in Ref. [10] and other recent research. These include:

- The practical arrangements including plant layout, steam mains, number of steam boilers, steam traps when applying TSHI.
- The capital investments and their payback when applying Site Integration still not predicted. Another issue is energy recovery targeting and proper application of inter-plant integration.
- The selection of the temperature levels of the intermediate energy carriers in the utility system is challenging. Until now, the only systematic attempts include the selection steam main temperatures in utility system optimisation. These start from the simple T-H cogeneration targeting model [4], moving to the first version of the T-M steam turbine model, and the complete utility system synthesis model [38].

The main trade-off in optimising heat recovery systems (for new designs or for retrofit) is the one between the energy-saving and capital cost. The outcome of this trade-off depends on the relative weight of the operating costs and the investment costs in the overall expenditure. The problem of investment efficiency in systems of such scale as Total Site is crucial due to different pressure levels of intermediate utilities, pipeline layout design, different types of insulation etc. It was proved by research and case study that the pipeline investments may be up to 34% of total investments to Total Site design [39].

The analysis above identifies a clear knowledge gap in the design of Total Site Heat Recovery (TSHR) systems in terms of practical network implementation issues and evaluation of the energy-capital trade-off at the Total Site level. In this paper, the research approach and practical recommendations for the design of Total Site Heat Recovery networks are provided, that reduce the capital investment for the site heat recovery network. A systematic selection of the utility temperature levels is performed, based on the formulated model. This allows identifying the optimal target for the global Total Site temperature difference where the total annual cost is minimised. A methodology is proposed for the systematic design of Total Site recovery system starting from the formation of enthalpy blocks (as collections of consecutive enthalpy intervals) to design a HEN with minimum total reduced cost. It presents the main principles to optimise the heat transfer area, the number of steam mains and minimum temperature difference inside blocks and for Total Site. The proposed model was tested on representative case studies, and the results were analysed and compared with the methodology proposed before.

2. Methods

2.1. Problem statement

A typical Total Site Integration presumes the complete use of utilities for heat recovery, power generation, CO_2 capture, regional energy planning and sustainability etc. The methodology is now used widely and is still developing to solve cross-sectoral problems. This paper focuses on the details of the recovery part of the TSA. As mentioned above, it is well described in the literature, but there are essential details that have to be analysed additionally. Simplified Total Site Profiles with heat recovery is shown in Fig. 1. Some amount of the waste heat of Source Profile supposes to use for Sink Profile heating. Nevertheless, the most common questions are:

- How much heat should be recovered?
- How should many intermediate utilities (steam mains) be used?
- What is the optimal temperature of intermediate utility?
- How many heaters/boilers, steam traps, pumps should be installed?
- What are the investment and payback?

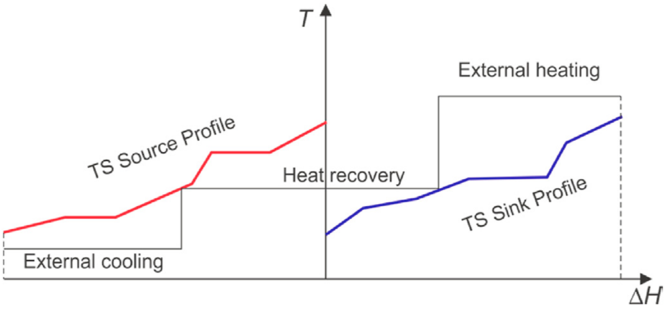


Fig. 1. A simplified Total Site Profiles with heat recovery (developed after [40]).

All these questions forced to go deeper in details of TSHR to provide feasibility and viability of the design of Total Site Exchanger Network (TSEN). It is supposed to decompose the TSHR to understand how the components, such as stream number, the slope of TS Profiles, film heat transfer coefficients etc., influence the technical and economic results of TSI.

The proposed approach follows the next methodological steps:

1) data collection for Total Site profiles;

To build Total Site profiles, stream data of individual processes are used; namely, streams are extracted that should be heated or cooled by utilities. For these process streams, the start and target temperatures, heat capacities flowrates and heat transfer coefficients are extracted.

2) putting maximum Heat Recovery of Total Site;

Total Site profiles are built from stream data of individual processes. Next, the minimum distance between the profiles along the enthalpy axis is determined, and the Sink Profile is shifted by this distance to the left relative to the Source Profile. As a result of such a shift, the profiles touch each other at the Total Site Pinch. This construction is similar to Composite Curves in the analysis of individual processes. Thus, a heat recovery area is formed between the profiles. In the case of touching the profiles, the heat recovery is maximum with minimal utilities.

3) decomposition of Total Site Profiles into enthalpy blocks;

Sink and Source Profiles have arrays of temperatures and enthalpies for breakpoints. These arrays are combined, and the array of enthalpy divides the Sink and Source Profiles into enthalpy blocks (see Fig. 2). Within each enthalpy block, thermal energy is transferred from the Source Profile to the Sink Profile through an intermediate utility. This methodology investigates heat transfer using intermediate utilities, assuming that the direct heat transfer between processes is not possible due to distance or other reasons. Heat transfer between Source and Sink Profile within separate enthalpy blocks simulates the recovery zone as a counter-flow heat exchanger, thereby reducing the required heat transfer area.

4) selection of intermediate utility (IM) temperatures by minimising heat transfer area;

At each enthalpy block, Source Profile heat is transferred to the Sink Profile using an intermediate utility. At the same time, the temperature of the intermediate utility may vary within each enthalpy block. The total heat transfer area consists of two parts: the heat transfer between the Source Profile and the intermediate

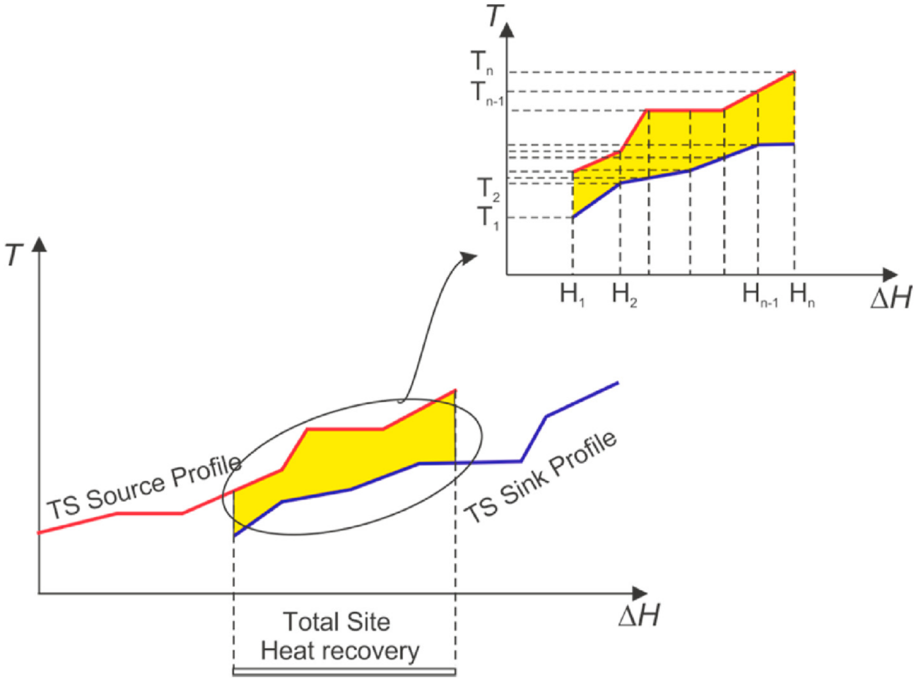


Fig. 2. Total site heat recovery.

utility and the heat transfer between the intermediate utility and the Sink Profile (see Fig. 3). When the temperature of the intermediate utility changes from the lower to the upper bound with a certain step, the heat transfer area is calculated within each enthalpy block. The minimum value of the surface area and the corresponding temperature of the intermediate utility are selected for each enthalpy block. Summation of heat transfer area of all enthalpy blocks provides a minimum heat transfer area of TSHR. In this case, the minimum temperature difference between the profiles and the intermediate utility overall enthalpy intervals will form a Pinch of the intermediate utility (see Fig. 4). The calculation of the heat transfer area is based on the heat duty within the enthalpy block, the logarithmic temperature difference and the film heat transfer coefficient of each stream included in the enthalpy block. The film heat transfer coefficient takes into account the thermal resistance of the wall and the thermal conductivity of the material.

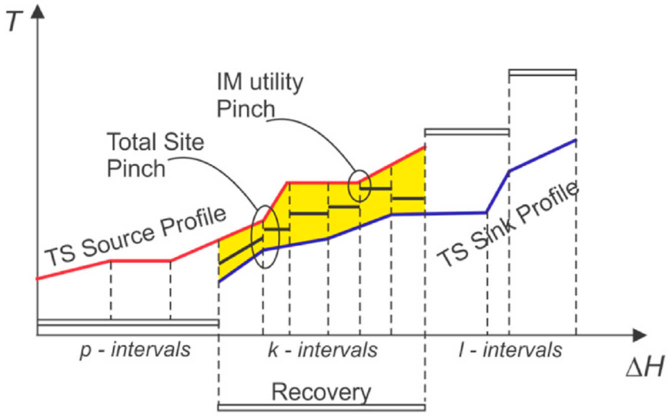
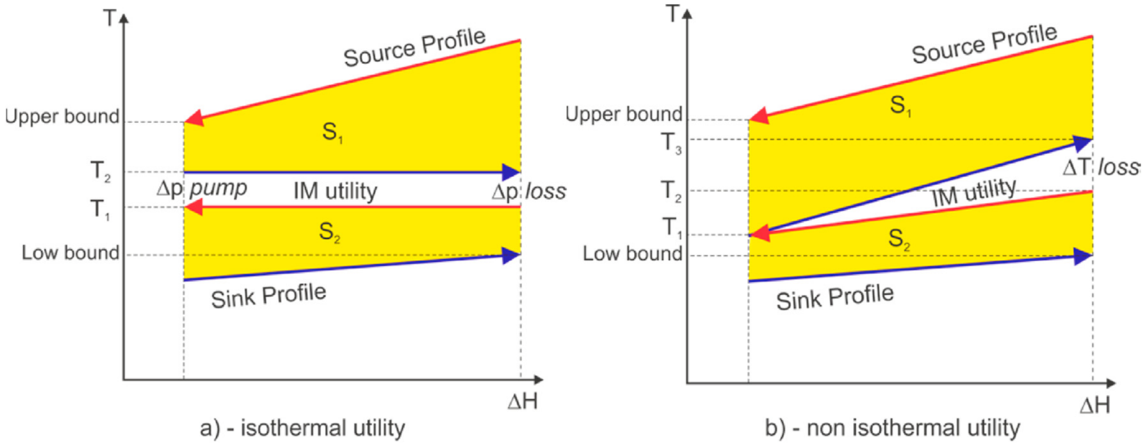


Fig. 4. Total Site Profile Targets. Intermediate utilities, Pinch Points after [10].



a) - isothermal utility

b) - non isothermal utility

Fig. 3. Enthalpy interval.

5) synthesis of Total Site HEN minimising the number of heat exchange units by enthalpy blocks aggregation (if possible);

A HEN is synthesised for each enthalpy block with each process stream forming a separate heat exchange match. Thus, the maximum number of heat exchangers is determined with a minimum heat transfer area (Fig. 5a). Further, the possibility of combining as much as possible enthalpy blocks for using one common intermediate utility is checked. The intervals are checked, starting with the first one with the minimum temperature. As a result of this procedure, the number of intermediate utilities can be reduced to 1, if it is not limited by the boundary temperatures of the enthalpy blocks. After combining the enthalpy blocks, the heat transfer area is re-calculated for each interval, taking into account the change in the temperature of the intermediate utility. Further, the HEN is analysed, and the heat exchange arrangements of each process stream located in the adjacent enthalpy block will be combined. This makes it possible to form a HEN with a minimum number of units, but the heat transfer area will be larger than the minimum (Fig. 5b).

6) calculation of external utilities;

The cold and hot utility loads required to meet the energy goals are calculated. Selects available utilities that satisfy the Source and Sink Profiles temperature levels.

7) calculation of annual capital and operating (energy) cost;

Capital cost is calculated based on numbers of heat exchangers and heat transfer area obtained from previous steps. The capital cost is calculated for both options assuming minimum heat transfer area and the minimum number of heat transfer units. Capital costs are reduced on an annual basis taking into account the interest rate on loan and the duration of the projectю Capital Operating (energy) cost is calculated with the use of utility heat duty and utility prices.

8) calculation of total annual cost;

Total cost is calculated by summation of reduced capital investments and annual energy cost.

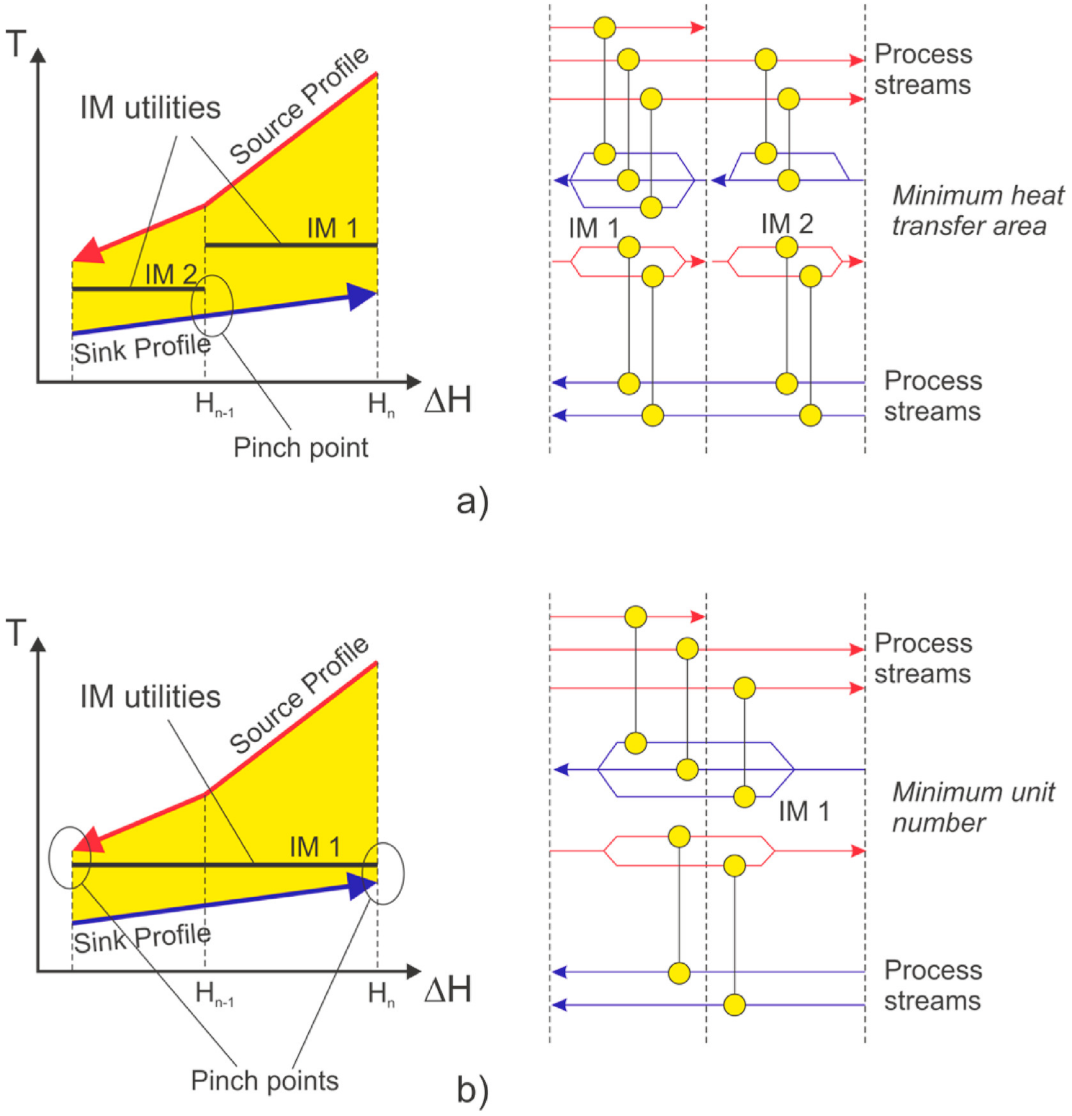


Fig. 5. Grid diagram of enthalpy intervals. a) – separated; b) – combined.

9) changing the global ΔT_{min} of Total Site and repeat steps 2–7;

TS ΔT_{min} is changed with step 1 °C and procedure of steps 2–7 is repeated until Source and Sink Profiles are overlapped within the enthalpy axis. For each TS ΔT_{min}, there are reduced capital cost, energy cost and total cost.

10) selection of the Total Site configuration with the minimum Total Annual Cost.

The correlations of reduced capital cost, energy cost and total annual cost versus ΔT_{min} are built. The entire cost function has a minimum at a certain point, selected as an optimum TS ΔT_{min}. This point demonstrates the targets for exchangers number, intermediate utilities number and temperatures, heat transfer area and external utility heat load temperatures. The TS exchanger network is then designed for selected energy-area targets.

Assumptions. The analysis of HEN was done under the following assumptions to simplify the model and get feasible solutions at this point:

1) The thermophysical properties of process streams are constant within the temperature intervals;
2) The heat exchangers of the same type with the same coefficient of counter-current are assumed;
3) The pressure drop of intermediate utility is neglected;
4) Heat losses of intermediate utility are neglected;
5) The cost of the utilities is constant.

2.2. Decomposition

Putting together TS profiles create an overlapping part that is the amount of heat to be recovered. The overlapping region has to be allocated, and TS Profiles should be divided into enthalpy and temperature intervals that are created by the breakpoints of TS Profiles (see Fig. 2).

$$A_{TSHR} = \sum_{z=1}^{k} \min_{t1 < t_{IM} < t2} \left(\frac{1}{\Delta T_{LM}^{H}} \left(\sum_{i=1}^{n} \frac{Q_i}{h_i} + \frac{Q_{IM}}{h_{IM}^{H}} \right) + \frac{1}{\Delta T_{LM}^{C}} \left(\sum_{j=1}^{m} \frac{Q_j}{h_j} + \frac{Q_{IM}}{h_{IM}^{C}} \right) \right)_z \quad (4)$$

A typical enthalpy interval is shown in Fig. 3. It consists of Source and Sink Profiles and (IM) that recover the heat from Source to Sink. The heat is transferred from the Source to IM by condensers/heaters with area S_1 and then delivered from IM to Sink by evaporators/coolers with area S_2. In case of IM is an isothermal utility (steam) (Fig. 3a) it is a pressure drop (Δp_{loss}) and temperature losses in steam mains when the steam is delivered to consumers. These losses should be compensated by the pumping (Δp_{pump}) at the condensate side. The similar situation if the utility is non-isothermal (e.g. hot water) as the IM (Fig. 3b). The temperature losses should be considered when selecting the heat transfer area for both Sink and Source sides. The balance between Sink (S_2) and Source (S_1) heat transfer areas is depended from IM temperatures. These temperatures are limited by low and upper bounds that are the lower temperature of Source Profile and high temperature of Sink Profile in the particular enthalpy interval. The temperatures (T_1, T_2) of IM utility are selected by minimising total heat transfer area of enthalpy interval. The losses (temperature and pressure) depend on different factors, such as thermal insulation, tube length, number of constriction devices, etc.

2.3. Synthesis

Heat transfer area. As specified above the overlapping part of Sources and Sink profiles in the enthalpy intervals is a heat that should be recovered by IM and heat transfer equipment. The heat transfer area is calculated for all enthalpy intervals and minimised, putting the IM temperature from low to upper bound (see Fig. 3). The heat transfer area of Total Site is calculated specifying Total Site different minimum temperature approach (Fig. 4) as previously reported in Ref. [41].

The heat transfer area of all steam boilers or/and heaters and condensers or/and coolers is assessed as the total heat transfer area of heat recovery using IM utility and hot and cold utility heat transfer. It is obtained from Source and Sink profiles specifying appropriate temperatures, heat load and heat transfer coefficient at each enthalpy block. Total heat transfer area is calculated from by (Eq. (1)):

$$A_{Total} = A_{TSHR} + A_{TSHU} + A_{TSCU} \quad (1)$$

The heat transfer area for hot and cold utility is calculated as reported in Ref. [42] but selecting the utility temperature to minimise heat transfer area (Eqs. (2) and (3)) summarising the initial data from Site Profiles at intervals p and l (Fig. 4).

$$A_{TSHU} = \sum_{i=1}^{l} \min_{t1 < t_{HU} < t2} \frac{1}{\Delta T_{LM}^{C}} \left(\sum_{j=1}^{m} \frac{Q_j}{h_j} + \frac{Q_{HU}}{h_{HU}} \right)_i \quad (2)$$

$$A_{TSCU} = \sum_{j=1}^{p} \min_{t1 < t_{CU} < t2} \frac{1}{\Delta T_{LM}^{C}} \left(\sum_{i=1}^{n} \frac{Q_i}{h_i} + \frac{Q_{CU}}{h_{CU}} \right)_j \quad (3)$$

Minimum heat transfer area of Total Site heat recovery is calculated by (Eq. (4)) that was previously modified in Ref. [41]:

The number of exchangers.

The number of heat exchangers in the decomposed enthalpy interval of TSHR may be found from (Eq. (5)):

$$N_{HR} = \sum_{i=1}^{k} \left(n_i^h + n_i^c \right) \quad (5)$$

This is also well illustrated in Fig. 5, but in this case, the number of heat exchangers is maximum while the heat transfer area minimised. Nevertheless, the heat exchanger network structure may be simplified by merging two enthalpy intervals. In this case, the borders of enthalpy interval are expanded, temperature bounds are changed, and one IM utility is used. The number of the heat exchangers is lowered but still could be calculated by (Eq. (5)) applying new borders of enthalpy intervals. It is well illustrated in Fig. 5b. The expanding of enthalpy intervals is carried out while it is possible to use one IM for several enthalpy intervals.

The number of steam boilers/heaters, condensers/coolers of external heating/cooling is calculated as described in Ref. [42] assuming the number of units equals the number of streams:

$$N_{HU} = \sum_{i=1}^{l} n_i^c N_{CU} = \sum_{i=1}^{p} n_i^h \tag{6}$$

The number of heat exchange units of TSHR is calculated as a sum of all units calculated above:

$$N_{Total} = N_{HR} + N_{HU} + N_{CU} \tag{7}$$

Super targeting., It is possible to get the external energy consumption putting together the Sink and Source Profiles and calculate heat transfer area by (Eqs. (1)–(4)). The number of IMs, boilers/heaters, condensers/coolers, steam traps and steam mains are obtained too by the method described above. Specifying different Total Site temperature approach from minimum to the maximum value (see Fig. 6), the capital cost (Eqs. (8)–(11)) of the Total Site exchanger network (Fig. 7a) and energy cost (Fig. 7b) are calculated for a whole range of ΔT_{min}. The function of total annual cost (TAC) is obtained as a sum of reduced capital investment (RCC) (Eq. (11)) and reduced operating cost (ROC) (Eq. (12)) (Fig. 7c) and is analogous to the super targets defined for Heat Exchanger Network synthesis [43]. This function is similar to the TAC function of the Pinch Analysis [42] with features of TSHR described above. TAC function has an extremum that is a minimum of the reduced cost of TSHR of the Total Site ΔT_{min} (Total Site Pinch). At the same time, IMs create IM Pinches at the enthalpy intervals; herein Total Site Pinch is not a ΔT_{min} of Total Site exchanger network. ΔT_{min} may be allocated at IM Pinches depending on the structure of the heat exchanger network and selected IM temperature.

The calculation of the capital cost of the TSHR network and utility network made by (Eqs. (8)–(10)) with the use of Hall correlation [44] for two different types of shell-and-tube unit:

$$CC = aN_{HR} + bA_{TSHR}^{c} \tag{8}$$

$$CC1 = a1N_{HU} + b2A_{TSHU}^{c1} \tag{9}$$

$$CC2 = a2N_{CU} + b2A_{TSCU}^{c2} \tag{10}$$

where a, b, c, a1, b1, c1, a2, b2, c2 are coefficients that depend on materials of shell-and-tube units.

Annualized investment was calculated from Eq. (11):

$$RCC = (CC + CC1 + CC2)\frac{i(i+1)^n}{(i+1)^n - 1} \tag{11}$$

where i is fractional interest rate, %; n is project lifetime, y.

Reduced operating cost is defined as the saved energy of both hot and cold utilities (Eq. (12)):

$$ROC = Q_{Recovery}(Cost_{HU} + Cost_{CU}) \tag{12}$$

The simple payback period was estimated from Eq. (13):

$$PBP = \frac{RCC}{ROC} \tag{13}$$

TAC is defined as a sum of reduced capital investments and reduced operating (energy) cost (Eq. (14)):

$$TAC = RCC + ROC \tag{14}$$

3. Case study

3.1. Case study 1

The case study of TSHR was considered to prove the methodology and show the difference with the approach presented before. The case study is considered for data from Ref. [36] and presented in Table 1.

Super targeting procedure defined the optimum temperature of Total Site of 31 °C. Sink and Source profiles of such driving forces are shown in Fig. 8. There are three enthalpy intervals at the overlapping part of TS Profiles. TS Profiles provides targets for the design of the Total Site exchangers network to recover the heat from Source to Sink Profiles. Nevertheless, the intervals #2 and #3 may be merged and considered as one block [45] while designing the exchanger network. The Total Site Grid Diagram is shown in Fig. 9, and it consists of 6 heat exchangers. The temperatures of IMs were optimised, and it is hot water for interval #1 with temperature range 83 °C–93 °C. The IM of interval #2 is steam with a temperature of 122 °C. The minimum total heat transfer area of enthalpy blocks provides an optimal IMs temperature, as presented

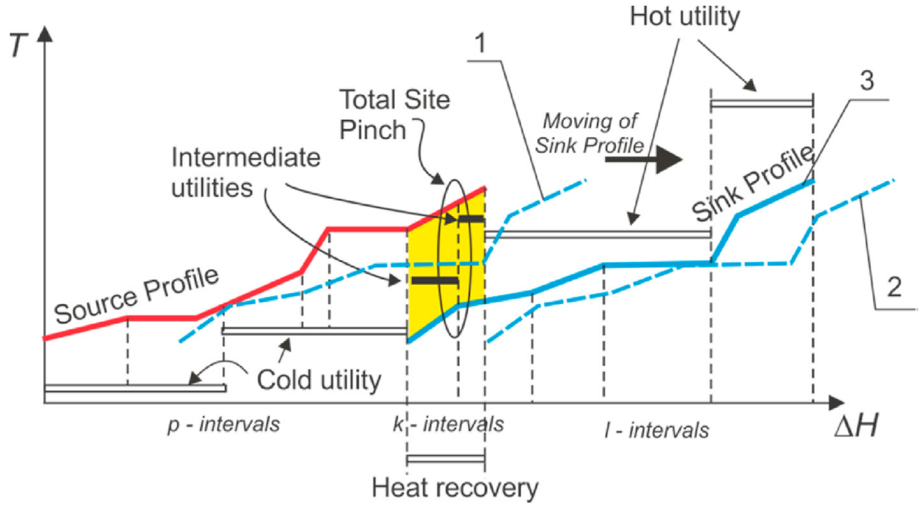


Fig. 6. Total Site Profiles: 1 – ΔT_{TSmin}, max TS Heat Recovery; 2 – ΔT_{TSmax}, min TS Heat Recovery; 3 – ΔT_{TSopt} optimal TS Heat Recovery (developed after [40]).

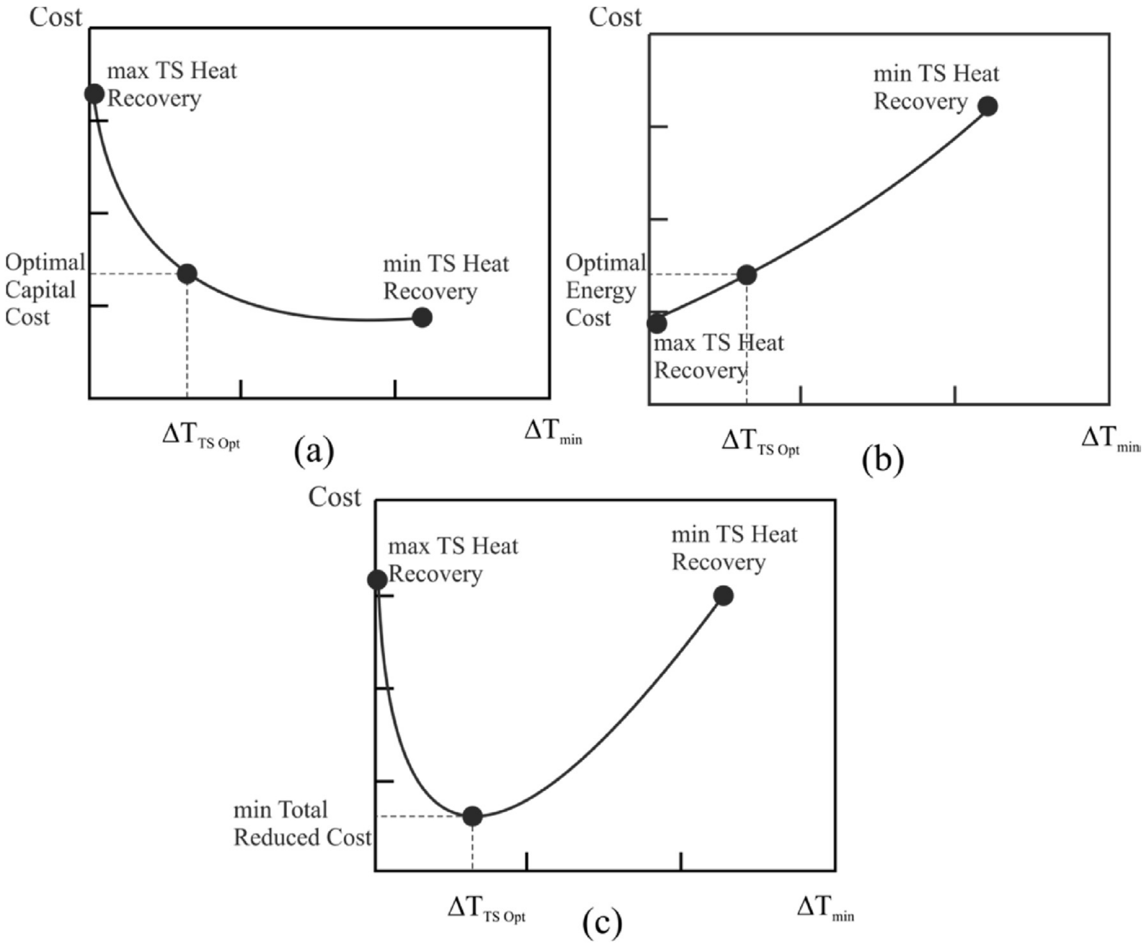


Fig. 7. Total Site Super Targets. (a) – reduced investment cost; (b) – reduced energy cost; (c) – reduced cost of the utility system.

Table 1
Stream data for Site Profiles (used after [36]).

Stream	Type	TS (°C)	TT (°C)	CP (MW/°C)	ΔH (kW)	*h* (MW/(m^2 C))
Process A – liquid 1	hot	100	60	0.05	2.0	0.0007
Process B – Gas 1	hot	180	130	0.03	1.5	0.0001
Process C – liquid 1	hot	80	40	0.02	0.8	0.0005
Process D – liquid 1	hot	145	85	0.01	0.6	0.0006
Process A – liquid 2	cold	70	120	0.03	1.5	0.0005
Process B – liquid 1	cold	100	140	0.04	1.6	0.0009
Process B – Gas 2	cold	150	240	0.02	1.8	0.0002
Process D – liquid 2	cold	130	160	0.01	0.3	0.0007

in Fig. 10. The utility Pinch is located at the IM #2 with approach 7 °C, at the Source side. Such a small difference needs a special requirement for steam boilers, which will be used for the retrofit.

The calculation of capital cost was made for two types of heat exchangers that use stainless steel (SS-SS) and carbon steel (CS-CS) as material for tube and shell sides. The next coefficients for Eq. (9) were used:

SS-SS units: a = 10,000; b = 324; c = 0.91; CS-CS units: a = 7000; b = 360; c = 0.80 [44].

The utility prices were calculated based on the lowest EU prices of the natural gas for non-household users 0.03 EUR/kWh; the currency exchange rate was 1.11 USD/EUR [46]. As the hot utility in the current case study is steam, the conversion efficiency gas-to-steam was accepted of 91% and the number of working hours is 8760. The price of cold utility was used as 10% of hot utility.

3.2. Case study 2

This case study demonstrates the application of the developed approach for hydrocarbon processing site utilising the waste heat different process units. The initial data is presented in Table 2.

The calculation of capital cost was performed with the use of heat exchangers with carbon steel in both tube and shell sides. The utility prices are used similar to case study 1. The correlation of capital investments, energy costs, and TAC against ΔT_{min} were obtained for ΔT_{min}, range from 1 °C to 100 °C with step 1 °C. The coefficient of heat transfer counter-current was assumed as 0.9 for all heat exchangers.

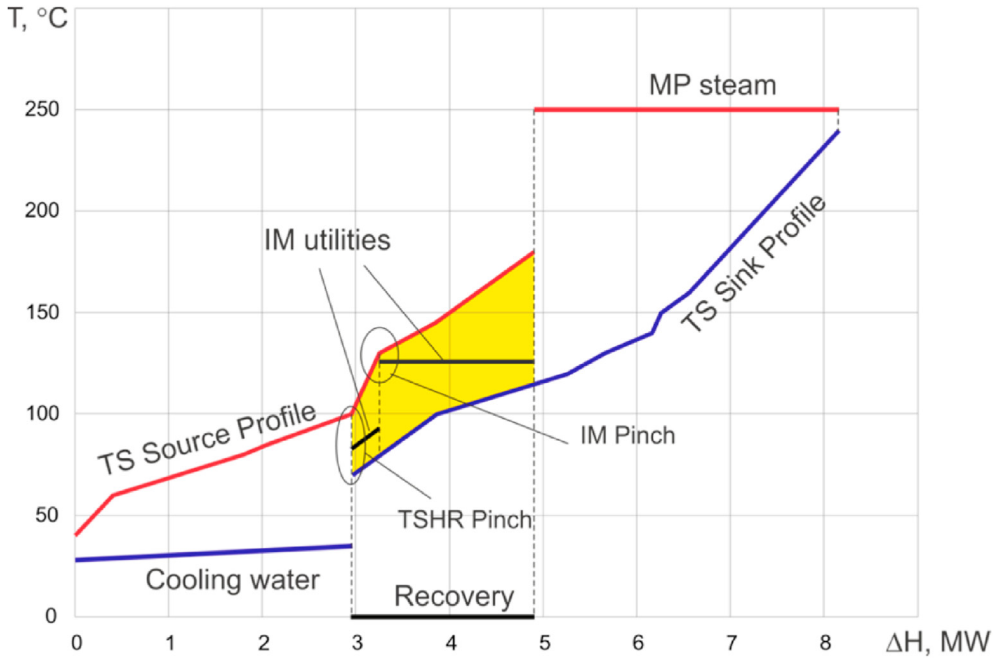


Fig. 8. Total Site Profiles for the current case study 1.

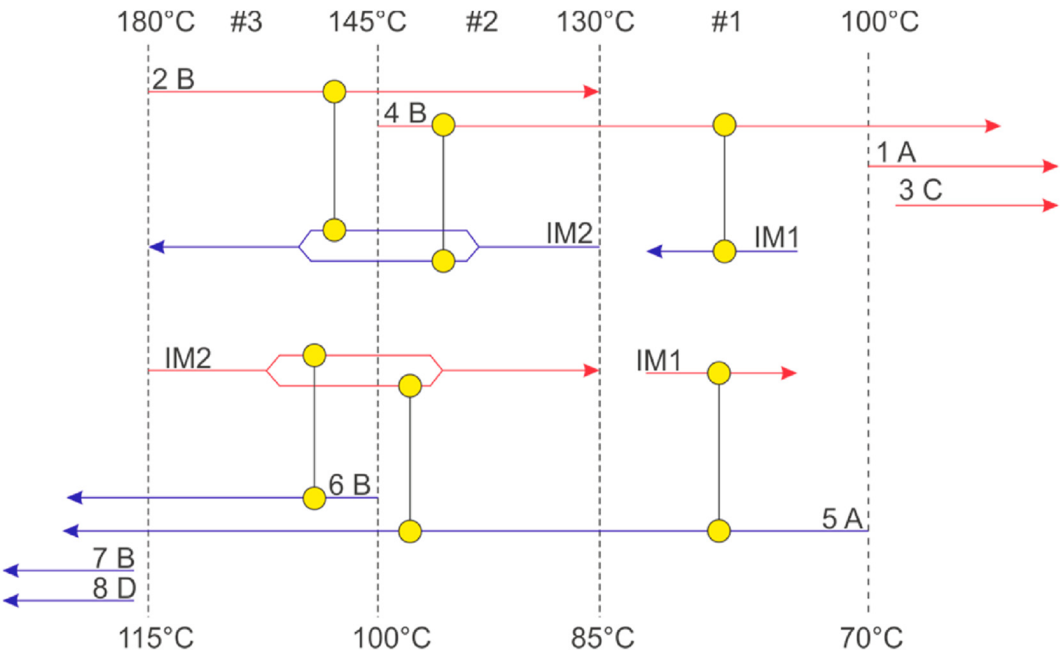


Fig. 9. Heat exchanger network of the current case study.

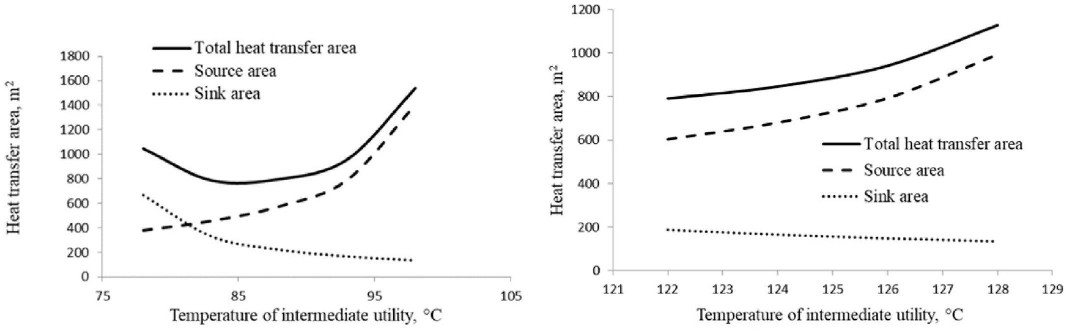
4. Results and discussion

4.1. Case study 1

The results of the current case study are presented in Table 3. It is shown that the heat transfer area of enthalpy interval #1 is very close to the second one while the recovered heat is 5.5 times less. It is due to the difference in film heat transfer coefficient of water heating/cooling and condensation/evaporation. This means that considering IM utilities in enthalpy intervals the use of steam as a heat carrier should be prioritised apart from cases where it is not appropriate due to specific reasons, e.g. safety, process constraints and limits etc.

The proposed structure of the heat exchanger network has 6 units, 2 in the first interval and 4 in second. The total number was lowered by 25% compared to the case study presented in Ref. [36]. The number of steam mains is reduced compared to the analysis presented in Ref. [36]. However, the total heat transfer area is increased by 7%. The comparison of the results of case studies is shown in Table 4.

There are advantages of both approaches, current and presented in Ref. [36]. The method and the case study 1 provide a minimum



a) b)

Fig. 10. Selection of IM temperature. a) enthalpy block #1 and IM1; b) merged enthalpy blocks #2 and #3 of IM2.

Table 2
Stream data for case study 2.

Stream	Type	TS (°C)	TT (°C)	CP (MW/°C)	ΔH (kW)	*h* (MW/(m^2 C))
Process A - gas condensation 1	hot	95	71	422.1	10,130	2.00
Process B - liquid 1	hot	114	32	1.7	139	0.50
Process C - liquid 1	hot	164	43	36.9	4465	0.50
Process D - gas condensation	hot	84	67	148.2	2519	2.00
Process E – liquid 1	hot	67	15	1.6	83	0.50
Process A - liquid 1	hot	121	22	13.7	1356	0.50
Process C - Liquid 2	hot	180	121	108	6372	0.70
Process A - Liquid 2	cold	70	121	64.7	3300	0.50
Process C - Liquid 3	cold	163	180	826.5	14,051	0.60
Process D - liquid	cold	70	101	16	496	0.50
Process B - liquid 2	cold	121	130	615	5535	0.20
Process G - liquid	cold	21	101	90	7200	0.20

Table 3
The results of case study 1.

Enthalpy block	ΔH, MW	TS, °C	TT, °C	ΔT_{min}, °C	h_{IM1}, MW/(m^2·°C)	h_{IM2}, MW/(m^2·°C)	S, m^2	N_{HR}
#1	0.30	83	93	8	0.00011	0.00012	786.16	2
#2+#3	1.65	122	122	7	0.0079	0.0053	790.99	4

Table 4
Comparison of case studies results.

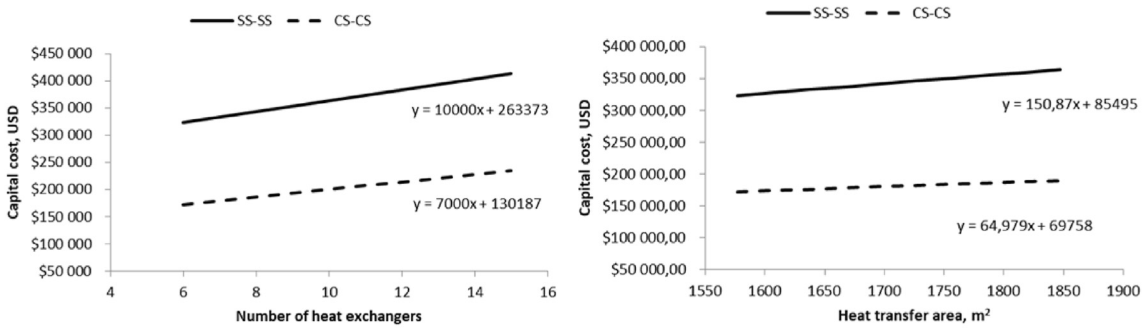
Case studies	Heat recovery, MW	S, m^2	Number of heat exchangers	Number of steam mains	TSHR Pinch, °C	Utility Pinch, °C
Case study presented in [36]	1.95	1468	8	3	31	8
Case study 1 of the current paper	1.95	1577	6	2	31	7

heat transfer area while approach and case study 2 reduce the number of steam mains and heat transfer equipment. These results may be used for the design of TSHR when calculating a capital investment. Both approaches may be used depending on the heat recovered, the number of heat exchange units, heat transfer coefficients, prices of heat transfer area, utility etc. The approach presented in the current paper is beneficial if the number of heat exchangers, steam traps, steam mains should be reduced, and installation price of heat exchangers and piping is defining.

The economic evaluation of the case study demonstrates that the energy-saving is 1.94 MW. It means the reduction of hot and cold utility by the same amount. This saving is achieved by the implementation of HEN (Fig. 9.) that needs investments. The calculation of HEN capital cost for two types of unit materials, carbon and stainless steel, was performed for both case studies and compared in Table 5. As it is shown in Table 5 capital cost of case

Table 5
The results of economic calculations.

Case studies	Number of units	Heat transfer area, m^2	Capital cost of TSHR network with SS-SS units, USD	Capital cost of TSHR network with CS-CS units, USD	Payback period of SS-SS, months	Payback period of CS-CS, months
Case study 1 [36]	8	1468	326,754.86	178,937.21	5.72	3.13
Case study of current paper	6	1577	323,373.36	172,187.07	5.66	3.02



a) b)

Fig. 11. The impact of unit numbers (a) and heat transfer area (b) to HEN capital cost.

study 1 is lower, but the final results are very close, and the difference of units' numbers is compensated by the heat transfer area. However, it should be noted that the current case study includes only 4 process stream at heat recovery blocks. It means that the results should be checked by the sensitivity of the capital cost of heat recovery network from the size of the processing system. It might be converted from stream number and heat recovered to the unit (heat exchangers) number and heat transfer area. In Fig. 11 the impact of both components to the final capital cost of heat recovery network presented in the current case study is demonstrated.

As it shows in Fig. 11, the units' numbers are influencing more to the final investment cost that demonstrates the importance of presented methodology in the development of large scale industrial clusters. However, it should be noted that the viability and applicability of the design of Total Site Recovery depend on many variables from the accuracy of stream data to material and energy prices.

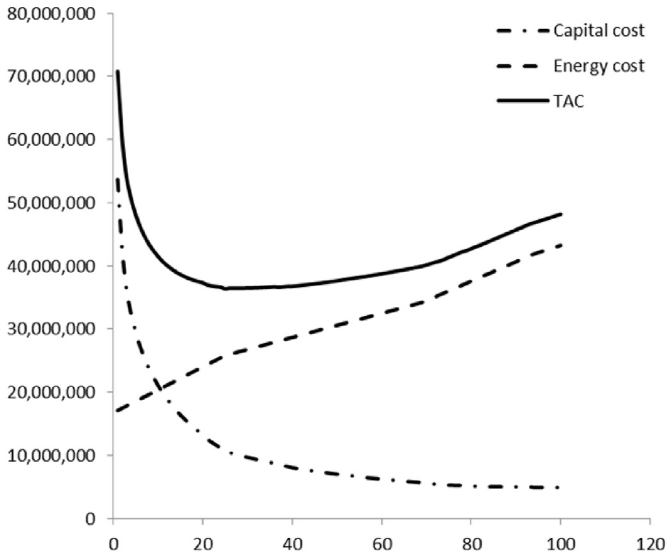


Fig. 12. Correlation between cost functions and ΔT_{min}.

4.2. *Case study 2*

Case study No. 2 demonstrates how the proposed methodology can be used to analyse the possibilities of integrating production processes. In addition, it shows the potential for further development of the approach for the design and retrofit of the Total Site.

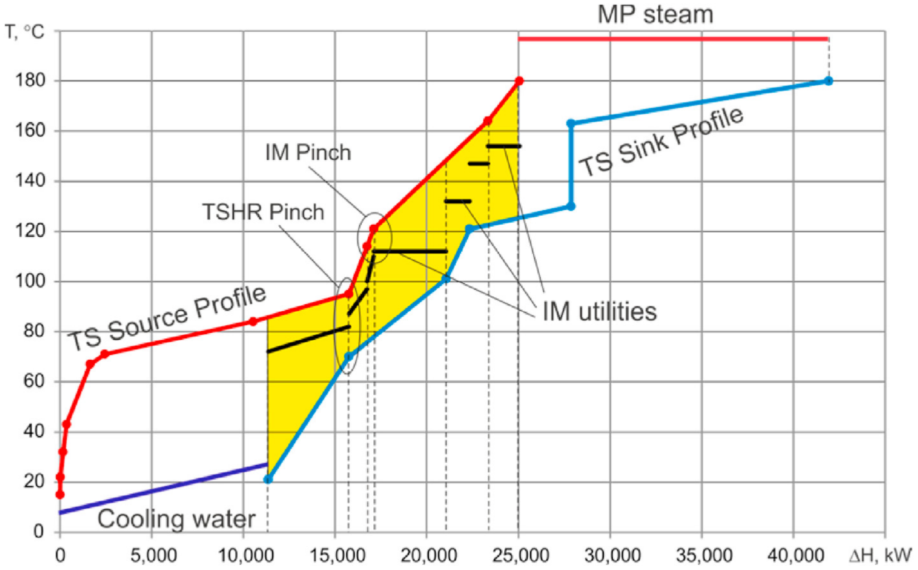


Fig. 13. Total Site Profiles of the case study 2 for minimum heat transfer area approach.

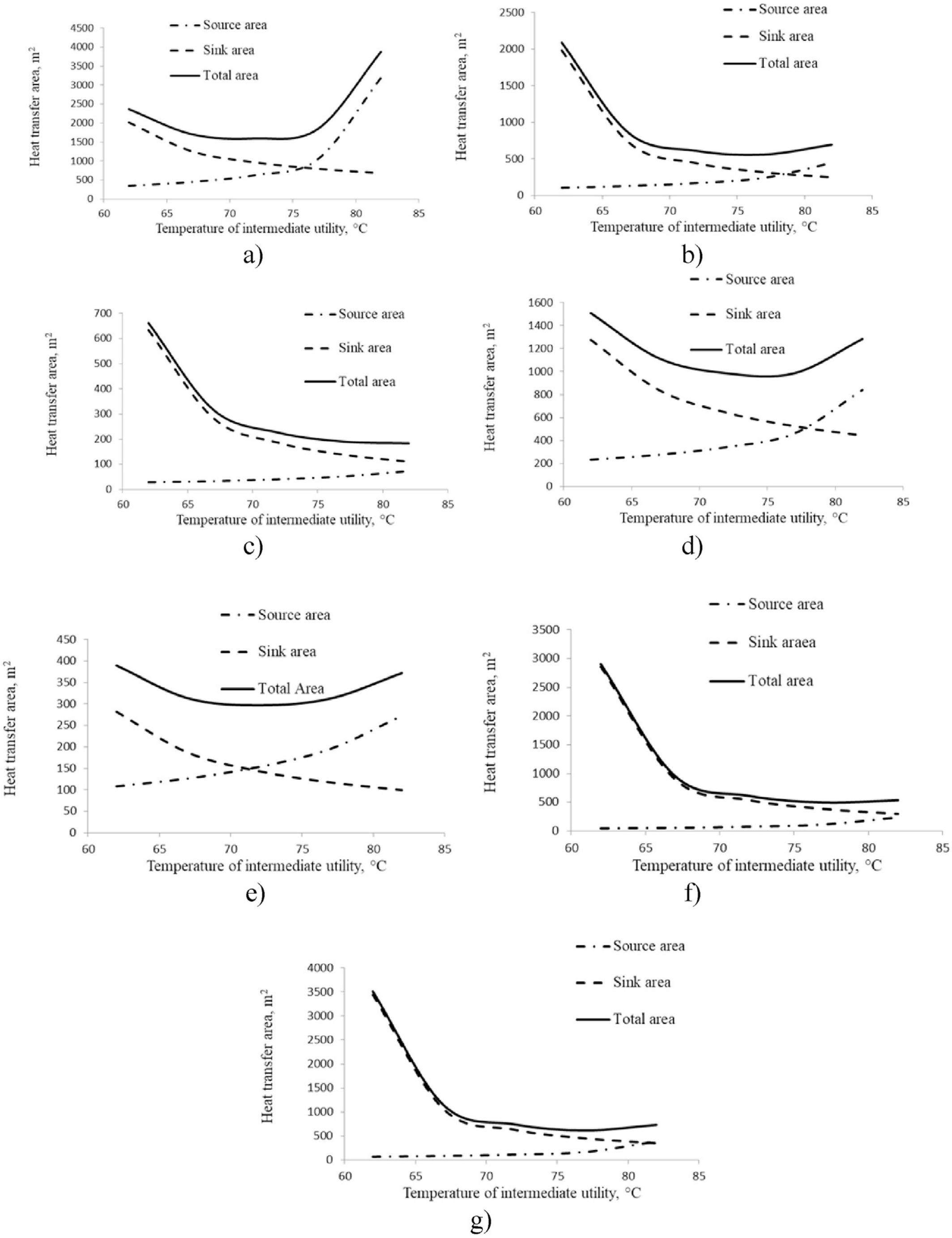


Fig. 14. Selection of IM temperature for minimum heat transfer area. a) enthalpy block #1 and IM1; b) enthalpy block #2 and IM2; c) enthalpy block #3 and IM3; d) enthalpy block #4 and IM4; e) enthalpy block #5 and IM5; f) enthalpy block #6 and IM6; g) enthalpy block #7 and IM7.

Table 6
The results of case study 2 for minimum heat transfer area.

Enthalpy block	ΔH, kW	TS, °C	TT, °C	ΔT_{min}, °C	h_{IM1}, kW/(m^2·°C)	h_{IM2}, kW/(m^2·°C)	S, m^2	N_{HR}
#1	4410	72	82	12	1	1.1	1597.71	5
#2	994	87	97	8	1.1	1.2	560.21	6
#3	354	100	110	11	1.2	1.2	183.39	5
#4	3944	112	112	9	5.3	7.2	985.06	5
#5	1294	132	132	11	5.4	7.2	296.94	3
#6	993	147	147	11	5.4	7.3	495.19	3
#7	1728	154	154	10	5.4	7.4	614.92	2

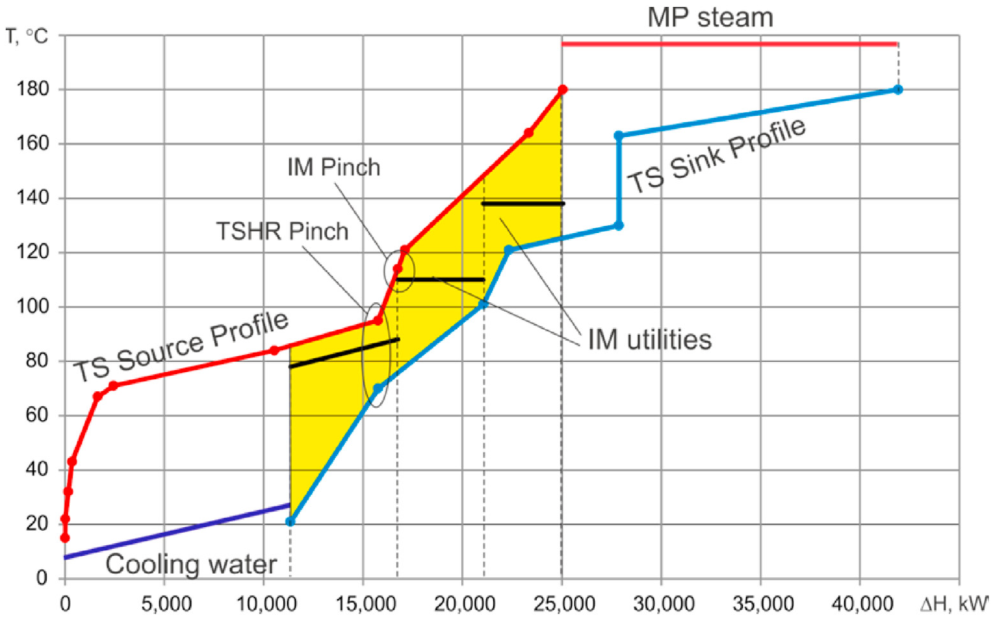


Fig. 15. Total Site Profiles of the case study 2 and minimum units' number.

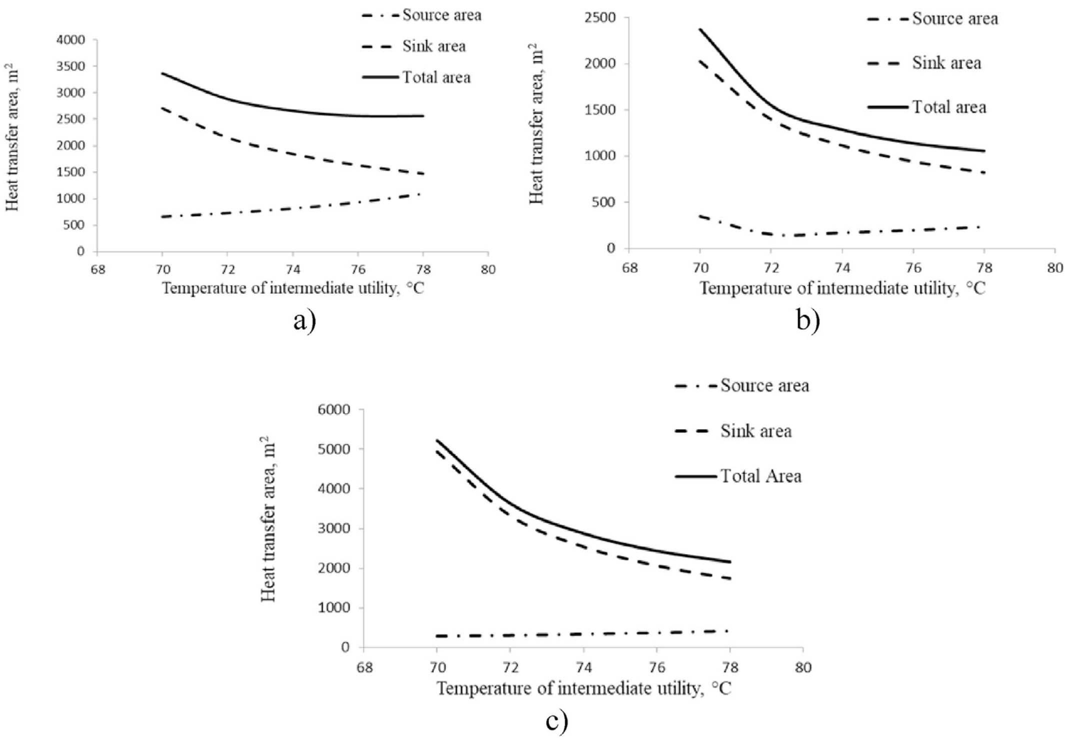


Fig. 16. Selection of IM temperature for minimum unit number. a) enthalpy block #1 and IM1; b) enthalpy block #2 and IM2; c) enthalpy block #3 and IM3.

Table 7
The results of case study 2 for minimum units number.

Enthalpy block	ΔH, kW	TS, °C	TT, °C	ΔT_{min}, °C	h_{IM1}, kW/(m^2·°C)	h_{IM2}, kW/(m^2·°C)	S, m^2	N_{HR}
#1	5404	78	88	6	1	1.1	2562.93	7
#2	4298	110	110	4	5.3	7.2	1054.64	6
#3	4015	138	138	8	5.4	7.2	2157.10	4

Table 8
Comparison of results obtained by different approaches.

Approach	Heat recovery, kW	S, m^2	Number of heat exchangers	Number of steam mains/piplines	TSHR Pinch, °C	Utility Pinch, °C
Min heat transfer area	13,717	4733	29	7	25	8
Min unit number	13,717	5775	17	3	25	4

Table 9
Economic results of case study 2.

Approach	Saving, USD/y	Capital cost of TSHR network with CS-CS units, USD	Difference in capital cost, %	Payback period, months
Min heat transfer area	4,836,807	516,648	–	1.28
Min unit number	4,836,807	486,726	−6%	1.21

TS super targeting. The dependences of the reduced capital costs, annual energy costs and the total yearly costs of the studied hydrocarbon processing are shown in Fig. 12. The correlations of total expenses have an extremum at $\Delta T_{min} = 25°C$ and the HEN of the TS should be designed, taking into account this indicator. It is important to note that the $\Delta T_{min} = 25°C$ is the optimum under the current scenario economic conditions, i.e. the cost of energy and the cost of the heat exchangers. The assessment of total reduced cost at an optimum point is 36.4 million $ and includes expenses for capital investments for TSHR and TS utility exchanger network, and for energy cost. Further analysis is focused on the TSHR network.

TS design with minimum heat transfer area. TS profiles built for the optimum minimum temperature difference are shown in Fig. 13. In the section of overlapping profiles along the утерфдзн axis, 7 enthalpy blocks are formed, within which the site heat recovery network can be synthesised. Within each enthalpy block, the temperature of the intermediate heat carrier is optimised. The IM temperature changes within each interval from the lower to the upper bound and the total heat transfer area is calculated. The minimum is taken within each interval shown in Fig. 14 and Fig. 13 as well.

Total heat transfer area of TS recovery is 4733 m^2, and 29 heat exchangers are needed to recover 13.7 MW from Source to Sink Profiles. More detailed information about generated site HEN with minimum heat transfer area is shown in Table 6.

TS design with minimum number of heat exchangers. Further analysis of TS recovery network demonstrates that several enthalpy blocks can be merged as described above by methodology. After merging enthalpy block, the procedure of IM optimisation within the merged enthalpy blocks in order to minimise heat transfer area. Merged enthalpy blocks are shown in Fig. 15. The TSHR Pinch point remains the same, but IM Pinch changed and appeared at IM 2 at T = 110 °C and Source Profile temperature 114 °C. The optimisation results of IM temperature within merged enthalpy blocks are demonstrated in Fig. 16. After joining, there are only three IM utility used and the number of heat exchangers reduced to 17, but the heat transfer area of heat recovery is increased to 5775 m^2. Detailed results of the recovery network are presented in Table 7.

Comparison of the results. The results obtained by the two approaches is presented in Table 8. Both networks utilise 13.7 MW, but in the first case, the heat transfer area minimised, and it is less than in the second approach by 18%. The opposite situation with unit numbers, the second approach with merged enthalpy blocks has less number of heat exchangers on 41%. Economic results of case study 2 are shown in Table 9, and capital investment for heat recovery network is less by 6% for the approach that assume merging enthalpy blocks.

4.3. Common issues

Direct heat exchange is also possible between sink-source profiles, but only if there are no restrictions (distances, pressure losses, etc.). This occurs mainly if the streams of one unit (plant) are used as a direct heat supply to another unit or if the units are at a small distance from each other. This paper discusses the Total Site design option using intermediate heat transfer fluids. This presupposes the use of heat carriers, which increases the number of units for heat exchange between intermediate heat carriers and process flows, as well as an increase in the heat exchange surface. These issues require research to develop further recommendations for the design of Total Site thermal systems, since overall Site integration is an essential element in reducing energy consumption, and reducing capital costs can significantly affect the choice of the economically viable optimum.

The capital cost obtained by two approaches is close, but this methodology does not take into account the pipelines that will increase the capital cost obtained by both techniques. Thus, in case of minimum heat transfer area is assumed 7 pipelines/steam mains are needed comparison to 3 ones for minimum unit number approach. It makes additional advantage of the method that presumes enthalpy blocks merging. Nevertheless, both approaches should be applied individually depending on the specifics of the production site.

Further issues should be discussed additionally. These are the pressure and temperature losses and power generation potential. Both problems have much impact on capital investments when designing a Total Site Recovery Network. Temperature and pressure losses may be resized if the scale of site recovery network is known. Thus this issue should be additionally studied, especially for some standard pipe sizes and different types of thermal insulations. The power generation opportunities have to be estimated together with heat recovery to find a more profitable option and provide more flexible operation mode to industrial clusters as some of them are usually the big number of stakeholders and end-users with different demands.

5. Conclusion

The presented methodology provides a system design of the heat recovery network of Total Sites. It gives an approach to reduce the number of steam mains and heat exchangers optimising the heat transfer area in enthalpy blocks. The capital cost is reduced by compromising heat transfer area and the number of units. The results of current work may be used for the design of TSHR of big industrial clusters to increase: first, the energy efficiency; second, the efficiency of capital investment and payback reduction. The case study 1 has shown that the unit number is reduced by 25%

while the heat transfer area is increased by 7%. The case study 2 demonstrates the differences between approaches assuming minimum heat transfer area and minimum unit numbers. First one delivers 18% fewer area targets while the second provides 41% fewer exchanger units. Additionally, the number of steam mains and ancillary equipment is reduced too. Besides, it was proved that the unit number has more impact on the final investment of site recovery network than the heat transfer area. This work moves ahead to practical arrangements on TSHR specifying different temperature driving forces between intermediate heat carriers and process streams as well as finding global minimum temperature approach of Total Site. This issue would be beneficial for the future development of Total Site methodology to get real solution and definition of the heat transfer contexts allowing the users to specify ΔT_{min} values for different heat exchangers [5]. The results of this work may be used for big industrial clusters when doing a grassroots design, for decision-makers when investing new projects and for better understanding the Total Site heat recovery by students and engineers. Further research will be focused on detailed analysis of pipelines modelling and assessment of distance between plant within the industrial cluster to get a more reliable solution for TS design and modelling.

Credit author statement

Stanislav Boldyryev: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. Anatoly A. Shamraev: Data curation, Formal analysis. Elena O. Shamraeva: Investigation, Visualisation, Writing – review & editing, Investigation,

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

TSHR Pinch	Total Site Heat Recovery Pinch
IM Pinch	intermediate utility Pinch
T	temperature, °C
TS	supply temperature, °C
TT	target temperature, °C
ΔH	enthalpy, kW
Atotal	total heat transfer area, m2
ATSHR	minimum heat transfer area of heat recovery, m2
ATSHU	minimum heat transfer area of hot utility, m2
ATSCU	minimum heat transfer area of cold utility, m2
Δp loss	a pressure drop, kPa
Δp pump	pump pressure, kPa
ΔTmin	minimal temperature difference between two process streams, °C
ΔTmin1	minimal temperature difference for source side, °C
ΔTmin2	minimal temperature difference for sink side, °C
ΔTTS Opt	optimal minimum temperature difference of Total Site, °C
ΔT_{LM}^{H}	logarithmic temperature difference for source side, °C
ΔT_{LM}^{C}	logarithmic temperature difference for sink side, °C
ΔT loss	heat losses, °C
t1	temperature low bound, °C
t2	temperature upper bound, °C
Qi	the heat of i-th hot stream, kW
Qj	the heat of j-th cold stream, kW
QIM	heat of intermediate utility in enthalpy interval, kW
QRECOVERY	a load of heat recovery, kW
QHU	the heat of hot utility in enthalpy interval, kW
QCU	the heat of cold utility in enthalpy interval, kW
QHmin	hot utility target, kW
QCmin	cold utility target, kW
hi	film heat transfer coefficient of i process stream, W/(m2 °C)
hj	film heat transfer coefficient of j process stream, W/(m2 °C)
h_{IM}^{C}	film heat transfer coefficient for condensation/cooling of intermediate utility, W/(m2 °C)
h_{IM}^{H}	film heat transfer coefficient for boiling/heating of intermediate utility, W/(m2 °C)
hHU	film heat transfer coefficient of hot utility, W/(m2 °C)
hCU	film heat transfer coefficient of cold utility, W/(m2 °C)
hIM1	film heat transfer coefficient of intermediate utility on the source side, W/(m2 °C)
hIM2	film heat transfer coefficient of intermediate utility on sink side, W/(m2 °C)
n	number of hot streams in enthalpy interval
m	number of cold streams in enthalpy interval
k	number of enthalpy intervals for heat recovery
l	number of enthalpy intervals for hot utility
p	number of enthalpy intervals for cold utility
NHU	number of heat exchangers for hot utility
NCU	number of heat exchangers for cold utility
NHR	number of heat exchangers for heat recovery
NTotal	total number of heat exchangers
IM	intermediate utility
S	heat transfer area, m2
n_i^h	number hot streams in enthalpy interval
n_i^c	number hot streams in enthalpy interval
n	project lifetime, y;
i	fractional interest rate, %
CC	capital cost, USD;
CC1	capital cost of the hot utility network, USD;
CC2	capital cost of the cold utility network, USD;
RCC	total reduced capital cost, USD;
ROC	reduced operating cost, USD/y
TAC	total annual cost, USD;
a, b, c	coefficients
CostHU	cost of hot utilities, USD/kWy
CostCU	cost of cold utilities, USD/kWy
PBP	simple payback period, months
SS-SS	stainless steel heat exchanger
CS-CS	carbon steel heat exchanger

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