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Energy Integration of Large-Scale Industrial Sites with Target-Compatible Sub-System Division Strategy

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This paper presents a targeting strategy to solve the heat load distribution (HLD) problem for large-scale plant by dividing the system into sub-systems while considering the heat transfer opportunities between them. The methodology is based on a sequential approach. The optimal flow rates of utilities are first defined using a Mixed Integer Linear Programming (MILP) model. The site is then divided into the sub-systems where the overall interaction is resumed into a pair of virtual hot and cold stream with nonlinear T-H profile. The HLD problem is solved between these subsystems in a sequential procedure by considering a MILP model between these virtual representative streams, while each time one of the sub-systems is switched from virtual streams to the real ones. The main advantages are to reduce the size of the HLD problem and to find a feasible solution which is compatible with the minimum energy requirement (MER) objective. The potential of direct heat recovery between sub-systems are considered and the method can be practically adopted to consider the restricted matches between sub-systems as well. This methodology has been currently applied on a real site scale process integration industrial example and in this paper its application is illustrated through a case study with 23 streams.

1. Introduction

Pinch Analysis technique (Linnhoff and Boland, 1982) has shown to be a promising tool to optimize the energy efficiency of industrial processes based on the process integration concept. In this technique targets are primarily defined as a minimum energy requirement (MER) of the system and are later satisfied by properly designing the heat exchanger network (HEN). The pinch design method (PDM), presented by (Linnhoff and Hindmarsh, 1983) for the heat exchanger network, has successfully been used in a large number of industrial companies around the world. Meanwhile, the methodologies for grassroots and retrofit design of HENs based on the Pinch Analysis and the PDM suffer from a couple of limitations (Klemeš, 2013). They usually imply difficult manual procedure to generate a solution while there is no guarantee for the solution to be the optimal one. These limitations have motivated to alternatively use optimization methods for the HEN synthesis.

In mathematical programming (MP) approaches, the synthesis procedure of HEN generally includes three stages of problem analysis: minimum utility requirements calculation, heat load distribution (HLD) and network layout synthesis. The MP methods based on sequential approach solve those three stages of the HEN problem consecutively (Papoulias and Grossmann, 1983). The HLD with an objective function of minimizing the number of connections can be formulated as a Mixed Integer Linear Programming (MILP) model (Maréchal and Kalitventzeff, 1989). Meanwhile, the search space of optimization problems with integer variables grows exponentially with the number of binary variables. Therefore, for a large-scale industrial site, the correspondent MILP problem becomes either infeasible or very expensive to solve with the available mathematical software. It has been reported that dealing with problems with more than 30 streams is considered to be complicated (Klemeš, 2013). On the other hand, HLD has multiple solutions where each of them results into different total area and cost of network. In order to have an optimal solution with respect to both operating and investment cost, simultaneous MINLP optimization models were developed (Yee and Grossmann, 1990). Frequently in the literature, the HEN synthesis problem with MP is addressed by either sequential methods or simultaneous MINLP models with gradient-based or

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stochastic search algorithm. An extensive review of the main research in this area can be found in the annotated bibliography of (Furman and Sahinidis, 2002). It provides some classification of the publication and the chronological milestones in development of the HEN problem in the 20th century. A review of the available design methods with the evaluation of their usefulness and applicability is also presented by (Van Reisen et al., 2008) and recent publications on HEN synthesis are reviewed in (Gundersen, 2013) and (Klemeš et al., 2013). The simultaneous MINLP methods, however, come out to be quite problematical due to the computational complexity that resides on the number of binary variables and also the numerical problem related to non-convexity feature of the model that trend towards local optimum rather than global one.

The above cited insight along with the great tendency in most of industries towards the minimum heat exchange among different process sub-systems rather than between streams, have motivated us to propose a new methodology for targeting the energy integration of large-scale industrial sites. This methodology solves the HLD model in sequential steps among and inside process sub-systems to overcome the computational complexity of large-scale problem.

2. Methodology

The main idea is to systematically break down the problem into a number of sequential steps while compromising with the optimum operating cost target. The steps are as following:

- In the first step, a Mixed Integer Linear Programming (MILP) problem for the total site heating and cooling requirement is solved to define the optimal flow rates of the utilities and the minimum operating costs.
- Once energy saving targets identified, in the second step the site is divided into a number of sub-systems based on the characteristics of the plant (such as location, process type or working period) (Dalsgård et al., 2002). The sub-system division in the case of retrofit can be performed with help of result of multi-objective optimization over all available heat transfer interfaces of each energy requirement.
- All the streams belonging to of each the sub-systems are replaced by a pair of virtual hot and cold streams with nonlinear T-H profile built by solving the heat cascade internally in each of the sub-systems.
- The HLD problem is solved with a MILP model for the total site with these virtual streams.
- The HLD problem with MILP model is then solved repeatedly for each sub-system and its connection with outside streams, by switching the virtual pair streams into the original ones.

The result shows a practical heat integration solution which satisfies the MER target and the minimum numbers of connections between sub-systems, since the optimum flow rate of streams is fixed at the targeting level by MILP optimization solved beforehand. This strategy is applicable for both retrofit and grassroots design. It can also be used for the total site integration between industrial clusters. Another advantage of considering the sub-system rather than streams is to reduce the computational complexity of HLD model for large-scale problem.

This method is also compatible with the restricted matches methodology of (Becker and Maréchal, 2011), but unlike their method, it is not required to define heat transfer intermediates since the restricted matches are not imposed to the system.

3. Optimization algorithm

The overall optimization algorithm is summarized in the flowchart of Figure 1. A mixed integer linear programming (MILP) model proposed by (Maréchal and Kalitventzeff, 1998) is applied to identify the optimal integration of the energy conversion units. The objective is to minimize the operating costs including fuel and electricity contribution Eq. (1).

$$F_{obj_{opt-cost}} = min\left(\left(\sum_{f=1}^{nf}\left(c_f^+ \sum\nolimits_{u=1}^{nu} f_u \dot{E}_{f,u}^+\right) + c_{el}^+\dot{E}_{el}^+ - c_{el}^-\dot{E}_{el}^- + \sum_{u=1}^{nu} f_u c_u\right).t\right) \quad (1)$$

In the above expression f_u is the multiplication factor of unit u. The c_{el}^+ and c_{el}^- are respectively the electricity purchase cost and selling price. The fuel price is c_f^+ and the nominal energy which is delivered to unit u by the fuel is noted by $\dot{E}_{f,u}^+$. The total electricity demand and the supply of the system are respectively expressed by $\dot{E}_{el}^+$ and $\dot{E}_{f,u}^-$. Finally c_u is the nominal operating cost of unit u per hour. Eq(2) gives the expression for the heat cascade for each temperature interval k. In Eq(2), $\dot{Q}_{h,k,u}$ is the nominal heat load of hot (or cold $\dot{Q}_{c,k,u}$) stream in the interval k and which belongs to unit u and the cascaded heat from the temperature interval k to lower temperature intervals is noted by $\dot{R}_k$. Eq(3) formulates the thermodynamic feasibility of the heat recovery.

$$\sum_{h_k}^{ns_{h,k}} f_u \dot{Q}_{h,k,u} - \sum_{c_k=1}^{ns_{c,k}} f_u \dot{Q}_{c,k,u} + \dot{R}_{K+1} - \dot{R}_K = 0 \qquad \forall k = 1, \cdots, nk \tag{2}$$

$$\dot{R}_1 = 0 \qquad \dot{R}_{nk+1} = 0 \qquad \dot{R}_k \geq 0 \qquad \forall k = 2, \cdots, nk \tag{3}$$

For the retrofit problem, the all the existing heat transfer units of energy requirements have to be considered in the MILP problem as well by adding a new constraint to the original MILP formulation that guarantee the presence of only one interface for each energy requirement. (See Eq(4)) (Pouransari et al., 2014) This constraint is defined with an associated integer variable $y_{u,r}$ to each heat transfer interface of a process unit. If the process unit u is represented by representation r then $y_{u,r} = 1$, otherwise $y_{u,r} = 0$.

$$\sum_{r=1}^{nr_u} y_{u,r} = 1 \qquad \forall u = 1, \cdots, nu_p \qquad y_{u,r} \in \{0,1\} \tag{4}$$

Where $nr_u$is number of representation of process unit u and nu_p is the number of process units.
In order to apply the identified energy saving potential, the heat load distribution (HLD) based on process and optimal utility streams, has to be calculated first. The HLD is the sub-problem of the heat exchanger network (HEN) synthesis and can be formulated as a MILP model to minimize the number of connection between streams (see Eq(5)).

$$F_{obj_{hld}} = min\left(\sum_{j=1}^{ns_c}\sum_{i=1}^{ns_h} y_{ij}\right) \tag{5}$$

$$\sum_{j=1}^{ns_c} Q_{ijk} = Q_{ik} \qquad \forall i = 1, \cdots, ns_h, \qquad \forall k = 1, \cdots, nk \tag{6}$$

$$\sum_{i=1}^{ns_h}\sum_{k=1}^{nk} Q_{ijk} - Q_j \geq 0 \qquad \forall j = 1, \cdots, ns_c \tag{7}$$

$$\sum_{k=1}^{nk} Q_{\boldsymbol{ijk}} - y_{ij} Q_{\max ij} \leq 0 \qquad \forall j = 1, \cdots, ns_c\,, \qquad \forall i = 1, \cdots, ns_h \tag{8}$$

$$Q_{ijk} \geq 0 \qquad y_{ij} \in \{0,1\} \qquad \forall j = 1, \cdots, ns_c, \qquad \forall i = 1, \cdots, ns_h, \qquad \forall k = 1, \cdots, nk \tag{9}$$

Eq(6) and (7) describes the heat balances of the hot and cold streams. Eq(8) shows the existence of a connection between hot stream i and cold stream j. The heat load value has to be positive (Eq(9)).
When the industrial large-scale site is divided into sub-system the objective function of HLD model is replaced by Eq(10) to take into account heat exchange between sub-systems. The $nsub$ is the number of process sub-systems and $ns_{utility,h}$ and $ns_{utility,c}$ are the number of hot and cold utility streams. Then for each sub-system the HLD model is solved separately using the Eq(10) as an objective function to find the minimum number of connection between the streams of sub-system with outside streams. The $ns_{sub,c}$ is the number of cold stream of the sub-system and $ns_{outside,c}$ is the number of cold streams in outside of sub-system that has a connection with it. The same definition is valid for the hot streams terms.

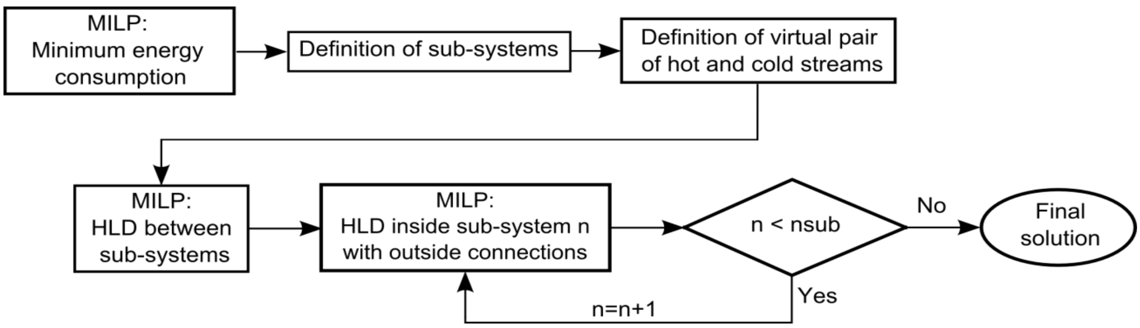


Figure 1: Schematic of the algorithm of solution procedure

$$F_{obj_{hld}} = min\left(\sum_{j=1}^{(nsub+ns_{utility,c})} \sum_{i=1}^{(nsub+ns_{utility,h})} y_{ij}\right) \quad (10)$$

$$F_{obj_{hld,sub}} = min\left(\sum_{j=1}^{(ns_{sub,c}+ns_{outside,c})} \sum_{i=1}^{(ns_{sub,h}+ns_{outside,h})} y_{ij}\right) \quad (11)$$

4. Numerical example

In order to illustrate the application of the method, a process system from a chemical industry with 19 process streams is studied. A midscale case study is chosen to be able to solve the HLD directly and compare it with the result of proposed methodology. The list of streams is given in Table 1.

Each step of the methodology is presented graphically for the case study in Figure 2. The red and blue vertices are the hot and cold streams respectively. The green edges represent the connection between vertices. The MILP formulation, presented in section 3 is applied to integrate the optimized utility system (Figure 2.a). In Figure 2.b the process streams are assigned to three sub-systems. The heat cascade is then calculated for each sub-system separately and the streams are replaced by the relevant hot and cold composite curves to reduce the number of streams from 23 to 10 (Figure 2.c). By solving the HLD model between the virtual and utility streams, the connection between sub-systems are distinguished with the minimum value of 11 (Figure 2.d). Then sub-system A with its connection to other sub-systems is separated from the rest of the graph (Figure 2.e). The HLD problem between the real streams of sub-system A and outside connections is then solved (Figure 2.f). The same procedure is followed for sub-system B and C (Figure 2.g-h). The graph of Figure 2.i shows the final solution HLD with total number of 23 connections between all streams, resulted from merging all the correspondent graphs for sub-system A, B and C.

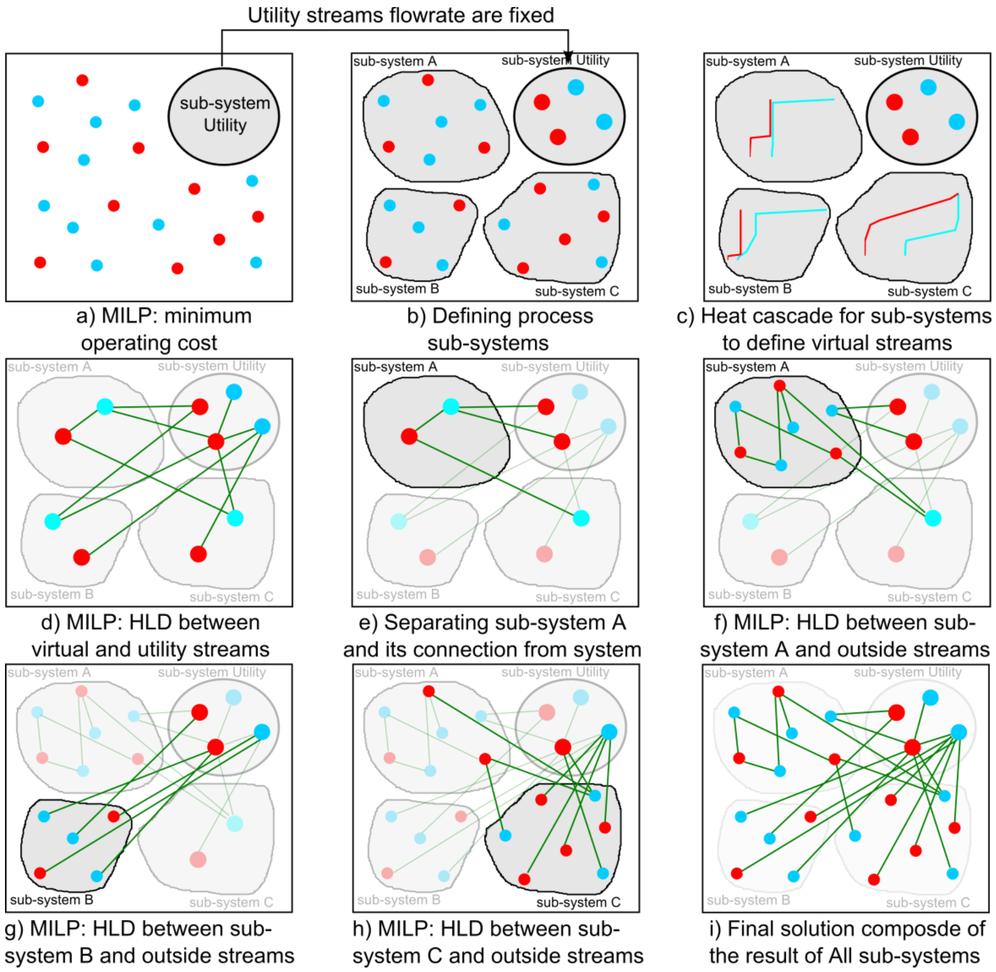


Figure 2: Schematic of the optimization procedure for the case study

Table 1: List of process streams of case study

Hot streams	T_{in} [°C]	T_{out} [°C]	Q [kW]	$\Delta T_{min}/2$ [°C]	Cold streams	T_{in} [°C]	T_{out} [°C]	Q [kW]	$\Delta T_{min}/2$ [°C]
h1	40	38	10	5	c1	25	38	10	5
h2	45	40	70	5	c2	25	40	70	5
h3	105	61	250	5	c3	44	98	250	5
h4	85	79	1195	3	c4	15	111	212	3
h5	38	30	11	5	c5	30	37	10	5
h6	79	41	50	3	c6	16	41	13	3
h7	41	35	131	3	c7	40	51	35	3
h8	150	95	1625	5	c8	52	74	1,625	5
h9	159	103	1441	3	c9	180	190	3,746	2
h10	250	250	3,447.3	25	c10	190	205	1,080	2
h11	250	160	2,900	25	c11	13	23	3,742.8	2
					c12	15	160	336.6	25

The complete heat load distribution result for both normal MILP and the sequential approach is shown in Figure 3. The result is separated for each zone created by two consecutive pinch points. These results can be later used to design the heat exchanger network.

In Figure 4.a-b, the graph of HLD result by sequential approach and normal MILP is compared. The HLD graph at the level of sub-system is also shown in Figure 4.c-d. The black edges show the additional/different connections in normal HLD. The comparison shows that minimum number of connection between sub-systems does not guarantee the minimum number of connection between streams. The analogous argument is valid as well.

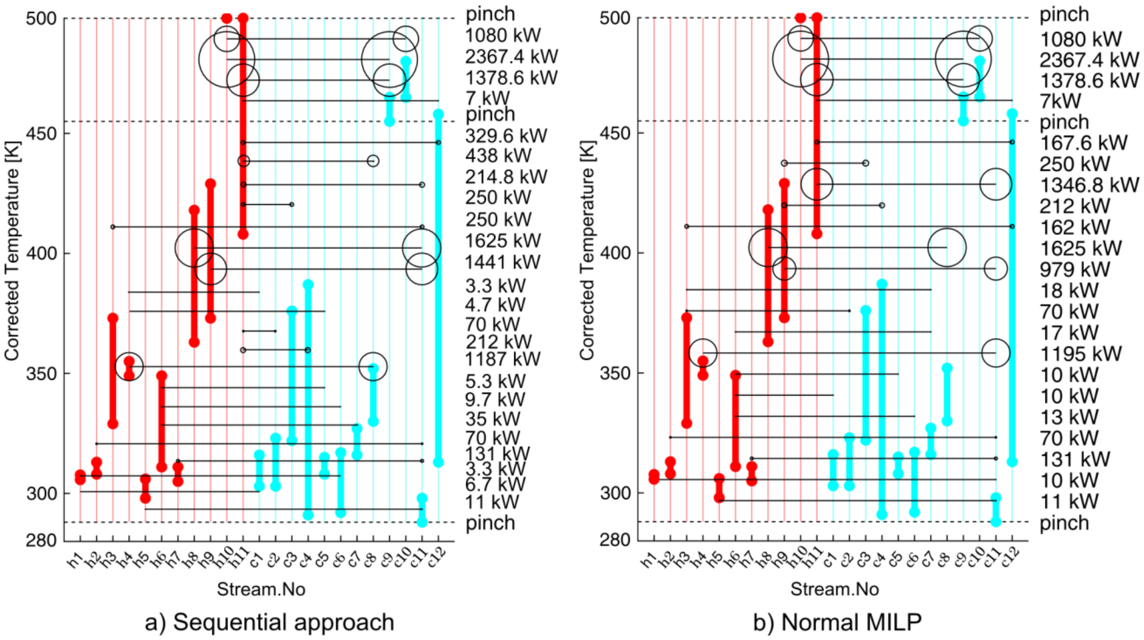
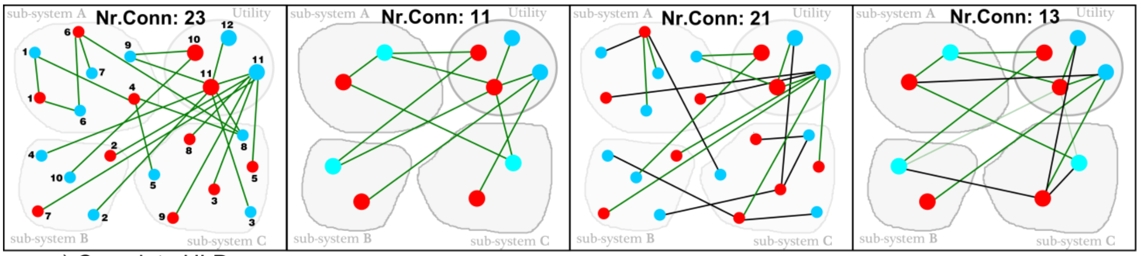


Figure 3: Heat load distribution result



a) Complete HLD with sequential approach | b) HLD between sub-systems with sequential approach | c) Complete HLD with normal MILP | d) HLD between sub-systems with normal MILP

Figure 4: Graphs of complete HLD and HLD between sub-systems

5. Conclusions

A sequential methodology for energy integration and optimization of site scale industries is proposed. The sub-system concept is used to solve rigorously the HLD problem in total site by respecting the operating cost target. The MILP model is solved between the sub-systems and then sequentially inside each of them. This feature of methodology solves the computational complexity issues of large size model by reducing the number of streams in each step and consequently number of binary variables. Another significant benefit of this approach is to define the minimum number of connection between process sub-systems rather than the streams of total site, which has a great interest in retrofit of industrial clusters. Although the method presented in this paper is demonstrated by a midscale sample with 23 streams, the method is appropriate to solve complex industrial problem with more populated streams. The method is also practical for both retrofit and grassroots design and it is adoptable for the system with restricted matches. Moreover, it considers the potential of heat recovery between sub-systems without imposing heat transfer intermediate, unlike previous methods.

References

Becker H., Maréchal F., 2011, energy integration of industrial sites with heat exchange restrictions, Computer and Chemical Engineering, 37, 104-118.

Dalsgård H., Maagoe P.P., Qvale B., 2002, Simplification of process integration studies in intermediate size industries, Energy Conversion and Management, 43(9-12), 1393-1405.

Furman K.C., Sahinidis N.V., 2002, A critical review and annotated bibliography for heat exchanger network synthesis in the 20th century, Industrial and Engineering Chemistry Research, 41, 2335-2370.

Gundersen T., 2013, Analysis and design of heat recovery system for grassroots and retrofit situations, chapter (8), In: Klemeš, J.J. (Ed.), Handbook of Process Integration (PI): Minimisation of Energy and Wateruse, Waste Emissions, Cambridge, United Kingdom, Woodhead Publishing/Elsevier.

Klemeš J., 2013, Handbook of Process Integration (PI): Minimisation of Energy and Wateruse, Waste Emissions, Cambridge, United Kingdom, Woodhead Publishing/Elsevier..

Klemeš J.J., Varbanov P.S., Kravanja Z., 2013, Recent developments in Process Integration, Chemical Engineering Research and Design, 91, 2037-2053.

Linnhoff B., Boland D., 1982, A user guide on process integration for the efficient use of energy.

Linnhoff B., Hindmarsh E., 1983, The pinch design method for heat exchanger networks, Chemical Engineering Science, 38, 745-763.

Maréchal F., Kalitventzeff B., 1989, Synep1: A methodology for energy integration and optimal heat exchanger network synthesis, Computers and Chemical Engineering, 13, 603-610.

Maréchal F., Kalitventzeff B., 1998, Process integration: Selection of the optimal utility system, Computers and Chemical Engineering, 22, S149-S156.

Papoulias S.A., Grossmann I.E., 1983, A structural optimization approach in process synthesis-I. Utility systems, Computers and Chemical Engineering, 7, 695-706.

Pouransari N., Bocquenet G., Marechal F., 2014, Targeting the Retrofit of industrial utility system and heat exchanger network, Ecos 2014. Turku, Finland.

Van Reisen J., Grievink J., Verheijen P., 2008, A structured approach to heat exchanger network retrofit design. PhD thesis, Technical University of Delf, the Netherlands,

Yee T.F., Grossmann I.E., 1990, Simultaneous optimization models for heat integration-II. Heat exchanger network synthesis, Computers and Chemical Engineering, 14, 1165-1184.