

Simultaneous Multiperiod Optimization of Rankine Cycles and Heat Exchanger Networks

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Abstract

This work addresses the multiperiod synthesis and optimization of integrated Heat Exchanger Networks (HEN) and Rankine cycles for plants with demanding operational flexibility requirements. A general and systematic synthesis methodology has been developed to optimize simultaneously the utility systems, Rankine cycles and HENs considering different expected operating modes, seeking for the solution with the minimum Total Annual Costs (TAC). Heat exchangers have been modelled with different approaches depending on the type of off-design control measure (with/without by-pass). The problem is formulated as a challenging nonconvex MINLP and solved with a bilevel decomposition method, specifically developed to address this class of problems.

We present the results of the proposed methodology applied to an extremely challenging problem, with 35 streams and 2 operating modes (periods), consisting in the design of an Integrated Gasification Combined Cycle (IGCC).

Keywords: Heat integration, Nonconvex MINLP, Bilevel decomposition, Multiperiod, Utility systems, Rankine cycle superstructure.

1. Introduction

Given the increasing share of intermittent renewable energy sources and the use of novel energy technologies, a new challenge for novel energy systems and poly-generation plants is to deal with the increased requirement of operational flexibility. This includes the capability of achieving stable and efficient operation in different operating modes. Among the operational issues, when dealing with plants featuring large volumetric flows of high-temperature gases, it is not possible to control the heat exchanger in the off-design conditions by using bypass streams, as typically done in chemical processes. Examples of this issue are the steam tube banks (superheaters and reheaters) of coal-fired boilers and combined cycles, for which it is impracticable to install a bypass duct for the stream of flue gases. Moreover, in steam generators, the steam acts as temperature moderator, as it keeps the metal temperature of the tubes exposed to high-temperature flue gases lower than the maximum allowed value of the material (Spliethoff, 2010). Thus, it is not feasible to use a bypass on the steam side, because the reduced flow of steam would cause an excessive increase in the steam outlet temperature and consequent overheating of the tubes. For the same reason, if steam is used as temperature moderator of the heat exchanger tubes and the hot stream (e.g., the flue gases) cannot be bypassed, the heat exchanger must exchange heat for all operating periods. The heat exchanger featuring this

kind of operational issue need to be modelled with ad-hoc constraints called “no-bypass HX” constraints (see Section 2).

In the process system engineering community, the design optimization approaches which can consider different expected operating modes and operating issues (e.g., off-design control measures of heat exchangers) are referred to as “multiperiod” design/synthesis methods. Among these methods, three main categories can be distinguished: multiperiod HEN synthesis approaches, multiperiod utility design/synthesis approaches, multiperiod HEN & utility synthesis approaches. Previous studies mainly focused on the first two approaches, optimizing only the HEN synthesis or only the utility synthesis. Only recently, some authors started to address both problems simultaneously in the multiperiod version (Mian et al., 2016; Isafiade et al., 2015).

In this work, we propose an MINLP formulation of the multiperiod HEN & utility synthesis problem, starting from an extension of the single-period model proposed by Martelli et al. (2017) and further extended in Elsidó et al. (2019), that enables the automated generation of Rankine cycles recovering heat from one or more heat sources, and the HEN of the overall heat integration.

2. Mathematical model

The general problem for the multi-period simultaneous synthesis of utilities, Rankine cycles and HENs, is formulated as follows:

“Given

- *a set of hot/cold process streams to be cooled/heated, with their heat capacity flow rates, input and output temperatures and heat transfer coefficients for different operating conditions,*
- *a set of hot and cold utility streams, with their specific heat capacity, input and output temperatures and heat transfer coefficients,*
- *information on process needs of hot water/liquid and steam/vapor, technical limitations (e.g., forbidden/forced matches, no stream splitting, etc.) and economic data (e.g., price of fuels, price of electricity, cost models of units, etc.),*

determine

- *the optimal arrangement and design of the heat recovery cycle, of the installed energy systems (e.g., gas turbines, boilers, etc.), and the design of the HEN,*
- *the optimal commitment (on/off status) and operation (loads) of the installed utility and energy systems for each period,*
- *the optimal load and mass flow rates of the Rankine cycle in each period,*

while taking into account a finite set of expected operating conditions of the process with their duration”.

The model is based on the SYNHEAT superstructure (Yee and Grossmann, 1990) for the optimal design of heat exchanger networks. The SYNHEAT model is extended to include the streams of the heat recovery cycle, with variable mass flow rate. It should be noted that a steady state condition is assumed in each working period (i.e., no dynamics).

The thermodynamic cycles are modelled with a very general “*p-h* superstructure” (Elsidó et al., 2017a, 2017b), capable of reproducing many configurations of Rankine cycles, both power cycles and inverse cycles (refrigeration cycles or heat pumps), steam cycles or organic Rankine cycles, with single or multiple pressure levels, as well as heat/steam distribution networks. The proposed approach allows to explicitly consider both technical

design constraints (i.e., the “no stream splitting” constraint, forbidden matches, etc.), which are extremely important when dealing with the detailed design of power plants and chemical processes, and heat integration equipment costs.

The multiperiod problem can be formulated as a non-convex MINLP problem (P1), that comprises Eqs. (1)-(10), extending the single-period formulation of Elsidio et al. (2019) to the multiperiod case. Two types of variables are defined: “operational” variables, depending on the periods, and “design” variables, for the selection of the components of the cycle and the layout of the network of heat exchangers. All the constraints are period-dependent, and they are linked by the design constraints defining the calculation of the installed areas and the logical constraints on the binary variables (i.e., complicating constraints). The multi-period objective function (Eq. (1)) is the sum of the annualized investment costs and the weighted sum of the operational costs and revenues of the plant at the different operating conditions, weighted for their expected duration.

$$\begin{aligned} \min TAC = CCR MF & \left(\sum_r C_{F,r} y_r + \sum_{i,j,k} C_{F,i,j} z_{i,j,k} + \sum_i C_{F,CU,i} z_{CU,i} + \sum_j C_{F,HU,j} z_{HU,j} \right. \\ & + \sum_r C_{S,r} S_{REF,r} \left(\frac{S_r}{S_{REF,r}} \right)^{\alpha_r} + \sum_{i,j,k} C_{A,i,j} A_{REF,i,j} \left(\frac{A_{i,j,k}}{A_{REF,i,j}} \right)^{\beta_{i,j}} \\ & + \sum_i C_{A,CU,i} A_{REF,CU,i} \left(\frac{A_{CU,i}}{A_{REF,CU,i}} \right)^{\beta_{CU,i}} \\ & \left. + \sum_j C_{A,HU,j} A_{REF,HU,j} \left(\frac{A_{HU,j}}{A_{REF,HU,j}} \right)^{\beta_{HU,j}} \right) + \sum_{i,p} h_{EQ,p} C_{CU,i,p} q_{CU,i,p} \\ & + \sum_{j,p} h_{EQ,p} C_{HU,j,p} q_{HU,j,p} \\ & - \sum_p h_{EQ,p} p_{EL,p} \left(\sum_{r \in TURB} \Gamma_{r,p} \Delta h_{r,p} - \sum_{r \in (PUMP \cup COMPR)} \Gamma_{r,p} \Delta h_{r,p} \right) \end{aligned} \quad (1)$$

$$\text{s. t. } B_1 \begin{bmatrix} \mathbf{z} \\ \mathbf{y}_p \end{bmatrix} + B_2 \begin{bmatrix} \mathbf{t}_p \\ \mathbf{dt}_p \\ \mathbf{\Gamma}_p \\ \mathbf{q}_p \\ \mathbf{A} \\ \mathbf{S} \end{bmatrix} - \mathbf{b} \leq \mathbf{0} \quad (2)$$

$$(t_{ic,k,p} - t_{ic,k+1,p}) \Gamma_{ic,p} C_{P,ic,p} = \sum_j q_{ic,j,k,p} \quad \forall k, ic \notin ISO, p \quad (3)$$

$$(t_{jc,k,p} - t_{jc,k+1,p}) \Gamma_{jc,p} C_{P,jc,p} = \sum_i q_{i,jc,k,p} \quad \forall k, jc \notin ISO, p \quad (4)$$

$$q_{i,j,k,p} \leq U_{i,j,p} A_{i,j,p} \left(dt_{i,j,k,p} dt_{i,j,k+1,p} \frac{dt_{i,j,k,p} + dt_{i,j,k+1,p}}{2} \right)^{1/3} \quad \forall i, j, k, p \quad (5)$$

$$q_{CU,i,p} \leq U_{i,CU,p} A_{CU,i} \left(dt_{CU,i,k,p} dt_{CU,i,k+1,p} \frac{dt_{CU,i,k,p} + dt_{CU,i,k+1,p}}{2} \right)^{1/3} \quad \forall i, \text{last}(k), p \quad (6)$$

$$q_{HU,j,t} \leq U_{HU,j,p} A_{HU,j} \left(dt_{HU,j,k,p} dt_{HU,j,k+1,p} \frac{dt_{HU,j,k,p} + dt_{HU,j,k+1,p}}{2} \right)^{1/3} \quad \forall j, \text{first}(k), p \quad (7)$$

$$q_{i,j,k,p} \leq \left(1 + \left(\frac{\Delta A}{A}\right)_{MAX,i,j}\right) U_{i,j,t} A_{i,j,p} \left(dt_{i,j,k,p} dt_{i,j,k+1,p} \frac{dt_{i,j,k,p} + dt_{i,j,k+1,p}}{2}\right)^{1/3} \quad (8)$$

$$\forall (i,j) \in MP,p$$

$$\left(1 - \left(\frac{\Delta A}{A}\right)_{MAX,i,j}\right) U_{i,j,t} A_{i,j,k} \left(dt_{i,j,k,p} dt_{i,j,k+1,p} \frac{dt_{i,j,k,p} + dt_{i,j,k+1,p}}{2}\right)^{1/3} \leq q_{i,j,k,p} \quad (9)$$

$$\forall (i,j) \in MP,p$$

$$z_{i,j,k}, z_{CU,i}, z_{HU,j}, y_{ic}, y_{jc}, y_r \in \{0,1\}$$

$$\Gamma_{ic,p}, \Gamma_{jc,p}, \Gamma_r,p, q_{i,j,k,p}, q_{CU,i,p}, q_{HU,j,p}, A_{i,j,k}, A_{CU,i}, A_{HU,j}, S_r, dt_{i,j,k,p} \in \mathcal{R}_+$$

$$t_{i,k}, t_{j,k} \in \mathcal{R}$$

The linear constraints (synthetically represented by Eq. (2)) of the multiperiod model are: the energy balances for each hot and cold stream for each period, the energy balances of non-isothermal process streams in each stage for each period, assignment of inlet temperatures, monotonic temperature variation, load of and utilities, logical constraints on the existence of heat exchangers, calculation of approach temperatures, “no stream splitting” constraint, forbidden matches, restricted/required matches, activation/deactivation of utility streams, mass and enthalpy balances for “ p - h superstructure”, calculation of nominal size of Rankine cycle units and utility, constraints for thermal energy storage system, logical constraints for heat exchanger areas.

The nonlinear constraints of the multiperiod model are: the objective function (Eq. (1)), the energy balances of non-isothermal “HEN utility” streams in each stage for each period (Eq. (3)-(4)), the calculation of the installed areas of heat exchangers (Eq. (5)-(7)), and the areas for “no-bypass HXs” (Eq. (8)-(9)). Eq. (8) and (9) impose that the areas of the heat exchangers between hot stream i and cold stream j in temperature stage k can only vary within a certain tolerance. This margin of error to the heat transfer rate equation allows avoiding possible numerical issues due to the adopted linearization technique of the equation (i.e., the Taylor expansion) and take into account the fact that in practice the outlet temperatures of streams can vary of some degrees.

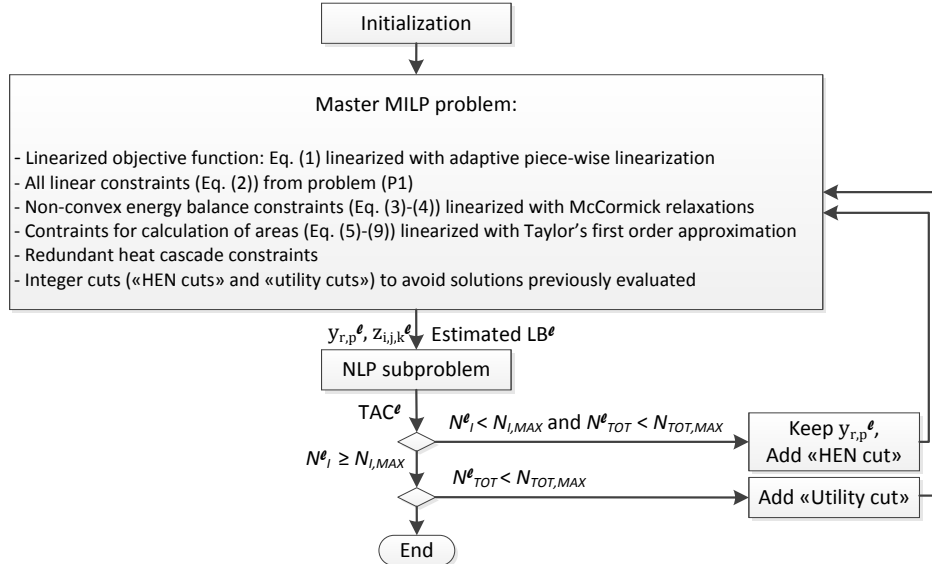


Figure 1: Scheme of the bilevel decomposition algorithm for the multiperiod MINLP problem.

3. Bilevel decomposition

The solution of the challenging nonconvex MINLP problem is tackled with a bilevel decomposition algorithm, extended from the single-period version of Elsido et al. (2019). The algorithm, represented in Figure 1, is based on an upper level (i.e., the “master” problem), comprising a linearized and relaxed version of the original problem (MILP) is solved, to minimize a linearized version of the original objective function; then a lower level problem is solved, in which the binary variables are fixed, and the continuous variables are re-optimized solving a non-convex nonlinear program (NLP). The master problem is obtained by the integration of multiple linearization techniques and the addition of redundant constraints and integer cuts to improve the algorithm convergence.

4. Case study

The methodology is applied to optimize the design and the HRSC and HEN of an Integrated Gasification Combined Cycle (IGCC) plant with 9 hot process streams and 4 cold process streams in addition to the streams of the superstructure. The HRSC superstructure includes 3 levels of evaporation (HP, MP, LP) and reheating. The single-period analysis of the same process is reported in Elsido et al. (2019).

Here we consider that the IGCC is asked to operate in two different modes:

- “IGCC mode” (5256 h/year): full load condition with gasifier and process at the nominal operating mode;
- “GT-only mode” (2628 h/year): GT is running on natural gas following the electric market/grid requirements while the gasification island is off (e.g., due to maintenance of the gasifier).

Technical limitations are taken into account as additional constraints in the model: the “no stream splitting” constraint is imposed to the GT flue gases; forbidden matches are imposed so that the HT syngas cooler can be matched only with the HP evaporator or the MP evaporator; in the same way the gasifier can be coupled only with the MP evaporator (Elsido, Martelli, & Grossmann, 2019). Besides, the “no-bypass HX” constraints have been imposed to the GT flue gases stream with a critical temperature level of 300°C. The full multiperiod MINLP problem has 30,680 equations and 19,930 variables (3,130 binaries). The proposed algorithm reached convergence to a promising solution in 9,000 s, while BARON, state-of-the-art general purpose MINLP solver, did not provide any feasible solution in 20,000 s. The scheme of the plant is plotted in Figure 2.

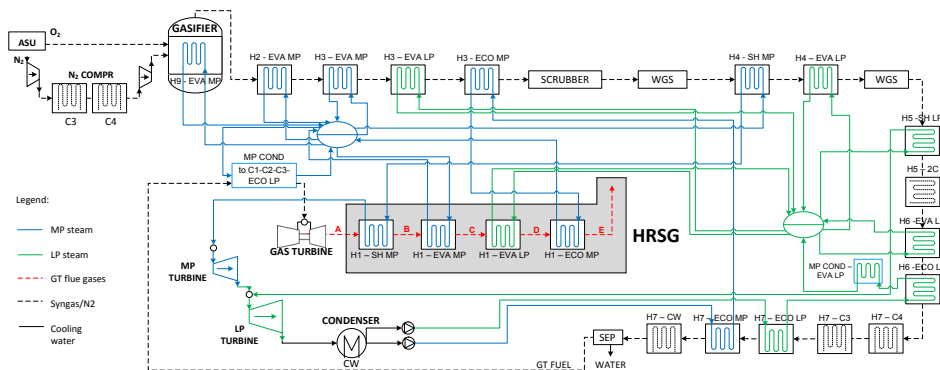


Figure 2: Scheme of the solution of the multiperiod IGCC case study.

The solution obtained by the proposed methodology is a double-level steam cycle (only the MP and LP levels are activated). Thanks to the flexible design, the HRSC can operate 90 % of the yearly hours, both in the “IGCC mode”, with net power output equal to 203.4 MW and 31.8 % net electric efficiency, and in the “GT-only mode”, with net power output equal to 106.6 MW and 34.0 % net electric efficiency of the HRSC. The MP steam is raised in the Heat Recovery Steam Generator (HRSG) with heat from GT flue gases, the gasifier cooling, and the high-temperature, low-temperature, and post-first WGS syngas coolers. During the “GT-only mode” the MP level flow rate decreases considerably (33.4%) compared to the “IGCC mode”, due to the reduction of heat available from the process, and the LP level is de-activated. The outlet temperature of the flue gases is 107°C in “IGCC mode” and 131°C in “GT-only mode”.

5. Conclusions

We have presented a multiperiod MINLP model and an ad-hoc bilevel decomposition method to solve complex optimization problems for the simultaneous design of utility systems, Rankine cycles and HEN considering multiple operating conditions. The proposed method is effectively applied to the design of an Integrated Gasification Combined Cycle featuring 10 hot process streams and 14 cold process streams. The design of the HEN and HRSC considers two different expected operating modes (“IGCC mode” and “GT-only mode”) making the problem extremely challenging for general purpose MINLP solvers. Nevertheless, the proposed MINLP model can include all the key design and operational constraints and the ad hoc bilevel decomposition algorithm can find promising solutions within a limited computational time.

Nomenclature

Indices

i, j hot/cold process or utility stream

k index for temperature stage

r component of Rankine cycle

p period

Parameters

T_{IN}, T_{OUT} inlet/outlet temperature of a stream

U heat transfer coefficient

h enthalpy, h_{EG} duration of periods

C, α, β specific cost and exponent for component/area cost

Binary Variables

z existence of heat exchanger

y existence of utility/Rankine cycle component

Continuous variables

Γ mass flow rates of streams

t temperature of streams at a stage

dt approach temperature difference

q, q_{CU}, q_{HU} heat exchanged

A, A_{CU}, A_{HU} heat transfer areas

S, S_r nominal size of a Rankine cycle component

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