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Incorporation of Scheduling Considerations in Retrofitting Design of Heat Exchange Networks

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The objective of this work is to introduce a systematic procedure for incorporating heat integration and process scheduling into the design phase. A hierarchical approach is developed. First, a formulation is developed to account for the anticipated schedules and heat integration during the design phase. Because of the complexity of the formulation for heat integration with varying flows and temperatures, a new targeting approach has been introduced. A linearization approach is adopted by discretizing the searched space for temperatures. Then, integer cuts are added to select the optimal temperatures. This results in a mixed-integer linear programming formulation for the targeting of minimum heating and cooling utilities for the various schedules. In order to synthesize a flexible configuration of the heat integration network, a multiperiod formulation is developed to account for the variations associated with the anticipated schedules.

1. Introduction

With changing market conditions and demands, various industries must develop design and operating strategies that enable the cost-effective operation of the process while addressing several key objectives. Production schedules should be determined so as to increase revenue, enhance efficiency, and conserve natural resources. Proper heat integration in chemical plant is one of the essential strategies for an efficient operation and can lead to considerable cost savings. Over the past 30 years, significant research contributions have been made in developing design techniques for the synthesis of heat exchange networks (HENs). Much of this work has focused on heat integration as the overarching goals with objectives such as minimizing heating and cooling utilities and total annualized cost of the network. On the other hand, much less work has been done in the area of reconciling heat integration with other process objectives. Mathematical programming techniques have been effectively used to address several important categories of HENs. In an attempt to exploit the interactions between the process operating conditions (stream temperatures and flowrates) and the heat recovery network, Papoulias and Grossmann (1983) developed a strategy for simultaneous optimization of the process and heat integration based on mixed integer linear programming (MILP) (Papoulias and Grossmann 1983). Scheduling is a critical issue in process operations and is crucial for improving production performance for a given process design. Scheduling can be short or long term. Short-term production scheduling

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deals with general problems of different sets of due dates of the products demand(Mendez and Cerda 2002; Shaik and Floudas 2007). The objective of short-term scheduling is to determine the optimal production plan utilizing the available resources over a given time horizon while satisfying production requirements at due dates and/or at the end of the time horizon(Ierapetritou and Floudas 1998; Ierapetritou and Floudas 1998; El-Halwagi 2006). For processes involving operational changes based on market-driven schedules, heat integration is typically included in the base-case design according to the nominal input data. As the process schedules are developed to accommodate market changes, there are two key limitations for the designed HEN, namely, inflexibility and optimality. To overcome these limitations, following will be addressed in this work:

1. Accounting for expected schedules in the base-case design
2. Incorporation of a flexible HEN synthesis into the design while considering expected schedules

The proposed approach establishes tradeoffs between design, economic aspects of scheduling, and net savings from heat integration. The proposed approach also synergizes and incorporates scheduling aspects of the process into the design of the HEN.

2. Problem Statement

The problem to be addressed by this work is that given a continuous process with:

- A set of unit operations U= {u|u= 1,2, …, N_u}. Each process unit, u, has a set of input streams $INPUT_u$ = $\{i_u \mid i_u = 1,2...,N_u^{in}\}$ and a set of output streams $OUTPUT_u$ = $\{j_u \mid j_u = 1,2...,N_u^{out}\}$. An input stream, i_u, has a flowrate, F_{i_u}, the composition of component q , $X_{i_u,q}$, and a temperature, T_{i_u}, while an output stream , j_u, has a flowrate, G_{j_u}, the composition of component q, $Y_{j_u,q}$ and a temperature, T_{j_u}.
- The input or output process streams that need to be cooled are defined as hot streams and given by the set HP={y|y= 1,2,…, N_{HP}}. On the other hand, the input or output process streams that need to be heated are defined as cold streams and given by the set CP={v|v= 1,2,…, N_{CP}}. Every hot or cold stream has a supply and target temperatures, i.e., T^s and T^{tg} for hot streams and, t^s and t^{tg} for cold streams.
- The process also has set of utility hot streams, HU={y|y= 1,…, N_{HU}}, and set of utility cold streams, CU={v|v= 1,…, N_{CU}}. The hot and cold utilities are used to provide the necessary heating and cooling requirements after heat integration of the process that is conducted simultaneously with the process operation and production scheduling. Flowrates and inlet and outlet temperatures of the process hot and cold streams are to be optimized.
- A given decision-making time horizon ($time_h$). Within this horizon, the variations in the market conditions are anticipated and expressed in terms of time-dependent changes in quantities and prices of supply (e.g., feedstocks, utilities, etc.) and demand (e.g., products and byproducts).

It is desired to develop a systematic procedure that can determine optimal process design that accounts for expected scheduling and heat integration.

3. Proposed Approach

To simplify the problem, the following assumptions are introduced:

- The decision-making time horizon is discretized into N_t periods leading to a set of operating periods: PERIODS = {t|t= 1,2, …,N_t}. Within each time period, the process operates in steady-state mode. Also, it is only allowed to have intra-period integration (i.e., no streams are stored, integrated, and exchanged over more than one period). In selecting the number and duration of the periods, one has to strike proper balance between capturing the market variations, significance to the process, and computational efforts.
- Process units' modifications are conducted by manipulating certain design and operating variables for each unit within permissible ranges, i.e.,

$$d_u^{\min} \le d_u \le d_u^{\max} \quad \text{and} \quad o_u^{\min} \le o_u \le o_u^{\max} \quad \forall\, u \in \mathrm{U} \tag{1}$$

  which implies that the design of the current process is flexible enough to produce any of the anticipated production schedules and that there is no economic incentive to add a process unit or reroute process streams.

The mathematical formulation is divided into three key steps as was described in Fig. 1. They are detailed in the following sections:

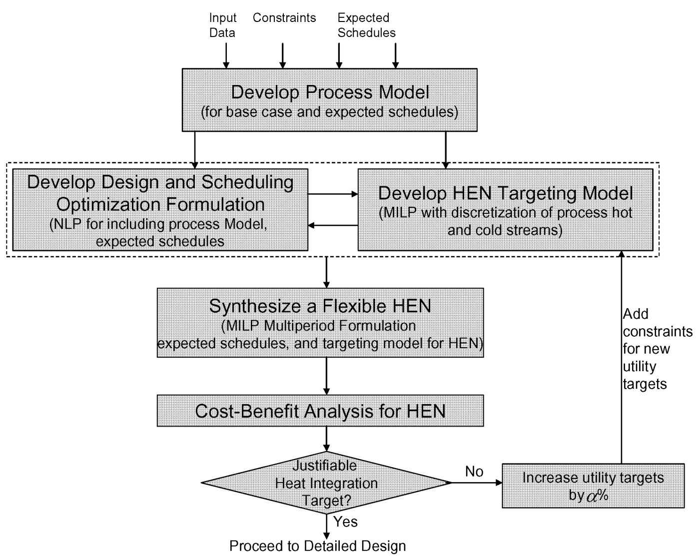

Figure 1. Flowchart of Simultaneous Heat Integration and Scheduling Approach

4. Mathematical Program

4.1 Design and scheduling model

In this section, design and scheduling models of the process are illustrated._The mass balance equation for unit u during period t is given by:

$$\sum_{j_u} G_{j_u,t} = \sum_{i_u} F_{i_u,t} \qquad \forall u,t \tag{2}$$

and the q^{th} component balance for unit u during period t is expressed as:

$$\sum_{j_u} G_{j_u,t} * Y_{j_u,q,t} = \sum_{i_u} \left(F_{i_u,t} * X_{i_u,q,t} + \mathrm{Net\_Gen}_{u,q,t} \right) \qquad \forall q,u,t \tag{3}$$

The energy balance is given by:

$$\sum_{j_u} G_{j_u,t} * h_{j_u,t} = \sum_{i_u} F_{i_u,t} * h_{i_u,t} \qquad \forall u,t \tag{4}$$

where the additional index, t, in the flowrates, compositions and temperatures refers to the time period over which these flowrates, compositions and temperatures are considered. Additionally, the performance model for unit u at period t is expressed as by a set of algebraic equations represented by:

$$(G_{j_u,t}, Y_{j_u,q,t}, T^{out}_{j_u,t} : j_u = 1,2,...,OUTPUT_u , q \in Q \text{ and } t \in PERIODS)$$

$$= f_u(F_{i_u,t}, X_{i_u,q,t}, T^{in}_{i_u,t} : i_u = 1,2,...,INPUT_u , q \in Q \text{ and } t \in PERIODS, d_{u,t}, o_{u,t}) \tag{5}$$

The flowrate, composition and temperature constraints for the i_u^{th} input to the process units and for the j_u^{th} output from the process units are given by:

$$F^{\min}_{i_u} \le F_{i_u,t} \le F^{\max}_{i_v}, F^{\min}_{j_u} \le F_{j_u,t} \le F^{\max}_{j_u}, X^{\min}_{i_u,q} \le X_{i_u,q,t} \le X^{\max}_{i_u,q}, X^{\min}_{j_u,q} \le X_{j_u,q,t} \le X^{\max}_{j_u,q},$$

$$T^{\min}_{i_u} \le T_{i_u,t} \le T^{\max}_{i_u} \quad T^{\min}_{j_u} \le T_{j_u,t} \le T^{\max}_{j_u} \tag{6}$$

4.2 HEN targeting model with discretization of process hot and cold streams

Because of the changing temperatures and flowrates, the targeting model for identifying minimum heating and cooling utilities of the HEN becomes an MINLP. As mentioned before, there are convergence problems coupled with the nonconvexity of the nonlinear terms leading which make it difficult to achieve the global solution. Therefore, we introduce a new targeting formulation which results in an MILP that readily converges to the global solution. The temperature interval diagram (TID) is used for the devised mathematical program of the variable temperature and flow HEN. Both supply and target temperatures are discretized in the feasible range where the mathematical programming will insure the choice of the supply and target temperatures linked to the optimal simultaneous scheduling and heat integration.

As explained before, the process has a set of CP cold streams and HP hot streams as indicated above as well as CU referring to cooling utilities and HU referring to hot utilities. The following indices are used: h for a process hot stream, g for a cold process stream, y for an external heating utility, v for external cooling utility, and z for temperature intervals. The hot and cold temperatures are separated by a minimum driving force, ΔT_m.

In order to avoid the nonlinearities and complexities associated with the the unknown supply and target temperatures, a discretization technique is used along with the use of integer cut. The basic idea is that each supply and target temperature is discretized into a number of scenarios spanning the feasibility range of the temperature. For instance, for the hot stream h in period t, a number $N_{h,t}$ of discretized streams are created. The index p_h is used for the various discretizations of hot stream h in period t. Each discretization is assigned the full flowrate of the h^{th} stream (i.e., $F_{h,p_h,t} = F_{h,t}$). Eventually, only one of the discretizations will be selected. For each p_h , a supply and a target temperatures are selected. These supply and target temperatures are designated by $T^s_{h,p_h,t}$ and, $T^t_{h,p_h,t}$, respectively. Their values are selected while satisfying the following constraints on the permissible range for each supply and target temperature:

$$T_h^{s,\min} \le T^s_{h,p_h,t} \le T_h^{s,\max} \quad \text{and} \quad T_h^{t,\min} \le T^t_{h,p_h,t} \le T_h^{t,\max} \quad \forall\, h, p_h \tag{7}$$

A similar discretization scheme is created for the process cold streams, i.e.

$$t_g^{s,\min} \le t_{g,p_g,t}^{s} \le t_g^{s,\max} \quad \text{and} \quad t_g^{t,\min} \le t_{g,p_g,t}^{t} \le t_g^{t,\max} \quad \forall\, g, p_g \tag{8}$$

Figure 2 shows the temperature interval diagram (TID) for the discretized streams.

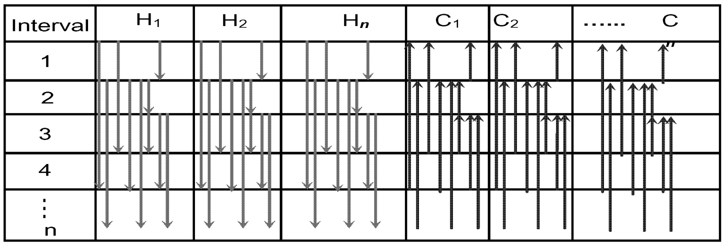

Figure 2. TID diagram for discretized supply and target temperatures

For the zth interval on the TID, the exchangeable load of the p_h^{th} or p_g^{th} scenarios of the hot and the cold streams passing through the zth interval are defined as:

$$HH_{z,h,p_h,t} = F_{h,t}C_{p,t}(T_{z-1,t} - T_{z,t}) \quad \text{and} \quad HC_{z,g,p_g,t} = f_{g,t}C_{p,t}(t_{z-1,t} - t_{z,t}) \tag{9}$$

where T_{z-1} and T_z are the hot-scale temperatures at the top and the bottom lines defining the zth interval and t_{z-1} and t_z are the corresponding cold scales.

Next, for each discretization of the process hot and cold streams, a binary integer variable is introduced. These binary variables are referred to as $I_{h,p_h,t}^{hot}$ and $I_{g,p_g,t}^{cold}$ for the hot and the cold discretization, respectively. To ensure that only one discretization exists for each hot and cold stream, binary integer variables are introduced and defined by the following constraints:

$$\sum_{p_h} I_{h,p_h,t}^{hot} = 1 \quad \text{and} \quad \sum_{p_g} I_{g,p_g,t}^{cold} = 1 \tag{10}$$

Now, the heating and cooling utilities are incorporated in the model. For temperature interval z, the heat load of the yth heating utility is given by:

$$HHU_{y,z,t} = FU_{y,t}Cp_y(T_{z-1,t} - T_{z,t}) \tag{11}$$

The sum of all heating loads of the heating utilities in interval is expressed as:

$$HHU_{z,t}^{total} = \sum_y HHU_{y,z,t} \tag{12}$$

Similarly the cooling capacity of the vth cooling utility in the zth interval is calculated as follows: $HCU_{v,z,t} = fU_{v,t}Cp_v(t_{z-1,t} - t_{z,t})$ (13)

where $fU_{v,t}$ is the flowrate of the vth cooling utility. The sum of all cooling capacities of the cooling utility is expressed as: $HCU_{z,t}^{total} = \sum_v HCU_{v,z,t}$ (14)

The flowrate assigned from j_u to the pth product stream is $p_{j_u,p,t}$. The flowrate of the pth product in period t is described by: $P_{p,t} = \sum_u \sum_j p_{j_u,p,t}$ (15)

The product demand and composition constraints are expressed as:

$$P_{p,t} \le P_{p,t}^{Demand} \tag{16}$$

The HEN targeting formulation can now be coupled with the previously-developed model for design and scheduling. The objective function of maximizing the gross profit of the process is given by:

Maximize Gross Profit =

$$\sum_t \sum_p C_{p,t}^{product} * P_{p,t} - \sum_t POC_t - \sum_t \sum_z \left(C_{hot,t} * HHU_z^{total} - C_{cold,t} * HCU_z^{total} \right) \qquad (17)$$

where $C_{p,t}^{product}$ is the unit selling price of product p during period t, POC_t represents the plant operating cost (e.g., feedstocks, utilities, etc.) during period t, $C_{hot,t}$ is the price of the heating utility and $C_{cold,t}$ is the price of cooling utility during period t. The foregoing model constitutes the optimization program for the problem. If the process model is linear, then the combined formulation for the design, scheduling and HEN targeting is a mixed-integer linear program (MILP). Otherwise, it becomes a mixed-integer nonlinear program (MINLP). The solution identifies the optimal scheduling, process modifications, and the optimum target of heating and cooling utilities. Next, the HEN configuration has to be synthesized to be flexible enough to accommodate the changes associated with the anticipated schedules. This is shown in the next section.

5. Conclusions

A novel methodology for simultaneous process scheduling and heat integration has been introduced. This approach includes design modifications, heat integration, and anticipated schedules. A formulation has been developed to account for the anticipated schedules and heat integration during the design phase. Because of the complexity of the formulation for heat integration with varying flows and temperatures, a new targeting approach has been introduced. It is based on discretizing hot and cold streams into substreams then using integer cuts to select the optimal temperatures and flows. A multiperiod formulation has been developed to insure flexibility of the designed HEN. This approach determines the optimal production while considering heat integration of the process. Trade-off between the two competing objectives has been established in this approach.

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