

# A Procedure for the Retrofitting of Large-Scale Heat Exchanger Networks for Fixed and Flexible Designs

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This contribution presents a novel three-step procedure incorporating software tools TransGen and HENSYN for the retrofitting of heat exchanger networks (HENs). This procedure is used for improving Heat Integration (HI) within individual plants and Total Sites (TSs) under fixed or steady-state conditions and under varying operational conditions. The software tool TransGen is used during the first targeting step and the second identification step for the most promising modifications, and HENSYN is used for the final synthesis of the retrofitted HEN. The targeting step is based on a combined Mathematical Programming/Pinch Analysis (MP/PA) approach, whilst the identification and the synthesis steps on the MP approach. The main objective of both tools TransGen and HENSYN is maximisation of the economic performance (annual incremental profit) of plants and/or TSs by minimisation of energy consumption and cost, and maximisation of economically-viable production of energy, such as production of hot water for district heating. Both tools consider the trade-offs between operating and investment cost but HENSYN considers it in more details. An illustrative example shows the capabilities of the developed software tools and the three-step procedure.

## 1. Introduction

Increased global competition and environmental awareness have forced industrial companies to improve the performances of their processes and also TSs and Locally Integrated Energy Sectors (Perry et al., 2008). HI, TS Integration (TSI) and waste heat utilisation within industrial processes and TSs are efficient ways of conserving energy and achieving emission reductions. Several approaches have been developed for this purpose. In general they are divided into an approach based on physical insights – PA, and an approach based on mathematical programming – MP (Klemeš and Kravanja, 2013). Both approaches have their own advantages and drawbacks. In order to optimise the energy consumption within large-scale process plants and TSs under varying operating conditions the MP and PA approaches should be combined and further extended. Over recent years combined MP/PA approaches for overcoming the drawbacks of both approaches have also been developed.

A novel three-step procedure incorporating software tools called TransGen and HENSYN has been developed for HI and TS optimisation of energy and cost in order to be applied for energy targeting and retrofitting of existing large-scale industrial plants and TSs. The software tool TransGen is intended for targeting during the first step and for identification of the most optimal retrofitting solutions during the second step. The targeting step is based on a combined MP/PA, and the identification step on MP and on the superstructure mixed-integer linear programming (MILP) approach. The identification step through pre-screening of modification alternatives also narrows the original search space and guides the optimisation towards obtaining (near) global as well as feasible solutions regarding retrofitting.

Further, during the third-step, the software tool HENSYN is used for more detailed HEN synthesis on the reduced space of alternatives. Only those data related to selected modifications during the second step are used during the third step. The third step also enables easy obtaining the final structure regarding the retrofitted HEN including positions and temperatures of heat exchangers within the network.

The three-step procedure and the methodology for the TSI within existing TSs is presented in the following and demonstrated on an illustrative example of a TS consisting of two process plants under varying operating conditions (modified from Čuček and Kravanja, 2014).

## 2. Problem Description

In order to perform the retrofitting of the HENs within large-scale industrial process plants and TSs, the combined MP/PA approach was applied, and the following three-step procedure was developed and applied:

- i) Targeting step based on MP/PA. By comparing the solutions obtained for target and existing designs, the potential is identified for HI, TSI and waste heat utilisation. The targeting step is performed using the software tool TransGen;
- ii) Identification step with forbidding unfeasible matches. This step is based on MP, on an extension of the expanded transshipment model developed by Papoulias and Grossmann (1983). This step enables the obtaining of the most optimal retrofitting modifications regarding energy consumption reduction and intermediate utilities production in regards to trade-offs between operating and investment costs. It should be noted that several loops could be required in order that the obtained results are (near) optimal, verified and feasible. Second step is also performed using TransGen;
- iii) Synthesis step based on MP on the stage-wise superstructure (Yee and Grossmann, 1991) extended for retrofits, different exchanger types (Soršak and Kravanja, 2004) and the dynamics of the operations. It enables the obtaining of detailed HEN retrofit from those modifications identified during the second step. The third step is performed using software tool HENSYN.

### 2.1 Methodology

The following methodology is used for HI and TSI using the novel three-step procedure and software tools TransGen and HENSYN, see also Figure 1:

- i) Data acquisition and incorporation of data within TransGen;
- ii) Targeting using software tool TransGen and a comparison with the existing energy consumption;
- iii) Identification of the most profitable modifications accompanied by pre-screening of the alternatives and forbidding the infeasible matches;
- iv) Verifications of the obtained solutions from step iii) and returning to step iii) as long as all proposed heat exchange matches are acceptable. Several loops could be required to obtain a near optimal, verified and feasible solution;
- v) Preparation of the data for selected modifications and the synthesis of the retrofitted HEN using software HENSYN.

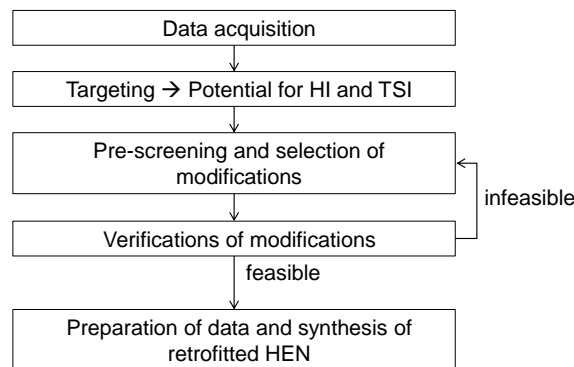


Figure 1: Methodology used for Heat and Total Site Integration

### 2.2 Software Tool TransGen

The software tool TransGen is composed of two parts: i) the data-independent algorithm 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 comparison of the target and existing designs in order to obtain the potential for HI, TSI and intermediate utility production;
- ii) Identification of modifications by considering forbidding the infeasible matches;
- iii) Preparation of the data for selected modifications to be used in software tool HENSYN.

TransGen is based on combined MP/PA, and the graphical and numerical output is obtained. Graphical output could be in the form of Composite Curves (CCs), Balanced CCs, Grand Composite Curves (GCCs) and Total Site Profiles (TSPs). It could be produced for targeted, existing and modified designs, and for both nominal designs under fixed conditions, and under uncertain conditions for flexible designs.

Numerical output provides economic parameters, e.g. incremental profit, investment cost, pipeline cost, and payback time, utility consumption reduction, modifications of existing heat exchange units, proposed new matches, etc. The features of software tool TransGen are presented in Čuček and Kravanja (2014), and those for improved version of TransGen in Čuček and Kravanja (2015).

### 2.3 Software Tool HENSYN

Software tool HENSYN is used for the detailed synthesis of the retrofitted HENs. HENSYN is also composed of two parts: i) the algorithm and ii) the data. Only the data file should be changed for the specific analysis.

HENSYN is based on MP and the following results could be obtained for synthesised HENs, such as the economic data, areas of proposed heat exchangers, temperatures at all the stages, locations of proposed modified heat exchangers and other results. By having such results, retrofitted HEN could be drawn.

The main features of software tool HENSYN are:

- i) Performing the detailed synthesis regarding the trade-offs between investment and operating cost on a smaller number of solutions. Only those modifications identified using TransGen are optimised within HENSYN;
- ii) Synthesis of modified HENs including positions and temperatures of heat exchanger units within networks under fixed and flexible designs. A multi-period model has been developed for obtaining a flexible design;
- iii) Accounting for different heat exchanger types. In the current version of HENSYN there are four optional heat exchanger types which can be selected in the proposed HEN design, such as double pipe, plate and frame, fixed plate shell and tube and shell and tube with U-tubes. Other types of heat exchangers could also be added.

The methodology used for HI and TSI using the three-step procedure and softwares TransGen and HENSYN is illustrated in the following on a simple illustrative example.

## 3. Illustrative example

### 3.1 Description of Illustrative Example

A simple illustrative example of TS consisting of two units A and B (Perry et al., 2008) with a small number of streams was selected to demonstrate the methodology and applicability of the developed procedure and software tools TransGen and HENSYN. Such an illustrative example was selected in order to be representative and easily verified. The case study under flexible varying operational conditions was analysed.

It was assumed that units A and B are located 1.5 km apart. All process streams were assumed to be liquids and for simplicity it was also assumed that the pressures of the process streams are at 1 bar.

The data for the plants A and B were taken from Perry et al. (2008), and were slightly modified to account for varying operating conditions (see Čuček and Kravanja, 2015). The HEN for TS under varying operating conditions is shown in Figure 2, where the case 1 is represented as “A1”, case 2 as “A2” and case 3 as “A3”.

### 3.2 Targeting and Identifying the Potential for Heat and Total Site Integration

The first step was to perform targeting. By comparing the target and existing designs, it was possible to identify the potentials for improvements within process plants and TSs in terms of energy consumption reduction. The main results obtained for the target and existing designs are shown in Table 1.

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	4.7 MW
Hot utility consumption		
Case 1   Case 2   Case 3	10.1 MW   9.6 MW   15.4 MW	1.7 MW   3.7 MW   6.7 MW
Cold utility consumption		
Case 1   Case 2   Case 3	9.8 MW   9.6 MW   9.8 MW	0.1 MW   2 MW   0.2 MW

Further, graphical outputs for target and existing designs were obtained, such as GCCs, CCs, Balanced CCs and TSPs. Figure 3 shows an example of graphical output under varying conditions. It shows TSPs for existing designs with the potential for hot water production. As there are varying conditions, the solutions are also varying, and TSPs show the ranges of the solutions.

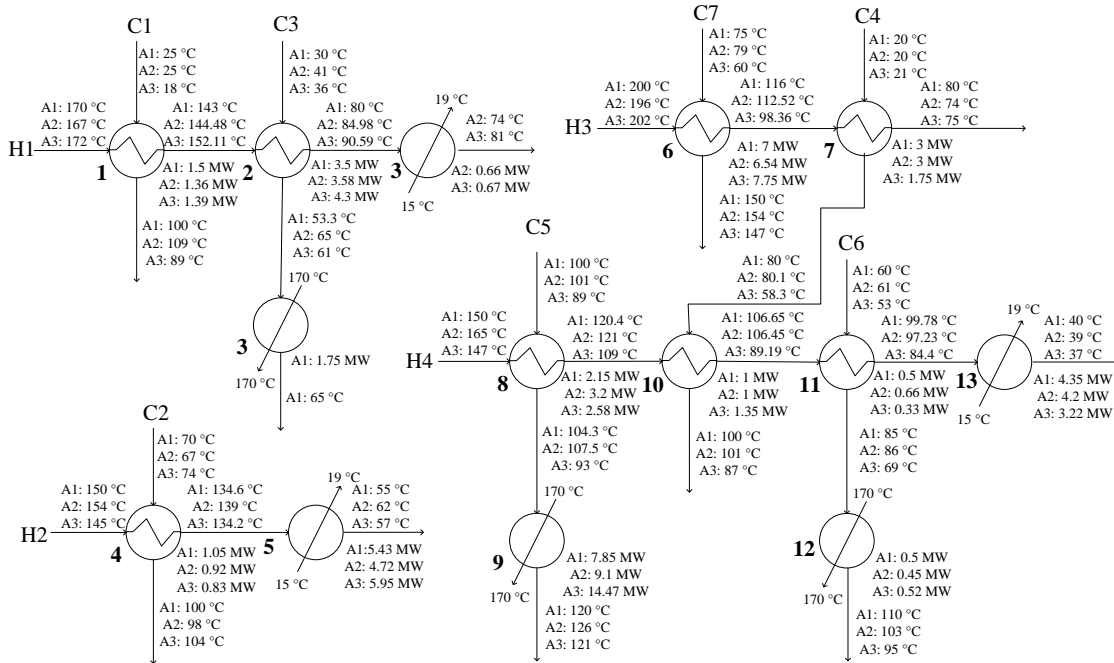


Figure 2: HEN for plants A and B under varying operating conditions

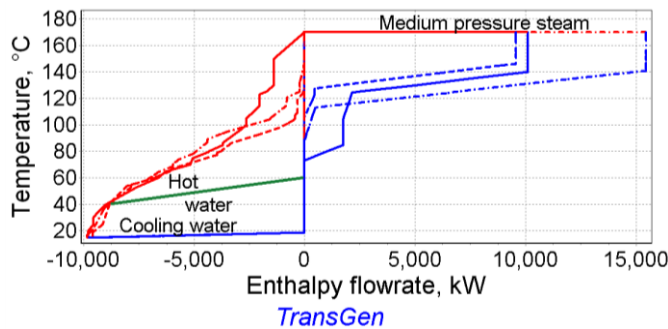


Figure 3: Total Site Profiles for existing design operating under varying conditions with the potential for hot water production

### 3.3 Identification of Modifications

As from the targeting stage significant potential for energy consumption reduction was shown, the next step was the pre-screening and selections of the modifications. It was also assumed that 2 MW of hot water should be produced. The analyses regarding the most optimal modifications by considering the trade-offs between energy and investment cost were thus performed. All the modifications were compared to the existing design, and thus the results directly showed possible improvements in terms of energy consumption and cost.

The retrofit modifications were analysed only for a TS under varying operating conditions. However the same analysis could be performed at the plant level, and under steady-state operating conditions.

Analysis was performed for a certain number of the most optimal new heat exchange matches, e.g. for 5 new matches. The main results regarding modified designs with 5 modifications are shown in Table 2, see also the contribution by Čuček and Kravanja (2015).

It could be seen again that all the results were obtained within ranges. Most of the new heat exchange matches were selected at TS level, whilst 2 MW of hot water was produced from hot stream 5 at plant A. The next step was verifications of the modifications and repeating this step until all the proposed heat exchange matches were acceptable for the leaders and engineers of the plant and/or TS. The identification step could be repeated several times by excluding infeasible (and difficult) modifications, before the final solution could be obtained. In this illustrative example it was assumed that all the modifications were acceptable and thus this step was not repeated. In the case where there would be infeasible modifications proposed, those infeasible (and difficult) matches would have been defined as forbidden.

*Table 2: Main results regarding modified design with 5 modifications*

	Modified design with 5 modifications
Average profit	1.25 M€/y
Average energy savings	7.96 M€/y
Retrofit area investment	0.72 M€
Pipe investment	0.83 M€
Payback time	0.94 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 %)
New heat exchange matches at process level	H6 – C9 (1.9 – 3.3 MW), H5 – hot water (2 MW)
New heat exchange matches at TS level	H2 – C9 (1 – 1.7 MW), H5 – C6 (2.2 – 3.7 MW), H13 – C2 (1.1 – 1.9 MW)
Hot utility consumption (absolute and relative reduction)	
Case 1   Case 2   Case 3	6.7 MW (3.4 MW – 33 %)   6.7 MW (2.9 MW – 30 %)   10.6 MW (4.9 MW – 31.6 %)
Cold utility consumption (absolute and relative reduction)	
Case 1   Case 2   Case 3	3.9 MW (5.9 MW – 60 %)   4.3 MW (5.3 MW – 55 %)   2.2 MW (7.6 MW – 77 %)

### 3.4 Synthesis of Retrofitted Heat Exchanger Network

Finally, the detailed synthesis of retrofitted HEN with the appropriate trade-offs between investment and operating cost was performed using the software tool HENSYN. The synthesis was performed only for those selected retrofitting modifications during the second identification step. The retrofitted HEN could be easily extracted from the HENSYN solution output. The main results from the detailed analysis are presented in Table 3, and compared with those results obtained from TransGen.

*Table 3: Main results obtained from TransGen and HEN SYN*

	Modified design with 5 modifications	
	TransGen	HENSYN
Average profit	1.25 M€/y	1.3 M€/y
Retrofit area investment	0.72 M€	0.79 M€
Pipe investment	0.83 M€	0.83 M€

Figure 4 shows the retrofitted HEN design when performing 5 of the most profitable modifications at the TS level under varying operating conditions. HEN also includes all the temperatures, exchanged heat, and areas and types of selected heat exchangers. Two heat exchanger types were selected, fixed plate shell and tube (“F”) and shell and tube with U tubes (“U”). This figure is available in colour online. Existing heat exchangers that now had the smaller heat exchanger area are highlighted in the online version in grey, and the new ones in yellow. The heaters are highlighted in red and the coolers in blue. It can be seen that there are 5 new heat exchangers, as was set. From those five, three are exchanging heat between the plants A and B, one within plant B, and one is used for hot water production (previously heat exchanger 5). Hot water production was completely satisfied.

## 4. Conclusions

This contribution presented and demonstrated a three-step procedure and software tools TransGen and HEN SYN for the retrofitting of existing process plants and TSs under varying conditions. It should be

noted that the analysis could be even more easily performed for plants and TSs under steady-state conditions.

Both software tools are based on MP, whilst TransGen uses also insights from PA, and the whole procedure is automated. Both software tools are written in data-independent ways and could be easily applied to any process plant or TS under steady-state and varying conditions with any number of heat exchange units just by changing the data. The proposed modifications which consider trade-offs between investment and operating cost, could be obtained in 'real' time. Problems of any size could be handled ranging from small processes up to complex industrial TSs, see also the contribution by Čuček et al. (2015) where the procedure is illustrated on the existing refinery's TS with more than 100 HE units.

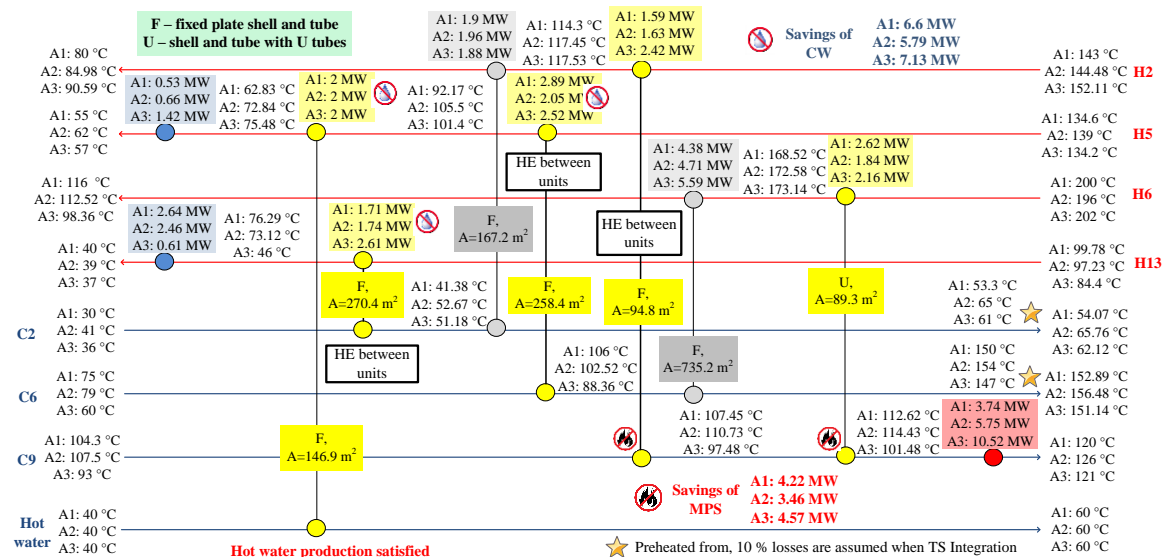


Figure 4: HEN of TS operating under varying conditions with 5 modifications

## Acknowledgments

The authors acknowledge the financial support from EC FP7 project ENER/FP7/296003/EFENIS 'Efficient Energy Integrated Solutions for Manufacturing Industries – EFENIS', and from the Slovenian Research Agency (programs P2-0032 and P2-0377).

## References

- Čuček L., Kravanja Z., 2014, Efficient Transshipment-Based Framework for Energy Targeting and Retrofitting Industrial Total Sites. *Chemical Engineering Transactions*, 39, 1813-1818
- Čuček L., Kravanja Z., 2015, Retrofitting of Large-Scale HENs within Total Sites under Uncertainty by considering Trade-Offs between Investment and Operating Costs. *Chemical Engineering Transactions*, 45
- Čuček L., Mantelli V., Yong J.Y., Varbanov P.S., Klemeš J.J., Kravanja Z., 2015, A Procedure for the Retrofitting of Large-Scale Heat Exchanger Networks for Fixed and Flexible Designs applied to Existing Refinery Total Site. *Chemical Engineering Transactions*, 45
- Klemeš J.J., Kravanja Z., 2013, Forty years of Heat Integration: Pinch Analysis (PA) and Mathematical Programming (MP). *Current Opinion in Chemical Engineering*, 2, 461-474
- Papoulias S. A., Grossmann I. E., 1983, A structural optimization approach in process synthesis – II: Heat recovery networks, *Computers & Chemical Engineering*, 7(6), 707-721
- Perry S., Klemeš J., Bulatov I., 2008, Integrating waste and renewable energy to reduce the carbon footprint of locally integrated energy sectors. *Energy*, 33, 1489-1497
- Soršak A., Kravanja Z., 2004, MINLP retrofit of heat exchanger networks comprising different exchanger types. *Computers & Chemical Engineering*, 28, 235-251
- Yee T. F., Grossmann I. E., 1991, A screening and optimization approach for the retrofit of heat-exchanger networks, *Industrial & Engineering Chemistry Research*, 30(1), 146-162