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Targeting industrial heat pump integration in multi-period problems

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Abstract

Process integration aims at optimizing industrial processes by identifying the heat recovery potential and the optimal integration of energy conversion systems. Most industrial processes especially in the food industry are non-continuous problems (batch problems) that are more difficult to tackle with process integration techniques. Process integration of multi-period problems can become complex and often the heat integration is realized by using time averaging approaches. The main disadvantages are that the sizing of equipments becomes more difficult and that the investment cost calculation is almost impossible at the targeting stage, since storage tanks are not included. This work presents a MILP method that targets simultaneously the heat recovery and the integration of energy conversion systems like heat pumps and other utilities in multi-period multi-time problems. In each time slice, the heat cascade constraints are considered together with the flows of the utility streams and the mass balances for storage, which create a link between the different operating times.

Keywords: energy integration, pinch analysis method, utility integration, industrial heat pumps, process design, multi-period, storage units

1. Introduction

Process integration was originally developed for continuous processes. But many processes have non-continuous operation tasks and therefore the approach has to be adapted for multi-period problems. Often pseudo multi-period heat integration is realized by using the time average model (TAM) or the time slice model (TSM) (Linnhoff et al., 1988). The time average model uses average values over all operating time slices. This approach is correct when it is assumed that all batch operations can take place at any time and in any order or when it is assumed that heat storage is available. On the other side, the time slice model cuts the process into several time slices where the process operations are simultaneous. Using the composite curves resulting from the TAM, Krummenacher and Favrat (2001) propose a heuristic targeting method to identify the minimum number of heat storage units for the heat recovery. According to Kemp and Macdonald (1987), the TAM or pseudo-continuous approach is too simple and may give over optimistic results, except when heat storage is available, the TAM results in the theoretical energy efficiency which can be achieved with the maximum heat storage. The authors propose analog to the graphical heat cascade the new "time cascade" to identify energy storage for batch problems. Applying mathematical programming techniques, Grossmann and Santibanez (1980) present a mixed integer linear programming (MILP) formulation for a given number of time slices with different prices and demand fluctuations. The problem

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not only optimizes the total annual costs but also gives the optimal scheduling solution. Later, Maréchal and Kalitventzeff (2003) developed a methodology, based on the TSM for multi-time problems. The times are only linked with the usage level of utilities but there is no possibility to integrate heat storage. To integrate indirect energy storage of batch problems in the heat exchanger network, Chen and Ciou (2008) use a mixed integer non-linear programming (MINLP) formulation. The problem can become very complex, since the storage tanks are included in the superstructure. Using the TSM and total site approach, Varbanov and Klemeš (2011) integrate heat storage to manage the heat supply from renewables. A systematic approach allows heat storage between process operations but the self-sufficient pockets are not considered, which may miss opportunities for combined heat and power integration. Stoltze et al. (1995) propose a combinatorial method to include the heat storage in the heat exchanger network design. Sadr-Kazemi and Polley (1996) propose an iterative search method based on the composite curves in terms of heat quantities to define the temperature interval. Heat storage and intermediate heat transfer networks enables the process to stay independent and more flexible. As shown from the literature review, heat storage is very important to improve the energy efficiency of a non-continuous process. The TSM seems to be more realistic for integrating multi-period and storage problems, since instant heat loads can be used. The purpose of this paper is to adapt the multi-period targeting method, using the TSM and to include the possibility to integrate heat storage tanks simultaneously with energy conversion units (e.g. heat pumps) to maximize the heat recovery in multi-period problems.

2. Methodology

This paper develops a methodology based on a MILP formulation, which is able to solve multi-scenarios (without storage) and multi-time slices (with storage between time slices). Each period is defined by the operating conditions and the operating time. A multi-time slice problem consists in several successive process operations in a given period. Non-continuous processes can easily be modeled, by dividing them for example into a certain number of typical days and each day is divided into necessary time slices depending on the process schedule (e.g. 12 typical days a year and 24 time slices corresponding to one hour of operation). The approach can also be useful for other application like the optimization of large scale process or urban systems.

2.1. MILP formulation for multi-time problems

A MILP problem that targets simultaneously the heat recovery and the integration of energy conversion systems like heat pumps and other utilities in multi-time problems, is developed. For each time slice, the heat cascade constraints are considered together with the flows of the utility streams and the storage tanks. The storage equations are added and create a link between the different time slices. Utility and storage units are optimized to satisfy the process demand for all time slices simultaneously. The MILP formulation developed for heat exchange restrictions (Becker and Maréchal, 2012) is extended to the time dimension. For a given period, the objective function minimizes the yearly operating costs (e.g. OpC_p from Eq. (1)) or the total costs including the annualized investment costs.

$$min(cy_p \sum_{t=1}^{nt} d_{p,t} (\sum_{f=1}^{nf} (c^{+}_{f,p,t} \sum_{u=1}^{nu} f_{u,p,t} \dot{E}^{+}_{f,u,p,t}) + c^{+}_{el,p,t} \dot{E}^{+}_{el,p,t} - c^{-}_{el,p,t} \dot{E}^{-}_{el,p,t} + \sum_{u=1}^{nu} f_{u,p,t} c_u)) \quad (1)$$

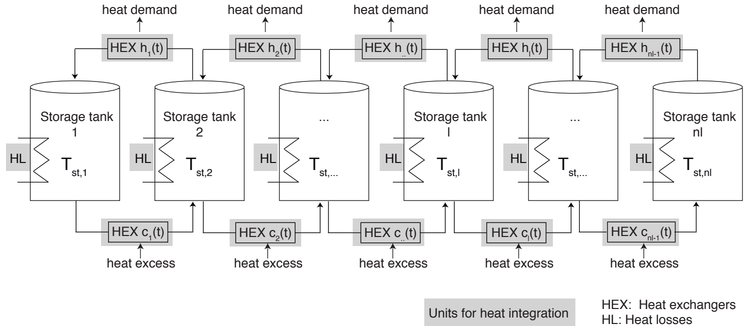

Figure 1. Definition of the storage network

nt is the number of time slices, cy_p is the number of cycles (e.g. number of days a year which can be represented by a chosen typical day), $d_{p,t}$ are the operating hours of time slice t in period p. The other terms concern the operating costs linked to fuel and electricity consumption and additional operating costs. For each time slice, the overall electricity import and the produced electricity in the process are defined. It becomes possible to take into account electricity price variations (e.g. peek hours or night prices). $f_{u,p,t}$ defines the multiplication factor of unit u in time t and period p. A unit can be a process ($f_{u,p,t} = 1$) or a utility ($f_{u,p,t}$ variable) unit. The flow rates of streams belonging to utility units are proportional to the multiplication factor. This factor is limited by a minimum and maximum value and corresponds to the usage level for a given time. The associated integer variable $y_{u,p,t}$ defines if the utility unit u is added to process ($y_{u,p,t} = 1$) or not ($y_{u,p,t} = 0$) in time t and period p. Thus, globally integrated utilities can be activated in a time slice and deactivated in another time slice.

$$y_{u,p,t} \cdot f_u^{min} \leq f_{u,p,t} \leq y_{u,p,t} \cdot f_u^{max} \tag{2}$$

Basically, the equations are extended to include the time dimension. In order to be able to integrate storage units, each time slice needs a link with its previous and next time slice.

2.2. Integration of storage tanks

Although the concept can be easily adapted to any kind of storage, only liquid (sensible) storage will be considered here. A given number of interdependent water tanks at discretized temperature levels can be integrated, as shown in Fig. 1. Water is heated up with available excess heat and will then be stored in a tank at higher temperature. In a following time slice, the water will be cooled down to satisfy a hot demand of the process. The cold water is then stored in a tank at lower temperature. The total maximal amount of water (M_{tot}) and the temperature levels of the tanks are defined as input parameters. The approach includes an estimation of heat losses which is linked to the temperature of the tank. The investment is evaluated as a function of the maximum needed storage capacity.

2.2.1. Mass balance

The overall mass balance is given as the cyclic constraint in Eq. (3), which states that the total stored mass has to be given back to the process. The water content after each time is calculated for each tank in Eq. (4). $ds_{p,t}$ is the operating time in seconds of time slice t in period p and $\dot{M}$ is the water flow rate. Furthermore, constraints have to be added to guaranty the positive level of the tank, and that the total volume of water is not exceeded.

$$\sum_{t=1}^{nt}(ds_{p,t}\sum_{l=1}^{nl}(\sum_{h_l=1}^{ns_{h,l}} f_{u,p,t}\dot{M}_{h,l,u,p,t} - \sum_{c_l=1}^{ns_{c,l}} f_{u,p,t}\dot{M}_{c,l,u,p,t})) = 0 \tag{3}$$

$$M_{l,p,t} = M_{0,l} + \sum_{t=1}^{t}(ds_{p,t}\sum_{l=1}^{nl}(\sum_{h_l=1}^{ns_{h,l}} f_{u,p,t}\dot{M}_{h,l,u,p,t} - \sum_{c_l=1}^{ns_{c,l}} f_{u,p,t}\dot{M}_{c,l,u,p,t})) \tag{4}$$

2.2.2. Definition of thermal streams for the heat integration

The heat exchange with other process or utility units is shown on Fig. 1. The cold storage stream $c_n(t)$ is heated up by process excess heat and is going from a lower temperature tank l to tank $l+1$. Whereas the hot storage stream $h_n(t)$ corresponds to water coming from a higher temperature level and giving back heat to process units. As an example, a cold stream from tank l to tank $l+1$ is defined with the inlet temperature $T_{in} = T_{st,l}$ and the outlet temperature $T_{out} = T_{st,l+1}$. The corresponding heat amount is calculated with Eq. (5). By analogy the heat load is given for the hot stream.

$$\dot{Q}_{c,l} = f_{u,p,t} \cdot \dot{M}_{c,l,u,p,t} \cdot c_p \cdot (T_{st,l+1} - T_{st,l}) \tag{5}$$

2.2.3. Heat losses in storage tanks

Heat losses can be included, by adding a cold stream which corresponds to maintaining the temperature of each tank. The difficulty is to estimate the heat losses of each tank, especially because the size of tank is an optimization result and not known in advance. Therefore Eq. (6) has been used to estimate the heat losses in the tank. Knowing the current stored mass from Eq. (4), the heat losses can be calculated by Eq. (6).

$$\dot{Q}_{hl,l,p,t} = k_{hl} \cdot \frac{f_{hl} \cdot 4 \cdot M_{l,p,t}}{\rho \cdot d} \cdot (T_{st,l} - T_a) \tag{6}$$

ρ is the density of the considered storage fluid in the tanks in kg/m^3. In the following examples water is used. d is the diameter of the tank in m. k_{hl} is the considered heat loss coefficient and f_{hl} is a factor to account the heat losses on the top and bottom of the storage tank. To model the heat losses, new cold streams corresponding to the heat losses and the associated temperature are added to the heat cascade. The multiplication factor has been fixed to consider the calculated heat losses as heat loads. The advantage of adding the heat losses are on the one hand to make the problem more realistic and on the other side, it ensures that the storage fluid will be used as soon as possible.

3. Example and conclusions

As example, Fig. 2 gives some typical results of the presented methodology. The case study consists in one period with 15 time slices. For each time slice the storage tank levels and the optimal utility usage rates are calculated, which allows to evaluate the corresponding investment costs for new storage and utility equipments in a next step. The above method is generic and can be adapted through the definition of temperature levels, number of tanks and the maximum content. Heat pump integration benefits can be increased when integrating storage units because the heat pump working hours and their profitability can, by this way, be increased.

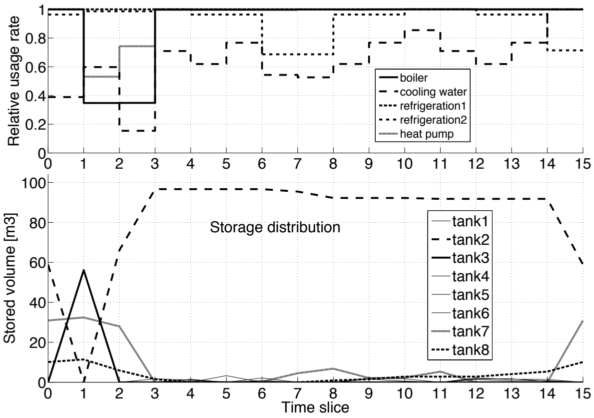

Figure 2. Storage tank distribution and relative utility utilization rate

4. Acknowledgements

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