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A Procedure for the Retrofitting of Large-Scale Heat Exchanger Networks for Fixed and Flexible Designs applied to Existing Refinery Total Site

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This contribution presents the application of a novel three-step procedure for the retrofitting of large-scale heat exchanger networks (HENs) under fixed and flexible designs of existing Total Sites (TS). The entire procedure for HEN retrofitting within the analysed industrial TS consists of three steps: i) targeting and identification of the potential for improvement; ii) identification and selection of feasible and profitable alternatives for modifications, and iii) performing detailed HEN retrofit designs on the reduced spaces of alternatives. The search for retrofit modifications was performed by the economic objective by considering trade-offs between investment cost (heat exchanger area and piping) and savings in energy cost. The first targeting and second pre-screening steps were performed using the software tool TransGen, and the third synthesis step using software tool HENSYN. The novel three-step procedure was applied on an existing refinery TS.

1. Introduction

Heat and TS Integration and waste heat utilisation within industrial processes and TSs is an efficient way of conserving energy and achieving emission reductions (Klemeš et al., 1997). Two situations exist regarding the analyses of HENs within processes and TSs: i) grassroots or minimum energy requirement (MER) designs for new plants and TSs, and ii) retrofitting (also reconstruction, revamp or redesign) of existing plants and TSs. This contribution deals with retrofits within existing process plants and TSs, which is considerably more complicated than for grassroots' networks (Yee and Grossmann, 1991) due to several reasons: i) the existing equipment and layout has to be considered, ii) plant downtime is required, which can be critical, and iii) existing heat exchange (HE) units should be more accurately modelled (Klemeš et al., 2013). There are many ways of improving the existing designs, such as changes in the usages of utilities, topological modifications, installing of additional areas, re-piping of streams, reassignments of matches and heat transfer enhancement (Wang et al., 2012). There are also several approaches for the tackling of retrofit projects: i) by inspection, ii) by computer search – Mathematical Programming (MP) approach, iii) by Network Pinch Approach (Asante and Zhu, 1996), and iv) by combined Mathematical Programming/Pinch Analysis (MP/PA) approaches (Klemeš and Kravanja, 2013).

This contribution deals with retrofitting the existing TS under dynamic conditions. The new software tools TransGen and HENSYN together with the novel three-step procedure consisting of targeting, identification and synthesis steps have been developed for energy targeting and retrofitting of existing industrial plants and TSs (Čuček and Kravanja, 2015). The novel three-step procedure and software tools were applied and demonstrated on an existing refinery's TS by analysing more than 100 HE units.

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Since the data and the results of the industrial case are confidential and consequently the comprehension might be lower, the reader may refer to contribution by Čuček and Kravanja (2015) where the methodology is explained in more details and demonstrated on a simplifies illustrative example.

2. Retrofit of Large-Scale Heat Exchanger Networks

2.1 Three-step procedure

The following three-step procedure and software tools TransGen and HENSYN can be used for retrofitting of existing large-scale HENs under steady-state or fixed and under dynamic or varying operating conditions, see Figure 1:

i) Targeting step using the software tool TransGen based on MP/PA and a comparison with the existing energy consumption. The potential for Heat and TS Integration and waste heat utilisation is identified.
ii) Identifications of alternatives for modifications based on MP using TransGen and selection of modifications by forbidding the infeasible matches. This step enables obtaining the most optimal retrofitting modifications regarding energy consumption reduction and intermediate utilities production in regards to trade-offs between operating and investment costs. All the proposed modifications should be verified and the procedure is repeated as long all the proposed HE matches are acceptable. Several loops could be required to obtain verified and feasible results.
iii) Synthesis of the retrofitted HEN design from those modifications identified during the second step using software tool HENSYN. Synthesis step is based on MP and enables obtaining the structure of the retrofitted part of HEN and basic parameters for the HE units involved.

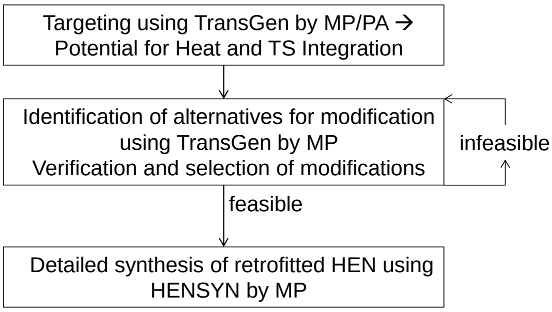

Figure 1: Three-step procedure and applied software tools

2.2 Software Tools TransGen and HENSYN

Two software tools TransGen and HENSYN have been developed regarding the retrofitting of dynamic TSs (Čuček and Kravanja, 2015). Both software tools are composed of two parts: i) the data-independent algorithm and model and ii) the data. In order to perform any study, only the data should be changed appropriately.

Software tool TransGen is used for:

i) Targeting and comparing the target and existing designs by combined MP/PA to obtain the potential for Heat and TS Integration and intermediate utility production
ii) Identifications of alternatives for modifications by MP, and selections of modifications by forbidding the infeasible matches
iii) Preparation of the data for selected modifications to be used in software tool HENSYN.

Software tool HENSYN is used for the detailed synthesis of the retrofitted HENs by MP approach. The main features of the software tools TransGen and HENSYN are presented in Čuček and Kravanja (2015).

Both developed tools TransGen and HENSYN are to be used jointly. TransGen enables analysing the large-scale HENs and provides globally-optimal solutions. However, TransGen does not provide the results in a form that makes it possible to draw HENs and it is impossible to analyse in detail the obtained modified HENs. The results are combined with the software tool HENSYN, which enables the obtaining such results from those modifications identified by TransGen with minimum efforts including the positions and temperatures of the proposed heat exchangers within the network, and also enables the performing of more detailed analysis of the trade-offs between investment and operating cost. However, HENSYN is based on non-linear programming (NP) hard mixed-integer nonlinear programming (MINLP) and has complex combinatorics and non-convexities involved. It could be used directly only for smaller problems. For performing Heat and TS Integration within large-scale industrial processes and TSs, especially under varying conditions, the combination with TransGen is beneficial to be used. This reduces the problem's feasible region close to global optimal solutions. In order for the procedure to be automated, the data regarding the final streams that are included in HEN are automatically generated in TransGen and loaded into software tool HENSYN.

3. Application of the Procedure and Software Tools TransGen and HENSYN to Existing Total Site of Oil Refinery

The three-step procedure and software tools TransGen and HENSYN have been developed for the purpose of retrofitting large-scale industrial TS under fixed and varying conditions. They could be applied for any TS, and are demonstrated within an existing refinery's TS. The refinery is operating under varying operating conditions due to ambient temperature fluctuations and crude oil feedstocks. The most significant differences are between the summer and winter months, and due to two different types of crude oil feedstocks, sweet and sour crudes. Four of the most significantly different operating conditions were selected in order to cover the extreme variations for the purpose of retrofitting. Four plants P1 – P4 within the refinery are analysed under four operating conditions C1 – C4. The motivation for retrofitting was two-fold, the main one being to find sources for producing a certain amount of hot water for district heating. The second task is to perform Heat and TS Integration to find out if there are still remaining potentials for reducing external utilities' consumption. It should be noted that the data are confidential and cannot be presented. The obtained results are regarded also as confidential and are presented in normalised or "hidden" form. However, the shapes of the curves and all the ratios between results are preserved.

3.1 Targeting and Identification of Potential for Heat and Total Site Integration

The first step when having the required data collected is the targeting step. When comparing the target and the existing designs it is possible to obtain the potential for improvement in terms of utility consumption reduction and intermediate utility production. Special emphasis was on estimating the hot water production potential. Table 1 shows the obtained results by different minimum temperature differences (ΔT_{min}) in comparison with the required amount of hot water produced. The lowest hot water potential is obtained under operating condition C4 by ΔT_{min} = 5 °C. In this case about 1.3 times the required amount of hot water could be produced.

Table 1: Main results regarding the potential for hot water production

	C1			C2			C3			C4		
ΔT_{min} (°C)	5	10	15	5	10	15	5	10	15	5	10	15
Hot water potential	1.8	1.9	2.1	2.1	2.2	2.4	1.9	2	2.1	1.3	1.4	1.5

Figure 2 shows an example of TS Profiles for C4. This Figure presents the normalised enthalpy on the x-axis; however the scale and the shapes of the Site Profiles are preserved. Site Source and Site Sink Profiles are presented in red and blue dashed lines, and Source and Sink Composite Curves in blue and red solid lines. The amount of hot water which could be produced is 1.3 times the required hot water production.

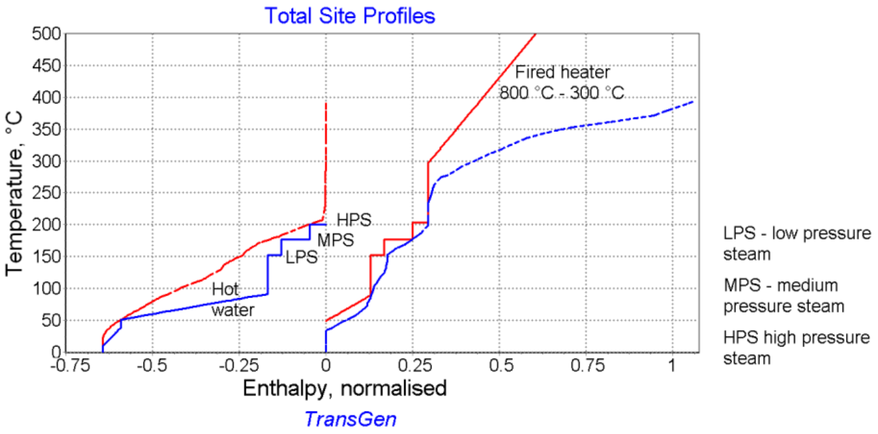

Figure 2: Total Site Profiles with hot water production for operating condition C4

3.2 Identification and Selection of Modifications

From the targeting step, significant potential for hot water production and for energy consumption reduction are shown. The next step was the identification and selection of retrofitting modifications. The analysis regarding the most optimal modifications with the main objective of maximising the incremental profit by considering the trade-offs between energy and investment cost was performed. The retrofit modifications were performed for a TS (for all four plants simultaneously) under varying conditions.

Prohibition of matches between some plants was considered for those matches identified to be not integrated due to safety and other operational constraints. Production and consumption of steam at different pressure levels was also considered as being fixed at current production and consumption levels. Integration between processes (TS Integration) was based on the distance between plants multiplied by 3 (multiplied by 6 for both directions). Only direct integration was considered when performing integration between plants. Heat loss of 10 % was considered when TS Integration was performed between plants; the energy of hot stream being 10 % higher compared to the energy of the cold stream in such cases. The average HE duties were considered for all hot and cold streams if there had been variations between the duties at the cold and hot sides. Any process cooling duty thus matches any heating duty in each HE unit.

Analysis was performed using software tool TransGen for a certain number of the most optimal new HE matches. As a multi-period model was used, the proposed modifications are valid for all four operating conditions C1-C4. Modifications were such that a certain number of new profitable HE matches were formed (e.g., 6, 9, 15) by relaxing a certain number of the restrictions in terms of existing HE units.

According to feedback regarding the feasibilities of the proposed modifications, the identification step was repeated several times by excluding infeasible (and difficult in some cases, see Table 2) modifications until all the proposed HE matches were acceptable, and the final solution had been obtained. The identification step contained several loops in order that all the solutions had been verified and feasible.

Several options were analysed for retrofitting. Those options differed in terms of reuse of the heat exchanger area where the entire load is released, minimum heat transfer for all the operating conditions (0 kW or at least 500 kW), and unfeasible or unfeasible and difficult modifications were excluded. Those options are summarised in Table 2.

Table 2: Analysed options

	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7	Option 8
Reuse of existing area with entire load released	NO	NO	YES	YES	NO	NO	YES	YES
Minimum heat transfer for conditions C1-C4	500 kW	0 kW	500 kW	0 kW	500 kW	0 kW	500 kW	0 kW
Excluded modifications	Unfeasible				Unfeasible and difficult			

Figure 3 illustrates an example of the obtained main results regarding those options in terms of the payback period. It shows the results obtained from the second set of proposed modifications by forming maximum 6, 9, 15 and all new profitable HE matches. However, it should be noted that this is not the final solution, and some modifications proposed had been infeasible or difficult and thus excluded from the next sets of proposed modifications.

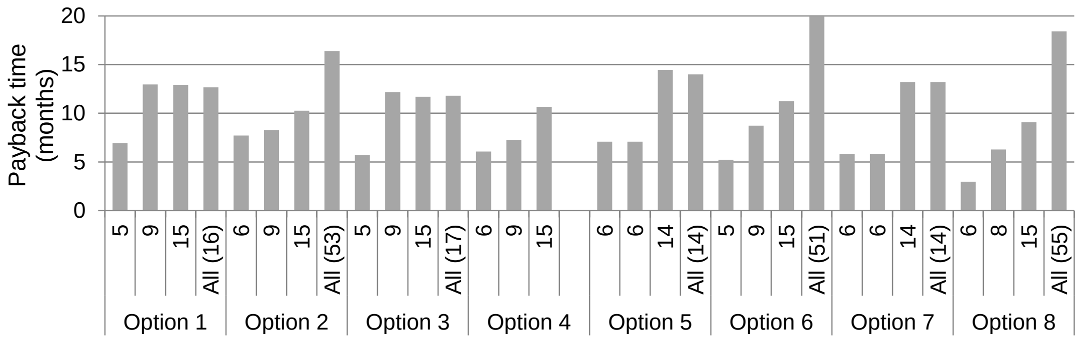

Figure 3: Payback period in months for the second set of proposed modifications

Figure 4 shows an example of the results obtained during the identification step, the results regarding a proposed certain number, e.g. 6, of new HE matches. Figure shows the data for the hot and cold streams (stream segments) which are modified, the other segments not identified during retrofitting modifications were suggested as being unchanged. First the data for the existing design are shown and further the data for the modified design (reallocations within each plant and between the plants – at TS level). The amounts of reallocated energy are written as Q1 to Q7 for operating conditions C1 - C4. The same letter always represents the same value. HE1 to HE7 represent HE units, HS1 to HS6 hot streams, CS1 and CS2 cold streams, Utility1 hot utility and Utility2 and Utility3 cold utilities.

Existing design				Heat duty			
Plant	HE unit	Hot stream	Cold stream	Operating condition C1	C2	C3	C4
	HE1	HS1	Utility2	$Q1_{C1}$	$Q1_{C2}$	$Q1_{C3}$	$Q1_{C4}$
P2	HE2	HS2	Utility2	$Q2_{C1}$	$Q2_{C2}$	$Q2_{C3}$	$Q2_{C4}$
	HE3	HS3	Utility2	$Q3_{C1}$	$Q3_{C2}$	$Q3_{C3}$	$Q3_{C4}$
	HE4	HS4	CS1	$Q4_{C1}$	$Q4_{C2}$	$Q4_{C3}$	$Q4_{C4}$
P3	HE5	HS5	Utility2	$Q5_{C1}$	$Q5_{C2}$	$Q5_{C3}$	$Q5_{C4}$
	HE6	Utility1	CS2	$Q6_{C1}$	$Q6_{C2}$	$Q6_{C3}$	$Q6_{C4}$
P4	HE7	HS6	Utility3	$Q7_{C1}$	$Q7_{C2}$	$Q7_{C3}$	$Q7_{C4}$
Modified design							
Plant	New HE matches at plant level			Heat Integration / Hot water production			
P2	HE1 → hot water production	HS1	Hot water	$Q1_{C1}$	$Q1_{C2}$	$Q1_{C3}$	$Q1_{C4}$
	HE2 → hot water production	HS2	Hot water	$Q2_{C1}$	$Q2_{C2}$	$Q2_{C3}$	$Q2_{C4}$
P3	HE4 → HE6	HS4	CS2	$0.07 \cdot Q4_{C1}$ $0.46 \cdot Q6_{C1}$	$0.05 \cdot Q4_{C2}$ $0.54 \cdot Q6_{C2}$	$0.02 \cdot Q4_{C3}$ $0.13 \cdot Q6_{C3}$	0
	HE5 → hot water production	HS5	Hot water	$Q5_{C1}$	$Q5_{C2}$	$Q5_{C3}$	$Q5_{C4}$
P4	HE7 → hot water production	HS6	Hot water	$0.32 \cdot Q7_{C1}$	$0.37 \cdot Q7_{C2}$	$0.48 \cdot Q7_{C3}$	$0.52 \cdot Q7_{C4}$
Plant	New HE matches at Total Site level			Total Site Integration			
P2 – P3	HE3 → HE4	HS3	CS1	$0.94 \cdot Q3_{C1}$	$Q3_{C2}$	$Q3_{C3}$	0

$Q4 = Q6 = 0.9 \cdot Q3$, feasible, difficult, should be evaluated for feasibility

Figure 4: Main results regarding proposed 6 modifications for option 4 (see Table 2)

Some of the proposed modifications have been identified as feasible or difficult from the previous steps (infeasible modifications had been excluded from the final analysis). Some modifications had to be evaluated for feasibility in this round. Some hot and cold streams were completely matched with another streams, the reallocated energy being 100 %, and the energy of some hot and cold streams were partially reallocated to another hot and cold stream (e.g. 7 % of energy of hot stream HS4 was reallocated from CS1 to CS2 under operating condition C1, see $0.07 \cdot Q4_{C1}$). This step was completed when all the identified modifications were feasible and accepted.

3.3 Synthesis of Retrofitted Heat Exchanger Network

Based on the identified feasible retrofitting modifications, the synthesis of retrofitted HEN was obtained using software tool HENSYN. Figure 5 shows an example of the obtained HEN with maximum 9 new HE matches. Only those stream segments are shown which should be changed. The other streams and stream segments within the process and/or TS remain unchanged. Several new heat exchangers (9) should be installed for new HE matches (shown with). Existing heat exchangers' area should be reduced (shown as) where part of the heat load of existing matches is reallocated (3). Heaters are highlighted as and coolers as . The heat exchanger network (HEN) includes also all the temperatures (in °C) separately for each scenario and exchanged duties (A…AR). Proposed types of heat exchangers identified using HENSYN are also shown in Figure 5, and the calculated reduction in existing heat exchanger area. The heat duties are denoted as A, B…AR.

4. Conclusions

This contribution presented the application of a three-step procedure and developed software tools TransGen and HENSYN at an existing refinery TS operating under dynamic conditions. From targeting step significant potential for energy consumption reduction and hot water production was obtained. Hot utility consumption could be reduced within plants P1 – P4 by 29 % on average and cold utility consumption by 90 % on average. The average maximum possible reduction in energy consumption in P1 – P4 is 49 %.

During the identification step the proposed modifications were selected at the plant and TS level. Finally, during the synthesis step the retrofitted HEN was obtained. The developed and demonstrated method and approach could be used for the other process plant or TS. There is a large potential for energy savings within the EU and worldwide within the industrial, domestic and service sectors.

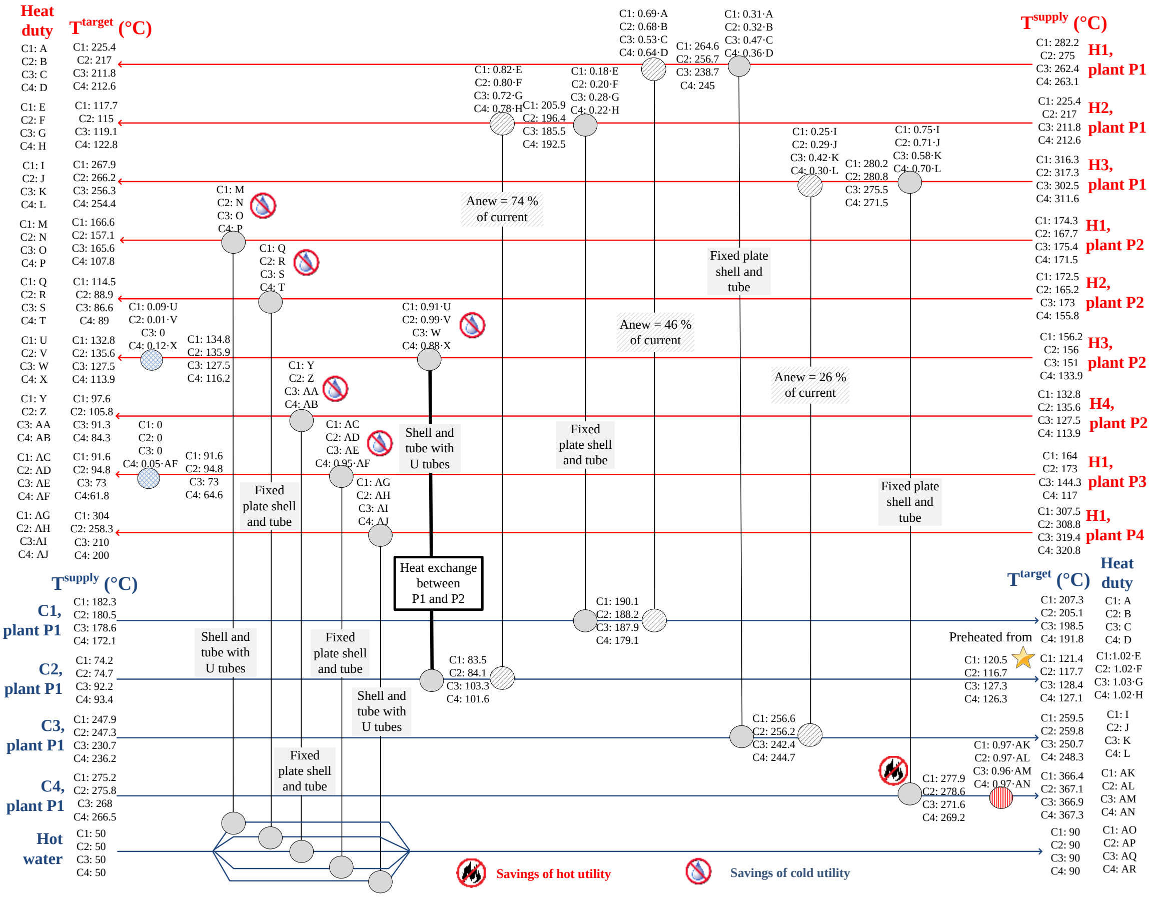

Figure 5: Heat exchanger network with maximum 9 new heat exchange matches

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