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Efficient Transshipment-Based Framework for Energy Targeting and Retrofitting Industrial Total Sites

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This work presents an efficient framework TransGen for the energy targeting and retrofitting of industrial Total Sites. An expanded transshipment model with constrained matches – forced and/or prohibited matches – has been further extended. An optimal production of intermediate utilities at different pressure levels is enabled including or excluding preheating depending on the percentage of condensate return. It also enables optimum identifications of modification in heat exchangers networks, which is practical for retrofitting. It includes the rules for obtaining optimistic and pessimistic scenarios by exploring the "Plus-Minus Principle". Finally, the insights from the Pinch Technology have been added within the framework. This framework could be applied for fixed and varying operational conditions. It is illustrated within the case-study of two process plants operating under fixed conditions. From the case-study it can be seen that significant improvements in energy efficiency and economic objective can be obtained when applying modifications.

1. Introduction

Due to several reasons, such as depletion of precious resources, environmental pollution and global competition, companies need to achieve the lowest production cost possible in order to remain competitive. Amongst the significant savings opportunities is when decreasing the energy consumption levels of the production plants and even selling the energy through district heating (DH) or cooling (DC). Possible energy savings within several industrial sectors (e.g. oil refining, pulp and paper, iron and steel etc.) are within the range of 10 – 35 % (CETC-Varennes, 2003).
There are two widely used methodologies for energy consumption targeting: Pinch Analysis – PA, and Mathematical Programming – MP (Klemeš and Kravanja, 2013), each with its advantages and drawbacks. In order to optimise the energy consumption within large companies or Total Sites (TSs), and/or under uncertain conditions, the methodologies should be combined and further extended.
This work presents an efficient transshipment-based framework which can be applied for energy targeting and retrofitting industrial plants and TSs. Several versions of the framework have been developed, each version for specific application. Several features of the transshipment-based framework are presented in the continuation. The framework is illustrated within an illustrated case-study of two process plants (Perry et al., 2008). This illustrated case-study presents an operation under fixed conditions; however, the framework is also applicable and practical for those sectors that operate under fluctuating conditions. This illustrated case study shows significant improvements in energy efficiency when retrofitting industrial TSs. For illustrating additional features of the transshipment-based framework for industrial TSs under uncertain conditions, see the contribution by Čuček et al. (2014).

2. Transshipment-based framework

The procedure for targeting and retrofitting industrial TSs could be with currently available tools very time-consuming, prone to make mistakes, and it could also be difficult to find the right opportunities for energy savings in several cases, especially under uncertain conditions. For this reason, general data-independent

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mathematical model has been developed for energy targeting and retrofitting industrial plants and TSs, which is based on an expanded transshipment model (Papoulias and Grossmann, 1983).
The developed framework has been significantly extended from expanded transshipment model by Papoulias and Grossmann (1983). The framework is therefore based on MP and combines the advantages of both, MP and PA. It has several features, such as:

i) Enabling the performing of the existing, target and modified (proposed) heat exchanger network (HEN) designs
ii) Accounting for constrained matches – existing, prohibited and enforced (should be unchanged during retrofitting) matches
iii) Rules for obtaining optimistic and pessimistic scenarios by exploring the “Plus-Minus” principle (Smith, 2005)
iv) Handling multiple utilities and the production of intermediate utilities, e.g. hot water and steam at different pressure levels including or excluding preheating depending on the percentage of condensate return
v) Selection of stream-specific contribution delta temperatures for different states of aggregation
vi) Optimal identifications of modifications for TS HEN under fixed and varying operational conditions – practical for retrofitting
vii) Proposed modifications could be such that all heat exchangers (HEs) could be modified, and also that some HEs are restricted from modifying
viii) Insights from Pinch Technology
ix) Data independence – could be applied to any industry (chemical, petrochemical, food, etc.)
x) Mixed-integer linear programming problem (MILP), and therefore the obtained solutions are globally optimal
xi) Enables single- and multi-objective optimisation, where the objective function could be energetic, economic, environmental, etc.
xii) Internal and TS Heat Integration (TSHI) under fixed and varying operational conditions. TSHI could be performed either directly using process streams, indirectly via intermediate utilities or combinations of direct and indirect TSHI
xiii) TSHI could be performed in two ways:
 - Total integration within each unit first, and only the remaining surpluses from each unit are transferred either directly or indirectly to other units with heat deficits
 - Integration could be performed with no restrictions that each unit should be integrated first internally and integration could be performed partly inside each unit, and partly at TS level

Several versions of the framework have been developed:

i) ***TransGen*** – framework for existing, target and modified designs for specific conditions for each plant and TS
ii) ***TransGen Extreme*** – framework for obtaining optimistic and pessimistic scenarios (extreme minimums and maximums of minimum utility consumption)
iii) ***TransGen Multiperiod TS*** – framework for direct and indirect TSHI for existing, target and modified designs under various scenarios, such as varying temperatures and flows

Frameworks *TransGen* and *TransGen Multiperiod TS* enable the obtaining of proposals regarding modifications for reducing energy consumption and the production of intermediate utilities. *TransGen* framework is suited for fixed operational conditions, and *TransGen Multiperiod TS* for varying conditions. In the following the *TransGen* framework is illustrated within a case-study of two process plants. *TransGen Multiperiod TS* is briefly illustrated in a contribution by Čuček et al. (2014).
The framework has several advantages over traditional tools, as will be presented and illustrated in the continuation. However, it should also be noted that it has few drawbacks, and should be further elaborated on and combined with other tools in the future. These drawbacks are:

i) Investment cost is currently excluded from the analysis in order to preserve convexity and linearity of the model. Therefore, only rough trade-off between utility cost and investment can be obtained due to the use of the stream-specific contribution delta temperatures. However, investment cost could be calculated later when retrofit modifications are validated and selected.
ii) Environmental objective(s) are currently excluded, yet retrofits usually improve environmental performance of the plant or TS by decreasing energy consumption.
iii) Fluctuations of energy prices (future utility prices) are yet unconsidered. The objectives are currently either energetic (minimisation of external utility consumption and maximisation of intermediate utility production), or economic (annual energy cost minimisation or annual energy profit maximisation). The entire life-time could be accounted for, and could consider forecasted future prices (Nemet et al., 2014).

iv) Pressure drops and heat losses are unconsidered.

3. Illustration case study of targeting and retrofitting industrial plants and TSs

As it was presented before, *TransGen* frameworks account for fixed and uncertain conditions, such as temperatures, flowrates and other parameters. This illustration case study is an example of TS with fixed operational conditions. Two process plants A and B are assumed, whose data are taken from Perry et al. (2008) and shown in Table 1 for Plant A and in Table 2 for Plant B.

Table 1: Process Plant A stream data (after Perry et al., 2008)

Stream name	Stream type	Supply temperature (°C)	Target temperature (°C)	Heat capacity flowrate (kW/K)
H1	Hot	170	80	55.56
H2	Hot	150	55	68.18
C1	Cold	25	100	20
C2	Cold	70	100	35
C3	Cold	30	65	150

Table 2: Process Plant B stream data (after Perry et al., 2008)

Stream name	Stream type	Supply temperature (°C)	Target temperature (°C)	Heat capacity flowrate (kW/K)
H3	Hot	200	80	83.33
C4	Cold	20	100	50
C5	Cold	100	120	500
H4	Hot	150	40	72.73
C6	Cold	60	110	20
C7	Cold	75	150	93.33

Assumed hot utility is medium pressure steam (MPS) with temperature of 177 °C and price of 30 €/MWh. Cold utility is cooling water with temperature 15/25 °C and price of 0.07 €/t (circulating flow is assumed). HENs for the existing designs of Plants A and B are assumed as shown in Figures 1 (Plant A) and 2 (Plant B). Also, temperatures and heat duties of HEs, heaters and coolers are inserted.

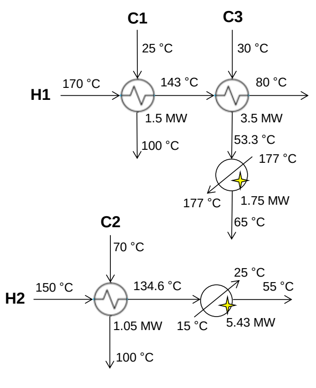

Figure 1: HEN for Plant A

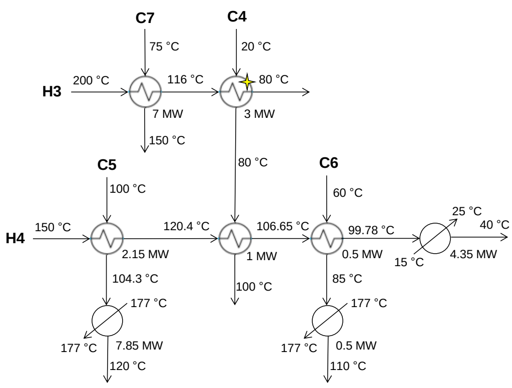

Figure 2: HEN for Plant B

4. Application of *TransGen* framework on an illustration case study

Within the above described case study the applicability and efficacy of the transhipment-based framework *TransGen* will be illustrated. Several features will be shown, such as i) performing existing, target and modified designs, ii) possibilities of intermediate utilities' productions, e.g. of hot water for DH, ii) insights from Pinch Technology, iii) optimum selection of modifications of existing HEs which is practical for retrofit suggestions. The main objective is maximisation of the annual profit accounting for energy flows. The

MILP model is formulated within GAMS environment (GAMS Development Corporation, 2013) and consists of approximately 1,950 constraints, 13,650 single variables and up to 13 binary variables for TS.

4.1 Analysis for target and existing designs by fixed conditions

First energy analysis for target and existing designs are obtained for each plant. Figures 3a – 3f show temperature-enthalpy profiles (Grand Composite Curves – GCCs) for target and existing designs. In particular, Figure 3a shows GCC of target design, and Figure 3b of existing design for Plant A. Similarly, Figure 3c presents GCC of target design of Plant B, and Figure 3d, the one of existing design of Plant B. Finally, Figures 3e and 3f show GCCs for target and existing designs for TS (both Plants, A and B). Indirect integration across Plants A and B using LPS is assumed.

Temperature-enthalpy profiles for target designs for Plants A and B are the same as within contribution by Perry et al. (2008), however here also external and intermediate utilities are presented. The possibility of hot water production with temperature regime of 95/75 °C for DH network is assumed. The following steam mains are considered: low pressure steam (LPS) with temperature of 125 °C and MPS of 177 °C.

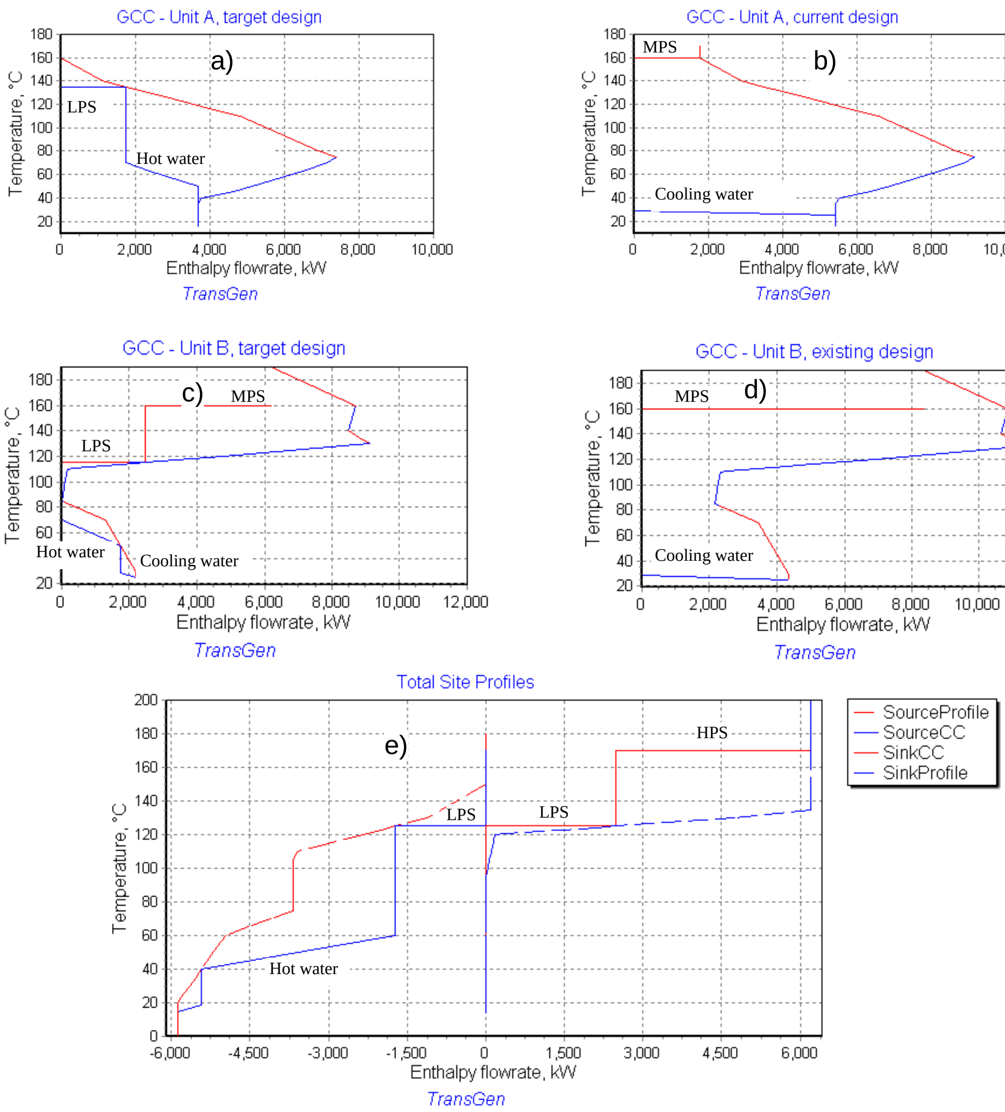

Figure 3: GCCs for target and existing designs for Plant A (a, b), B (c, d,), and TS Profiles

Possible energy recovery can be determined as the difference between existing and target utility consumptions. From Figures 3a and 3b it can be seen that there is a potential for 1.7 MW reduction of hot (MPS) and cold utility consumptions. In this case the consumption of hot utility would be vanished and the remaining cold utility can be supplemented by the production of 1.95 MW hot water and 1.7 MW LPS.

Altogether the consumption of MPS could be thus reduced for 1.7 MW and cooling water for 3.7 MW. Maximum savings in energy cost due to the integration are about 1 M€/y. Similarly, there is a potential to reduce energy consumption within Plant B. Hot utility (MPS) could be reduced for 2.1 MW (energy savings of 26 %), and cold utility (cooling water) also for 2.1 MW (energy savings of 49 %). Maximum savings from energy consumption reduction are about 0.6 M€/y. In addition about 2.5 MW of MPS can be substituted by cheaper LPS.

When performing heat integration across individual plants there are some additional opportunities for energy savings, as it can be seen from Figure 3e. 1.7 MW of intermediate LPS can be produced at the Source Side of Plant A and transferred to the Sink Side of Plant B, thereby reducing the consumptions of hot and cold utilities by the same amount. Note also that the remaining cold utility could be supplemented almost entirely by the production of hot water for DH (about 3.7 MW). Possible savings within and between Plant A and B are thus significant.

4.2 Proposed modifications on process and TS level

TransGen framework is especially efficient in proposing modifications of HENs. Search for modifications starts from the existing HEN, and continues iteratively with enabling changes of HEs one by one. Search ends when results are unchanged by changing more HEs.

Figure 4 shows the main results, how they are changed with number of HEs' modifications a) savings in energy cost, b) savings in energy consumption, c) hot utility consumption and d) hot water production. All the Figures present the main results when modifying only Plant A, only Plant B, when performing indirect sequential TSHI (integration is firstly performed within each unit, remaining surpluses are integrated at TS level via intermediate utilities), and when performing direct simultaneous TSHI (direct integration using process streams with no restriction that each unit should firstly be integrated internally).

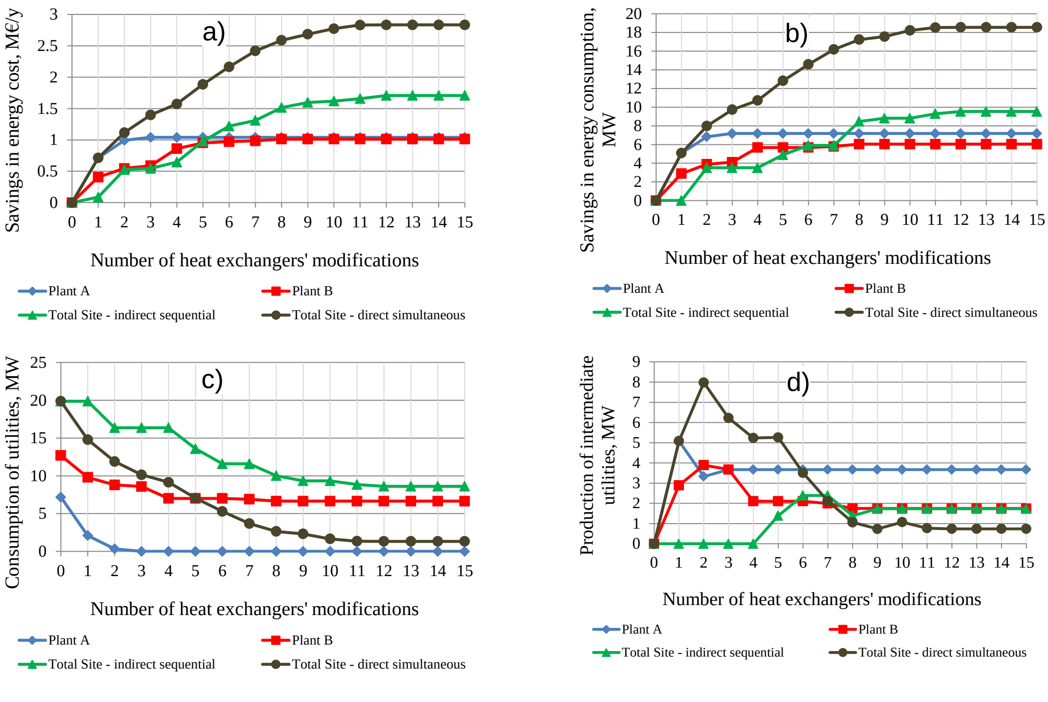

Figure 4: Main results changed with number of HEs' modifications

From Figure 4 it can be seen that savings in energy cost and energy consumption significantly increase, especially when performing direct TSHI. On the other hand hot utility consumption is decreased the most when applying internal HI within Plant A, and in this case also hot water production is among the highest. It can also be seen that within Plant A three modifications suffice to reach the target HEN design, within Plant B the number of modifications is seven, and on TS level twelve.

Finally an example of proposed HEN after three modifications of existing HEs using direct stream-to-stream heat transfer and the one after five modifications using indirect heat transfer via hot water and LPS are shown on Figures 5a and 5b, respectively.

5. Conclusions

This contribution presented an efficie ranshipmentent-based framework which could be applied for fixed and varying operational conditions. The framework is suited for performing analysis of target, existing and modified HEN designs. It is developed in several versions, *TransGen* (fixed conditions), *TransGen Extreme* (extreme limits of minimum energy consumption), and *TransGen Multiperiod TS* (considers fluctuations with time and direct and indirect TSHI). The main advantage of the proposed framework is that it enables obtaining various proposals regarding modifications of HENs according to certain priority (economic, thermodynamic, environmental, etc.). Framework *TransGen* was illustrated on the illustration case study, where it was shown that it has great potential for retrofitting industrial plants and TSs.

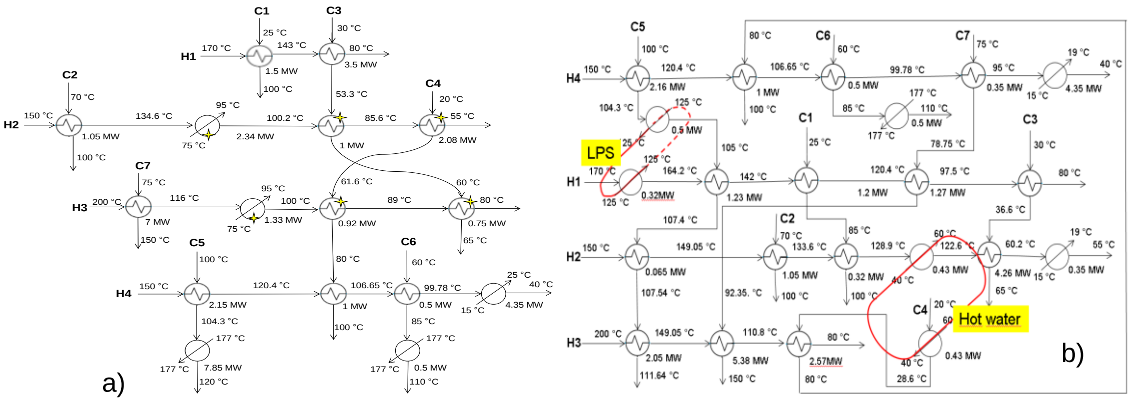

Figure 5: Examples of HEN designs for TS when performing modifications of HEN for: a) direct heat transfer by modifying the existing HEs and b) indirect heat transfer by modifying five existing HEs

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