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Design of Cost-Optimal Heat Exchanger Networks Considering Individual, Match-Dependent Cost Functions

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In this paper an approach is presented to incorporate different cost considerations for each match individually for the cost-optimal design of heat exchanger networks. The utilized Mixed Integer Non-Linear Programming model allows the use of different cost functions for each possible match allowing the simultaneous optimization of investment and operating costs. Distinct parameters for cost functions can be defined for each connection of heat source and sink independent of process stream or utility stream. The implementation of the proposed approach enables the use of match-based individual factors to account for fluid properties (e.g. hazardous or corrosive) and resulting engineering cost, plant layout-based factors like piping, piping bridges and pumping as well as other individual parameters. The model allows the embedding of additional cost factors to ensure the safety for specified streams or to take account for different types of heat exchangers used for different process conditions. In order to show the functionality of the chosen approach one small example and one medium example for heat exchanger network synthesis based on a given plant layout for heat sources and sinks are given. Starting from given Cartesian coordinates the individual distances of the heat sources and sinks utilizing the Manhattan distance (1-norm) is included to calculate individual piping costs in addition to the apparatus costs of the heat exchangers themselves. The impact on the heat exchanger network layout of different parametrizations to find the lowest total annual cost is shown.

1. Introduction

Heat integration via heat exchangers has a great impact on reducing the amount of utility used by a process. Especially against the background of increasing global competition, environmental specifications, climate change or assumedly increasing energy costs, heat exchanger networks (HENs) have a major positive effect on the economic efficiency of processes.

Both investment and operating costs have to be considered for optimal heat integration. Two main approaches have been successfully developed to tackle heat integration problems. These are the Pinch Technology (Linnhoff and Hindmarsh, 1983) and mathematical programming (Papouilas and Grossmann, 1983). These approaches have been further developed numerous times over the years by several researchers. Heat integration is still a vital topic today due to new challenges and the urge to further improve single processes or even total sites. Chew et al. (2013) formulated the main issues influencing the practical implementation of Total Site Heat Integration. One mayor topic in heat integration during the last years is the consideration of further impact factors for heat integration like safety issues. Liu et al. (2015) developed an assessment to identify the critical risk equipment and respective streams to help to determine an appropriate HEN design. An approach for including risk assessment with the aim of safer HENs already during the synthesis stage was made by Nemet et al. (2017). As a part of safety, operational issues have to be considered like disturbance propagation and controllability (Rathjens et al., 2016). Furthermore, plant layout issues became more and more important throughout the years. Liew et al. (2014) discussed pressure drop and heat losses in the utility system and improved the heat cascade algorithm for targeting the Total Site minimum utilities target. Heat integration across plants was considered by Wang et al. (2014) by investigating different connection patterns. They developed a graphical method for finding a solution for direct and indirect heat transfer and also combined both heat transfer

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types to find the optimal operation conditions. Later, mathematical methods were added to find the optimal operation conditions (Wang et al., 2015).
The reduction of utility costs by reducing the use of primary energy carriers using heat integration mostly comes along with an increased investment e.g. for additional heat exchangers or piping. Short payback times for investments have always been desirable for companies. Therefore, it is of great importance to consider detailed costs already during the design and optimization of HENs. Established Pinch Technology does not incorporate easy applicability of such facilities for cost optimization. Pouransari and Maréchal (2014) applied different distance costs for piping based on the Euclidean length and used a sequential methodology utilizing varying priority levels for different possible matches to achieve a network for Maximum Energy Recovery (MER).
Each connection of a heat source and a heat sink, the so-called match, has specific requirements for the installed heat exchanger and peripheral equipment used. This results in a different influence on the overall cost and relative weight of a possible match, based on the diverse fluid and layout constraints. In this work an approach will be presented to incorporate different cost considerations for each match individually. It is possible to add specific factors for representing diverse scenarios like safety issues or the use of different heat exchanger types for different process conditions during optimization. Considering piping, each heat source and sink has its position within the plant and therefore defined distances between them for possible heat integration. Based on the Manhattan distance (1-norm) it is possible to account for the length of each individual connection. The length-based costs are dependent on medium, flowrate, pressure drop, insulation or special layout issues like piping bridges. In the following the focus is put on pure piping costs due to improved traceability of the results shown. In order to show the capability of the chosen approach examples from literature with given Cartesian coordinates are examined and discussed. The impact of different parametrizations will be shown.

2. Mathematical model

The simultaneous optimization of the total annual costs (TAC) for heat exchangers is carried out utilizing a Mixed Integer Non-Linear Programming (MINLP) model which allows the use of different cost functions for each possible match. The MINLP model of Luo et al. (2009) was adopted and modified. The resulting objective function is given in Eq(1).

$$min\left\{\sum_{n=1}^{N_h+N_c}\left[C_{CU}\cdot max\{\dot{W}_n(T_{out,n}-T_{target,n}^{+}),0\}+C_{HU}\cdot\ max\{\dot{W}_n(T_{target,n}^{-}-T_{out,n}),0\}\right]\right.$$
$$+\sum_{i=1}^{N_s}\sum_{j=1}^{N_h}\sum_{k=1}^{N_c}z_{ijk}\left(a_{jk}+b_{jk}A_{ijk}^{c_{jk}}+X_{jk}\right) \tag{1}$$
$$\left.+\sum_{n=1}^{N_h+N_c}\left[z_{CU,n}\left(a_{CU,n}+b_{CU,n}A_{CU,n}^{c_{CU,n}}+X_{CU,n}\right)+z_{HU,n}\left(a_{HU,n}+b_{HU,n}A_{HU,n}^{c_{HU,n}}+X_{CU,n}\right)\right]\right\}$$

The nomenclature of HENs following Eq(1) is based on the superstructure of Yee et al. (1990) with N_s stages, N_h hot process streams, N_c cold process streams, hot utility (HU) and cold utility (CU) with the heat capacity flowrate ($\dot{W}$) of their respective process stream. Furthermore, the upper and lower bounds for the target temperatures ($T_{target}^{+/-}$), and the output temperatures of the last stage of the superstructure (T_{out}) are specified. The binary variable z describes the existence of a heat exchanger with an area A in the superstructure. The coefficients a, b and c characterize the area dependent individual costs of a heat exchanger while C describes the respective utility costs. The term X can be specified dependent on the additional costs, for example for safety issues, layout specific challenges or the above-mentioned piping costs. The MINLP model is computationally very complex because of the different combined cost functions. For the accomplishment of these difficult optimization tasks, different optimization strategies from previous works are incorporated. Amongst others these are local optimization strategies (Fieg et al., 2009), structural control strategy (Luo et al., 2009), heuristic approaches (Brandt et al., 2011) and vertical heat transfer strategies (Stegner et al., 2014).
The focus of this work is set on piping costs for each individual connection of each heat source and each heat sink. The piping length is approximated with the Manhattan distance between two streams j and k or a utility HU, CU and respective streams. The resulting cost function is given in Eq(2) with x, y and z being the Cartesian coordinates of the heat sources or heat sinks.

$$X_{j,k/j,CU/k,HU\dots}=2\cdot\left(\left|x_{j/HU}-x_{k/CU}\right|+\left|y_{j/HU}-y_{k/CU}\right|+\left|z_{j/HU}-z_{k/CU}\right|\right)\cdot f\left(D_{j,k/j,CU/k,HU}\right) \tag{2}$$

The correlation f between pipe diameter D and the corresponding cost per length unit is taken from Peters et al. (2003) for stainless-steel welded pipes. The diameter of the pipe D is calculated using the formula given in Pouransari and Maréchal (2014), i.e. Eq(3).

$$D_{j,k/j,CU/k,HU} = 0.363 \cdot \dot{m}_v^{0.45} \cdot \rho^{0.13} \cdot \mu^{0.025} \quad (3)$$

Eqs(1)-(3) result in a highly individualized optimization case. The chosen approach is not limited to just depict piping as pointed out above.

3. Case studies

The presentation of the developed approach is done with the help of two examples from literature with given Cartesian coordinates.

3.1 Case study 1

The first example is taken from Pouransari and Maréchal (2014). They took another example from literature and added arbitrary coordinates to the process streams and the supplied utilities. The associated problem data is given in Table 1.

Table 1: Problem data for case study 1

Stream	T_{supply} (°C)	T_{target} (°C)	Heat (kW)	*c* ($/kWa)	*x* (m)	*y* (m)	*z* (m)
H1	160	93	589		4	3	8
H2	249	138	1,170		6	7	4
H3	227	66	2,378		9	8	7
H4	271	149	1,532		2	2	5
H5	199	66	2,358		2	8	2
C1	60	160	762		7	4	1
C2	116	222	644		9	3	10
C3	38	221	1,545		1	4	2
C4	82	177	1,642		8	6	9
C5	93	205	1,557		4	5	3
HU	325	325		150	5	5	0
CU	38	82		20	6	9	5

Pouransari and Maréchal (2014) left out the hot utility for their problem because they investigated MER networks. The chosen problem case depicted in Figure 1 shows the possibility to generate a MER network with the usage of cold utility only. In this work, a hot utility was added because the optimization model requires the degree of freedom of a hot utility. Furthermore, specific costs for the utility usage were added. The heat transfer coefficients were chosen to match the required area results of Pouransari and Maréchal (2014). However, the results are not directly comparable because in this work the investment costs got annualized over a one-year period.

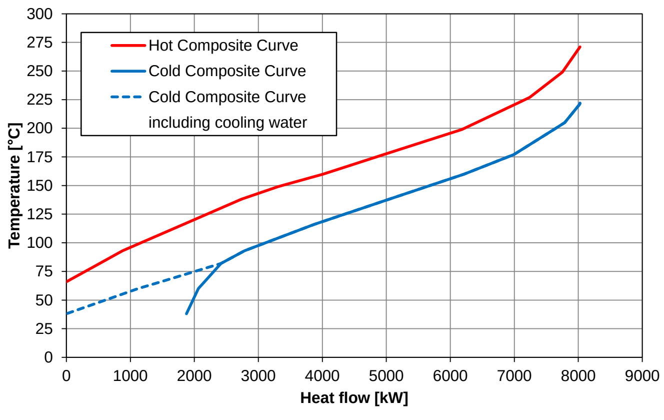

Figure 1: Composite curves for case study 1

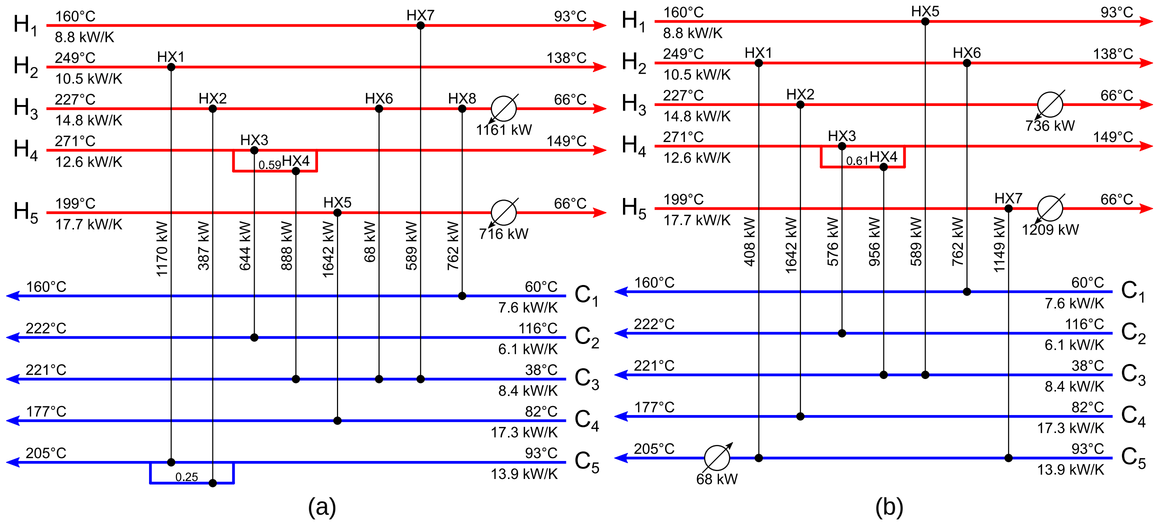

Figure 2: (a) Grid diagram representation of solution for case study 1 neglecting piping costs. (b) Grid diagram representation of solution for case study 1 including piping costs

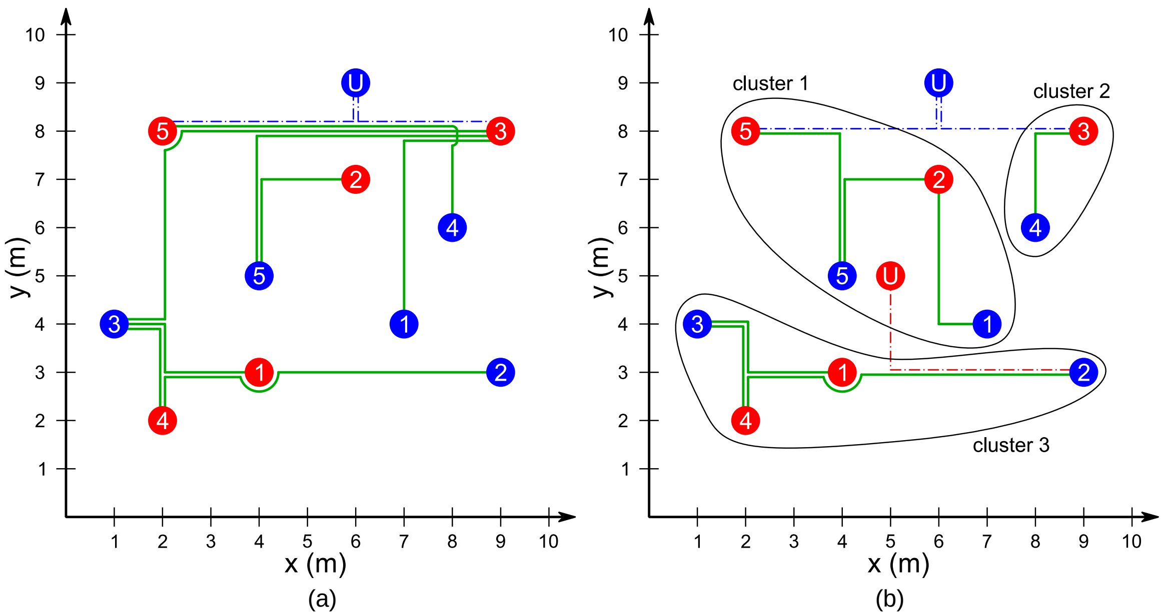

Figure 3: (a) Layout representation of solution for case study 1 neglecting piping costs. (b) Layout representation of solution for case study 1 including piping costs

The optimization results shown include two cases: for case a piping costs were neglected and for case b piping costs were incorporated. The Figures 2a through 3b show the optimization results for different parametrizations of the algorithm. The Figures 2a and 3a show the near optimal MER result for neglecting piping costs and the Figures 2b and 3b show the results for incorporating the piping costs. Figure 3b shows three clusters of process-to-process heat exchangers which are clearly distinguishable. Due to the different targets for the two cases, case a has 23.5 % lower annualized utility costs but the resulting HEN would have 26.8 % higher piping costs due to the fact that they got neglected for this case. The TAC for case b are 2.7 % lower. Despite the small difference in TAC, the structures of the HENs differ significantly.

3.2 Case study 2

In order to show the functionality of the presented approach for larger-sized examples, an example with 22 process streams was chosen as second case study. This example has also been given by Pouransari and

Maréchal (2014). For the cold utility specific costs of 15 $/(kWa) are assumed and for the hot utility 120 $/(kWa) are assumed. The other assumptions made are transferred from case study 1.

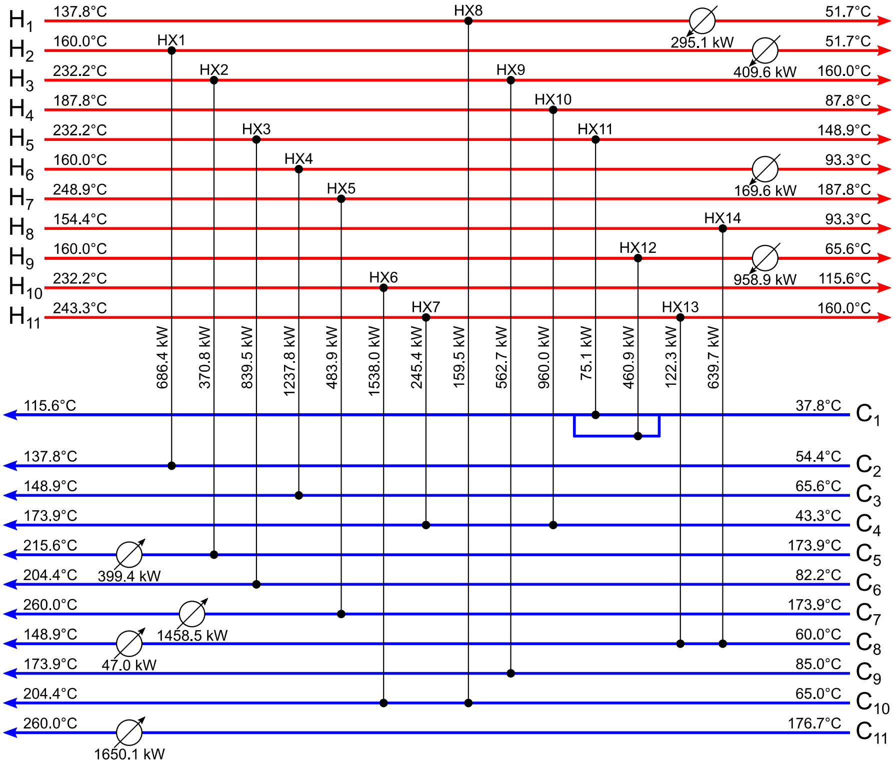

Figure 4: Grid diagram representation of the best result found for case study 2 including piping costs

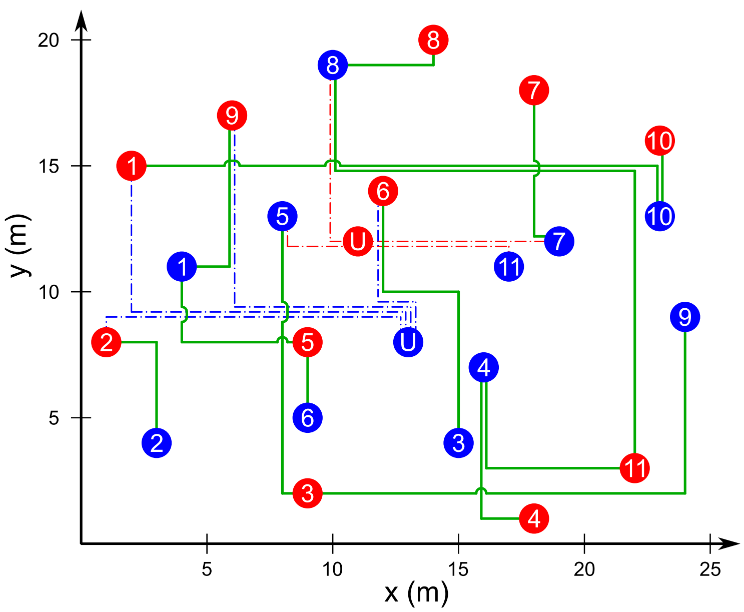

Figure 5: Layout representation of the best result found for case study 2 including piping costs

The solution depicted in Figures4 and 5 shows limited use of piping due to the resulting higher TAC in the optimization. The consideration of the piping costs during the optimization yields in a 2.1 % reduced TAC compared to the case without integration during the optimization. Comparing the case for including the piping costs the overall pipe length was reduced by 33.2 %. If more detailed costs like pumping and instrumentation are considered, a larger impact on the TAC difference is probable.

4. Conclusions

The presented approach to incorporate different cost considerations for each match individually for the cost-optimal design of HENs was carried out successfully and showed promising results. Two examples of different scale from literature are investigated utilizing different parametrizations of the presented approach. It is shown that the inclusion of piping costs into the optimization case can have a huge impact of the overall HEN structure and significantly different results are obtained. Local clustering of connections is observed as well as the general impact on the piping lengths, which in turn would result in lower maintenance costs and a lower probability of leakages. The solutions offer beneficial properties for practical implementation. In this special case the additional cost factor can be further extended to a raised weighted impact of the vertical component. The chosen approach shows good potential to incorporate further considerations, for example safety related questions, which can be tackled by constraining different matches with different penalties.

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