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On the use of risk-based Shapley values for cost sharing in interplant heat integration programs

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HIGHLIGHTS

- The cost-sharing plan of a multi-plant HEN is modelled as a cooperative game.
- Core and risk-based Shapley values of all plants are computed systematically.
- Cost burden of a plant is determined from its contribution and potential fallouts.
- A simple example is provided to illustrate the proposed methodology.

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ABSTRACT

The heat exchanger network (HEN) is traditionally used for optimal heat recovery in a single chemical plant, while the multi-plant counterparts have been studied in recent years primarily for the purpose of reaping additional overall energy savings. Since all these works focused primarily upon minimization of the total energy cost, the resulting interplant heat integration arrangements were often infeasible due to the fact that the individual savings are not always acceptable to all participating parties. Although a few studies addressed this cost-sharing issue, the existing methodologies are still not mature enough for realistic applications. The present paper outlines a rigorous model-based two-stage procedure to handle this practical problem in the spirit of a cooperative game. The minimum total annual cost (TAC) of each and every potential coalition was first determined with a conventional MINLP model, while the core and the risk-based Shapley values of all players were then computed with explicit formulas derived in this work to settle the benefit allocation issues. A simple example is presented at the end of this paper to demonstrate the feasibility of the proposed approach.

1. Introduction

Operating a typical chemical process usually calls for high consumption levels of hot and cold utilities, while the heat exchanger network (HEN) is indispensable in such a plant for the purpose of maximum heat recovery. Traditionally, a single-plant HEN design was generated with either a simultaneous optimization strategy [1] or a stepwise synthesis procedure [2,3]. The former usually yields a better trade-off between utility and capital costs, but the computational effort required for solving the corresponding mixed-integer nonlinear programming (MINLP) model can be quite demanding. On the other hand, although implementing a stepwise method is clearly easier, the sub-optimal solutions may often be obtained.

On the other hand, a number of recent studies have also been carried out for developing the multi-plant HEN designs on an industrial park, e.g., see Bagajewicz and Rodera [4] and Kralj [5] and Liew et al. [6]. The available synthesis methods for total-site heat integration (TSHI) can be roughly classified into three types: the insight-based pinch methods [7], the model-based methods [8] and the hybrid methods [6]. The corresponding interplant energy flows may be either realized with direct heat exchanges between process streams or facilitated indirectly with one or more extraneous fluid [9]. A comprehensive survey on the synthesis tools can also be found in Kastner et al. [10]

The main advantages of the first approach mentioned above are due to its target-setting strategy and flexible design steps based on engineering insights. Matsuda et al. [11] applied the R-curve analysis and site-source-sink-profile analysis for TSHI of the Kashima industrial park.

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Nomenclature

Indices

i	hot process stream
j	cold process stream
m	hot utility
n	cold utility
k	index of the stages $(1,\cdots,NOK)$ and the temperature locations $(1,\cdots,NOK+1)$

Sets

H	$=\{i\|i$ is a hot process stream in coallition$\}$
C	$=\{j\|j$ is a cold process stream in coallition$\}$
HU	$=\{m\|m$ is a hot utility in coallition$\}$
CU	$=\{n\|n$ is a cold utility in coallition$\}$
ST	$=\{k\|k$ is a stage in the super structure$\}$

Parameters

TIN_i, TIN_j	inlet temperature of hot process stream i or cold process stream j
$TOUT_i, TOUT_j$	outlet temperature of hot process stream i or cold process stream j
F_i, F_j	heat capacity flowrate of hot process stream i or cold process stream j
TI_m, TI_n	inlet temperature of hot utility m or cold utility n
$TT_{i,n}$	outlet temperature of cold utility n, when it exchanged heat with hot process stream i
$TT_{j,m}$	outlet temperature of hot utility m, when it exchanged heat with cold process stream j
$U_{i,j}$	overall heat transfer coefficient between hot process stream i and cold process stream j
$U_{i,n}$	overall heat transfer coefficient between hot process stream i and cold utility n
$U_{j,m}$	overall heat transfer coefficient between cold process stream j and hot utility m
$CQ_{i,n}$	per unit cost for cold utility n, when it exchange heat with hot process stream i
$CQ_{j,m}$	per unit cost for hot utility m, when it exchange heat with cold process stream j
$CF_{i,j}$	fixed charge for exchanger, when hot process stream i exchanged heat with cold process stream j
$CF_{i,n}$	fixed charge for exchanger, when hot process stream i exchanged heat with cold utility n
$CF_{j,m}$	fixed charge for exchanger, when cold process stream j exchanged heat with hot utility m
$CA_{i,j}$	area cost coefficient, when hot process stream i exchanged heat with cold process stream j
$CA_{i,n}$	area cost coefficient, when hot process stream i exchanged heat with cold utility n
$CA_{j,m}$	area cost coefficient, when cold process stream j exchanged heat with hot utility m
β	exponent for area cost
NOK	total number of stages
NST	upper bound of split streams in each stage
ΔT_{min}	minimum approach temperature difference
$\Omega_{i,j}$	an upper bound for heat exchange of match (i,j)
$\Omega_{i,n}$	an upper bound for heat exchange of match (i,n)
$\Omega_{j,m}$	an upper bound for heat exchange of match (j,m)
$\Gamma_{i,j}$	an upper bound for temperature difference of match (i,j)
$\Gamma_{i,n}$	an upper bound for temperature difference of match (i,n)
$\Gamma_{j,m}$	an upper bound for temperature difference of match (j,m)

Variables

$t_{i,k}$	temperature of hot process stream i at start of stage k
$t_{j,k}$	temperature of cold process stream j at start of stage k
$q_{i,j,k}$	heat exchanged between hot process stream i and cold process stream j in stage k
$q_{i,n}$	heat exchanged between hot process stream i and cold utility n
$q_{j,m}$	heat exchanged between cold process stream j and hot utility m
$z_{i,j,k}$	binary variable to denote existence of match (i,j) in stage k
$z_{i,n}$	binary variable to denote existence of match (i,n)
$z_{j,m}$	binary variable to denote existence of match (j,m)
$dt_{i,j,k}$	temperature approach for match (i,j) at temperature location k
$dtin_{i,n}$	temperature approach for match (i,n) (hot process stream i flow into utility exchanger)
$dtout_{i,n}$	temperature approach for match (i,n) (hot process stream i flow out utility exchanger)
$dtin_{j,m}$	temperature approach for match (j,m) (cold process stream j flow into utility exchanger)
$dtout_{j,m}$	temperature approach for match (j,m) (cold process stream j flow out utility exchanger)

Symbols of cooperative game

$N=\{1,2,\cdots,n\}$	set of players
n	total of players (positive integer)
i	player i
$v(\cdot)$	characteristic function
S	subset of N
S_{+i}	subset of N, which included the player i
$x_{S,i}$	the imputation of $v(S)$,which the player i who was from the coalition S could get
$\mathbf{x}_S$	imputation vector which was consisted by $x_{S,i}$
$C(v)$	The core which was defined by the characteristic function $v(\cdot)$
$\boldsymbol{\pi}_\sigma$	the σ th permutation from the n ! permutations of N
$\mathbf{m}^\sigma(v)$	marginal cost contribution vector which was defined by the characteristic function $v(\cdot)$ and the permutation $\boldsymbol{\pi}_\sigma$
$\mathbf{o}^\sigma(v)$	sorted marginal cost vector of $\mathbf{m}^\sigma(v)$
$\boldsymbol{\varphi}_N(v)$	Shapley Value vector of coalition N
$\varphi_{N,i}$	Shapley Value of the player i in grand coalition N
$\varphi_{S,i}$	Shapley Value of the player i in coalition S
L	subset of S
L_{+i}	subset of S, which included the player i
L^S	broken sub-coalition which was collapsed from the specific coalition S
P	subset of L
$w(L\colon L^S)$	total cost of coalition L in the case of L^S
$w(i\colon L^S)$	cost of player i in the case of L^S
$w(i\colon i^S)$	cost of player i, when the L^S collapsed into player i work alone
α_i	drop out probability of player i
$p(L\|S)$	occurrence probability of broken sub-coalition L^S
$r(i\colon L^S)$	risk loss of player i in the case of L^S
$\mathrm{E}[r(i\colon L^S)]$	expected loss of player i due to random plant shutdowns
$\mathbf{h}^\sigma(v)$	expected risk marginal cost vector which was defined by the characteristic function $v(\cdot)$ and the permutation $\boldsymbol{\pi}_\sigma$
$\boldsymbol{\theta}^\sigma(v)$	sorted expectation risk marginal cost vector of $\mathbf{h}^\sigma(v)$
$\boldsymbol{\Psi}_S(v)$	allocation coefficient of risk based Shapley Value of coalition N
$\hat{\boldsymbol{\varphi}}_S(v)$	risk based Shapley Value vector of coalition N
$\hat{\varphi}_{S,i}$	risk based Shapley Value of player i of coalition N

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