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A MILP algorithm for utilities pre-design based on the Pinch Analysis and an exergy criterion

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ABSTRACT

Designing Heat Exchangers Network for heat recovery is a challenge currently solved with optimization algorithms. However, making a tradeoff between HEN and utilities rely on how relevant are the proposed utilities. In this paper we propose a preselection algorithm for utilities, focused on chillers, heat pumps, Organic Rankine Cycles (ORC) units and Combined Heat & Power (CHP) units. The Pinch Analysis is used to provide input data such as the Grand Composite Curve (GCC). A MILP algorithm based on an exergy criterion automatically preselects and predesigns utilities from the GCC. The formulation of the optimization problem is described, and so the degrees of freedom for the user. Finally, an example from Food & Drink industry shows the performance of this algorithm. Fast and accurate, this algorithm has been implemented in a software named CERES to prepare the results for the HEN design, which is not described in this article.

1. Introduction

In the early 90s, Linnhoff (Linnhoff, 1990) developed a methodology for the study of chemical industry processes. To summarize hot and colds needs, he created Composites Curves and Grand Composite Curve (GCC) which allow a graphical representation of possible heat recovery. Then he suggested a graphical way to position utilities on GCC. To cover heat demand, he disposed three level of vaporized water (High, Middle and Low Pressure). For cooling needs, cooling water and chiller are used. Even if manual, this method shows the interest of the GCC for utilities integration. For instance, it has been used to design a CHP unit with superheated vapor (Zainuddin and Yee, 2004) or a heat pump on a biomass plants (Pavlas et al., 2010).

Others developed algorithmic methods to fit utilities to the MER at the lowest cost (Papoulias and Grossmann, 1983), and to optimize a set of three heat pumps coupled with energy storage (Murr et al., 2011). A multi-optimization has been run to optimize heat pumps and CHP units on both economic and environmental criteria (Dumbliauskaite et al., 2009). These cases deal with optimization of utilities which have been previously and manually preselected and defined by their temperature levels. The challenge lies in the fact that the amount of heat transferred and the efficiency of utilities tightly rely on temperature levels. In literature references, these lasts are set up before optimization step, and trial-and-error are required. Such iterations could be time-consuming if there are too many utilities to explore.

Moreover, the present algorithm is a part of a research project (Ceres Project, 2011–2014). We have to keep in mind this following step: the Heat Exchangers Network (HEN) design. If some algorithms exist to design HEN, in different ways of programming (MILP, NLP, MINLP, EA, SA, ...), inputs data have to be set very precisely. For minimizing the global cost (HEN and utilities), the algorithm picks up utilities in a set defined by the user. If too many utilities are available in the set, algorithm may crash down because of complexity. Moreover, relevant utilities that are not submitted will never be chosen.

The objective of the present article is to describe an algorithm that makes in one step automatic utilities preselection and predesign. This MILP algorithm is based on the Grand Composite Curve (GCC) utilization and a simplified exergy definition. Independently from their cost, utilities proposed by the present algorithm will be chosen according to their energy efficiency, based on exergy criteria. It has the following features:

- Defines the number of utilities of each type.
- Makes a useful step between data extraction and HEN design.
- Tests various, fitted combinations of utilities.

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CHP_{max} maximum number of CHP units to pre-design
CondP mean pinch at condenser [K]
$COPGf_{y,j}$ coefficient of performance for chiller which evaporates at $T_{y,j}$
$COPPacPr_{y,j,z,k}$ coefficient of performance for heat pump between $T_{y,j}$ and $T_{z,k}$
$COPPacUt_{z,k}$ coefficient of performance for heat pump between T_0 and $T_{z,k}$
$EffOrc_{y,j}$ efficiency of ORC unit at $T_{y,j}$
$EffChp_j$ efficiency of CHP unit at $T_{y,j}$
EvaP mean pinch at evaporator [K]
GF_{max} maximum number of chillers to pre-design
MER minimal energy requirement
ORC_{max} maximum number of ORC units to pre-design
PAC_{max} maximum number of heat pumps to pre-design
$Q_{z,k}$ heat load of element k in zone z (input data) [kW]
RdtEx mean exergetic efficiency of thermodynamics utilities
S_z number of elements in zone z
T_0 ambiant temperature [K]
$T_{Condmax}$ maximum temperature for heat pumps condensers [K]
T_f flame temperature [K]
$T_{z,k}$ temperature of element k in zone z (input data) [K]
Z number of temperature areas

Variables
$BoolChp_k$ auxiliary binary variable that determines whether the kth CHP unit exists
$BoolGf_{z,k}$ auxiliary binary variable that determines whether the chiller at $T_{z,k}$ exists
$BoolOrc_{z,k}$ auxiliary binary variable that determines whether the ORC at $T_{z,k}$ exists
$BoolPacPr_{y,j,z,k}$ auxiliary binary variable that determines whether the process heat pump between $T_{y,j}$ and $T_{z,k}$ exists
$BoolPacUt_{z,k}$ auxiliary binary variable that determines whether the utility heat pump between T_0 and $T_{z,k}$ exists
InitExergy initial exergy requirements [kW]
InitMexr initial MExR (Minimum Exergy Requirements) [kW]
FinalExergy final exergy requirements [kW]
FinalMexr final MExR [kW]
$FChp_k$ continuous variable corresponding to the ratio between the heat load provided at $T_{Z,k}$ by the kth CHP unit and the heat load needed $Q_{Zones,k}$
$FGf_{z,k}$ continuous variable corresponding to the ratio between the heat load provided by the chiller at $T_{z,k}$ and the cooling need $Q_{z,k}$
$FOrc_{z,k}$ continuous variable corresponding to the ratio between the heat load taken by the ORC unit at $T_{z,k}$ and the cooling need $Q_{z,k}$
$FPacPr_{y,j,z,k}$ continuous variable corresponding to the ratio between the heat load taken at $T_{y,j}$ by the heat pump working between $T_{y,j}$ and $T_{z,k}$ (with $T_{y,j} < T_{z,k}$) and the heat load $Q_{y,j}$
$FPacUt_{z,k}$ continuous variable corresponding to the ratio between the heat load provided at $T_{z,k}$ by the heat pump working between T_0 and $T_{z,k}$ and the heat load $Q_{z,k}$
$NHL_{y,j}$ net heat load at $T_{y,j}$ [kW]
$PApp_{y,j}$ sum of heat loads provided by utilities at $T_{y,j}$ [kW]
$PElec_{z,k}$ electric consumption of utilities which operates at $T_{z,k}$ [kW]
$PPrel_{z,k}$ sum of heat loads taken by utilities at $T_{z,k}$ [kW]
PPrelChp heat load needed to feed CHP units [kW]
TEC total electric consumption of utilities [kW]
TEP total electric production of utilites [kW]
$THL_{z,k}$ net heat load at element k of zone z [kW]
ZEC_z electric consumption in zone z [kW]
ZEP_z electric production in zone z [kW]

2. Mathematical model

2.1. Definitions

2.1.1. Input data

The algorithm described in this paper is based on the Grand Composite Curve. As the GCC represents the net heat load needed for each temperature level, the implicit assumption is that possible direct heat exchanges have been performed. The remaining heat needs have to be provided by external utilities. In addition to basic utilities (e.g. boilers.), the algorithm pre-design advanced thermodynamics utilities, like heat pumps, ORC or CHP Units.

The algorithm uses GCC as input data. It is automatically generated by software CERES which applies the transshipment model. The vertical axis, the temperature range, is subdivided into several sections, delimited by the main pinch point (MPP) and other heat load minimum, thereafter called Potential Pinch Point (PPP) (Fig. 1). This defines a number of zones (Z), each of them delimited by 2 pinch points (main one or potential). At each PPP, self-sufficient pockets appear: when there is the same heat load at two different temperatures, an increase followed by a decrease of heat load required generates a self-sufficient pocket.

In each zone z, the angular points of the GCC are considered to create a first set of temperature intervals. These correspond to incoming or depleted heat flow. Moreover, a maximal temperature step is introduced as a parameter. Any higher temperature interval will be halved until it respects this parameter. It is a key parameter to balance speed and accuracy of the algorithm that should be fit to the studied process.

Once the temperature intervals defined, the parameter S_z defines the number of temperature segments in each zone z. Each point is therefore described by two parameters $T_{z,k}$ and $Q_{z,k}$, respectively temperature and heat load, with $z \in [1, Z]$ *et* $k \in [1, S_z]$.

2.1.2. Utilities modeling

The aim of this algorithm is to pre-design utilities that fit the best the process for the exergy criteria. At this preliminary step, simplified models based on thermodynamic laws have been developed, instead of consistent models. To pre-design utilities means find the optimal operating temperature levels for technology. Simple models are defined for each technology, based on ideal cycle efficiency and exergy efficiency. Defined as the ratio between the real cycle performance and the ideal one, the exergy efficiency is commonly set between 0.5 and 0.6. This value is considered as achievable for most of the technologies that are investigated (Ayachi et al., 2014)

Neither temperature levels nor heat load is known a priori for the utilities to be used. In the case of heat pumps, heat loads are linked to temperature with COP, which is temperature dependant, the problem could be non linear. To avoid non-linearity, but also to drastically limit the number of utilities and ease post-processing, a linear formulation with Boolean variables is proposed. A very large number of utilities will be described, using each couple of elements