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Combined Flexibility and Energy Analysis of Retrofit Actions for Heat Exchanger Networks

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Retrofitting of industrial process heat recovery systems can contribute significantly to meeting energy efficiency targets for industrial process plants. One issue to consider when screening retrofit design options is that industrial heat recovery systems must be able to handle external variations, e.g. in ambient temperature, in such a way that operational targets are reached. There exist different approaches to incorporate flexibility considerations in the design process of retrofit proposals for heat exchanger networks (HEN). However, due to mathematical complexity, lack of suitable cost data, and difficulty to handle large-scale systems, the adoption of those methods in industrial retrofit projects has been limited. Therefore, this paper proposes to decouple the design and analysis steps in retrofitting processes. This allows well-proven retrofit design methods to be used in the design step to generate different alternatives. These design alternatives are thereafter evaluated in a separate analysis step in which the initial set of designs is narrowed down to one or several design options that are operable and energy efficient for a priori defined variations of operating conditions. The proposed approach is based upon traditional flexibility analysis combined with energy performance analysis. With such performance data available, a fair evaluation over different operating points can be obtained. The proposed approach is used for analysing the flexibility and energy performance of a HEN case study to illustrate its application.

1. Introduction

Retrofit projects in industrial heat recovery systems are constrained by operability issues (Marton, 2018), i.e. retrofit measures are supposed to have as little impact as possible on the core production process. One issue arising with this is the flexibility to cope with external variations, e.g. variations in ambient temperature or production adjustments due to price variations. There exist different approaches to incorporate flexibility during the design process of retrofit projects of heat exchanger networks (HEN). Kotjabasakis and Linnhoff (1986) developed an approach to mitigate unwanted response of a HEN to variations by means of sensitivity tables and systematic utilisation of downstream paths. Papalexandri and Pistikopoulos (1993) developed a multiperiod MINLP model which is based on multiperiod hyperstructures to obtain HEN retrofit design options with minimum total annualised cost which are operable for a predefined range of operating conditions. More recently, Kang and Liu (2014) introduced a 2-step method to address multiperiod HEN retrofit by first applying the multiperiod HEN synthesis model and then relocate existing exchangers to meet required area demands identified in step 1. However, these approaches have proven to be unable to handle certain situations. Super- or hyperstructure approaches assume that detailed cost data is available for all design alternatives considered, which is often not realistic. Furthermore, mathematical complexity of methods, system size and accessible computational power are additional reasons why industry has not adopted those methods when working with retrofit solutions. It is worth mentioning that many existing retrofitting methodologies address only single period operation, i.e. do not address flexibility concerns (examples can be found in review by Sreepathi and Rangaiah (2014)) while there is a scarcity of retrofit methodologies which address flexibility concerns (Kang and Liu, 2014).
To meet this demand, a novel approach is proposed in this paper which is based on decoupling the design and analysis steps of retrofit design projects. In this way, proven retrofit design methods can be applied to generate different design alternatives with a reasonable level of effort (for suitable HEN retrofitting methodologies see e.g. Sreepathi and Rangaiah (2014)). These design options are then evaluated in the analysis step to eventually

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achieve an energy efficient design that is able to operate for a predefined range of operating conditions. For performing the analysis step, a systematic approach is needed to guide retrofit projects for HENs by combined flexibility and energy analysis. The aim of this paper is to introduce the outline of such a novel approach and to demonstrate benefits of a combined flexibility and energy analysis by applying it to a case study.

2. Flexibility analysis of HENs

Flexibility analysis of HENs has been investigated since the early 1980s. Marselle et al. (1982) introduced the concept of resilient HENs with respect to a predefined disturbance range in the inlet conditions. In 1985, Saboo et al. (1985) introduced a HEN resilience index. In the same year, Swaney and Grossmann (1985) extended the concept of the resilience index to a flexibility index which is applicable not only to HENs but also to chemical processes in general. Both the resilience and the flexibility index indicate the maximum disturbance range in which inlet conditions may vary while at the same time achieving feasible operation. This maximum disturbance range can be interpreted as a hyperrectangle in the space of the varying inlet conditions (see e.g. Li et al. (2015)). In both index formulations, feasibility is achieved if all constraints describing the physical performance of the HEN or the chemical process are satisfied at the point of operation. It is worth mentioning, that not all feasible operating points within the expected variations can be identified by the index formulations but rather the maximum feasible fraction of all expected variations. This concept of flexibility assessment has been applied in numerous publications and is continuously used also in recent publications (see e.g. Kachacha et al. (2018)).

3. Combined flexibility and energy analysis

With flexibility analysis, it can be proven that network operation remains feasible within a certain predefined range of disturbances. From these results, no conclusions can be drawn regarding the energy performance of that network when the disturbances occur. The idea of combined flexibility and energy analysis is to extend traditional flexibility analysis by providing information on the level of flexibility and (additionally) on the energy performance of a HEN when exposed to variations. A priori, it can be concluded that certain variations have certain consequences on the energy performance, e.g. if all inlet temperatures vary in a negative direction, the heating requirements will increase (Marselle et al., 1982). However, such statements may only provide vague information on the performance of a HEN as the following examples demonstrate: 1. If the utility maximum energy recovery (MER) targets of a stream data set result in high utility demand, a network achieving these targets performs optimally from an energy perspective although the utility demand is high in absolute numbers. 2. If a network's utility demand is higher than the utility MER targets, this network does not perform at the optimal energy level although the utility demand may be low in absolute numbers.

Consequently, it is necessary to define assessment criteria for the energy performance of a HEN exposed to variations. In literature little is found on assessing the energy performance of a HEN exposed to variations. Attempts were made by Marselle et al. (1982) and Saboo et al. (1985). According to Marselle et al. (1982) a HEN (with fixed heat exchanger areas) is resilient if it can achieve MER for the specified disturbance range. MER for the specified disturbance range is explicitly defined as "that for a specific ΔT and any inlet condition within the disturbance range, maximum energy recovery, as determined by the assumed perturbed inlet conditions, can be achieved". In the formulation of the resilience index, Saboo et al. (1985) introduced an MER-constraint (which can be relaxed) to define feasible operation if the utility consumption at any point within the disturbance range does not exceed the MER-conditions specified for the initial design point. However, this constraint does not allow a fair comparison since due to the variations in the stream data, the utility MER targets change for every operating point, as indicated by Marselle et al. (1982). Therefore, in this paper a novel assessment criterion is proposed for analysing the energy performance of a HEN exposed to variations by energy performance ratios (EPR). The ratios between the "updated" utility MER targets ($Q_{MER,i}$) which are derived for the changed stream data and the actual utility demands ($Q_{utility,i}$) of the network for each possible set of variations (i) are proposed to achieve energy performance ratios (EPR_i) which allow for fair comparison of all sets of variations (I) (see Eq (1)).

$$EPR_i = Q_{MER,i}/Q_{utility,i} \ \forall \ i \in I \tag{1}$$

This bears two essential problems: 1) For each possible set of variations (which can be interpreted as individual stream data sets) the MER targets need to be calculated. Since there are infinitely many sets of variations in a defined range of disturbances this requires calculations of an infinite number of MER targets. 2) The network response needs to be calculated for each possible set of variations to know the utility demand the HEN considered which consequently results in an infinite number of problems.

Thus, it is necessary to explicitly define operating points to do the above-mentioned calculations which implies that the problem size is depending on the number of chosen operating points. A further difficulty arising with the second problem mentioned above is the large number of degrees of freedom or control variables of a HEN. For example, bypass ratios, split ratios, etc. may be manipulated to achieve the optimal utility consumption for each unique set of variations. Thus, trial and error network simulation and/or optimisation of these control variables is necessary.

3.1 Proposed procedure for combined flexibility and energy analysis

1. Generation of different retrofit design proposals:
   Well-proven retrofit methodologies can be applied to avoid difficulties which arise if flexibility concerns are addressed during the design step (see section 1).
2. Flexibility assessment and identification of network modifications to resolve flexibility bottlenecks:
   This requires a formulation for the flexibility index problem including area constraints as inequalities, as proposed by Floudas and Grossmann (1987). If the flexibility index problem initialised with the installed/preliminary area values results in a value for the flexibility index which is ≥ 1, the designer can proceed directly to the energy analysis part (see step 3). If the flexibility index indicates that the operability of the network over the entire range of expected variations cannot be guaranteed, measures must be taken to increase the flexibility. In this paper, the flexibility is increased by means of increased heat transfer in the heat exchangers which can be modelled by increased UA-values. In practice, increased UA-values are equivalent to either increase of area or heat transfer enhancement.
3. Analysis of energy performance:
   This involves the calculation of MER targets and of the utility demand as well as the calculation of the above defined EPR (see Eq (1)) for each point of interest. Trial and error network simulation and/or optimisation of the control variables is necessary to calculate the utility demand for each chosen point of operation. From an energy perspective, high values of the EPR are desired as they imply an energy performance close to optimality.
4. Evaluation of combined flexibility and energy analysis:
   The results provided by the combined flexibility and energy analysis allows for rigorous cost calculations and investment evaluations that require these values as inputs.

4. Motivating example

In Figure 1a, the network structure of a HEN is shown. This network and its performance are discussed in Gundersen (2002) in the context of possible retrofit actions to optimise operating cost while keeping investment cost low. Several retrofit options are discussed including one which reduces utility demand to MER targets. To achieve MER targets, investment in two new units and in increasing area of the existing units is necessary. Thus, solutions which achieve a reasonable balance between investment and operating cost are favoured. Two of these solutions are shown in Figure 1b and 1c. In retrofit proposal A (Figure 1b) heat exchanger (HEX) 1 and 2 are not increased and investment is necessary for an additional unit HEX6. In retrofit proposal B (Figure 1c), HEX1 and HEX3 are repiped (without increasing area) and again an additional unit HEX6 is installed.

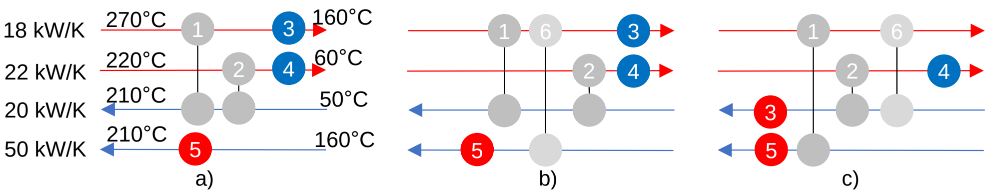

Figure 1: Network structure of a) the motivating example; b) retrofit proposal A; c) retrofit proposal B.

4.1 Combined flexibility and energy analysis

It was assumed that the network depicted in Figure 1a is the existing network and a preliminary cost evaluation revealed that the two retrofit solutions depicted in Figure 1b and 1c achieve lower total annualised cost than the existing network. The UA-values of HEX1 and HEX2 were specified and a preliminary design for HEX6 was defined according to nominal temperature specifications (as depicted in Figure 1a and its position in the respective proposal. Table 1 shows the UA-values of all three process HEXs (utility exchangers are not listed) and the hot utility demand for nominal temperature specifications of the existing network and of the two retrofit proposals. The new unit HEX6 is smaller in proposal B than in proposal A (see Table 1) which is reflected in the hot utility demand of the proposals. It is worth mentioning, that increasing HEX6's UA-value in proposal B to 20.9 kW/K (HEX 6's UA-value in proposal A) would not decrease the hot utility demand of proposal B.

Table 1: UA-values of the heat exchangers and hot utility demand of the initial structure and the two retrofit proposals of the example.

HEX UA-value [kW/K]	Initial	Proposal A	Proposal B
HEX1	17.5	17.5	17.5
HEX2	33.9	33.9	33.9
HEX6	-	20.9	7.6
Hot utility demand [kW]	2500	1880	2066

For performing flexibility analysis, a formulation for the flexibility index problem was chosen which includes area constraints as inequalities. The logarithmic mean temperature difference in the area constraints was approximated with Chen's approximation (Chen, 2019) to avoid numerical difficulties. Variations of ±10 °C in inlet temperatures were specified in accordance to apply the proposed analysis. For retrofit proposals A and B with the UA-values listed in Table 1, the flexibility index was calculated to 0. This indicates that variations in inlet temperatures cannot be handled by any of the network structures. To increase the flexibility, the UA-values were increased stepwise. When analysing the network structures, it was observed that HEX6 in proposal A has no downstream effect on the target temperature of stream 3 which is the only target temperature not controlled by a utility (see Figure 1b). Thus, a UA-value increase of HEX6 has no impact on the flexibility because it cannot contribute to controlling the critical temperature (with respect to flexibility) and was discarded for further analysis. A similar reasoning was made for HEX2 in proposal B which has no downstream effect on the target temperature of stream 1 (see Figure 1c). Instead, the options presented in Table 2 were further investigated.

Table 2: Considered options to increase the flexibility of retrofit proposals A and B.

Option	Proposal A	Proposal B
A/B-1	Uniform UA increase of HEX1 and HEX2	Uniform UA increase of HEX1 and HEX6
A/B-2	UA increase of HEX1 only	UA increase of HEX1 only
A/B-3	UA increase of HEX2 only	UA increase of HEX6 only

Table 3 shows the results of the flexibility analysis for the three options for proposal A. For a preliminary interpretation of the results, it was assumed that increased heat transfer is penalised equally for the two HEXs. Option A-2, in which the UA-value of HEX1 is increased by 8.3 kW/K, was identified to lead to the smallest total UA-value increase. According to the assumption on equal cost penalty, option A-2 would be the most favourable option from an investment cost perspective (the total UA-value increase in Table 3 includes the new unit HEX6).

Table 3: Results of the flexibility analysis for the three options of retrofit proposal A: A-1 Uniform UA increase of HEX1 and HEX2, A-2 UA increase of HEX1 only, A-3 UA increase of HEX2 only.

Option	UA-value HEX1 [kW/K] (relative increase)	UA-value HEX2 [kW/K] (relative increase)	Total UA-value increase [kW/K]	Flexibility Index
A-1	21.9 (25 %)	42.4 (25 %)	33.6	1
A-2	25.8 (47.5 %)	33.9 (0 %)	29.2	1
A-3	17.5 (0 %)	54.4 (60.5 %)	41.5	1

Table 4 shows the results of the flexibility analysis for the three options for proposal B. However, the investment cost situation is more complex for proposal B since the flexibility can be manipulated by the new unit HEX6. It cannot be assumed that increased heat transfer in HEX1 and HEX6 are penalised equally, since the cost functions for retrofitting an existing HEX and for buying a new HEX may be different. However, it was observed that the total demand for increased heat transfer in all three options considered for proposal B is smaller than the minimum total demand for increased heat transfer for proposal A (29.2 kW/K for option A-2).

Table 4: Results of the flexibility analysis for the three options of retrofit proposal B: B-1 Uniform UA increase of HEX1 and HEX6, B-2 UA increase of HEX1 only, B-3 UA increase of HEX6 only.

Option	UA-value HEX1 [kW/K] (relative increase)	UA-value HEX6 [kW/K] (relative increase)	Total UA-value increase [kW/K]	Flexibility Index
B-1	20.7 (18 %)	9 (18 %)	12.2	1
B-2	25.7 (46.8 %)	7.6 (0 %)	15.8	1
B-3	17.5 (0 %)	10 (31.6 %)	10	1

After having conducted the flexibility analysis (step 2 in section 2.1), an energy analysis was conducted (step 3 in section 2.1). As a compromise between accuracy and problem size, 16 operating points were investigated, which represent different combinations of the maximum and minimum values for the inlet temperatures of the network streams (i.e. each inlet temperature in Figure 1a was varied by + or - 10 °C from its nominal value). The labelling of these operating points (see Figure 2) refers to the variation of the inlet temperatures of streams 1-4 and "+" corresponds to a variation of +10 °C while "-" corresponds to a variation of -10 °C. To be able to calculate EPR (see Eq (1)) values for different designs and operating points, the minimum hot utility demand needs to be determined for given design and operating conditions (cold utility demand is discarded). This requires the adjustment of control variables, in this case the bypass ratios of HEX1 and/or HEX2 and HEX6. Figure 2 shows the resulting EPRs for each of the investigated 16 operating points, and for the nominal operating point ("0,0,0,0") for different HEN designs. Figure 2a shows the EPRs for the three design options for proposal A (UA values indicated in Table 3). Figure 2b shows the EPRs for the design options of proposal B (Table 4).

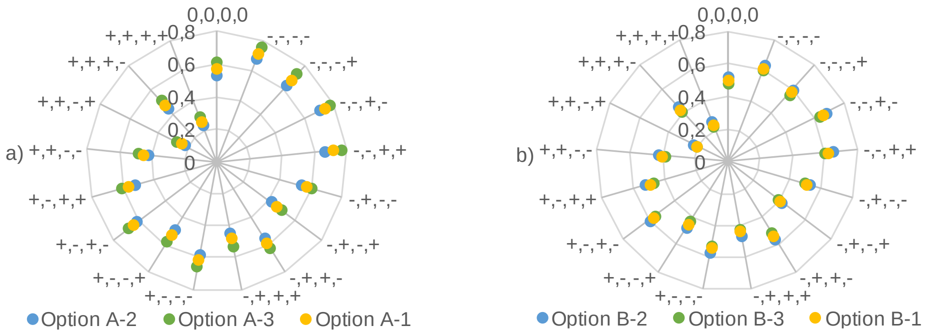

Figure 2: Energy performance ratios at the investigated points of operation for retrofit proposals A (Figure 2a) and B (Figure 2b) and the considered options for flexibility increase according to Tables 3 and 4.

Figure 2 shows that for proposals A and B the option with highest demand for increased heat transfer (A-3 and B-2 respectively) also achieves the highest EPRs at all operating points considered and vice versa. This well-known trade-off between HEX surface area and utility consumption can thus be observed not only for the nominal design point but also for the 16 operating points considered. Correspondingly, options A-1,2,3 demand less hot utility than options B-1,2,3. However, Figure 2 shows that the difference between the EPRs of the best option of proposal B (option B-2) and the corresponding EPRs of the worst option of proposal A (option A-2) is small. Yet, the difference in required heat transfer increase is considerable (13.4 kW/K). To enable a fair comparison of options A-2 and B-2, a new design option B-2* ("upgrade" of option B-2) was considered. The total UA-value of option B-2* was increased by the difference between the total UA-value increase of option A-2 and B-2. To avoid additional cost, only HEX1 and HEX6 were considered for additional UA-value increase. While the EPRs of option B-2*, compared to option B-2, could not be increased by an increased UA-value of HEX6, they could be increased by further increasing the UA-value of HEX1. The EPRs of option B-2* (UA-value of HEX1 is increased by additional 13.4 kW/K compared to option B-2) are shown in Figure 3a.

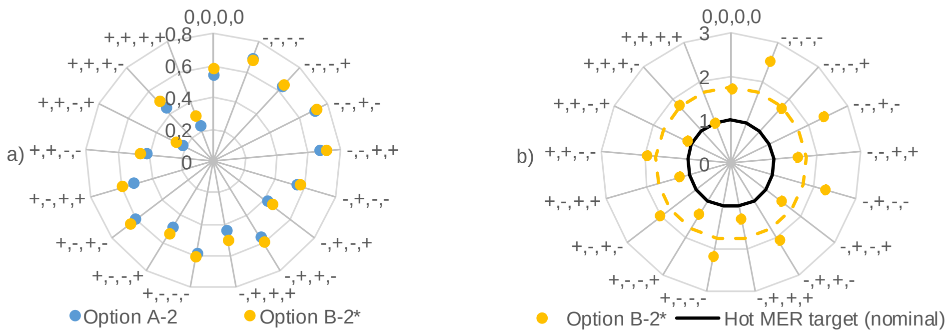

Figure 3: a) Energy performance ratios at the considered operating points for option A-2 and option B-2; b) Hot utility demand for option B-2* and hot MER target for nominal conditions (both in MW).*

For almost all operating points, option B-2* achieves a higher EPR value than option A-2. In fact, comparing Figure 2a and 3a reveals that option B-2* can compete energy-wise with option A-1. However, option A-1 demands a higher increase in heat transfer than option B-2* which encourages further investigations. It is worth mentioning that the option to increase the UA-value of HEX1 was motivated by following the proposed approach. Figure 3b shows the hot utility demand for option B-2* for all operating points considered as well as the hot utility MER target for nominal conditions (values in Figure 1a). It can be observed that for eight of the operating points considered, the hot utility demand is higher than the hot utility demand at the nominal point of operation (dashed line in Figure 3b). This is also true for the operating point at which the highest hot utility demand occurs (compare "-,-,-,-") although a high EPR is achieved at this point. However, at some operating points the hot utility demand is lower than at nominal conditions and the EPR is also low (compare "+,+,+,+" or "+,+,-,+" in Figure 3a and 3b). Additionally, Figure 3b shows that the hot utility demand is larger than the hot utility MER target at nominal conditions for almost all operating points considered. Thus, it is questionable to include the MER-constraint (or a comparable relaxed constraint e.g. with the utility demand at nominal conditions) introduced by Saboo et al. (1985) since the network considered might show bad energy performance at points with lower utility demand while at other points the energy performance is better although the utility demand is higher.

5. Conclusions

In this paper, a novel step-wise approach has been outlined for combined flexibility and energy analysis of HENs. In this way, the design and analysis steps within a retrofit design project can be decoupled and proven retrofit design methods can be applied in the design step. The proposed approach has been applied to a simple example to demonstrate the proposed procedure. It has been demonstrated that flexibility bottlenecks can be identified, and a strategy was outlined to resolve these bottlenecks by increased heat transfer. Furthermore, the need for energy performance analysis of HENs exposed to variations was identified to be able to fully compare different retrofit proposals. A novel assessment criterion in the form of energy performance ratios was defined to evaluate the utility demand of a HEN exposed to variations. However, the success of a HEN retrofit project based on combined flexibility and energy analysis is dependent on the quantity and quality of the design alternatives generated in step 1 of the proposed procedure. The purpose of the proposed approach is to enable designers to identify trade-offs of the generated design alternatives prior to their quantification via rigorous but also time-consuming cost calculations. With the existing variety of proven retrofitting methodologies for single-period operation, it is therefore likely that the effectiveness of early design stage screening process can be increased by following the proposed approach. Future work will focus on applying the proposed approach to more complex examples which may demand adjustments if the current version reveals limitations.

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