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Retrofitting of Large-Scale Heat Exchanger Networks within Total Sites under Uncertainty by Considering Trade-Offs between Investment and Operating Cost

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This contribution presents a developed procedure for retrofitting of large-scale heat exchanger networks within industrial plants and Total Sites by considering trade-offs between investment and operating costs. Investment cost includes costs for additional heat exchange areas and pipes at Total Site level, and operating cost (savings) includes energy savings due to reduced energy consumption and intermediate utility production, e.g. production of hot water for district heating. A transhipment-based framework TransGen for the energy targeting and retrofitting industrial plants and TSs has been developed for this purpose. Retrofitting of heat exchanger networks could be performed for problems of any size – from few heat exchange units up to hundreds of them. This procedure could be applied for both nominal designs under fixed conditions and under uncertain conditions for flexible designs by considering several scenarios. TransGen is illustrated on a simplified demonstration case study of two plants in order to clearly represent the features of the developed procedure.

1. Introduction

Retrofitting of heat exchanger networks (HENs) within existing industrial plants and Total Sites plays an important role regarding energy savings, and emissions and cost reductions. Several mixed-integer nonlinear programming (MINLP) models for the synthesis and retrofitting of HENs have been developed so far, as well as for entire Total Sites. However, those models are non-linear programming-hard and cannot be used for retrofitting of large-scale industrial processes and Total Sites, especially under varying conditions, due to the complex combinatorics and non-convexities involved. Therefore, a combined Mathematical Programming / Pinch Analysis (MP/PA) approach for targeting and mixed-integer linear programming (MILP) for retrofitting HENs have been developed and upgraded for fixed and uncertain operating conditions.

This contribution presents an upgraded version of the recently-developed code TransGen (Čuček and Kravanja, 2014) that proposes optimal modifications within industrial plants and Total Sites and provides options for producing intermediate utilities such as hot water for district heating from process low-grade heat. The TransGen framework is suitable for analysing energy targets and existing HEN designs, and especially for proposing optimal modifications for the retrofitting of each plant and Total Sites under nominal and uncertain conditions. It has been further upgraded to propose certain number of modifications (new heat exchange matches) that are (or could be) feasible in terms of economical, technological, safety and other limitations. An additional constraint within the code is added in order to obtain a certain pre-specified number of proposed modifications (new heat exchange matches). With regards to the set objective (e.g. minimising cost, maximising net present value etc.) the most optimal retrofitting modifications are then found which now consider also investigations regarding the trade-offs between the investment and operating costs by accounting for HEN design at plant and Total Site levels. In addition pipeline layout, heat and pressure losses and insulation are included within the TransGen (Nemet et al., 2015).

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The main features of TransGen are thus possibility of obtaining certain pre-defined number of the most optimal retrofitting modifications in regards to the trade-offs between investment and operating cost. The new features of the framework are illustrated here within a demonstration case study of two units and applied also on an existing refinery Total Site (see the contribution by Čuček et al., 2015). From the demonstrated case study it can be seen that significant energy and cost savings could be obtained when applying the developed procedure.

2. Methodology

2.1 Transshipment based framework TransGen

Framework TransGen (Čuček and Kravanja, 2014) is an extended version of an expanded transshipment model by Papoulias and Grossmann (1983). It is based on a combined MP/PA approach and overcomes the drawbacks of both approaches. The framework is coded in GAMS (GAMS Development Corporation, 2013) within mixed-integer linear programming (MILP) form, and provides numerical and graphical outputs of the solutions, e.g. by producing Grand Composite Curves and Total Site Profiles.

The more significant features of the framework are (Čuček and Kravanja, 2014): i) enabling the obtaining of existing, target and modified (proposed) HEN designs, ii) handling multiple utilities and production of intermediate utilities by including preheating when appropriate, iii) insights from Pinch Technology, iv) data independence, v) MILP form and therefore the globally-optimal solutions, vi) internal and Total Site Heat Integration under fixed and varying operational conditions, vii) possibility of analysing HENs of all scales, from few up to hundreds of heat exchange units.

However, there were several weaknesses of the previous version (Čuček and Kravanja, 2014), such as investment cost, pressure drops and heat losses at the Total Site level, due to retrofit were unconsidered. Also, search for modifications was performed iteratively based on utility consumption reduction until there was no significant improvement in the subsequent modification. Those weaknesses have now been overcome by proposing a three-step procedure, where the potential for improvement is identified in the first step, the most optimal retrofitting modifications are obtained in the second step, and more detailed HEN design in the third step.

2.2 Improvements of TransGen framework

The TransGen framework has been significantly modified and improved in order for it to be possible to propose the most optimal HEN's retrofitting modifications. The most important new feature is that the solutions consider trade-offs between investment cost (cost in new heat exchange units' areas and the cost of piping) and savings in energy cost. There are several possibilities regarding the proposed retrofitting modifications solutions: i) to propose the solutions for specific unit and/or the entire Total Site, ii) to propose all the solutions which have positive impact on the profit, iii) to propose a limited number of the retrofitting solutions, e.g. to propose modifications of a certain number of new/modified heat exchange matches, and iv) to propose solutions which fall in the limit of the specified payback period or for available money for retrofit investment.

Using an improved TransGen framework it is thus possible to identify under both fixed and uncertain conditions i) optimal number of modifications, locations, heat contents and areas of rearranged heat exchange units, and ii) matches that are rearranged only partially or completely, and also matches that are newly-formed. It is also possible to fix or limit intermediate utility consumption and production such as e.g. the production of a certain amount of hot water for district heating, and steam at various pressure levels which is used within the plant or Total Site. It also enables eventual utilisation of existing heat exchangers in those cases where the entire load is released. The obtained solutions under nominal and flexible conditions could be obtained in 'real' time even if the number of heat exchange units is large (e.g. they are hundreds of them). Several features of the improved TransGen framework will be illustrated within a demonstration case study of two process plants (Perry et al., 2008).

2.3 Three-step procedure for the retrofitting of large-scale HENs

It is proposed that a three-step procedure is performed for the retrofitting of large-scale HENs. During the first and second steps the TransGen framework based on a developed MILP transshipment model is used. TransGen could be used for i) obtaining the potential for the improvement within the process plant and/or Total Site (target design) in the first step and ii) identification of alternatives, and also to narrow the original search space in the second step. The second step also guides optimisation towards obtaining (near) global as well as feasible solutions regarding retrofitting. Usually several loops are required in order to obtain (near) optimal, verified and feasible results. During the third step detailed investigation of the trade-offs between investment and operating cost is performed on the reduced space of alternatives, as identified during the second step.

There have been several models developed for this purpose such as e.g., the model by Yee and Grossmann (1991) for counter-flow exchangers or the model by Soršak and Kravanja (2004) accounting for different heat exchanger types. Third step also enables obtaining positions and temperatures of heat exchange units within modified HEN. It should be noted that the main disadvantage of the third step in general is that it is impossible to solve large-scale problems, and with this proposed three-step procedure this could be overcome. This three-step procedure can namely be applied for any size of plant or Total Site and is applicable for those sectors that operate under steady-state and varying conditions. This three-step procedure is introduced and presented in more details within contribution by Čuček and Kravanja (2015).

It should be noted that in this contribution the improved version of TransGen - in terms of obtaining the most optimal retrofitting modifications from operating and investment viewpoint - is introduced and illustrated on an illustration case study. In the contribution by Čuček and Kravanja (2015) the novel three-step methodology is introduced which combined this improved TransGen framework and the framework for the detailed analysis of modified HENs.

3. Illustration case study

A simple illustration case study of two units A and B (Perry et al., 2008) under uncertain conditions will show the applicability of the improved TransGen framework.

3.1 Description of the illustration case study

The data for process units were taken from Perry et al. (2008) and had been slightly modified to account for fluctuations of temperature and flows. Operating within three representative conditions was assumed (three cases). The HENs for the existing designs of units A and B were assumed as shown in Figures 1 – 3 for cases 1 – 3. Also, the temperatures and heat duties of the heat exchangers, heaters and coolers are shown.

Several assumptions were made for retrofitting such as units A and B being located 1.5 km apart, 2 MW of hot water for district heating would be produced in all cases, the price of hot water would be 25 €/MWh, all streams except the low and medium pressure steam (LPS and MPS) would be liquids, the amortisation period would be of 5 y and the discount rate 8 %, heat loss would be 10 % when applying Total Site Heat Integration, and the minimum heat transfer for reallocations for each case would be at least 0.5 MW. The data for investment cost of heat exchange area and pipes were taken from Nemet et al. (2015). For simplicity it was also assumed that the pressures of the process streams would be at 1 bar.

The MILP model consists of approximately 7,200 single equations, 37,500 single variables, and 300 binary variables, and was solved within a few seconds with GAMS 23.6 (GAMS Development Corporation, 2013) using a CPLEX solver.

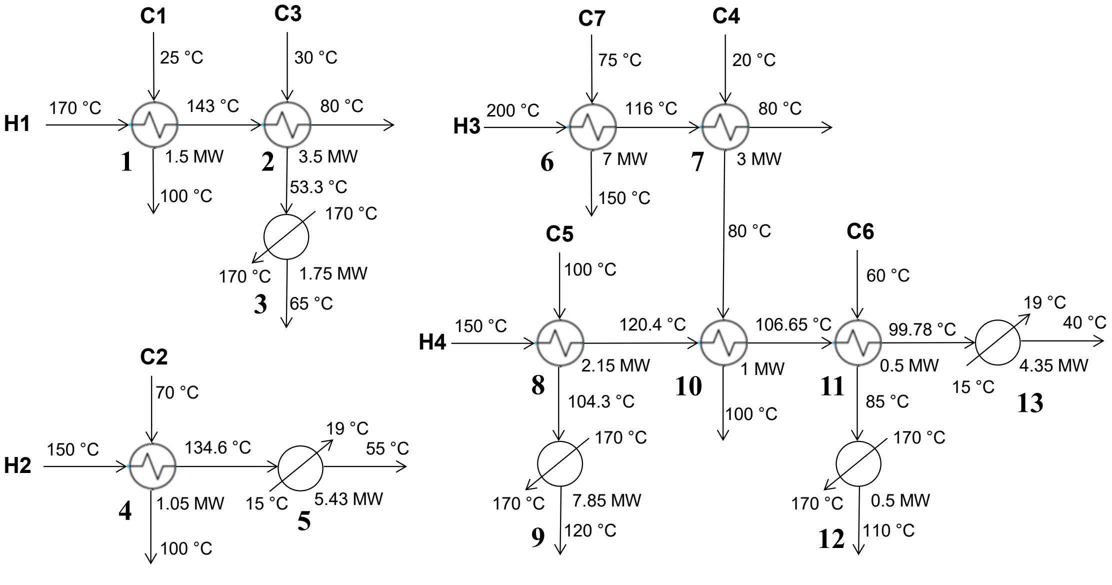

Figure 1: HEN for units A and B for case 1

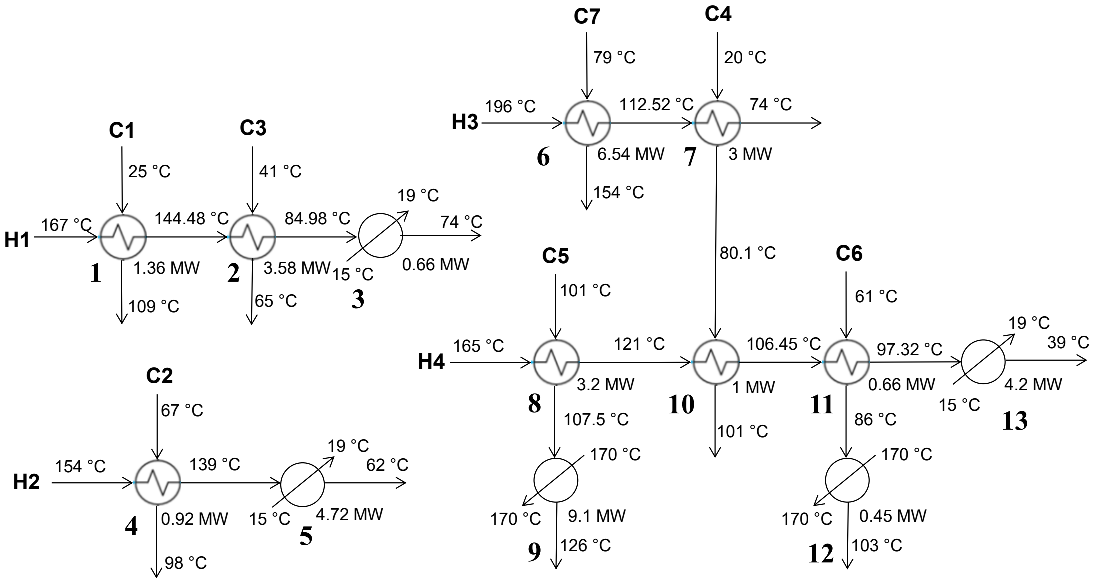

Figure 2: HEN for units A and B for case 2

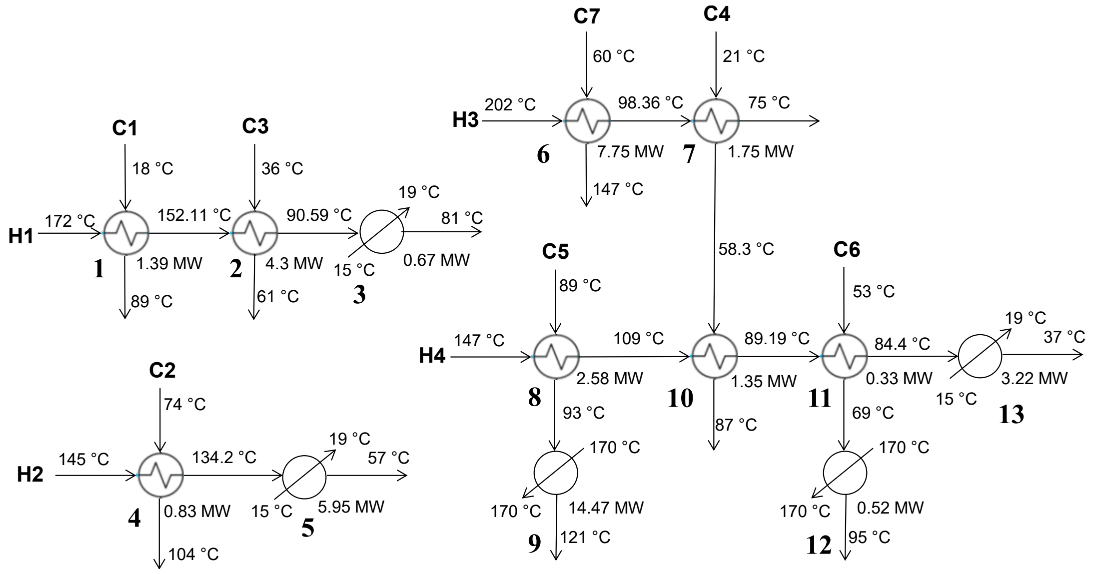

Figure 3: HEN for units A and B for case 3

3.2 Results and discussion

The demonstration case study was solved using the improved TransGen framework. Analysis was performed in order to obtain existing, targeted and modified designs. Analysis regarding modifications was performed for a certain number of new heat exchange matches (five heat exchange matches), and also for optimum design, when all the profitable solutions were obtained in regard to the trade-off between investment and operating costs. The main results regarding existing and target designs are shown in Table 1, and the main results regarding modified designs with 5 modifications and all profitable modifications are shown in Table 2. Both modified designs are compared to an existing design.

When comparing the existing and target designs it can be seen that there is a large potential for improvement. Energy cost and energy consumption could be significantly reduced.

Table 1: Main results regarding existing and target designs

	Existing design	Target design
Average energy cost	3.4 M€/y	0.9 M€/y
Average energy consumption	21.4 MW	4.8 MW
Hot utility consumption		
Case 1	10.1 MW	1.7 MW
Case 2	9.6 MW	3.7 MW
Case 3	15.4 MW	6.7 MW
Cold utility consumption		
Case 1	9.8 MW	0.1 MW
Case 2	9.6 MW	2 MW
Case 3	9.8 MW	0.2 MW

Table 2: Main results regarding modified design with 5 modifications, and optimal design

	Modified design with 5 modifications	Modified optimal design with all profitable modifications
Number of modifications	5	13
Average profit	1.23 M€/y	1.55 M€/y
Average energy savings	7.96 M€/y	12.08 MW
Retrofit area investment	0.78 M€	1.72 M€
Pipe investment	0.84 M€	1.09 M€
Payback time	0.99 y	1.25 y
Modified heat exchange units (fraction of rearranged heat exchange unit's energy)	2 (29 – 40 %), 5 (87 – 96 %), 6 (30 – 43 %), 9 (32 – 43 %), 13 (27 – 60 %)	1 (98 – 100 %), 2 (75 – 97 %), 4 (100 %), 5 (100 %), 6 (62 – 75 %), 7 (51 – 74 %), 8 (31 – 46 %) 9 (40 – 79 %), 13 (72 – 79 %)
New heat exchange matches at process level	H5 – hot water (2 MW)	H2 – C1 (1.33 – 1.5 MW), H5 – C2 (2.7 – 3.92 MW), H5 – C4 (0.83 – 1.05 MW
New heat exchange matches at Total Site level	H2 – C9 (1 – 1.7 MW), H5 – C6 (2.2 – 3.7 MW), H13 – C2 (1.1 – 1.9 MW)	H1 – C6 (1.33 – 1.5 MW), H2 – C6 (1.37 – 2.53 MW), H4 – C6 (0.83 – 1.05 MW), H5 – C8 (1 – 1.19 MW), H7 – C6 (0.55 – 1.28 MW), H13 – C7 (1.28 – 1.78 MW), H6 – C9 (4.26 – 5.27 MW), H8 – C9 (0.9 – 1.07 MW), H7 – hot water (0.5 – 0.74 MW), H13 – hot water (1.26 – 1.5 MW)
Hot utility consumption (absolute and relative reduction)		
Case 1	6.7 MW (3.4 MW, 33 %)	3.9 MW (6.2 MW, 61 %)
Case 2	6.7 MW (2.9 MW, 30 %)	4.3 MW (5.2 MW, 55 %)
Case 3	10.6 MW (4.9 MW, 31.6 %)	9.5 MW (5.9 MW, 38 %)
Cold utility consumption (absolute and relative reduction)		
Case 1	3.9 MW (5.9 MW, 60 %)	1.1 MW (8.7 MW, 89 %)
Case 2	4.3 MW (5.3 MW, 55 %)	1.9 MW (7.7 MW, 81 %)
Case 3	2.2 MW (7.6 MW, 77 %)	1.3 MW (8.5 MW, 86 %)

By performing retrofitting modifications quite significant profit due to Total Site Heat Integration is obtained, and also energy consumption is substantially reduced. Most modifications are proposed for implementations at the Total Site level, and due to hot water production. It can be seen that all the results were obtained within ranges, as the conditions vary. It can also be seen that the average profit did not improved much when performing a large number of modifications. Usually with just a few modifications significant profit could be obtained. Also the payback period was shorter when performing lower number of modifications. Finally, from Table 2 it can be seen that in most cases the hot or cold streams' energies were partially reallocated and only a few of the existing matches were completely eliminated (heat exchange units 4 and 5, and heat exchange unit 1 in some cases).

4. Conclusions and future work

This contribution described the upgraded version of MP/PA framework TransGen which has been included in the three-step procedure (Čuček and Kravanja, 2015). The TransGen can be applied for retrofitting of HENs of any scale at process and Total Site levels under uncertainty by considering trade-offs between investment and operating costs. This contribution was focused on proposing a certain pre-specified number of retrofitting modifications (new heat exchange matches) in regards to the trade-off between investment and operating cost. A small demonstration case study covering three representative cases was solved in order to show the features of the improved framework. Software tool TransGen now enables to obtain a certain number of the most optimal new heat exchange matches as shown in Table 2. It should be noted that the previous version of TransGen presented in Čuček and Kravanja (2014) enabled to obtain the results which consider a certain number of modifications from existing heat exchange matches and only in terms of operating cost. Also, the results presented in Čuček and Kravanja (2014) considered deterministic designs, whilst now the results are presented for both deterministic and flexible designs. From the results from improved version of TransGen it was shown that significant energy and economic savings could be obtained.

The improved TransGen is also applied to a large-scale HEN within an existing refinery (Čuček et al., 2015). The third and more detailed step employs the model by Soršak et al. (2004) considering different types of heat exchangers, and was upgraded in terms of pipeline cost (Nemet et al., 2015) and investigation of the proposed HEN modifications under varying conditions.

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