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Energy Integration Manager: A Workflow for Long Term Validity of Total Site Analysis and Heat Recovery Strategies

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Abstract

The data basis for a Total Site study is only valid for a static snapshot of the whole industry Site. Changes to single process units throughout the design phase of new industrial solutions as well as subsequent process modifications to existing plants necessitate an actualization of the Total Site analysis. Previously identified potentials to increase the energy efficiency may have become outdated or infeasible.

As a first step in the development of an Energy Integration Manager, a conceptual approach for the implementation of an interface to an existing heat exchanger network (HEN) synthesis tool is proposed. Certain improvements to the HEN synthesis tool according to heuristic rules are described for enabling a suitable workflow.

Keywords: Total Site analysis, heat recovery, genetic algorithm

1. Introduction

In the state-of-the-art engineering workflow for investment projects in case of structural planning or modification of individual process units, simulating and updating of adequate computer-aided process models is obligatory. Very often these models include all heating and cooling stream data, the local utility system as well as all transfer streams to the super ordinated side-wide utility system. In fact, there is mostly no other alternative to close all mass and enthalpy balances without the simulation of missing measured data with the help of process models.

Using these process models as the data basis for consequent up to date Total Site energy analysis is most promising. The development of a conceptual workflow to determine the required work effort and the required amount of data will be the starting point in the development of an automated Total Site update procedure.

2. Conceptual structure of an Energy Integration Manager

To establish a comprehensive framework for updating Site-wide energy studies, several software tools have to be connected via interfaces. As mentioned in the introduction, the most promising way of retrieving process data is the usage of computer-aided process models, but for the simulation of former long term plant behavior the use of recorded data from plant control systems might be interesting as well. The overall software architecture is shown in Figure 1. The highlighted modules of the Data Interface and the HEN Optimisation Framework will be of further interest in this context.

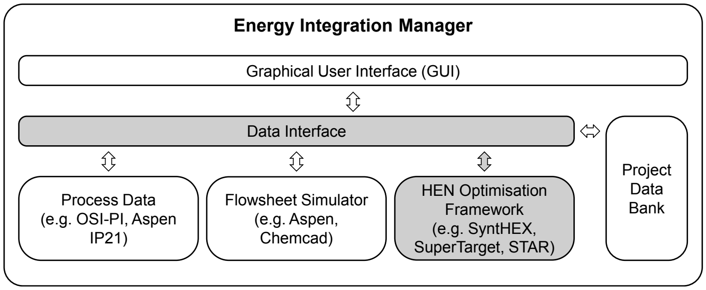

Figure 1. Structure of Energy Integration Manager

There are some advantages to start the design of the Energy Integration Manager with the embedment of a HEN synthesis tool using genetic algorithms instead of a synthesis tool which relies on the pinch technology. The mayor criterion is the complexity of the generated HEN solution. A high amount of heat exchanger sub-networks on the consideration level of a single process simplifies to track down the influence of a single process change to the super ordinated utility system. Furthermore the effectiveness of Mixed Integer Non Linear Programming (MINLP) methods such as genetic algorithms has already been demonstrated in recent papers (Escobar and Trierweiler 2013). Due to these reasons an existing software tool called SyntHEX was advanced by the incorporation of selected heuristic rules to improve the amount of sub-networks as well as the capability of finding the global optimum.

3. HEN synthesis using genetic algorithms

3.1. Data Interface: Input data set

A typical characterization of a HEN optimization task is described by Table 1. There are a number of hot process streams N_h and a number of cold process streams N_c which have to be cooled down or heated up, respectively. This data has to be provide by the Data Interface, as presented in Figure 1.

3.2. HEN Optimization: Objective function

The objective function is employed to generate a HEN solution with the least total annual costs for a given data set, as described in chapter 3.1. To achieve this each utility stream is linked to a specific cost factor c_{cu} in order to calculate the operating costs. Apart from the utility consumption no other operation costs are considered. The annualized investment costs are based on an empirical approach. There are two investment costs segments: The fix costs a and the area depending costs bA^c. The objective function can be formulated as follows:

$$C_{TAC} = \sum_{n=1}^{N_u} \left(c_{cu,n} \cdot \dot{Q}_{u,n}\right) + N_{HX} \cdot a + \sum_{n=1}^{N_{HX}} (b \cdot A_n^c) \tag{1}$$

Table 1: Characterization of optimization task

Name [ ]	Inlet temp. T_{in} [°C]	Outlet temp. T_{out} [°C]	Heat transfer coefficient h [W/(m²·K)]	Heat capacity flowrate $\dot{W}$ [W/K]	Cost factor c_{cu} (utilities) [\$/(W·h)]
⋮	⋮	⋮	⋮	⋮	⋮

In Eq.(1) N_U is the number of available utility streams and N_{HX} is the number of heat exchangers (HXs) present in the respective HEN. For the calculation of the heat exchanging area an ideal counter current heat exchanger is assumed. Due to minor influences of the thermal resistance of the apparatus partition wall only heat exchange coefficients are used to calculate the thermal transmittance.

3.3. HEN Optimization: The genetic algorithm

A brief overview for the mathematical background of the genetic algorithm used for this work will be presented. A deeper insight can be acquired with the help of the publication by Luo et al. (2009).

For representation of a HEN a stage-wise superstructure (Yee et al., 1983) is adopted. In each stage i of this superstructure every hot process stream j is connected to every cold process stream k. The index ijk of a HX can be calculated as follows:

$$ijk = (i-1) \cdot N_h N_c + (j-1) \cdot N_C + k \tag{2}$$

Summarized, a HEN is defined by the heat exchangers which build up the structure. For these HX it is sufficient to specify the heat transfer area A_{ijk} and the heat capacity flow rates $W_{h,ijk}$ and $W_{c,ijk}$ through the HX. The temperatures within a HEN can then be calculated analytically or by a sequential iterative procedure.

For the genetic algorithm the key operations are selection, crossover and mutation. At first, an initial population of solution candidates, called individuals, are generated. In each generation the genetic operations are applied in order to build a new population. The better an individual is fitted to the objective function the higher are its chances to be selected for the crossover operations or to be sent directly into the next generation.

The quality of an individual is therefore expressed by its fitness value.

$$f = \frac{C_{TAC}^{-1} - C_{TAC,avg}^{-1}}{C_{TAC,min}^{-1} - C_{TAC,avg}^{-1}} \tag{3}$$

In Eq.(3) $C_{TAC,min}$ represents the minimum total annual costs within the current population and $C_{TAC,avg}$ represents the average total annual costs of this population.

4. Incorporation of heuristic rules

4.1. Concept and motivation

Even though genetic algorithms do have advantages compared to heuristic procedures like the pinch technology, there are also mentionable drawbacks. The HEN synthesis is carried out for a fixed formulation of a given task, strictly mathematical. Because of the huge amount of binary variables in the problem formulation and their stochastic character these algorithms can be trapped into a local optimum. Conventional genetic algorithms do not possess methods for neglecting selected heat exchangers apart from the entirely stochastic methods of mutation and recombination. The possibilities to simplify complex HEN structures which may have been agglomerated during the optimization are limited.

4.2. Heuristic rules: Breaking of Loops & Recalculation of paths

As an iterative way to improve given HEN solutions the identification of loops and paths inside a network structure is well known and widely used The standard procedure

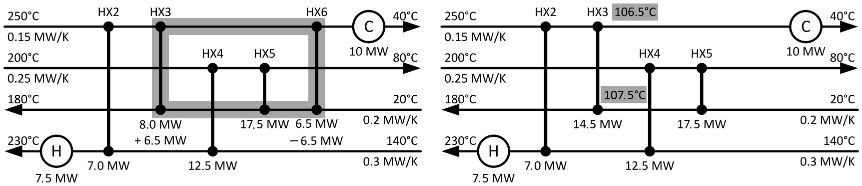

Figure 2. Identified loop and reallocation of heat load

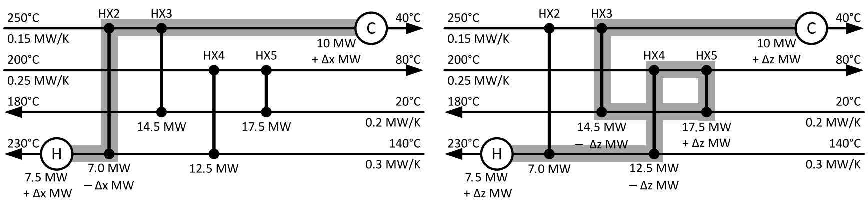

Figure 3. Identified paths and feasible solutions

is as follows: Identify existing loops within the HEN. Reallocate the heat duty of the heat exchanger with the smallest heat exchanging area.

Identify and exploit paths to ensure feasible temperature differences and the best compromise between utility cost and investment cost. These heuristic rules are visualized in Figure 2 and Figure 3 by using a small example. The embedment of loop breaking and path analysis into the evolutionary workflow of a genetic algorithm as astochastically applied procedure instead of an iterative procedure following to the actual HEN design is a new development approach. The implementation of a loop breaking algorithm has already been described in recent work (Brandt et al., 2011). This will now be extended by a procedure for path identification and optimization.

As in the example shown the temperature difference adjacent to HX3, after the removal of the loop, violates the second law of thermodynamics. Exploiting an existing path and shifting of heat duties along this path will solve this issue. Figure 3 demonstrates different solutions depending on the length of the chosen path. If all HXs should have a minimum temperature difference of 10°C adjacent to them, it would be $\Delta x = 1.6\ MW$ or $\Delta z = 6.5\ MW$.To determine the most favorable solution both alternatives have to be calculated. Depending on the underlying costs functions, the right choice is not always obvious.

4.3. Degree and identification of paths

Similar to the definition of a degree (or level) of a loop (Su and Motard, 1984), which is used to point out the amount of heat exchangers in the loop structure, a degree g_P for path structures can be defined. Assuming that the identified paths do not include loops along their track through the network, g_P can be calculated as follows:

$$g_P = (2 \cdot \min\{N_h, N_c\}) - 1 \tag{4}$$

Therefore the amount of hot and cold streams inside a path structure ($N_{h,P}$, $N_{c.P}$) for a given degree is always:

$$N_{h,P} = N_{c,P} = \frac{(g_P + 1)}{2} \tag{5}$$

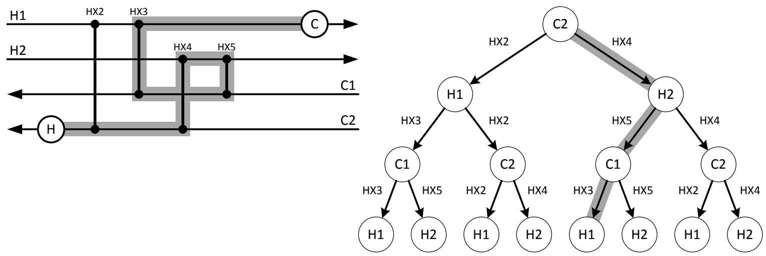

Figure 4. Binary search tree for path identification

For the identification of paths it is reasonable to use the prerequisites of paths namely the HXs which are connected to the supplied utilities as starting and ending points.

In this case the identification algorithm was developed "from left to right", which means it starts with HXs using the hot utility and advances through the structure towards the HXs using cold utility. The identification can be visualized as a binary search tree as shown in Figure 4. Detected paths will be optimized by numerical analysis regarding the objective function.

5. Application of improved genetic algorithm

To demonstrate the effectiveness of the enhanced HEN synthesis method a literature case was chosen (Luo et al., 2009). The problem definition is given in Table 2. Investment costs for heat exchanging units are calculated according to Equation 6.

$$C_{inv} = 8000 + 800 \cdot A^{0.8} \; (A \text{ in } m^2) \tag{6}$$

Table 2. Problem data according to Luo et al. (2009)

Name	T_{in}	T_{out}	h	$\dot{W}$	Name	T_{in}	T_{out}	h	$\dot{W}$
[ ]	[°C]	[°C]	[W/(m^2·K)]	[W/K]	[ ]	[°C]	[°C]	[W/(m^2·K)]	[W/K]
H1	180	75	2.0	30	C1	40	230	1.5	20
H2	280	120	0.6	15	C2	120	260	2.0	35
H3	180	75	0.3	30	C3	40	190	1.5	35
H4	140	45	2.0	30	C4	50	190	2.0	30
H5	220	120	0.08	25	C5	50	250	2.0	20
H6	180	55	0.02	10	C6	40	150	0.06	10
H7	170	45	2.0	30	C7	40	150	0.4	20
H8	180	50	1.5	30	C8	120	210	1.5	35
H9	280	90	1.0	15	C9	40	130	1.0	35
H10	180	60	2.0	30	C10	60	120	0.7	30
HU	325	325	1.0		CU	25	40	2.0	
Annual cost of hot utility: 70 $/(kW·a)					Annual cost of cold utility: 10 $/(kW·a)				

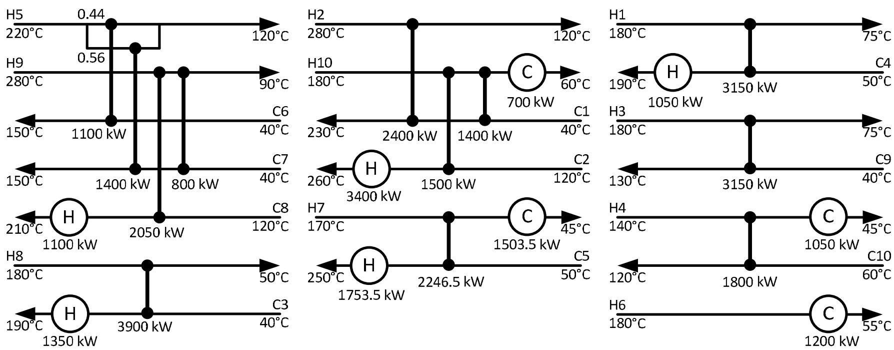

Figure 5. HEN solution for the example case

Compared to the solution published by Luo et al. (1,753,271 $/a) the solution shown in Figure 5, which was generated by the new HEN synthesis method, is characterized by 2.1% lower annualized costs (1,717,295 $/a). Remarkable is the total amount of heat transferring units, which has been reduced from 26 to 21. A reduced amount of paths inside the HEN structure (from 5 to 2) as well as a reduced amount of utility heat exchangers (from 15 to 9) state the effectiveness of the new path analyzing method.

6. Conclusions

To extent the exclusively mathematical approach of genetic algorithms, a new optimization procedure was suggested and successfully applied. This new optimization method implements the advantages of certain heuristic strategies while maintaining the capability of synthesizing low complexity HEN solutions due to the high amount of sub networks or respectively the low amount of loops and paths. The reduction of the amount of heat transferring units is in many cases of major industrial relevance. Summarized quantitatively these HEN solutions are mostly cheaper and easier to control regarding temperature or mass flow uncertainties. Single changes to the overall process have a smaller impact on other unchanged process units. The initial objective to establish a basis for an energy integration management system was achieved.

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References

M. Escobar, J. O. Trierweiler, 2013, Optimal heat exchanger network synthesis: A case study comparison, Applied Thermal Engineering, 51, 1-2, 801-826.

C. Brandt, G. Fieg, X. Luo, 2011, Efficient synthesis of heat exchanger networks combining heuristic approaches with genetic algorithm, Heat Mass Transfer, 47, 8, 1019-1026.

X. Luo, Q.-Y. Wen, G. Fieg, 2009, A hybrid genetic algorithm for synthesis of heat exchanger networks, Computers and Chemical Engineering, 33, 1169-1181.

J. L.Su, R. L. Montard, 1984, Evolutionary Synthesis of Heat-Exchanger Networks, Computers and Chemical Engineering, 8, 2, 67-80

T. F. Yee, I. E. Grossmann, Z. Kravanja, 1983, Simultaneous optimization models for heat integration-I. General framework and MER optimal synthesis, Chemical Engineering Science, 38, 5, 745-763