Operational Flexibility of Heat Exchanger Networks

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Abstract Process integration is motivated from economic benefits, but it also impacts on the plant behavior introducing interactions and in many cases making the process more difficult to control and operate. A prerequisite for optimal operation is that the HEN is sufficiently flexible, i.e. it must have the ability to operate over a range of conditions while satisfying performance specifications. In this work it is defined the Operational Flexibility related not only to the size of the feasible region but also to the costs involved to put the HEN into operation. In order to provide an appropriated metric, the operational flexibility index is defined. Five different networks structures designed for the nominal conditions of a case study are used to illustrate the proposed ideas. It was noticed that a great feasible region does not point out the more economic operation, and the costs must be considered together with the flexibility analysis. These characteristics are taken into account by the novel proposed operational flexibility index, which can also consider during the analysis the increasing in the utility duties, extra utility exchangers and bypass installation. These results clearly point out for the need of a simultaneous framework for flexible design and profitability.

Keywords: Heat Exchanger Networks, Optimal Operation, Operational Flexibility.

1. INTRODUCTION

Operability issues are very important for heat integrated process, since the economic performance of a process is greatly affected by process variations and the ability of the system to satisfy its operational specifications under external disturbances or inherent modelling uncertainty.

Methods based on pinch analysis and mathematical programming for fixed operating conditions hve been largely developed. An extensive review of these methods can be found in Furman and Sahinidis (2002). Compared to design of HENs for nominal operating conditions, less effort has been dedicated to the operability and controllability aspects of such networks.

Since the concept of resilient HENs firstly developed by Marselle et al. (1982) and the introduction of the flexibility index by Swaney and Grossmann (1985) several design methods based on the multiperiod approach were proposed. Floudas and Grossmann (1986) introduced a multiperiod case based on the synthesis with decomposition. Papalexandri and Pistikopoulos (1994) and Konukman et al. (2002) extended the simultaneous synthesis to the multiperiod case in an MINLP problem.

All these works relates the flexibility with the size of the feasible region and they do not take into account explicitly all the trade-offs involved in a HEN design. In this work a new metric for comparing different HEN structures is proposed based on the concept of operational flexibility. A case study with 5 different synthesized HENs is used to illustrate the proposed metric.

2. OPERATION OF HENs

A HEN is considered optimal operated if the targets temperatures are satisfied at steady state (main objective); the utility cost is minimized (secondary goal); and the dynamic behaviour is satisfactory (Glemmestad, 1997).

During HEN operation, degrees of freedom or manipulated inputs are needed for control and optimization. The different possibilities are shown in Figure 1: 1-Utility Flowrates; 2-Bypass fraction; 3-Split fraction; 4-Process Streams flowrates; 5-Exchanger area (e.g. flooded condenser); 6-Recycle (e.g. if exchanger fouling is reduced by increased flowrates).

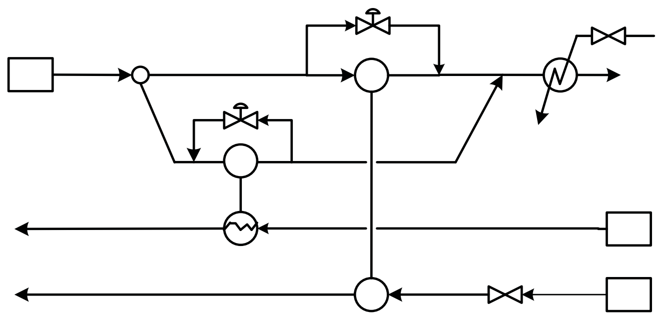


Fig. 1. Possible manipulated inputs in HENs.

In this work, we will consider the outlet target temperatures as controlled variables and utility loads, bypasses or splits, when they are present, as manipulated variables. The idea is to maintain the targets temperatures using the minimal increase of the external utilities. The best HEN is the one where the effect of a given set of disturbances can be accommodated internally without requiring too much external "help" from the utilities heat exchangers. These ideas are illustrated through the case study of the next section.

3. CASE STUDY

To analyze the flexibility problem we have synthesized 5 different HENs for the plant illustrated in Figure 2.

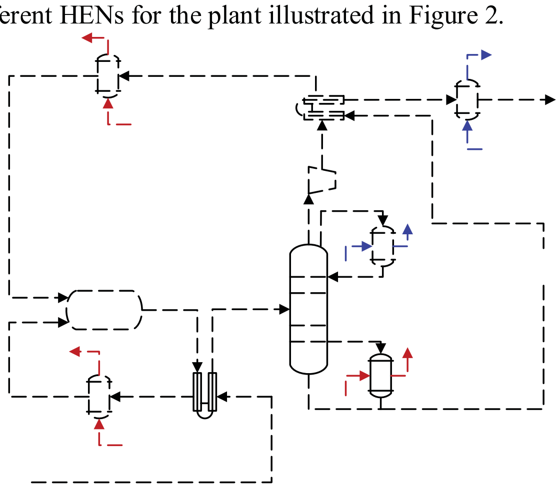


Fig. 2. Simple process with reaction, separation and heat exchangers.

Table 1. Nominal operating condition for the Case Study.

Stream	T_{in} (°C)	T_{out} (°C)	F (kW°C^{-1})	h (kW m^2 °C^{-1})
H1	270	160	18	1
H2	220	60	22	1
C1	50	210	20	1
C2	160	210	50	1
CU	15	20		1
HU	250	250		1

Cost of Heat Exchangers (\$y^{-1}) = 4000+500[Area (m^2)]$^{0.83}$
Cost of Cooling Utility = 20 (\$kW^{-1}y^{-1})
Cost of Heating Utility = 200 (\$kW^{-1}y^{-1})

Table 1 summarizes the corresponding data of the nominal operating conditions. This data and a ΔT_{min} of 10 °C were used to design the 5 different HENs depicted in Fig. 3. The five HENs have been designed by the following approaches:

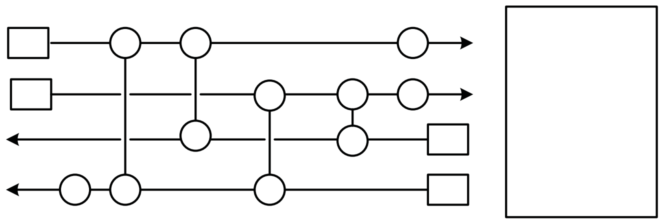
S01-Pinch Technology (Linnhoff & Hindmarsh, 1983);

S02-NLP Superstructure proposed by Floudas, Ciric, and Grossmann (1986) using Pinch Technology as initial guesses;

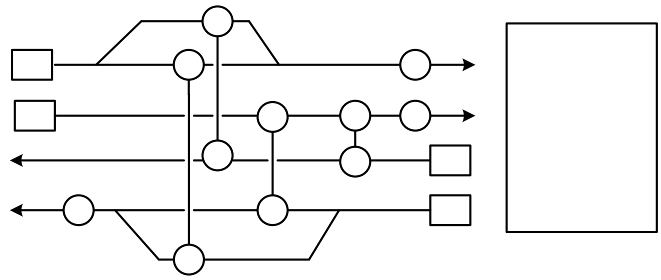
S03-NLP Superstructure in the Sequential procedure (Floudas, Ciric, and Grossmann, 1986);

S04-Hyperstrucutre proposed by Ciric and Floudas (1991); and

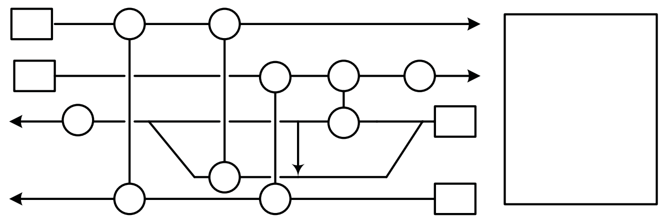
S05- the stage-wise Synheat model proposed by Yee and Grossmann (1990) with the assumption isothermal mixing.



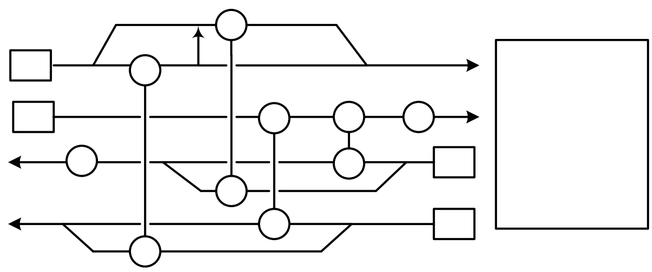
S01: Pinch Technology



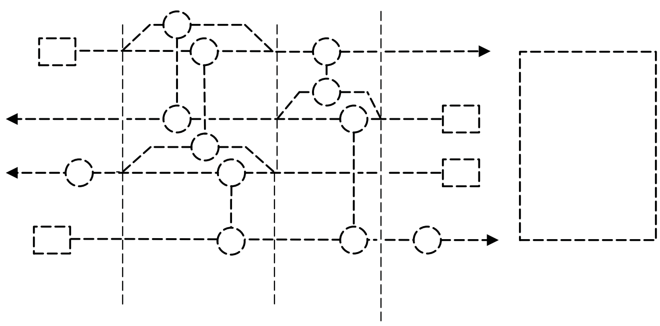
S02: NLP Superstructure (initial point by Pinch Technology)



S03: NLP Superstructure (Sequential Procedure)



S04: MINLP Hyperstrucuture (Simultaneous Procedure



S05: MINLP Synheat Model (Isothermal Mixing)

Fig. 3. Synthesized HENs for the Case Study using different approaches.

4. OPERATIONAL FLEXIBILITY

The flexibility is defined by Swaney and Grossmann (1985) as the size of the region of feasible operation in the space of possible deviations of the parameters from their nominal values. In order to analyze the flexibility, a disturbance scenario is explored on the basis of the vertices of the polyhedral region of uncertainty (Konukman et al., 2002) trough a scalar δ (flexibility target). For a fixed HEN topology and design the 'flexibility index' is defined by Swaney and Grossmann (1985) as the maximum scalar δ* (Figure 4).

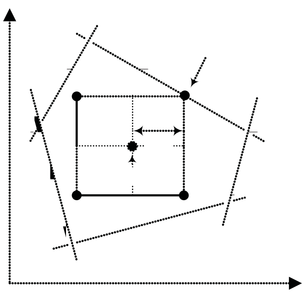


Fig. 4. Geometric representation of vertex-based flexibility target.

As the feasible region is convex when it is considered the inlet temperatures as uncertain parameters, the critical point that limits the operation lies at a vertex of the polyhedral region of uncertainty. For non-convex region the vertex-based formulation should be replaced by a more general active-constraint-strategy-based on MINLP formulation (Floudas, 1995).

Considering the four inlet temperatures as disturbances, a total of 16 vertices are enumerated. Each vertex represents an operating condition and it is formed by a deviation of ±δ from the nominal values In order to calculate the expected variations in the operating conditions that potentially could happen for a given flexibility target, each HEN configuration was implemented in Excel® using the heat exchanger model described by the set of equations (1), (2), and (3) and notation shown in Fig. 5.

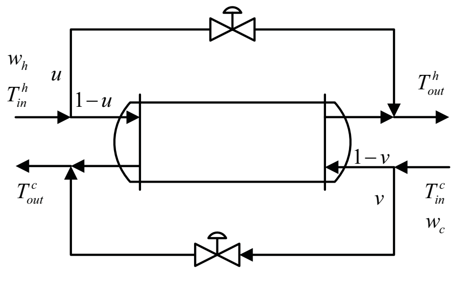


Fig. 5. General structure of a heat exchanger with bypasses.

$$T_{out}^h = (1-u)\left[\frac{(R_h-1)}{R_h-a}T_{in}^h + \frac{(1-a)}{R_h-a}T_{in}^c\right] + uT_{in}^h \qquad (1)$$

$$T_{out}^c = (1-v)\left[\frac{R_h(1-a)}{R_h-a}T_{in}^h + \frac{a(R_h-1)}{R_h-a}T_{in}^c\right] + vT_{in}^c \qquad (2)$$

Where

$$R_h = \frac{w_h(1-u)}{w_c(1-v)}; NTU_h = \frac{UA}{w_h(1-u)}; a = e^{NTU_h(1-R_h)} \qquad (3)$$

The individual heat exchanger model was connected according to the topology for each HEN structure and the outlet temperatures deviations from their target values are calculated together with the additional utility requirement. A free simulation for fixed bypass and split fractions was carried out for each operating condition. Positive values encountered of heat duties at the stream where no utility exchanger exist mean that an extra utility exchanger must be included. Moreover, the negative values indicate an infeasible operation without any structural modifications, even for adding a new utility exchanger.

4.1 Optimal Operation of HENs

To overcome an infeasible operation it is possible to use the degrees of freedom, such as split fractions and bypasses placement in order to increase the feasible region and ensure that the optimal operation can be achieved by minimizing the utility consumption. The optimal steady-state operation or network optimization problem (Marselle et al., 1982):

Optimal Steady State Operation: *(For each operating point n)*

*Minimum Utility Consumption (**secondary objective**)*

$$\min_{u,v} \quad \sum_{i=1}^{NH} Q_{i,n}^{CU} + \sum_{j=1}^{NC} Q_{j,n}^{HU}$$

subject to.

*Hot and Cold target temperatures (**primary goal**)*

$$T_{i,n}^{out} - T_i^{sp} = 0; T_{j,n}^{out} - T_j^{sp} = 0$$

Positives or zero heat loads coolers and heaters

$$T_i^{sp} - T_{i-1,n}^{out} \leq 0; T_{j,n}^{out} - T_j^{sp} = 0$$

Hot and Cold Utility loads

$$Q_{i,n}^{HU} = w_i^H\left(T_{i-1,n}^{out} - T_{i,n}^{out}\right)$$

$$Q_{j,n}^{CU} = w_j^C\left(T_{j,n}^{out} - T_{j-1,n}^{out}\right)$$

Heat Exchanger Static Model

(3), (4), and (5)

*Topology Constraints**

Bypass bounds

$$0 \leq u, v \leq 1$$

** The topology constraints define the configuration, and are expressed as appropriated model variables connections.*

The optimal optimization problem for each configuration was implemented using the software GAMS and solved using the solver CONOPT considering δ_T is equal to 10ºC (flexibility target). The new requirements for the each HEN structure are exhibited in Table 2.

According to the initial analysis, the maximum or critical utility exchanger operation is not a good metric since it was not able to distinguish the configurations S01 and S02. Furthermore, comparing the configurations S03 and S04, even though the critical loads are greater for the first one the total heat load (summation for each operation point) and the averages are not.

Table 2. Utility loads (kW) for a feasible operation for each case study using extra utility units.

Struc.	*Utility*	*Maximum*	*Average*	*Total*
S01	***cold***	1000	446	7584
	hot	1300	646	10984
S02	***cold***	1000	445	7563
	hot	1300	645	10963
S03	***cold***	1300	570	9886
	hot	1480	769	13073
S04	***cold***	1287	586	9966
	hot	1466	782	13306
S05	***cold***	1000	497	8455
	hot	1480	696	11840

According to the results the configurations S03 and S04 are the worst from a flexibility point of view, since they require more utility to a feasible operation. On the other hand, S04 is the HEN with lowest TAC (3.619×10^5 \$/year) as shown in Fig. 3, but considering the flexibility this is not the best option and clearly points out that flexibility issues must be considered in an early stage of the process design, since the nominal optimum .

4.2 Optimal Operation with no extra utility units

The solution provided in the previous analysis is trivial and may guarantee the operation for a large range. Furthermore, it is an expensive solution. Providing a more reasonable analysis, a second optimal operation problem was considered. The new problem definition differs from the previous one by the addition of constraints that ensure no extra utility exchangers. The general results are presented in Table 3.

Table 3. Utility loads (kW) for a feasible operation for each case study using no extra utility units.

Struc.	*Utility*	*Maximum*	*Average*	*Total*
S01	***cold***	1000	494	8425
	hot	1714	694	11825
S02	***cold***	1003	502	8534
	hot	1540	702	11934
S03*(8)	***cold***	1058	521	8851
	hot	1480	721	12251
S04*(14)	***cold***	902	499	8410
	hot	1480	699	11810
S05*(7)	***cold***	1000	530	9011
	hot	1587	730	12411

* (*ni*) indicate *ni* infeasible operating points.

Due to extra constraints, greater utility consumption in general was need. Moreover, how it was expected not always a feasible solution could be found. The main difficult faced by the configurations S03, S04 and S05 was the presence of only two utility exchangers, i.e. these configurations are more penalized with the additional constraints. The bad performance of the configuration S05 may be also explained possibly by the "inflexible" isothermal mixing constrain applied to the design.

A new analysis was made considering the possibility of variation for the extra degrees of freedom, when they take place. Whereas the configuration S01 has no one split fraction, the best possible results has already presented in Table 3. Conversely, all other configurations have split fractions. For the configurations S03 and S04 was also considered as an extra degree of freedom the recycle stream, from the outlet of a heat exchanger to another. The results are presented in Table 4.

Table 4. Utility loads (kW) for a feasible operation for each case study using no extra utility units but using extra degrees of freedom (split and recycle fractions).

Struc.	*Utility*	*Maximum*	*Average*	*Total*
S01	***cold***	1000	494	8425
	hot	1714	694	11825
S02	***cold***	900	435	7396
	hot	1430	635	10796
S03*(7)	***cold***	990	458	7780
	hot	1383	658	11180
S04*(8)	***cold***	780	417	7088
	hot	1368	641	10904
S05	***cold***	900	456	7745
	hot	1431	656	11145

* (*ni*) indicate *ni* infeasible operating points.

Like it was expected the extra degrees may be used to achieve the targets and decreases the utility consumption increasing the feasible region, which is proven by the increase of the number of feasible operating points. For the configuration S05, allowing the manipulation of the split fractions automatically removes the isothermal mixing assumption and hence increases considerably the flexibility.

Comparing the results, the configurations S03 and S04 must be discarded because they do not provide a suitable operation. The results are a sign of designs with splits are good from the flexibility viewpoint because these extra degrees of freedom can be used to decrease the investment cost during the design phase and be used to decrease the utility consumption during operation. In addition, the installed areas are utilized completely for all operating points, which not occurs using bypasses. In the overall design the dynamic behaviour must be analysed carefully once split fractions can give competitive effects.

4.3 Flexibility Range

All the previous analysis considered the flexibility target (δ_T) of 10°C, in order to analyze the flexibility range, the total utility consumption (δQ) levels corresponding to the critical operating conditions versus the flexibility targets (δ_T) for structures S01, S02 and S05 and the virtual structure (Maximum Energy Recovery) MER were calculated and they are shown in Figure 6.

The illustration reveals plateaus of total utility requirements levels for a given value of δ, under the correspondent δQ level the configuration is operable, i.e. it will not violate the temperatures specifications as long as the deviations in the source streams temperatures along the vertex directions have magnitudes within $0< \delta_T < \delta$.

The analysis reveals the trade-off between the flexibility target and the total utility load need to maintain a feasible operation pointing out that a more flexible is more expensive. For practical purposes, increasing the flexibility target trough penalization of total utility consumption is possible until a limit (δ^*), which is reached when at least one bypass saturation occurs.

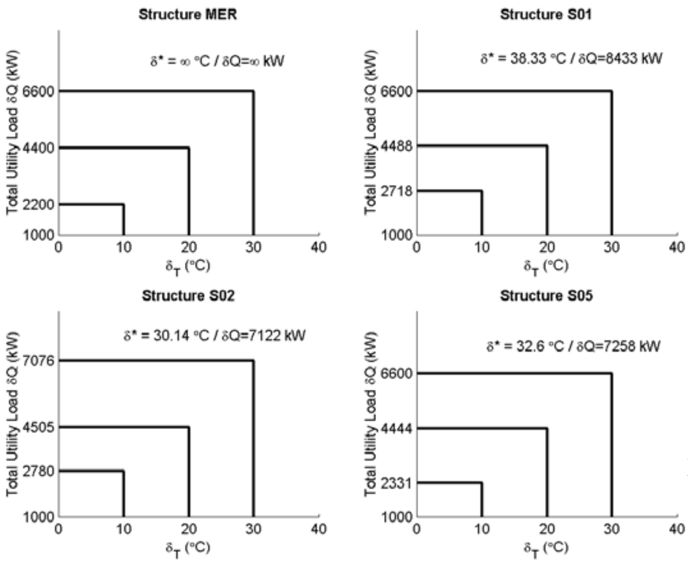


Fig. 6. Total utility consumptions at the critical operating conditions versus the flexibility ranges for structures MER, S01, S02 and S05.

In Table 4, the structure S02 (δ^*=38.33^{0}C) depicted the lowest total utility load in general (considering all operating points) and the lowest average utility load. Therein, the critical loads define the feasibility operational range and it must be checked, but a selection of a structure using purely the analysis provided by the Figure 6 will not be appropriated because it would assume that most of the time the process would operate in the critical conditions what is not correct.

5. OPERATIONAL FLEXIBILITY INDEX

An appropriated metric to compare different HENs is based on the operational flexibility that is reached if the operation is possible and the maximum energy recovery is obtained for the entire feasible region with a minimum investment cost.

The structure of the HEN has a direct influence on the flexibility. Disintegrated structures are highly flexible, but that trivial solution is not interesting under an economic point of view. The other highly flexible possibility is a totally integrated structure, with the maximum number of units and maximum areas with bypasses across all units, but very expensive from an investment point of view.

Here we introduce the operational flexibility index to take into account in addition to the feasible range related with a flexibility target the most important costs involved during a "flexible operation". The Operational Flexibility Index for a specific flexibility target (OF_δ) is defined in equation (4), where the two terms correspond to operating cost (φ_{oc}) and the investment cost (φ_{ic}) penalties for an operational flexibility, and these terms are defined in equations (5) and (6). The operational flexibility index varies form 0 to 100%. Its upper bound indicates feasible operation without much economic penalty. On the other hand, when bypasses, new units, increased areas, and increased utility consumption are considered the indice will be penalized.

$$OF_\delta(\%) = 100(1 - \varphi_{oc} - \varphi_{ic}) \tag{4}$$

$$\varphi_{OC} = w_1 \frac{1}{2(V+1)} \sum_{n=1}^{V} \frac{\sum_{k=1}^{NH+NC} \delta q_{k,n}^{U} - \sum_{k=1}^{NH+NC} \delta q_{k,n}^{U,\min}}{\sum_{k=1}^{NH+NC} \delta q_{k,n}^{U,\max} - \sum_{k=1}^{NH+NC} \delta q_{k,n}^{U,\min}} \tag{5}$$

$$\varphi_{IC} = w_2 \frac{N_{bp}}{N_{hx,retrofit}} + w_3 \left(1 - \frac{N_{hx}}{N_{hx,retrofit}}\right) + w_4 \left(N_{hx} - \sum_{m=1}^{N_{hx}} \frac{A_{m,installed}}{A_{m,retrofit}}\right) \tag{6}$$

The parameters w_i (7) correspond to the normalized weight for each contribution to the penalty. A suggested set may be calculated by the constants k_i (8) that depends on economic data from the process, i.e. the utility costs and the exchanger costs, considering the bypass cost. For the case study these parameters are provided in Table 1.

$$w_i = \frac{k_i}{\sum_{i=1}^{4} k_i} \tag{7}$$

$$k_1 = \frac{cu.}{2(V+1)} \left(\sum_{k=1}^{NH+NC} \delta q_{k,n}^{U,\max} - \sum_{k=1}^{NH+NC} \delta q_{k,n}^{U,\min} \right)$$
$$k_2 = 0.2aN_{hx,ret}; k_3 = aN_{hx,ret}; k_4 = b\sum_{m=1}^{N_{hx}} A_{m,ret}^{\beta} \tag{8}$$

The parameters N_{bp}, N_{hx} and A_m correspond to the number of bypasses placed, the number of heat exchangers and the area of the heat exchanger m, respectively. Moreover, the subscript 'retrofit' indicates the variable in the flexible operation, i.e. the retrofitted design.

To evaluate the potential of each structure, the operational flexibility index was calculated. The calculation requires the bounds for the utility loads. It was used the LP transshipment model (Papoulias and Grossmann, 1983) for each operating point to estimate the minimum utility consumption for the design case (ΔT_{min}=10^{0}C) and the minimum case (ΔT_{min}=0^{0}C). Furthermore, it was calculated the utility loads for the no heat integration case; all the targets are exhibited in Table 5.

Table 5. Utility loads (kW) for a feasible operation for each case study using no extra utility units.

Case	*Utility*	*Max.*	*Average*	*Total*
MER	*cold*	900	412	7000
ΔT_{min}=10^{o}C	*hot*	1300	612	10400
MER	*cold*	900	219	3720
ΔT_{min}=0^{o}C	*hot*	1080	360	6120
No Heat	*cold*	5900	5500	93500
Integration	*hot*	6400	5700	96900

The main results are expressed in Table 6. The term corresponding to the energy cost is dominant due to its greater economic impact in the total cost; the investment cost is worthless for most cases. The structure S02 showed the best performance for the required flexibility target. The interpretation inside the context of a feasible operation is that a greater index indicates that operation occurs inside a more economic way, using a lower average utility consumption with the lower investment cost. Otherwise different conditions will penalize the operational flexibility.

Table 6. Operational Flexibility Index for the structures S01, S02 and S05.

	S01	***S02***	***S05***
φ_{oc}	0.0605691	0.0498255	0.0536638
φ_{ic}	0.00203939	0.00271918	0.00000000
$OF_{\delta=10}$	93.73916%	94.74553%	94.63362%

5.1 Flexibility x Installed Area

All the previous analysis was carried out using the areas as fixed parameters, and these areas were designed at nominal conditions. If it was considered the whole feasible region, trough a multi-period design these areas would have better usage in order to reduce the utility consumption in the entire region. A new optimization problem was performed for the structure S01, considering varying areas. In order to avoid extreme solutions, a practical consideration for the areas bounded between 1 and 1000 m^2 were imposed and new optimizations were performed. The areas for each operating point are presented in Table 7. In order to satisfy all operating points, the maximum areas obtained in Table 7 where fixed and the optimal operation problem was solved with the increased areas.

Table 7. Nominal and maximum areas (m^2) for the HEN structure S01.

	$A_{H1,C1}$	$A_{H1,C2}$	$A_{H2,C1}$	$A_{H2,C2}$
Nominal	318.12	56.55	609.97	209.79
Maximum	1000.00	97.46	1000.00	1000.00

Comparing the values obtained with the results presented in Table 4 for the structure S01, the total utility loads decreased from 8425.3kW to 4370.9 kW (cold utility) and 11825.3 kW to 7770.9 kW (hot utility); and the average consumption decreased from 494kW to 257kW(cold utility) and 694kW to 457kW (hot utility). The flexibility index (δ*) provided in the Figure 6 increased from 38.33^{0}C to 49.8^{0}C, i.e. the feasible region increased. Furthermore, the operational flexibility index (OF_δ) exhibited in Table 6 increased from 93.73916% to 98.197858% considering only the energy cost and considering the capital cost for the oversize of the areas the index is 97.02954%.

6. CONCLUSIONS

The flexibility analysis of different structures previously designed was accomplished through optimal operation problem taking into account the trade-offs between energy cost, capital cost and the flexibility in order to ensure an economic operation. The formulation presumed that the feasible region in the space of uncertain input parameters was convex, and thus the optimal solution was explored based on the vertices of the polyhedral uncertainty region in the space of source-stream temperatures. It was defined the operational flexibility index as a measure of operational flexibility that was assumed to be different of structural flexibility. The first one considers the impacts on the total annual cost, since infinity areas, high levels of utility loads and disintegrated structures are according with this work highly structural flexible but present a poor (expensive) operation and hence a low operational flexibility.

The HEN structure provides an upper bound for the flexibility that should be expected during operation. The increasing of flexibility target reveals the flexibility dependent on structural modifications and total utility consumption until the unfeasible operation may be achieved. It was showed that more important that the size of the feasible region it is the cost involved in a feasible operation around the desired flexibility target. It has shown the real need of taking into account the flexibility in a simultaneous framework, once the utility loads, heat exchangers (units and areas), and the arrange (configuration of flows, temperatures) are determined in only one step, and all these variables strongly affect the flexibility.

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