This is a previous version of the article published by Elsevier in Energy Conversion and Management. 2015, 94: 377-393. doi:10.1016/j.enconman.2015.02.002

Retrofit of heat exchanger networks with pressure recovery of process streams at sub-ambient conditions

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ABSTRACT

This paper presents a new mathematical programming model for the retrofit of heat exchanger networks (HENs), wherein the pressure recovery of process streams is conducted to enhance heat integration. Particularly applied to cryogenic processes, HENs retrofit with combined heat and work integration is mainly aimed at reducing the use of expensive cold services. The proposed multi-stage superstructure allows the increment of the existing heat transfer area, as well as the use of new equipment for both heat exchange and pressure manipulation. The pressure recovery of streams is carried out simultaneously with the HEN design, such that the process conditions (streams pressure and temperature) are variables of optimization. The mathematical model is formulated using generalized disjunctive programming (GDP) and is optimized via mixed-integer nonlinear programming (MINLP), through the minimization of the retrofit total annualized cost, considering the turbine and compressor coupling with a helper motor. Three case studies are performed to assess the accuracy of the developed approach, including a real industrial example related to liquefied natural gas (LNG) production. The results show that the pressure recovery of streams is efficient for energy savings and, consequently, for decreasing the HEN retrofit total cost especially in sub-ambient processes.

Keywords: Generalized disjunctive programming (GDP); mixed-integer nonlinear programming (MINLP); retrofit; heat exchanger network (HEN); pressure recovery; sub-ambient processes

1. Introduction

Reducing energy consumption through the implementation of more efficient and innovative strategies is one of the major concerns in processing plants. In this way, heat exchanger networks (HENs) are responsible for the integration of thermal streams, playing a crucial role in the energy efficiency enhancement of industrial processes [1–3]. Despite the considerable effort over the past few decades to solve the problem of HENs synthesis [4,5], a much smaller portion of the research was directed to the retrofit of existing networks [6,7]. Nowadays, the HENs retrofit are getting more attention in both academic and industrial fields [8,9], due to increased interest in energy conservation and its efficient use for economic reasons, as well as the rising demands to reduce environmental impacts related to high energy consumption [10,11].

It is worth to remember that energy savings by the minimization of energy-related costs in the design of industrial process is also a fundamental strategy to improve the performance of industries in the market, increasing their competitiveness [12]. Thus, the retrofit emerge as an effective way to enhance heat recovery and to achieve the desired energy savings from an established HEN [13,14]. The HENs retrofit is aimed at reducing the consumption of thermal utilities, by minimizing changes needed for the heat transfer enhancement in terms of restructuring the possibilities of thermal exchange between streams (i.e., re-piping), and modifying or replacing existing heat exchangers, often translated as a process costs function [15–17]. Conventional approaches for HENs retrofit include increasing the heat exchange area and/or installation of new equipment, the use of technologies for heat transfer enhancing, in addition to the reconfiguration of the heat exchange structure [8,18–20]. Among the above approaches, the structural changes related to the rearrangement of existing networks usually require a higher capital cost of investment to implement the retrofit design of HENs. Jiang et al. [21] point out that the most cost-effective HEN retrofit frequently involves the application of the lowest number of possible modifications into the existing network.

In general, three groups of optimization methods are used for HENs retrofit. The first includes approaches based on heuristics and thermodynamic concepts, including pinch analysis; the second is related to methods based on mathematical programming and the third, the hybrid methods combining both techniques [6,18]. The pioneering work with a proposal to solve HENs retrofit by pinch analysis was introduced by Tjoe and Linnhoff [22]. The referred authors proposed a two-step approach—targeting and design—for the systematic solution of the problem. In mathematical programming, HENs retrofit is considered as an optimization problem, comprising the field with the highest advances due to its ability to obtain better solutions. Yee and Grossmann [23] presented a mathematical approach to achieve some main goals in HENs retrofit, including the maximum use of existing heat exchangers, allocation of available units to obtain new streams combinations at minimum piping cost, and minimal utilization of new heat transfer equipment. Later, Yee and Grossmann [24] extended their simultaneous model for HENs synthesis—presented in Yee and Grossmann [25]—for the HENs retrofit. Asante and Zhu [26] proposed a method for HENs retrofit combining mathematical programming and pinch analysis. The authors developed an iterative procedure to gradually remove the network pinches, in which the potentially most convenient configuration obtained after the diagnosis is optimized by means of deterministic optimization techniques. Note that, although being very useful for the design of intensive and complex energy processes, pinch analysis-based approaches do not guarantee the global optimal solution, since they cannot be used simultaneously with material balances [27].

According to Onishi et al. [28], despite a significant number of efforts to optimize the recovery of heat by synthesizing new HENs, few studies in the literature have tried to solve the optimization problem of integration between heat and work. It should be emphasized that none of these researches considers the possibility to retrofit existing networks. In fact, the streams pressure manipulation consumes considerable energy amounts, playing an especially important role in sub-ambient processes such as the liquefied natural gas (LNG) production [29–32]. In the offshore section of the LNG production chain shown in **Fig. 1**, the high pressure natural gas (NG) undergoes pre-heating by liquid carbon dioxide (LCO_2) across a heat exchanger. Then, it is expanded to achieve a lower pressure for thermal exchange with the liquid inert nitrogen (LIN). In the next stage, the NG is expanded by a turbine to attain the desired pressure for storage. The LIN at high pressure is cooled by way of two heat exchangers [33–36]. It is highlighted that the elevated consumption of cold utilities—extremely expensive in this type of process—is accountable for the high operating costs.

Clearly, it is possible to integrate heat and work in the same network in order to save energy and reduce process costs as indicated in the references [28,29,31,32,37]. Doubtless, this concept can be extended to the retrofit problem of existing HENs with significant advantages.

Wechsung et al. [30] presented a model for the HENs synthesis, enabling the pressure levels adjustment of process streams at sub-ambient conditions. The proposed formulation combines mathematical programming, exergy analysis and pinch analysis for HENs optimization by minimizing the system total irreversibilities. The authors demonstrated that a specific expansion and compression route based on the “plus-minus” principle [38] may result in an optimal design of HENs with minimal irreversibility. Onishi et al. [28] proposed a model for the new HENs synthesis, considering the pressure manipulation of process streams to improve heat integration. The mathematical formulation involves mixed-integer nonlinear programming (MINLP) and generalized disjunctive programming (GDP); aiming to get an optimal HEN synthesis by the total annualized cost minimization. The authors demonstrated through the study of various configuration possibilities including expanders and compressors that the pressure recovery during the HEN design reduces the need for thermal utilities, decreasing the process total cost. Onishi et al. [29] presented a MINLP-based model for the synthesis of work exchange networks (WENs) formulated analogously to the optimization problem of HENs design. Thus, high-pressure and low-pressure streams exchange work through pressure manipulation equipment acting on a common shaft to minimize the total cost. Moreover, the WEN is connected to the HEN to enhance the pressure recovery. The authors showed that the streams heat integration in a HEN between the WEN stages is crucial to improve the energy efficiency and, consequently, for the reduction of the total cost of the process. Although the aforementioned works represent important contributions to the processes synthesis field, they do not contain any assessment concerning the HEN retrofit of existing networks under sub-ambient conditions.

To address this issue, this paper introduces a new mathematical programming model for HENs retrofit, wherein the pressure recovery of process streams is conducted aiming to enhance heat integration. A multi-stage superstructure based on the model by Onishi et al. [28] is developed to deal with the problem. Thus, the streams pressure recovery is performed simultaneously with the retrofit through pressure manipulation stages connected to the heat integration in the HEN. Consequently, the process conditions (i.e., streams pressure and temperature) must be treated as optimization variables. Moreover, the proposed approach allows increasing the existing heat transfer area and the use of new equipment, for the heat exchange and pressure manipulation, as well as the turbine and compressor coupling with a helper motor for further energy savings. The model is developed via GDP and a MINLP-based formulation, aiming to minimize the objective function composed by the total annualized cost for the retrofit implementation. Three case studies are performed to assess the correctness of the model, including the real application of the LNG production.

2. Problem statement

This model considers a set of cold and hot streams with a given supply state (inlet temperature and pressure), and target state (outlet temperature and pressure), mass flowrates and heat capacities. In addition, thermal services for heating and cooling fluids, electricity, and equipment for heat exchange and pressure manipulation, and their respective costs, are also provided. The goal is to find an optimal design for HENs retrofit, considering the pressure recovery of process streams by the total annualized cost minimization. The objective function comprises the contributions associated to the capital cost of investment in new network units—for heat exchange and pressure manipulation—and the increment of the existing heat transfer area, as well as additional operating expenses associated to cold and hot utilities and electricity services, including revenues from power generation.

It should be emphasized that the focus of this study is to demonstrate that the correct pressure manipulation of process streams at sub-ambient conditions may result in a HEN retrofit with enhanced energy integration, as verified by the decrease of the need for thermal services and, consequently, the reduction of total annualized cost. Thus, the aim is to show the improvement in the process of the HEN retrofit with simultaneous pressure recovery of streams, assuming that the retrofit of the HEN is really necessary a priori. The HEN retrofit is needed, for example, when the network does not meet the energy specifications of the process, presenting an excessive consumption of thermal utilities. The main motivation is to perform the retrofit of the network, incorporating the possibility of streams pressure recovery, since in Onishi et al. [28] it is demonstrated that the design of new HENs can be significantly benefited (in economic and energetic terms) from the correct pressure manipulation of streams. Obviously, this result can be extended to the retrofit of existing HENs with substantial benefits.

The mathematical model for HENs retrofit is based on the model by Onishi et al. [28], in which the well-known superstructure by Yee and Grossmann [25] (please see **Appendix A**) for the synthesis of new HENs is extended to consider the pressure recovery of process streams. Accordingly, the proposed multi-stage superstructure for HENs retrofit allows stream splits and assumes that the heat capacity flowrates are constant in an isothermal mixing. Moreover, it is postulated that at each HEN superstructure stage can occur the thermal exchange between all hot streams and all cold streams, and vice versa. Heaters and coolers are allocated at the streams ends to ensure that the desired final temperature is reached.

The number of stages in the HEN should match the maximum count of possible heat exchanges between the cold and hot streams. However, a stage-wise model can be applied to easily solve problems with large number of process streams. Due to the elevated number of possible combinations of thermal exchange between streams, this type of problem usually requires a large computational effort and cannot be solved within an appropriate CPU time leading to suboptimal solutions. According Kovač Kralj [39], the number of stages in the HEN superstructure should be reduced when dealing with existing complex industrial processes. Hence, in a stage-wise model, the minimum number of cold or hot streams is divided by two and rounded off. It should be highlighted that despite this result cannot guarantee optimal global solutions, near optimal solutions are expected.

In this new proposed approach, certain cold streams are subjected to compression and expansion, so that the pressure recovery is used to enhance heat integration in the HEN retrofit. Thus, equipment for pressure manipulation—namely, compressors and turbines—are also used for the retrofit of the network. Consequently, the streams temperature and pressure become optimization variables at the frontiers of the superstructure for the HEN retrofit. Analogously to Wechsung et al. [30] and Onishi et al. [28], some cold streams must be subjected a specific heat exchange and pressure manipulation route. Therefore, a cold stream should theoretically pass for the following steps: heating, expansion, heating, compression, cooling, expansion, and heating (please see **Fig. 2**). It is important to note that the selection of this route is not arbitrary. In Wechsung et al. [30], the "plus–minus" principle [38] in pinch analysis is applied to obtain the best way for the pressure modification of streams, in order to reduce the energy requirements of the system. Thus, the authors identify that the most beneficial direction for handling pressure allied with heat integration of a cold stream is by the aforementioned route, resulting in the best trade-off between the process energy efficiency intensification and the increment in the capital cost of investment.

The streams that undergo handling pressure are attached to the HEN superstructure via pressure manipulation equipment, so that the input state in the network must match the stream output state of the compressors and turbines. It should be emphasized that this problem definition is considerably more difficult to solve than the standard heat recovery problem in HEN synthesis as assumed by Yee and Grossmann [24,25]. This is mainly due to factors including the need to address the streams temperature as an optimization variable, as well as adding a new variable referring to the streams pressure. Moreover, during the pressure manipulation process the streams may temporarily change their identity, allowing a cold stream to behave as a hot stream. The streams can also operate as thermal utilities, acting as energy sinks or sources to a temperature outside the range produced by available utilities. Consequently, in this problem type there is no clear difference between cold and hot streams, or between streams and utilities. Additionally, the need for a mathematical operator for the streams pressure manipulation considerably increases the non-convexity and nonlinearity of the model. The pressure manipulation operator is presented in **Appendix B**. Further details about the problem of HENs synthesis with pressure recovery are reported in the references [28] and [30].

During the HEN retrofit all of the existing heat exchange equipment, including heat exchangers, heaters and coolers, can be used in the network. Moreover, the model considers the installation of new equipment for heat transfer, expansion and compression, and the increase of the available heat transfer area. However, this model does not allow the restructuration of the heat exchanges (i.e., re-piping of process streams). The optimization model also allows the turbines and compressors coupling on a common shaft. When this occurs, a helper motor is used to supply the remaining energy demand of the compressor and meet the energy balance on the common shaft.

To simplify the mathematical formulation, the following assumptions are assumed for the HENs retrofit with simultaneous pressure recovery of process streams:

(i) All streams compressions and expansions are isentropic.

(ii) All streams behave as ideal gases.

(iii) All compressors and turbines are centrifugal and built with carbon steel.

(iv) Starter energy required for any compressor and/or turbine is neglected.

(v) All streams heat capacities are known constants.

(vi) All heat transfer coefficients are known constants.

(vii) Heat losses and pressure drops in all heating equipment are neglected.

The proposed mathematical model formulation including additional constraints and equations for the HENs retrofit and equipment coupling is shown in the next sections.

3. Mathematical programming model

The proposed mathematical optimization model is formulated based on Onishi et al. [28], wherein the HENs synthesis model of Yee and Grossmann [25] is extended to consider the simultaneous pressure recovery of process streams. The streams compression and expansion is performed through a specific pressure manipulation route, with intermediate heat integration in the HEN as proposed by Wechsung et al. [30].

The developed approach for the HENs retrofit with pressure recovery includes the use of all available heat exchange equipment, as well as the increase of the existing heat transfer area. However, the possibility of displacement of the existing heat exchangers and streams re-piping are not allowing in the model.

3.1 Sets/indices definition

The definition of the following indices is required for the development of the model:

$$
\begin{gathered}
I = \{ i / i = 1, 2, ..., I \text{ are hot streams} \} \\
J = \{ j / j = 1, 2, ..., J \text{ are cold streams} \} \\
K = \{ k / k = 1, 2, ..., K \text{ are the number of HEN stages} \} \\
N = \{ n / n \text{ is the cold utility} \} \\
TU = \{ turbine / turbine = 1, 2, ..., TU \text{ are the turbines} \} \\
CO = \{ compressor / compressor = 1, 2, ..., CO \text{ are the compressors} \}
\end{gathered}
$$

In the model, k is the number of stages in the superstructure that is set as the maximum amount of hot or cold streams. Note that TU and CO indicate the set of positions of the turbines and compressors, respectively, in the network.

3.2 Mathematical formulation for the HENs retrofit

The energy integration between the streams i and j should occur only once, which is guaranteed by the following constraint:

$$\sum_{k=1}^{K} y_{i,j,k} \le 1 \quad i \in I,\ j \in J \tag{1}$$

At each superstructure stage, the heat exchangers could be larger or smaller than the available heat exchangers of the existing network, but only one possibility should be chosen. If the heat transfer area is bigger than the available area, the additional heat transfer area is calculated to be accounted in the process total cost. Otherwise, if the heat transfer area is smaller—or equal—than the available area, the existing heat exchanger is used in the network design. In this last case, the additional heat transfer area and capital cost should be equal to zero. The next disjunction should be utilized to guarantee this decision.

$$\begin{bmatrix} y_{i,j,k}^{bigger} \\ A_{i,j,k}^{add} = A_{i,j,k} - A_{i,j,k}^{ex} \\ C_{capital}^{add} = f\left(A_{i,j,k}^{add}\right) = \left[CPO_{Hex} \cdot FBM_{Hex}\right] \end{bmatrix} \underline{\vee} \begin{bmatrix} y_{i,j,k}^{smaller} \\ A_{i,j,k}^{add} = 0 \\ C_{capital}^{add} = 0 \end{bmatrix} \forall i \in I, j \in J, k \in K$$

Through the big-M formulation, the previous disjunction should be written as follows.

$$\left.\begin{aligned} & y_{i,j,k}^{bigger} + y_{i,j,k}^{smaller} = 1 \\ & A_{i,j,k}^{add} \leq \left[A_{i,j,k} - A_{i,j,k}^{ex}\right] + M_1\left(1 - y_{i,j,k}^{bigger}\right) \\ & A_{i,j,k}^{add} \geq \left[A_{i,j,k} - A_{i,j,k}^{ex}\right] - M_1\left(1 - y_{i,j,k}^{bigger}\right) \\ & A_{i,j,k}^{add} \leq M_1\left(1 - y_{i,j,k}^{smaller}\right) \\ & A_{i,j,k}^{add} \geq \left[A_{i,j,k} - A_{i,j,k}^{ex}\right] - M_1 \cdot y_{i,j,k}^{smaller} \\ & C_{capital}^{add} \leq \left[CPO_{Hex} \cdot FBM_{Hex}\right] + M_2\left(1 - y_{i,j,k}^{bigger}\right) \\ & C_{capital}^{add} \geq \left[CPO_{Hex} \cdot FBM_{Hex}\right] - M_2\left(1 - y_{i,j,k}^{bigger}\right) \\ & C_{capital}^{add} \leq M_2\left(1 - y_{i,j,k}^{smaller}\right) \\ & C_{capital}^{add} \geq \left[CPO_{Hex} \cdot FBM_{Hex}\right] - M_2 \cdot y_{i,j,k}^{smaller} \end{aligned}\right\} i \in I,\ j \in J,\ k \in K \tag{2}$$

Wherein, M is a positive parameter large enough, but also as small as possible to certify the big-M formulation Eq. (2). Here, the parameter M_1 is estimated by the difference between the upper and lower bounds of the heat transfer area. Similarly, the parameter M_2 is estimated by the difference between the upper and lower capital cost bounds for heat exchangers.

The coolers allocated at the streams ends could be larger or smaller than the available coolers on the existing HEN. However, only one option should be chosen. Thus, if the heat transfer area of the cooler is smaller—or equal—than the available area, the existing cooler is used in the network design. In this case, as there is no need for additional heat transfer area and heat duty, this variables as well as the capital cost related to this equipment should be equal to zero. On the other hand, if there is a need to increase the heat transfer area of the cooler, the additional area and heat duty are calculated to be accounted in the total retrofit cost. The next disjunction can be utilized to ensure the selection between bigger and smaller areas of the coolers.

$$\begin{bmatrix} y_{i,n}^{bigger} \\ A_{i,n}^{add} = A_{i,n} - A_{i,n}^{ex} \\ Q_{i,n}^{add} = Q_{i,n} - Q_{i,n}^{ex} \\ C_{capital}^{add} = f\left(A_{i,n}^{add}\right) = \left[CPO_{Cooler} \cdot FBM_{Cooler}\right] \\ C_{operational}^{add} = f\left(Q_{i,n}^{add}\right) = \left[CC \cdot Q_{i,n}^{add}\right] \end{bmatrix} \underline{\vee} \begin{bmatrix} y_{i,n}^{smaller} \\ A_{i,n}^{add} = 0 \\ Q_{i,n}^{add} = 0 \\ C_{capital}^{add} = 0 \\ C_{operational}^{add} = 0 \end{bmatrix} \forall i \in I, n \in N$$

Through a big-M formulation, the previous disjunction should be written as follows.

$$
\left.
\begin{aligned}
& y_{i,n}^{bigger} + y_{i,n}^{smaller} = 1 \\
& A_{i,n}^{add} \le \left[A_{i,n} - A_{i,n}^{ex} \right] + M_3 \left(1 - y_{i,n}^{bigger}\right) \\
& A_{i,n}^{add} \ge \left[A_{i,n} - A_{i,n}^{ex} \right] - M_3 \left(1 - y_{i,n}^{bigger}\right) \\
& A_{i,n}^{add} \le M_3 \left(1 - y_{i,n}^{smaller}\right) \\
& A_{i,n}^{add} \ge \left[A_{i,n} - A_{i,n}^{ex} \right] - M_3 \cdot y_{i,n}^{smaller} \\
& Q_{i,n}^{add} \le \left[Q_{i,n} - Q_{i,n}^{ex} \right] + M_4 \left(1 - y_{i,n}^{bigger}\right) \\
& Q_{i,n}^{add} \ge \left[Q_{i,n} - Q_{i,n}^{ex} \right] - M_4 \left(1 - y_{i,n}^{bigger}\right) \\
& Q_{i,n}^{add} \le M_4 \left(1 - y_{i,n}^{smaller}\right) \\
& Q_{i,n}^{add} \ge \left[Q_{i,n} - Q_{i,n}^{ex} \right] - M_4 \cdot y_{i,n}^{smaller} \\
& C_{capital}^{add} \le \left[CPO_{Cooler} \cdot FBM_{Cooler} \right] + M_5 \left(1 - y_{i,n}^{bigger}\right) \\
& C_{capital}^{add} \ge \left[CPO_{Cooler} \cdot FBM_{Cooler} \right] - M_5 \left(1 - y_{i,n}^{bigger}\right) \\
& C_{capital}^{add} \le M_5 \left(1 - y_{i,n}^{smaller}\right) \\
& C_{capital}^{add} \ge \left[CPO_{Cooler} \cdot FBM_{Cooler} \right] - M_5 \cdot y_{i,n}^{smaller} \\
& C_{operational}^{add} \le \left[CC \cdot Q_{i,n}^{add} \right] + M_6 \left(1 - y_{i,n}^{bigger}\right) \\
& C_{operational}^{add} \ge \left[CC \cdot Q_{i,n}^{add} \right] - M_6 \left(1 - y_{i,n}^{bigger}\right) \\
& C_{operational}^{add} \le M_6 \left(1 - y_{i,n}^{smaller}\right) \\
& C_{operational}^{add} \ge \left[CC \cdot Q_{i,n}^{add} \right] - M_6 \cdot y_{i,n}^{smaller}
\end{aligned}
\right\} i \in I, n \in N \qquad (3)
$$

Wherein, M is again a positive parameter. Evidently, the parameter M should be as small as possible, but large enough to certify the Eq. (3). In this case, M_3 is estimated by the difference between the upper and lower heat transfer area bounds for the cooler. M_4 is estimated by the difference between the upper and lower heat duty bounds. Likewise, M_5 and M_6 are estimated by the difference between the upper and lower capital cost bounds for coolers and operational expenses for cooling fluids, respectively.

Analogously, the heaters allocated at the streams ends could be larger or smaller than the available heaters on the HEN. Thus, if the heat exchange area of the heater is bigger than the available area, the additional area and respective heat duty are calculated to be accounted in the network total cost. On the other hand, if there is no need to increase the heat transfer area of the heater, the additional heat exchange area, heat duty and capital cost related to this equipment should be equal to zero. Thus, the mathematical formulation is very similar to the previous presented formulation for the selection of the cooler. For this reason, this formulation will be omitted in this paper.

As previously mentioned, the proposed model for the HENs retrofit with pressure recovery allows the stream splits. However, the constraints given by Eq. (4) and Eq. (5) can be easily added to the model to prohibit the streams splits in the stages of the superstructure.

$$\sum_{i=1}^{I} y_{i,j,k} \leq 1 \quad j \in J,\ k \in K \tag{4}$$

$$\sum_{j=1}^{J} y_{i,j,k} \leq 1 \quad i \in I,\ k \in K \tag{5}$$

Note that the constraint given by Eq. (1) is necessary to ensure that each heat exchanger is used only once. Moreover, the big-M formulation described by the set of equations Eq. (2) and Eq. (3) is necessary to ensure the selection between bigger and smaller equipment. Notwithstanding, these equations further restrict the search space of the optimal solution compared to the original model by Onishi et al. [28]. According to Björk and Nordman [40], the addition of the extra constraints Eq. (4) and Eq. (5) to the model can compromise the quality of obtained solutions, and increase even more the processing time for solving the problem.

3.3 Formulation for the equipment coupling

The proposed model for the HENs retrofit with pressure recovery of process streams allows the compressors and turbines coupling with a helper motor on a common shaft, aimed at saving energy and reducing costs. However, if a turbine and/or compressor exist in the network, they may be allocated on the common shaft or act as stand-alone equipment. Clearly, both possibilities cannot occur simultaneously. Thus, the following logical constraints are needed to ensure that decision.

$$y^{a}_{turbine} + y^{s}_{turbine} \leq 1 \quad turbine \in TU \tag{6}$$

$$y^{a}_{compressor} + y^{s}_{compressor} \leq 1 \quad compressor \in CO \tag{7}$$

When the equipment coupling occurs, only one turbine and one compressor should exist on the common shaft. This fact is ensured by Eq. (8) and Eq. (9).

$$\sum_{turbine=1}^{TU} y^{a}_{turbine} \leq 1 \tag{8}$$

$$\sum_{compressor=1}^{CO} y^{a}_{compressor} \leq 1 \tag{9}$$

To avoid very small or large pressure manipulation equipment, the compression and expansion work should be limited between a minimum and a maximum value. Therefore, if a stand-alone turbine exists in the network, it should perform a minimum work. Otherwise, the expansion work should be zero.

$$We^{s}_{turbine} \geq We^{LO}_{turbine} \cdot y^{s}_{turbine} \quad turbine \in TU \tag{10}$$

$$We^{s}_{turbine} \leq We^{UP}_{turbine} \cdot y^{s}_{turbine} \quad turbine \in TU \tag{11}$$

Similarly, if a stand-alone compressor exists in the network, it should consume a minimum work. Otherwise, the work of compression should be zero.

$$Wc^{s}_{compressor} \geq Wc^{LO}_{compressor} \cdot y^{s}_{compressor} \quad compressor \in CO \tag{12}$$

$$Wc^{s}_{compressor} \leq Wc^{UP}_{compressor} \cdot y^{s}_{compressor} \quad compressor \in CO \tag{13}$$

Likewise, if a turbine is allocated on the common shaft, it should perform a minimum work. Otherwise, the work of expansion in the shaft should be equal to zero.

$$We^{a}_{turbine} \geq We^{LO}_{turbine} \cdot y^{a}_{turbine} \quad turbine \in TU \tag{14}$$

$$We^{a}_{turbine} \leq We^{UP}_{turbine} \cdot y^{a}_{turbine} \quad turbine \in TU \tag{15}$$

In the same way, if a compressor is allocated on the common shaft, it should consume a minimum work. Otherwise, the compression work on the shaft must be equal to zero.

$$Wc^{a}_{compressor} \geq Wc^{LO}_{compressor} \cdot y^{a}_{compressor} \quad compressor \in CO \tag{16}$$

$$Wc^{a}_{compressor} \leq Wc^{UP}_{compressor} \cdot y^{a}_{compressor} \quad compressor \in CO \tag{17}$$

As recommended by Couper et al. [41], the works of compression and expansion should be restricted between the following lower and upper limits: $100 \leq We^{s}_{turbine}(\text{kW}) \leq 1500$, $100 \leq We^{a}_{turbine}(\text{kW}) \leq 1500$, $18 \leq Wc^{s}_{compressor}(\text{kW}) \leq 950$ and $18 \leq Wc^{a}_{compressor}(\text{kW}) \leq 950$.

In this model, the compression work consumed on the shaft should be greater than the expansion work generated on the same shaft. In other words, it is assumed that the turbine located on the coupling shaft is not able to meet all energy requirements by the compressor in the same shaft.

$$Wc^{a}_{compressor} \geq We^{a}_{turbine} \quad compressor \in CO,\ turbine \in TU \tag{18}$$

This constraint is necessary to ensure that the coupling of the turbine and compressor on the common shaft should only occur with a helper motor, such that the helper motor should be used to provide the remaining energy demand consumed by the compressor on the shaft. Consequently, a global energy balance is needed on the common shaft to ensure that the sum of the work of expansion performed by the turbine and by the helper motor should be equivalent to the work required by the compressor.

$$\sum_{turbine=1}^{TU} We^{a}_{turbine} + Wh = \sum_{compressor=1}^{CO} Wc^{a}_{compressor} \tag{19}$$

In industrial practice, is more common the use of equipment coupling with the help of an auxiliary motor (i.e., helper motor). Nevertheless, if the designer desires, this constraint can be easily removed from the model.

3.4 Objective function

The retrofit total annualized cost (C_{total}) comprises the capital cost of investment ($C^{add}_{capital}$) and the additional operating expenses ($C^{add}_{operational}$). Here, the operational expenses include all additional cost inherent to the use of heating and cooling fluid services, and electric power needed by the compressor and the helper motor. It is also considered the sale of electricity generated by stand-alone turbines to other sectors of the process. The compression work consumed by compressors is added to the additional operating expenses associated to electricity just in case the equipment coupling does not occur (i.e., when the compressor is used as stand-alone unit). Additional capital cost involves expenses related to increase of the heat transfer area, and the cost associated to the utilization of new equipment for heat exchange and pressure manipulation, including the helper motor. The objective function is expressed by Eq. (20).

$$C_{total} = C_{capital}^{add} + C_{operational}^{add} \tag{20}$$

In which,

$$\begin{aligned} C_{operational}^{add} = {} & \sum_i \sum_n CC \cdot Q_{i,n}^{add} + \sum_m \sum_j CH \cdot Q_{m,j}^{add} + \sum_{compressor} CE \cdot Wc_{compressor}^{s} + CE \cdot Wh \\ & - \sum_{turbine} CV \cdot We_{turbine}^{s} \end{aligned} \tag{20a}$$

$$C_{capital}^{add} = f \cdot \left[\begin{aligned} & \sum_{Hex} CPO_{Hex} \cdot FBM_{Hex} + \sum_{Cooler} CPO_{Cooler} \cdot FBM_{Cooler} + \sum_{Heater} CPO_{Heater} \cdot FBM_{Heater} \\ & + \sum_{compressor} CPO_{compressor} \cdot FBM_{compressor} + \sum_{turbine} CPO_{turbine} \cdot FBM_{turbine} + CPO^{hm} \cdot FBM^{hm} \end{aligned} \right] \tag{20b}$$

Wherein, *CE*, CV, *CC* and *CH* are the parameters of cost for electricity, sale of electricity, and cold and hot services, respectively. *FBM* is the factor of correlation for the basic cost of equipment and *CPO* is the cost of an unit of equipment (in US$), estimated by the Turton et al.'s correlations [42] for heat exchangers, heaters and coolers. To estimate the cost of compressors, turbines and helper motors, the Couper et al.'s correlations [41] are used in the model. All the cost correlations used should be corrected for the relevant year with the Chemical Engineering Plant Cost Index (CEPCI).

The cost of the turbine and compressor allocated on the common shaft are considered 20% higher than the same equipment outside the shaft. f is the factor of annualization for the cost of capital as defined by Smith [43]. Lastly, if r is the fractional interest rate per year and ny as the number of years, then:

$$f = \frac{(1+r)^{ny} - 1}{r} \tag{21}$$

4. Computational aspects

The model is programmed using GAMS (version 24.1.3), and a priori, it can be solved by any MINLP-based solver. Because of its nonlinear and non-convex features, this problem type generates a large amount of local solutions often leading to suboptimal results. However, the application of a BB (branch-and-bound)-based solver, such as the solver SBB, should conduce to a solution near to the global optimal. This is due to the fact that the branch-and-bound algorithm is typically less sensitive to non-convexities of the model.

All cases studied are solved utilizing a personal computer running under Windows 7 Ultimate with 3.00 GB RAM and an Intel Core 2 Duo 2.40 GHz processor. For the model solution is crucial that all variables bounds are well established. It should be emphasized that the lower and upper bounds for the streams pressure and temperature are essential for the HEN retrofit design. The variable bounds used in this model are specified in the following examples.

5. Case studies

Three examples are conducted to assess the correctness of the developed model for the HENs retrofit with pressure recovery of process streams. In all cases studied, the benefits of the streams pressure manipulation at sub-ambient conditions is evaluated during the network retrofit, including a real industrial example associated to the LNG offshore production.

Example 1. This first example is adapted from Wechsung et al. [30]. In this case study, the pressure manipulation of streams during the HEN retrofit in a sub-ambient process composed by one hot stream (H1) and two cold streams (C1 and C2) is evaluated in terms of its economic viability. The pressure recovery of process streams is performed simultaneously to the heat integration in the HEN. Thus, the cooling stream C1 and the heating stream H1 are streams at constant pressure, while the cold stream C2 undergoes expansion between 0.4–0.1 MPa. C2 is submitted to the following route of pressure manipulation and heat integration: heating, expansion, heating, compression, cooling, expansion and heating. As a consequence, the stream C2 acts as the cold stream C3 after expanded, as the hot stream H2 after compressed and, finally, as the cold stream C4 after the final stage of expansion. **Fig. 2** presents the possible arrangement of process streams for Example 1.

In this example, the pressure limits for the stream C3 are 0.1–0.4 MPa, the unknown streams inlet temperatures are restricted to 103 K and 373 K, and the pressure of H2 is can vary between 0.1–0.6 MPa. Note that the existing HEN does not meet the energy specifications of the process therefore requiring the retrofit, since the existing network considered for the retrofit presents some undersized heat transfer equipment, resulting in an excessive consumption of thermal utilities and, in consequence, elevated process cost. The process stream data and the available thermal equipment considered for HEN retrofit are shown in **Table 1**. All heat capacity flowrates of process streams are defined constants. The heat transfer coefficient (h) for all streams is equal to 0.1 kW/m^{2}K, while for the cold and hot utilities this coefficient is equal to 1.0 kW/m^{2}K. A factor of annualized capital cost of 0.18—corresponding to 10% interest rate over a period of 8 years—is assumed for estimating retrofit costs of the HEN. A superstructure with 4 heat integration stages and possible streams splits are considered in the retrofit design.

Two different case studies are performed in this example. Initially, the HEN retrofit is designed without pressure manipulation of the stream C2. Secondly, the proposed model for HENs retrofit with pressure recovery is used to synthesize the network considering the existing heat equipment, as well as the use of compressor and turbine coupled with a helper motor, in addition to the sale of electricity generated by the stand-alone turbine. The retrofit is performed by minimizing the network total annualized cost.

In Case 1, optimal configuration obtained for the HEN retrofit is composed by two heat exchangers units with heat transfer areas of 115.83 m^2 (Q = 120.21 kW) and 160.00 m^2 (Q = 211.67 kW), one cooler (A = 86.80 m^2–Q = 163.12 kW), and two heaters units (A = 4.44 m^2–Q = 29.79 kW and A = 8.00 m^2–Q = 85.83 kW). **Fig. 3** shows the optimal configuration obtained for the HEN retrofit in this case. Note that all existing heat exchange units are used in the HEN retrofit design. However, the cooler placed on the stream H1 need an additional heat transfer area of 66.80 m^2, equivalent to an additional heat duty of 103.12 kW. The heaters allocated at the streams ends of C1 and C2 do not require additional heat transfer area, reducing their amounts of heat in 24.21 kW and 4.17 kW, respectively, in comparison with the consumption of hot services by the network before the retrofit. These values correspond to a reduction of 9,564 US$/year (i.e., 19.7%) in the expenses with heating utilities in relation to the HEN without retrofit. The retrofit total annualized cost (C_{total}) comprised by additional heat exchange area, and additional thermal services associated to cooling streams is equal to 144,772 US$/year ($C_{capital}$ = 26,184 US$/year and $C_{operational}$ = 118,588 US$/year).

In Case 2, the obtained optimal HEN retrofit with pressure recovery of streams is composed by three heat exchangers with heat transfer areas of 120 m^2 (Q = 125.59 kW), 243.79 m^2 (Q = 156.52 kW), and 195.89 m^2 (Q = 160.78 kW). In addition, two heaters of same area equal to 8 m^2 (Q = 24.41 kW and Q = 85.83 kW), and one cooler of 20 m^2 (Q = 52.12 kW) are used in the heat integration process. Thus, all existing heat exchange equipment is again used in the HEN retrofit design. However, as a result of the handling pressure of the stream C2, the heat exchanger H1.C2.k2 requires an additional heat exchange area of 83.79 m^2, and a new heat exchanger located at H1.C4.k2 needs to be used for the heat recovery. **Fig. 4** shows the optimal configuration obtained in this case for the HEN retrofit, wherein the heat exchangers highlighted—shaded equipment—indicate the existing units that have been used in the network.

In Case 2, the heater allocated on stream C2 is displaced to the stream end of C4, due to pressure manipulation process. Nevertheless, the two heaters needed in the process (i.e., allocated at the streams ends of C1 and C4) do not require any additional heat transfer area and their amounts of heat are reduced in 29.59 kW and 4.17 kW, compared with the consumption of hot services by the network before the retrofit. These values correspond to a reduction of 11,377 US$/year (i.e., 23.4%) in the expenses with hot utilities in relation to the HEN without retrofit. Besides the thermal equipment, a stand-alone turbine with capacity of 105.62 kW is utilized for the expansion of stream C2. As a consequence, the heat duty needed to thermal utilities is reduced—in 5.38 kW (C1), 0 kW (C4), and 111 kW (H1) for the cooler—as compared to Case 1. The retrofit total annualized cost associated to the additional heat transfer area, new equipment and additional thermal services is equal to 52,855 US$/year, composed by 95,103 US$/year in capital investment. Note that in this case, there are no additional operational expenses related to thermal utilities. The sale of electricity generated by the stand-alone turbine is responsible for revenues of 42,248 US$/year already discounted of the total annualized cost.

Table 2 shows the obtained results for the HEN retrofit configurations and the decision variables for Case 1 and Case 2. The retrofit total annualized cost with pressure recovery (Case 2) is 37% lower than the total cost found in Case 1, in which the retrofit design of the HEN is performed without pressure manipulation of C2. This result demonstrates the effectiveness of the streams pressure recovery applied to the process of HENs retrofit. The reduction of the retrofit total annualized cost is due to the use of the stand-alone turbine. Note that besides producing energy that can be sold and/or harnessed in other process stages, the turbine is also responsible for expenses reduction related to the cooling of fluids, as a result of the significant decrease in the need of cold services.

The model statistics and computational efforts for obtaining the solutions in the Example 1 are shown in **Table 3**.

Example 2. Here, the cold stream C2 is subjected to pressure manipulation from an initial state of 3.0 MPa to a final state of 0.1 MPa, while C1 and H1 are process streams submitted to a constant pressure. The HEN retrofit design with streams at sub-ambient conditions is carried out so that the thermal integration in the HEN occurs between the pressure manipulation stages. Thus, the route of pressure manipulation and heat integration of stream C2 includes the following consecutive steps: heating, expansion, heating, compression, cooling, expansion, and heating. As a consequence, the stream C2 acts as C3 after expansion, H2 after compression and, finally, as C4 after final expansion. **Fig. 2** shows the possible streams configuration for Example 2.

The unknown streams temperatures are restricted between 103 K and 383 K; the pressure limits for the stream C3 are 0.1 and 2.0 MPa. Additionally, the pressure of H2 is restricted to 2.0–3.0 MPa. It should be highlighted that the existing network considered in this case does not meet the energy specifications of the process therefore requiring the HEN retrofit. This is because the network considered for the retrofit presents some undersized heat transfer equipment, resulting in an excessive consumption of thermal utilities. The process stream data, as well as the existing heat exchange equipment are shown in **Table 4**. All streams flowrates and heat capacities are given constants. The heat transfer coefficient (h) for all streams is equal to 0.1 kW/m^{2}K, and the same coefficient for the cold and hot utilities is 1.0 kW/m^{2}K. A factor of annualized capital cost of 0.18—corresponding to 10% interest rate over a period of 8 years—is assumed for estimating retrofit costs of the HEN. A superstructure with 4 stages of heat integration and possible streams splits are assumed for the HEN retrofit optimization.

Two different case studies are conducted to evaluate the economic viability of the retrofit design considering the simultaneous pressure recovery of streams. In the first case, the HEN retrofit is performed without pressure manipulation of process streams. In the second case, the proposed model for the HEN retrofit with pressure recovery of streams is used to design the network, considering the existing heat exchange equipment, and allowing the pressure equipment coupling with a helper motor. Moreover, the retrofit is performed by minimizing the network total annualized cost.

In Case 1, the optimal configuration obtained for the HEN retrofit consists of two heat exchangers with heat transfer areas (heat duty) of 120.00 m^2 (Q = 336.00 kW) and 161.51 m^2 (Q = 277.12 kW), one heater with area of 8.32 m^2 (Q = 59.48 kW), and one cooler unit with area of 94.66 m^2 (Q = 286.38 kW). Thus, all heat exchange units existing in the network are used in the HEN retrofit design. However, the cooler placed on the stream H1 requires an additional heat transfer area of 14.66 m^2, with an additional heat duty of 186.38 kW. In this case, the heater used in the process (C2) does not require additional heat transfer area and its amount of heat is reduced in 20.52 kW compared with the consumption of hot services by the network before the retrofit. This value corresponds to a reduction of 6,915 US$/year (i.e., 25.65%) in the expenses with hot utilities in relation to the HEN without retrofit. **Fig. 5** shows the optimal configuration obtained for the HEN retrofit in this case. The retrofit total annualized cost is equal to 238,136 US$/year, composed by 23,795 US$/year associated to the capital cost of investment, and 214,341 US$/year related to additional operating expenses with cooling fluids.

In Case 2, the optimal configuration obtained for the HEN retrofitted with pressure recovery consists of four units of heat exchangers with heat transfer areas (heat duty) of 120 m^2 (Q = 336.00 kW), 180.00 m^2 (Q = 119.11 kW), 81.47 m^2 (Q = 97.35 kW), and 102.32 m^2 (Q = 256.60 kW). Moreover, one heater with area equal to 10 m^2 (Q = 80.00 kW), and one cooler of 80 m^2 (Q = 90.45 kW) are used in the network. Therefore, all existing heat exchange equipment is again used in the HEN retrofit design. However, two additional heat exchangers located on H1.C3.k2 and H1.C4.k3 are needed in the process, corresponding to an additional heat exchange area of 183.79 m^2. **Fig. 6** shows the optimal configuration obtained for the HEN retrofit design in this case, wherein the heat exchangers highlighted indicates the previous existing heat exchangers that have been used in the network. Due to pressure manipulation process, the heater allocated on stream C2 is replaced to the stream end of C4.

In Case 2, in addition to the thermal equipment, one stand-alone turbine with capacity of 241.46 kW, and one compressor (125 kW) coupled to a second turbine (100 kW) with one helper motor (25 kW) are also used for the pressure manipulation process. The turbine allocated on the common shaft is not able to supply all of the energy demand of the compressor, for this reason a helper motor is required to satisfy the balance of energy of such shaft. As a result of the pressure recovery of streams, no additional heat duty is required to thermal utilities. Therefore, no additional cost related to cooling and heating services is added to the process. Moreover, the cooler allocated at the stream end of H1 does not require additional heat transfer area, reducing its amount of heat in 9.55 kW in comparison with the consumption of cold services by the network before the retrofit. This value corresponds to a reduction of 10,983 US$/year (i.e., 9.55%) in the expenses with cooling utilities in relation to the HEN without retrofit. The retrofit total annualized cost related to additional heat transfer area and new equipment for pressure manipulation and heat exchange is equal to 212,076 US$/year (composed by 297,282 US$/year associated to the capital cost of investment, and 85,206 US$/year in revenue from the sale of electricity generated by the stand-alone turbine, already discounted the electricity cost spent by the helper motor).

Accordingly, the retrofit total annualized cost with pressure recovery of streams (Case 2) is 11% lower than the total cost found in Case 1, in which the retrofit is performed without pressure manipulation of stream C2. Once again, this result highlights the effectiveness of the streams pressure recovery applied to the process of HENs retrofit, even when coupled pressure manipulation units are used requiring a higher capital investment. The obtained results for the HEN retrofit configurations and the decision variables for both Case 1 and Case 2 are shown in **Table 5**.

Note that the reduction of the retrofit total annualized cost is entirely due to the pressure manipulation of streams. Besides producing energy that can be sold and/or harnessed in other process stages (in the case of the stand-alone turbine), the pressure recovery is also responsible for expenses reduction related to the cooling of fluids, as a result of the significant decrease in the need of cold services. It should be remarked that despite the considerable increase in the capital cost of investment in new equipment, the revenue obtained from the electricity sale generated in the network, allied to the expenses reduction with cooling fluids, make the HEN retrofit with pressure recovery economically viable.

The model statistics and computational efforts for obtaining the solutions in the Example 2 are shown in **Table 3**.

Example 3. This example is again adapted from Wechsung et al. [30]. Here, a NG stream is used to produce LNG in the offshore process, by cooling it with streams of LIN and LCO_2 (please see **Fig. 1**). The nitrogen is released to the atmosphere at ambient conditions, and the high pressure CO_2 is transported to the offshore oil field [30,33–35,44–46].

As a real application, the streams heat capacity is not constant in this example. Therefore, as suggested by Wechsung et al. [30], the NG flowrate is separated into three distinct streams (H1–H3), which results in a good fit in the cooling curve. Similarly, the LCO_2 stream is separated into the two streams C1 and C2, and the LIN stream is separated into three distinct streams (C3–C5) for a more precise adjustment of the heat capacities of these streams. The inlet and outlet streams temperatures of LCO_2 and NG, as well as the stream inlet temperature of LIN are known parameters for the HEN retrofit design. Once again, note that the existing network does not meet the energy specifications of the process therefore requiring the HEN retrofit, since the network considered for the retrofit presents some undersized heat transfer equipment, resulting in an excessive consumption of thermal utilities. **Table 6** shows the stream data and the existing heat exchange equipment in the network.

The pressure of the LCO_2 and NG streams are fixed, while the LIN stream is expanded of 10 MPa to 0.1 MPa, according to **Fig. 7**. The intermediate pressures and temperatures of the stream of LIN are optimization variables of the problem. The LIN flowrate is set to be equal to 1.0 kg/s.

The route of pressure manipulation of the stream of LIN (C5) includes three consecutive stages of expansion and compression, with heat integration between each one of these stages. As a result, the stream C5 acts as a cold stream C6 after the first expansion stage, as H4 after compression and, finally, as C7 after the last expansion stage. The pressure recovery of streams is performed through two units of turbines and one unit of compressor, in which the compressor may be coupled to one turbine with a helper motor. Due to the low temperature and high pressure of the stream of LIN (C5), the handling pressure of C5 cannot be considered as an ideal expansion. To model the non-ideal behaviour of this stream a polytrophic exponent equal to 1.51 is assumed for the process design. In this example, the pressure of C6 is limited between 0.3–1 MPa, while the pressure of H4 is limited between 1–3.5 MPa. All unknown inlet temperatures of streams are limited between 95.15 K and 380.15 K.

The heat transfer coefficient for all streams is equal to 0.1 kW/m^{2}K, and for the thermal utilities this coefficient is equal to 1.0 kW/m^{2}K. Moreover, an annualized cost factor of 0.18—corresponding to a 10% of interest rate over a period of 8 years—is assumed for estimating retrofit costs of the HEN. In this example, a stage-wise superstructure with 4 stages of heat integration and the streams splits are assumed for the HEN retrofit design. Moreover, the existing heat exchange equipment comprised by four heat exchangers, two heaters, and two coolers are assumed for the HEN retrofit, aiming to obtain a minimized retrofit total annualized cost. The retrofit total cost is composed by additional capital cost and operating expenses in new network units.

In this case study, the optimal equipment configuration found for the HEN retrofit with pressure recovery is composed by six heat exchangers with heat transfer areas of 50.00 m^2 (H1.C2.k1 with Q = 103.23 kW), 20.91 m^2 (H1.C4.k2 with Q = 85.86 kW), 6.12 m^2 (H2.C3.k2 with Q = 29.74 kW), 29.61 m^2 (H2.C6.k3 with Q = 95.88 kW), 60.00 m^2

(H3.C3.k4 with Q = 137.91 kW) and, 7.74 m^2 (H4.C2.k4 with Q = 13.69 kW). Thus, all existing heat exchangers are used in the HEN retrofit, and two new units—H2.C6.k3 and H4.C2.k4—are added to the network. In addition, two heaters allocated on C1 and C2 with areas of 15 m^2 (Q = 222.88 kW and Q = 187.12 kW) each one, and two coolers located on H2 and H3 with areas of 27.74 m^2 (Q = 163.14 kW) and 83.99 m^2 (Q = 130.77 kW), respectively, existing on the previous network are used in the HEN retrofit. Thereby, 45.09 m^2 of additional heat transfer area is required in the process. It should be noted that the heaters needed in the retrofit—allocated at the streams end of C1 and C2—do not require additional heat transfer area, reducing their amounts of heat in 27.13 kW and 42.88 kW, respectively, in comparison with the consumption of hot services by the network before the retrofit. This value corresponds to a reduction of 23,593 US$/year (i.e., 14.59%) in the expenses with heating utilities in relation to the HEN without retrofit. Moreover, the coolers used in the process (H2 and H3) reduce their amounts of heat in 36.86 kW and 49.23 kW, respectively, again in comparison with the consumption of cold services by the network before the retrofit. This value represents a reduction of 99,004 US$/year (i.e., 22.66%) in the expenses with cooling utilities in relation to the HEN without retrofit.

Besides the thermal equipment required in the network, two turbines (172.92 kW and 100 kW) and one compressor unit (125 kW) are also used for the stream pressure recovery of LIN, in which the compressor and the first expander are coupled with a helper motor (25 kW). **Fig. 8** shows the optimal configuration found for the HEN retrofit with pressure recovery in the LNG offshore production. The work of expansion generated by the stand-alone turbine (i.e., 172.92 kW) can be used in other stages of the process or sold as electricity, while the work required by the compressor is supplied by the turbine and helper motor allocated on the common shaft. As a consequence, only the helper motor consumes electricity in the process reducing further the operational expenses. The obtained results for the HEN retrofit configuration and the decision variables are shown in **Table 7**.

The retrofit total annualized cost is 256,187 US$/year, consisting of 302,602 US$/year on the capital cost of investment in additional heat transfer area and new equipment—including turbines, compressor, helper motor and heat exchangers—and 11,376 US$/year related to additional operating costs with electricity. The revenue from the sale of electricity generated by the turbine corresponds to 57,791 US$/year.

The model statistics and computational effort for obtaining the solution in the Example 3 are shown in **Table 3**.

6. Conclusions

A new mathematical model is developed for the retrofit of heat exchanger networks (HENs), wherein the pressure recovery of process streams is performed to enhance energy integration. The proposed multi-stage superstructure is formulated via generalized disjunctive programming (GDP) and optimized using mixed-integer nonlinear programming (MINLP). The pressure recovery of streams is carried out simultaneously with the retrofit of the network, throughout expansion and compression stages connected to the HEN. Consequently, the model allows the use of new equipment for both heat exchange and pressure manipulation, in addition to considering the increase of the existing heat transfer area. Due to the attachment of the streams subjected to pressure manipulation to the HEN superstructure by means of compressors and turbines, the process conditions become unknown variables to be optimized during the design task. This fact significantly increases the complexity of the model in comparison to the standard approaches for HENs retrofit. It is also pointed that the model allows the equipment coupling with a helper motor on a common shaft, aiming to minimize the retrofit total annualized cost.

The model is solved with the solver SBB under GAMS software. Three examples are performed to assess the correctness of the proposed MINLP-based model. In all cases studied, the HEN retrofit under pressure manipulation of streams at sub-ambient conditions is evaluated, including a real industrial example related to the liquefied natural gas (LNG) production. The results obtained for the HEN retrofit with pressure recovery indicate a significant reduction of the additional total annualized cost compared to the retrofit without pressure manipulation. Although the equipment coupling considerably increases the capital cost of investment, these pressure manipulation units are responsible for decreasing operational expenses associated to the fluids cooling, as a result of the considerable decrease in the need for cold services. Furthermore, the equipment coupling also reduces the electricity expenses, which in addition to the revenue obtained from the energy sale generated by the stand-alone turbines make the retrofit with pressure recovery economically viable. Lastly, the application of the MINLP-based model to a real industrial example shows the effectiveness of the proposed approach to optimally retrofit the HEN, demonstrating its applicability also to complex cryogenic processes.

Nomenclature

Roman letters

A	heat transfer area
A^{add}	additional heat transfer area
A^{ex}	existing heat transfer area
C	cost
C^{add}	additional cost
CC	cost parameter for the cooling
CE	cost parameter for the electricity
CH	cost parameter for the heating
Cp	heat capacity
CPO	cost of a unitary equipment
CV	cost parameter for the electric power revenue
f	factor of annualization for capital cost of investment
FBM	correction factor for cost
h	individual coefficient of heat transfer
M	big-M formulation parameter
ny	number of years
p	pressure
Q	heat duty
Q^{add}	additional heat duty
Q^{ex}	existing heat duty
r	fractional interest rate per year
T	temperature
T_{in}	streams inlet temperature

T_{out}	streams outlet temperature
T_U^c	cold utility temperature
T_U^h	hot utility temperature
ΔT_{min}	temperature minimal approximation
W	work
Wc^a	work of compression of the compressor allocated on the shaft
Wc^s	work of compression of the stand-alone compressor
We^a	work of expansion of the turbine allocated on the shaft
We^s	work of the stand-alone turbine
Wh	helper motor work
y	binary variable defining the energy integration between heating and cooling streams
y^a	binary variable defining the use of compressors and turbines coupling
y^{bigger}	binary variable defining the use of heat exchangers larger than existing equipment
y^s	binary variable defining the use of stand-alone turbines and compressors
$y^{smaller}$	binary variable defining the use of heat exchangers smaller than existing equipment

Acronyms

BB	branch-and-bound
CEPCI	chemical engineering plant cost index
GAMS	general algebraic modeling system

GDP	generalized disjunctive programming
HEN	heat exchanger network
LCO2	liquid carbon dioxide
LIN	liquid inert nitrogen
LNG	liquefied natural gas
MINLP	mixed-integer nonlinear programming
NG	natural gas
WEN	work exchange network

Greek letters

η	isentropic efficiency
κ	polytrophic exponent

Subscripts

compressor	compressors
H_{ex}	heat exchangers
i	hot streams
j	cold streams
k	superstructure stages
m	heating utility
n	cold utility
turbine	turbines

Acknowledgements

Financial support provided by the Brazilian agencies: Coordination for the Improvement of Higher Level -or Education- Personnel (process 10758/12-7) and the National Council for Scientific and Technological Development of Brazil (process 151132/2014-3), and the Spanish Ministry of Science and Innovation and Ministry of Economy and Competitiveness (project CTQ2012-37039-C02-02) is gratefully acknowledged.

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APPENDIX A: Simultaneous model of Yee and Grossmann [25]

Yee and Grossmann [25] presented a robust MINLP-based model for the HEN synthesis. The solution of this model allows identifying the network with the minimum cost within the superstructure, by finding the heat exchangers units required, as well as the temperatures and heat duty of each process stream. One of the advantages of this model resides in its ability to easily handle prohibitions in the split of streams. This is one of the models with greater acceptance among simultaneous approaches using superstructures.

Indices/Sets

To develop the model is necessary to define the following indices.

$$\begin{gathered} HP = \{ i \,/\, i \text{ is a hot stream} \} \\ CP = \{ j \,/\, j \text{ is a cold stream} \} \\ ET = \{ k \,/\, k \text{ is a stage in the superstructure} \} \end{gathered}$$

Inlet data

The following data are known.

C	=	area cost coefficient
CCU	=	unit cost for cold utility
CF	=	fixed cost of heat exchangers
CHU	=	unit cost for hot utility
F	=	heat flow associated with each stream
NOK	=	total number of stages
Tin	=	streams inlet temperature
$Tout$	=	streams outlet temperature

U = global coefficient of heat transmission

β = exponent in the cost area

Ω = upper limit to the heat exchanged in a heat exchanger

Γ = upper limit for the temperature difference

Variables

The variables of the problem are as follows.

$dt_{i,j,k}$ = temperature difference to the exchange (i, j) at stage k

$dtcu_i$ = temperature difference for the exchange between the hot stream i and cold utility

$dthu_j$ = temperature difference for the exchange between the cold stream j and hot utility

$q_{i,j,k}$ = heat exchanged between hot stream i and cold stream j in stage k

qcu_i = heat exchanged between hot stream i and cold utility

qhu_j = heat exchanged between cold stream j and hot utility

$t_{i,k}$ = temperature of hot stream i at hot extreme of stage k

$t_{j,k}$ = temperature of the cold stream j at hot extreme of stage k

$z_{i,j,k}$ = binary variable indicating the existence of exchange (i, j) in stage k

zcu_i = binary variable indicating the heat exchanged between cold utility and stream i

zhu_i = binary variable indicating the heat exchanged between hot utility and stream j

MINLP Model

The model includes the following equations.

Global energy balance for each stream

The global energy balance is necessary to ensure enough heating or cooling for each process stream. The constraint specifies that the total heat transferred for each stream must be equal to the sum of the amount of heat that each stream exchanges with all other process streams in all stages, plus the heat exchanged with the service stream.

$$\begin{aligned} &\left(Tin_i - Tout_i\right)F_i = \sum_{k\in ET}\sum_{j\in CP} q_{i,j,k} + qcu_i \qquad i \in HP \\ &\left(Tout_j - Tin_j\right)F_j = \sum_{k\in ET}\sum_{i\in HP} q_{i,j,k} + qhu_j \qquad j \in CP \end{aligned} \tag{A.1}$$

Energy balance in each stage

An energy balance is needed at each stage of the superstructure for determination of temperatures. Due to the assumption of isothermal mixing, the flow variables are not necessary.

$$\begin{aligned} &\left(t_{i,k} - t_{i,k+1}\right)F_i = \sum_{j\in CP} q_{i,j,k} \qquad k \in ET,\ i \in HP \\ &\left(t_{j,k} - t_{j,k+1}\right)F_j = \sum_{i\in HP} q_{i,j,k} \qquad k \in ET,\ \mathrm{j} \in CP \end{aligned} \tag{A.2}$$

Assignment of inlet temperatures in the superstructure

Fixed inlet temperatures (*Tin*) of all process streams are assigned to the superstructure inlet temperatures.

$$Tin_i = t_{i,1} \qquad i \in HP$$
$$Tin_j = t_{j,NOK+1} \qquad j \in CP \tag{A.3}$$

Feasibility of temperatures

The temperature throughout the different stages should decrease monotonically. Furthermore, it is necessary to specify that the outlet stream temperature at each stage must be lower than the final output temperature of each stream.

$$t_{i,k} \geq t_{i,k+1} \qquad k \in ET,\ i \in HP$$
$$t_{j,k} \geq t_{j,k+1} \qquad k \in ET,\ \mathrm{j} \in CP$$
$$Tout_i \leq t_{i,NOK+1} \qquad i \in HP$$
$$Tout_j \geq t_{j,1} \qquad j \in CP \tag{A.4}$$

Calculation of the utility heat duty

The necessary cold and hot utilities are determined for each process stream through a balance of energy at the exit points of each stream.

$$\left(t_{i,NOK+1} - Tout_i\right) F_i = qcu_i \qquad i \in HP$$
$$\left(Tout_j - t_{j,1}\right) F_j = qhu_j \qquad j \in CP \tag{A.5}$$

Logical constraints

The logical constraints are expressed through the use of binary variables to determine the existence or not of the heat exchange (i, j) at each stage k, as well as exchanges between utilities and process streams.

$$
\begin{aligned}
&q_{i,j,k} - \Omega z_{i,j,k} \le 0 && i \in HP,\ j \in CP,\ k \in ET \\
&qcu_i - \Omega zcu_i \le 0 && i \in HP \\
&qhu_j - \Omega zhu_j \le 0 && j \in CP
\end{aligned}
\tag{A.6}
$$

Calculation of approximation temperatures between streams

The necessary area for a particular exchange is incorporated in the objective function. For the calculation of these areas is necessary to determine the differences of temperature (approximation temperature) at each extreme of the heat exchanger. Notwithstanding, these differences of temperature are only active if there is a heat exchange. Therefore, binary variables are used to enable or disable the calculation of these differences.

$$
\begin{aligned}
&dt_{i,j,k} \le t_{i,k} - t_{j,k} + \Gamma\left(1 - z_{i,j,k}\right) && i \in HP,\ j \in CP,\ k \in ET \\
&dt_{i,j,k+1} \le t_{i,k+1} - t_{j,k+1} + \Gamma\left(1 - z_{i,j,k}\right) && i \in HP,\ j \in CP,\ k \in ET \\
&dtcu_i \le t_{i,NOK+1} - Tout_{CU} + \Gamma\left(1 - zcu_i\right) && i \in HP \\
&dthu_j \le Tout_{HU} - t_{j,1} + \Gamma\left(1 - zhu_j\right) && j \in CP
\end{aligned}
\tag{A.7}
$$

It is appropriate to specify a minimum approach temperature in the network, such that the temperature difference between the cold and hot streams at any point in the network is at least equal to this value.

$$
dt_{i,j,k} \ge EMAT \tag{A.8}
$$

Objective function

The objective function is defined as the HEN total cost. The total cost consists of the cost of services, the fixed capital costs of the heat exchangers and the cost related with each heat exchanger area. To calculate the exchange area of the heat exchanger, the logarithmic mean temperature difference is required. Yee and Grossmann [25] proposed the use of Chen's [47] approximation:

$$\Delta Tml_{i,j} = \left(\theta^{1}_{i,j} - \theta^{2}_{i,j}\right) \big/ \ln\left(\theta^{1}_{i,j} \big/ \theta^{2}_{i,j}\right) \approx \left[\theta^{1}_{i,j} \cdot \theta^{2}_{i,j} \left(\theta^{1}_{i,j} + \theta^{2}_{i,j}\right) \big/ 2\right]^{1/3} \tag{A.9}$$

This approach is used to avoid numerical difficulties associated to the logarithmic mean when temperature differences ($\theta^{1}_{i,j}$; $\theta^{2}_{i,j}$) on both sides of the heat exchanger are equal. Furthermore, if the temperature difference on either side tends to zero, the approximation of Chen [47] also tends to zero. The objective function is defined as follows.

$$\begin{aligned}
\min:\ & \sum_{i\in HP} CCU \cdot qcu_i + \sum_{j\in CP} CHU \cdot qhu_j + \sum_{i\in HP}\sum_{j\in CP}\sum_{k\in ET} CF_{i,j} \cdot z_{i,j,k} + \sum_{i\in HP} CF_{i,CU} \cdot zcu_i + \\
& \sum_{j\in CP} CF_{j,HU} \cdot zhu_j + \sum_{i\in HP}\sum_{j\in CP}\sum_{k\in ET} C_{i,j} \left\{ q_{i,j,k} \big/ U_{i,j} \left[dt_{i,j,k} \cdot dt_{i,j,k+1} \left(dt_{i,j,k} + dt_{i,j,k+1} \right) \big/ 2 \right]^{1/3} \right\}^{\beta_{i,j}} + \\
& \sum_{i\in HP} C_{i,CU} \left\{ qcu_i \big/ U_{i,CU} \left[dtcu_i \left(Tout_i - Tin_{CU} \right) \left(dtcu_i + \left(Tout_i - Tin_i \right) \right) \big/ 2 \right]^{1/3} \right\}^{\beta_{i,CU}} + \\
& \sum_{j\in CP} C_{HU,j} \left\{ qhu_j \big/ U_{HU,j} \left[dthu_j \left(Tin_{HU} - Tout_j \right) \left(dthu_j + \left(Tin_{HU} - Tout_j \right) \right) \big/ 2 \right]^{1/3} \right\}^{\beta_{HU,j}}
\end{aligned} \tag{A.10}$$

In which, $1/U_{i,j} = 1/h_i + 1/h_j$; $1/U_{i,CU} = 1/h_{CU} + 1/h_i$; $1/U_{HU,j} = 1/h_j + 1/h_{HU}$ (A.11)

The resulting MINLP-based model includes the objective function and all constraints commented before. It is important to emphasize that all constraints that appear on this method are linear. The non-linearities are only on the objective function. However, the non-convex character of the solution of this problem can lead to local minima.

An important feature of this model is that it allows, in general, avoiding configurations in which stream splits appear. This is achieved by adding the condition that each stream cannot have more than one exchange at each stage. Mathematically, this can be expressed as follows:

$$\sum_{i \in HP} z_{i,j,k} \leq 1 \quad j \in CP,\ \mathrm{k} \in \mathrm{ET}, \quad \sum_{j \in CP} z_{i,j,k} \leq 1 \quad i \in HP,\ \mathrm{k} \in \mathrm{ET} \qquad \text{(A.12)}$$

APPENDIX B: Pressure manipulation operator

The reversible adiabatic process of pressure manipulation of an ideal gaseous stream *s* can be defined by the following mathematical operator (this operator was originally presented in Wechsung et al.[30]):

$$
\begin{aligned}
&(\kappa-1)\cdot\left(\ln p_{s,in}-\ln p_{s,out}\right)=\kappa\left(\ln T_{s,in}-\ln \tilde{T}_{s,out}\right) \qquad \forall\left(s_{in},s_{out}\right)\in CO\cup EX\\
&\eta_{co}=\left(\tilde{T}_{s,out}-T_{s,in}\right)/\left(T_{s,out}-T_{s,in}\right) \qquad \forall\left(s_{in},s_{out}\right)\in CO\\
&\eta_{ex}=\left(T_{s,in}-T_{s,out}\right)/\left(T_{s,in}-\tilde{T}_{s,out}\right) \qquad \forall\left(s_{in},s_{out}\right)\in EX\\
&WC_{co}=F_sCp_s\left(T_{s,out}-T_{s,in}\right) \qquad \forall\left(s_{in},s_{out}\right)\in CO\\
&WE_{ex}=F_sCp_s\left(T_{s,in}-T_{s,out}\right) \qquad \forall\left(s_{in},s_{out}\right)\in EX
\end{aligned}
\qquad \text{(B.1)}
$$

In which, (s_{in}, s_{out}) are the inlet and outlet stream states, respectively, in the equipment for pressure manipulation. The variable WC_{co} indicates the work required by the compressors and WE_{ex} the work of expansion produced in by the expanders. Moreover, κ is the polytrophic exponent, $\tilde{T}_{s,out}$ is the outlet streams temperature in the reversible process. η_{co} and η_{ex} indicates the respective isentropic efficiencies of the pressure manipulation equipment. It should be emphasized that the inlet stream state in the compressor (*CO*)/expander (*EX*) should match with the outlet stream state in the superstructure for the HEN. Note that the Eq. (B.1) is related to only physical quantities that assume positive values. In consequence, all variables should be restricted to upper and lower bounds to prevent that the equation becomes undefined.

List of Figure Captions

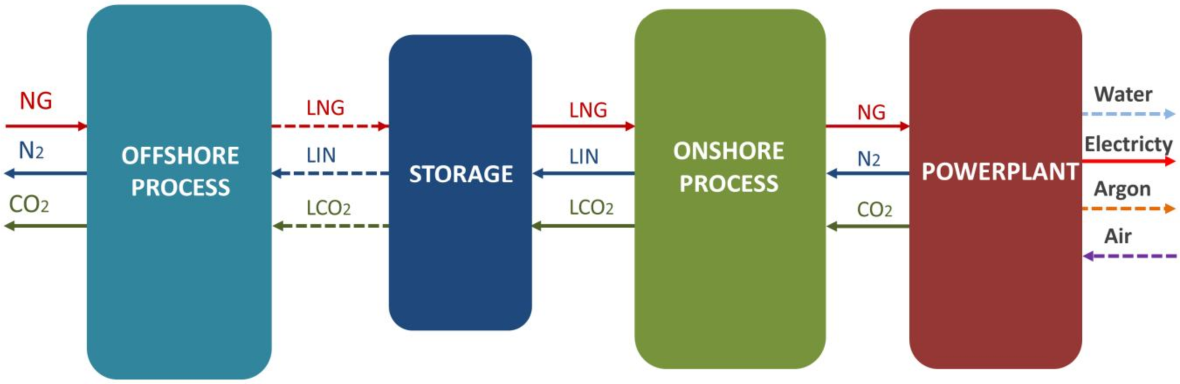

Fig. 1. Production chain for the liquefied natural gas (LNG).

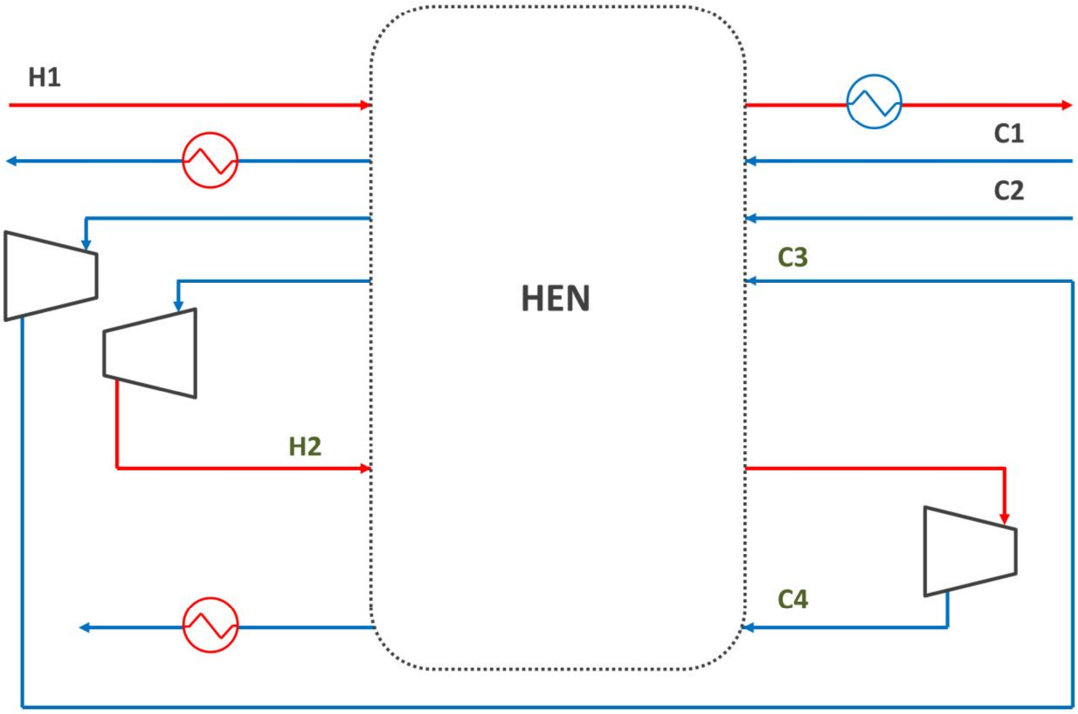

Fig. 2. Possible arrangement of process streams for Example 1 and Example 2.

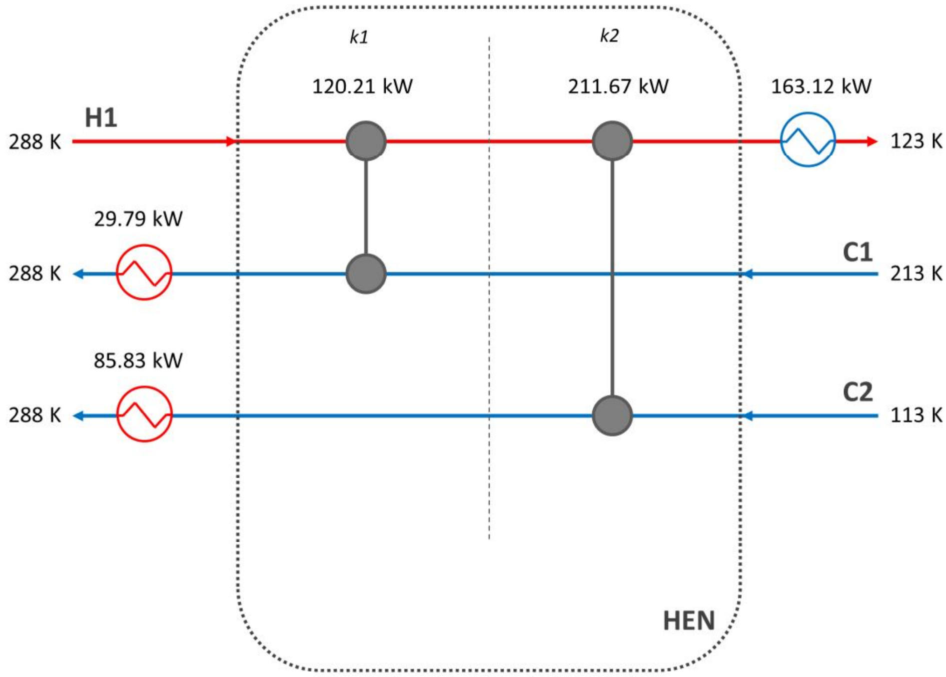

Fig. 3. Optimal configuration obtained for the HEN retrofit in Example 1 – Case 1.

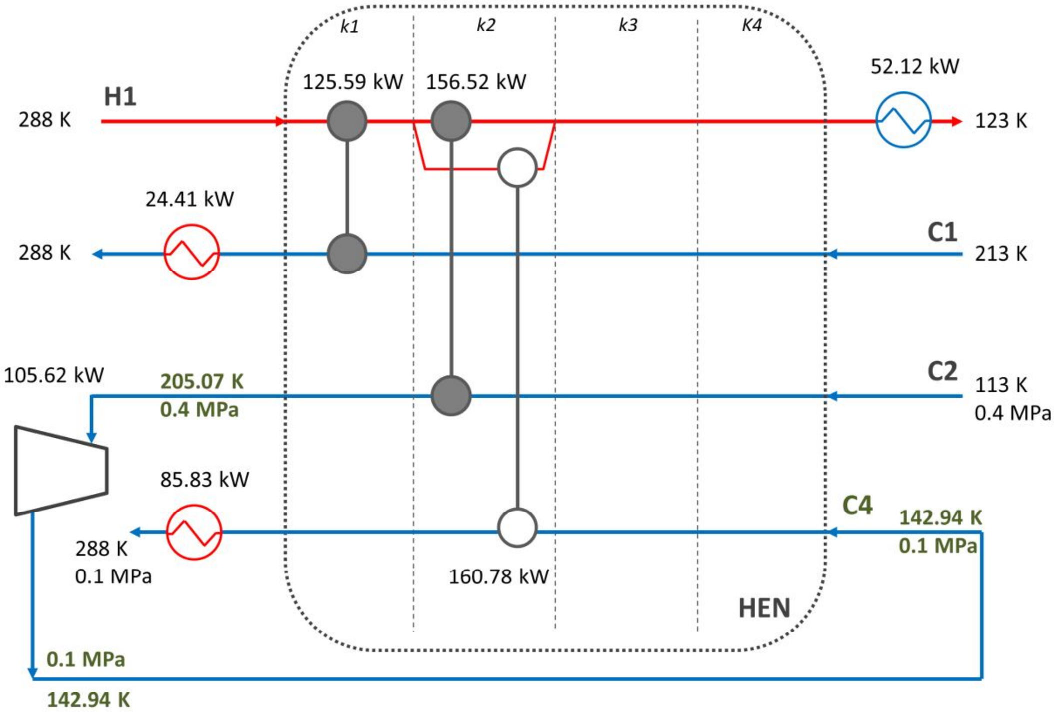

Fig. 4. Optimal configuration obtained for the HEN retrofit with streams pressure recovery in Example 1 – Case 2.

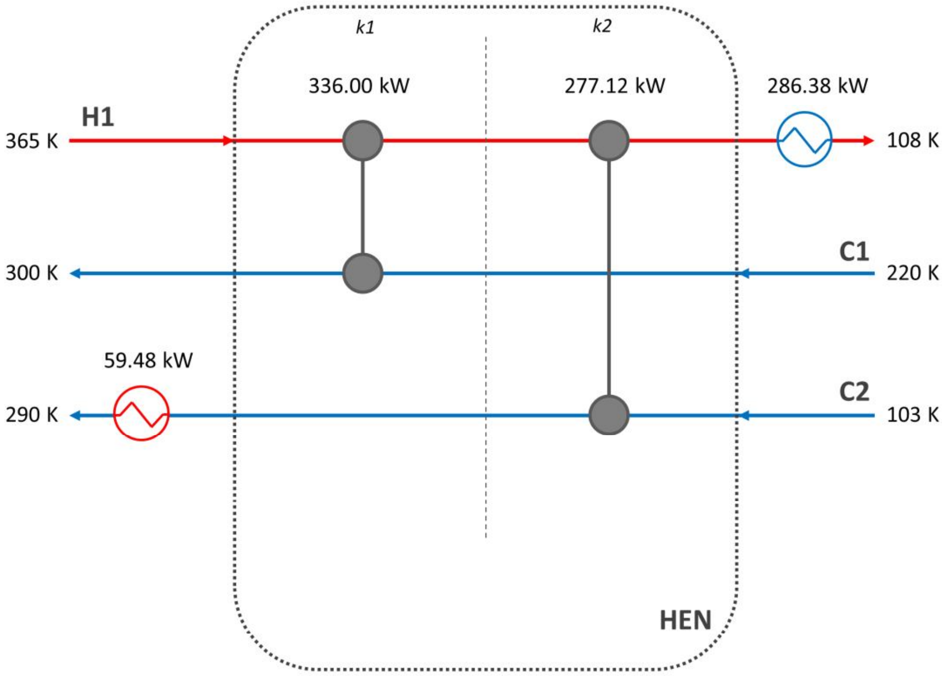

Fig. 5. Optimal configuration obtained for the HEN retrofit in Example 2 – Case 1.

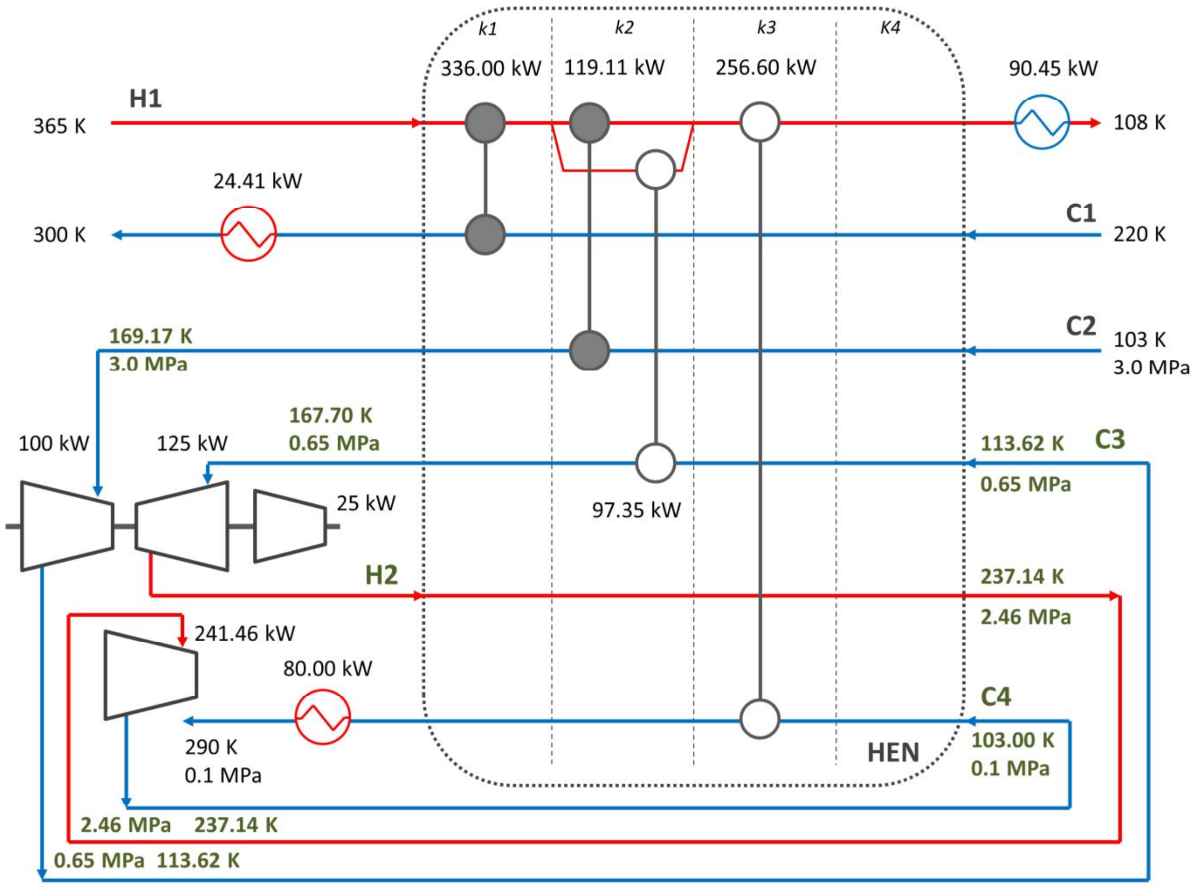

Fig. 6. Optimal configuration obtained for the HEN retrofit with streams pressure recovery in Example 2 – Case 2.

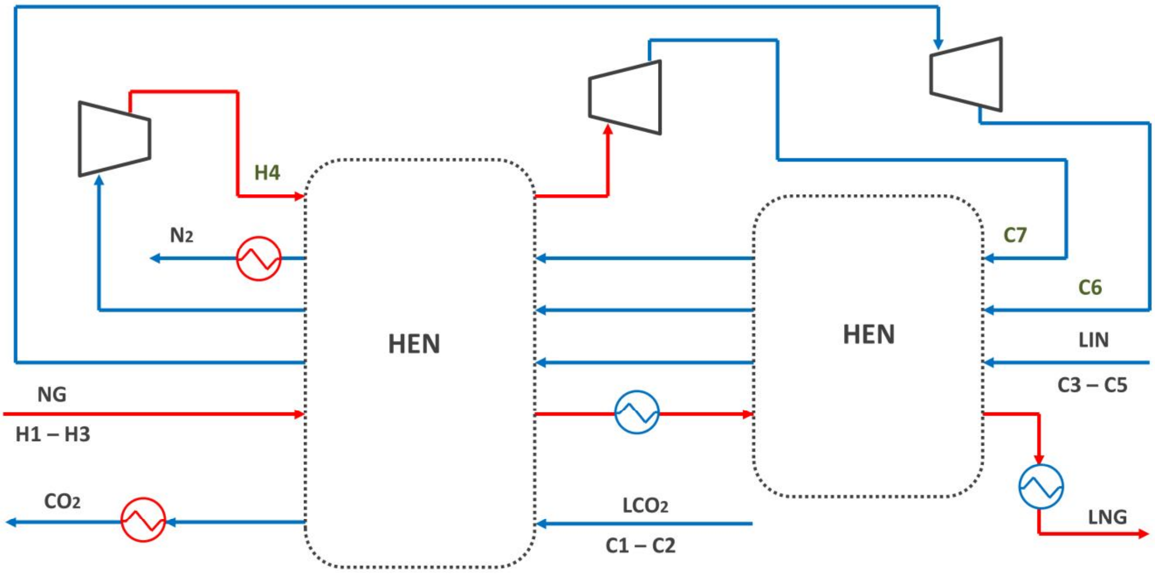

Fig. 7. Diagram for the offshore process of the liquefied natural gas (LNG) production.

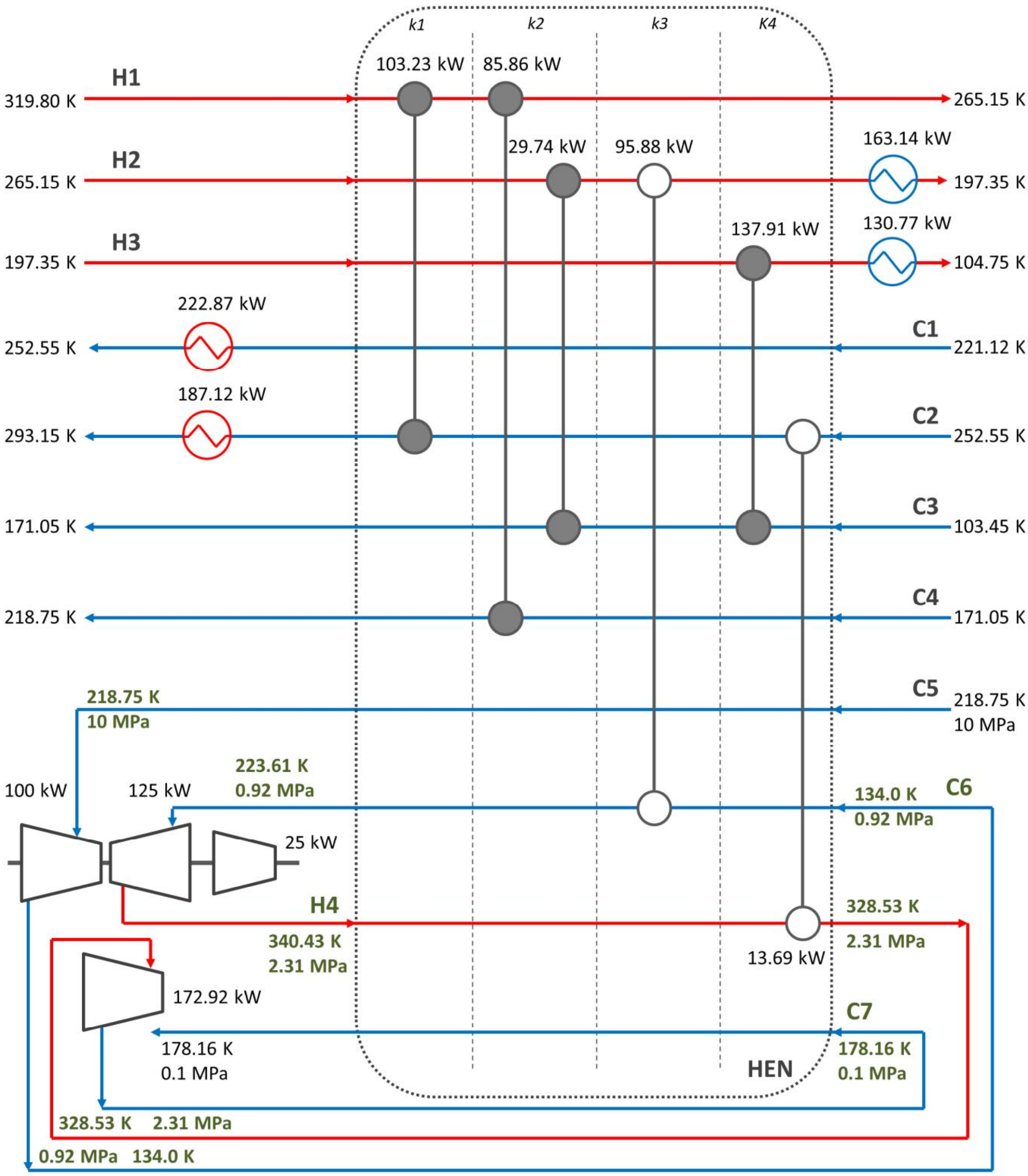

Fig. 8. Optimal configuration obtained for the HEN retrofit in Example 3.

Table 1

Stream data and existing heat exchange equipment for Example 1.

Stream	*FCp* (kW/K)[†]	*h* (kW/m²K)	T_{in} (K)	T_{out} (K)	*p* (MPa)
H1	3.0	0.1	288	123	0.1
C1	2.0	0.1	213	288	0.1
C2	1.7	0.1	113	-	0.4
C3	1.7	0.1	-	-	-
H2	1.7	0.1	-	-	-
C4	1.7	0.1	-	288	0.1
Existing network		*A* (m²)	*Q* (kW)		
H1.C1.k1		120	-		
H1.C2.k2		160	-		
H1		20	60		
C1		8	54		
C2		8	90		
Additional data					
$\Delta T_{\min} = 4$ K		$T_U^h = 383$ K	$\eta_{turbine} = 0.7$		
$\kappa = 1.352$		$T_U^c = 93$ K	$\eta_{compressor} = 0.7$		
Cost data (US$/year kW)					
CC = 1150.00		*CH* = 337.00	*CE* = 455.04	*CV* = 400.00	

[†] Heat capacity flow rates (i.e., product of flow rate and heat capacity).

Table 2

Optimal HEN retrofit configuration and decision variables obtained for Example 1.

Case 1				*Case 2*			
Decision variables	T_{in} (K)	T_{out} (K)	p (MPa)	Decision variables	T_{in} (K)	T_{out} (K)	p (MPa)
C2	-	-	-	C2	-	205.07	-
C3	-	-	-	C3	205.07	205.07	0.4
H2	-	-	-	H2	205.07	205.07	0.4
C4	-	-	-	C4	142.94	-	-
HEN	Q (kW)	A (m^2)	W (kW)	HEN	Q (kW)	A (m^2)	W (kW)
H1.C1.k1	120.21	115.83	-	H1.C1.k1	125.59	120.00	-
H2.C2.k2	211.67	160.00	-	H1.C2.k2	156.52	243.79	-
H1	163.12	86.80	-	H1.C4.k2	160.78	195.89	-
C1	29.79	4.44	-	H1	52.12	20.00	-
C2	85.83	8.00	-	C1	24.41	8.00	-
				C4	85.83	8.00	-
				stand-alone turbine	-	-	105.62
	C_{total} (US$/year)		144,772		C_{total} (US$/year)		52,855

Table 3

Model statistics and computational efforts for obtaining the solutions in the different examples.

	Example 1		Example 2		Example 3
	Case 1	*Case 2*	*Case 1*	*Case 2*	
Discrete variables	23	110	23	110	373
Continuous variables	105	534	105	534	1,634
Constraints	134	697	134	697	2,077
Non-null elements	349	1,852	349	1,852	5,801
CPU time (*s*)[†]	15	68.4	15	388.8	624

[†] Using SBB solver under GAMS software.

Table 4

Stream data and existing heat exchange equipment for Example 2.

Stream	*FCp* (kW/K)[†]	*h* (kW/m^{2}K)	T_{in} (K)	T_{out} (K)	*p* (MPa)
H1	3.5	0.1	365	108	3.0
C1	4.2	0.1	220	300	3.0
C2	1.8	0.1	103	-	3.0
C3	1.8	0.1	-	-	-
H2	1.8	0.1	-	-	-
C4	1.8	0.1	-	290	0.1

Existing network	*A* (m^2)	*Q* (kW)
H1.C1.k1	120	-
H1.C2.k2	180	-
H1	80	100
C2	10	80

Additional data

$\Delta T_{\min} = 4$ K	$T_U^h = 383$ K	$\eta_{turbine} = 0.7$
$\kappa = 1.352$	$T_U^c = 93$ K	$\eta_{compressor} = 0.7$

Cost data (US$/year kW)

CC = 1150.00	*CH* = 337.00	*CE* = 455.04	*CV* = 400.00

[†] Heat capacity flow rate (i.e., product of flow rate and heat capacity).

Table 5

Optimal HEN retrofit configuration and decision variables obtained for Example 2.

Case 1				*Case 2*			
Decision variables	T_{in} (K)	T_{out} (K)	p (MPa)	Decision variables	T_{in} (K)	T_{out} (K)	p (MPa)
C2	-	-	-	C2	-	169.17	-
C3	-	-	-	C3	113.62	167.70	0.65
H2	-	-	-	H2	237.14	237.14	2.46
C4	-	-	-	C4	103.00	-	-
HEN	Q (kW)	A (m^2)	W (kW)	HEN	Q (kW)	A (m^2)	W (kW)
H1.C1.k1	336.00	120.00	-	H1.C1.k1	336.00	120.00	-
H2.C2.k2	277.12	161.51	-	H1.C2.k2	119.11	180.00	-
H1	286.38	94.66	-	H1.C3.k2	97.35	81.47	-
C2	59.48	8.32	-	H1.C4.k3	256.60	102.32	-
				H1	90.45	80.00	-
				C4	80.00	10.00	-
				stand-alone turbine	-	-	241.46
				compressor (axis)	-	-	125.00
				turbine (axis)	-	-	100.00
				helper motor	-	-	25.00
	C_{total} (US$/year)		238,136		C_{total} (US$/year)		212,076

Table 6

Stream data and existing heat exchange equipment for Example 3.

Stream	F (kg/s)	Cp (kJ/kg K)	h (kW/m^{2}K)	T_{in} (K)	T_{out} (K)	p (MPa)
H1-NG	1.0	3.46	0.1	319.80	265.15	10.0
H2-NG	1.0	5.14	0.1	265.15	197.35	10.0
H3-NG	1.0	3.51	0.1	197.35	104.75	10.0
C1-LCO_2	2.46	2.11	0.1	221.12	252.55	6.0
C2-LCO_2	2.46	2.48	0.1	252.55	293.15	6.0
C3-LIN	-	2.48	0.1	103.45	171.05	10.0
C4-LIN	-	1.80	0.1	171.05	218.75	10.0
C5-LIN	-	1.18	0.1	218.75	-	10.0
C6-LIN	-	1.07	0.1	-	-	-
H4-LIN	-	1.15	0.1	-	-	-
C7-LIN	-	1.04	0.1	-	-	0.1

Existing network	A (m^2)	Q (kW)
H1.C2.k1	50	-
H1.C4.k2	25	-
H2.C3.k2	30	-
H3.C3.k4	60	-
H2	20	200
H3	85	180
C1	15	250
C2	15	230

Additional data

$\Delta T_{\min} = 4$ K $T_U^h = 383.15$ K $\eta_{turbine} = 0.7$

κ = 1.352 T_U^c = 93.15 K $\eta_{compressor}$ = 0.7

Cost data (US$/year kW)

CC = 1150.00 CH = 337.00 CE = 455.04 CV = 400.00

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Table 7

Optimal HEN retrofit configuration and decision variables obtained for Example 3.

Decision variables	T_{in} (K)	T_{out} (K)	p (MPa)
C5-LIN	-	218.75	-
C6-LIN	134.00	223.61	0.92
H4-LIN	340.43	328.53	2.31
C7-LIN	178.16	178.16	-
HEN	Q (kW)	A (m^2)	W (kW)
H1.C2.k1	103.23	50.00	-
H1.C4.k2	85.86	20.91	-
H2.C3.k2	29.74	6.12	-
H2.C6.k3	95.88	29.61	-
H3.C3.k4	137.91	60.00	-
H4.C2.k4	13.69	7.74	-
H2	163.14	27.74	-
H3	130.77	83.99	-
C1	222.87	15.00	-
C2	187.12	15.00	-
stand-alone turbine	-	-	172.92
compressor (axis)	-	-	125.00
turbine (axis)	-	-	100.00
helper motor	-	-	25.00
	C_{total} (US$/year)		256,187