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An optimization-based cooperative game approach for systematic allocation of costs and benefits in interplant process integration

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ABSTRACT

The use of process integration (PI) tools in industrial ecology (IE) applications, particularly industrial symbiosis (IS), can lead to greater sustainability gains than is possible for single plants or companies. Such integration is facilitated by the advent of eco-industrial parks (EIPs) which use geographic clustering to promote sustainable exchange of materials and energy streams among different plants and companies. In particular, PI methods have been developed for total site integration and successfully implemented in documented industrial cases. However, one aspect of interplant integration is not easily done using classical PI methods, since each potential partner company will participate in a symbiosis scheme specifically with the motivation of increasing its own profits. The self-interest of each partner thus results in conflict of interest which, if not resolved, may result in the failure of the initiative. To address this problem, it is necessary to use an approach based on cooperative game theory which involves pooling the benefits, and then subsequently developing a rational and defensible scheme for sharing the incremental profits among the partners. In this work, we propose the application of a linear programming (LP) cooperative game model to allocate benefits that accrue from interplant integration in an EIP. The approach is first demonstrated using a literature case study, and the results are compared with those determined via alternative cooperative game techniques. Two industrial case studies on interplant integration in palm-based biomass processing complex and sago-based biorefinery (SBB) are then solved to further illustrate the applicability of this technique to problems of more realistic scale.

Abbreviations: ACA, alternate cost avoided; BTS, biomass-based tri-generation system; CHP, combined heat and power; CO_2, carbon dioxide; DME, dimethyl-ester; EFB, empty fruit bunches; EIP, seco-industrial parks; FBBs, fresh fruit bunches; HPS, high pressure steam; IE, industrial ecology; IS, industrial symbiosis; LP, linear programming; LPS, low pressure steam; MeOH, methanol; MPS, mid pressure steam; PBB, palm-based biorefinery; PEIP, palm oil eco-industrial park; P, Iprocess integration; PKS, palm kernel shells; PMF, palm mesocarp fiber; POM, palm oil mill; POME, palm oil mill effluent; SBB, sago-based biorefinery; SBP, bioethanol plant; TS, total sites; WWTP, wastewater treatment plant; BFW, boiler feed water; COD, chemical oxygen demand; HP, high pressure; LP, low pressure; NREL, National Renewable Energy Laboratory; SBP, sago-based bioethanol plant.

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Nomenclature

Indices

i	index of company or plant
S	index of coalition
ℵ	index of set of all companies/plants from coalition S
c	index of coalition
o	index for palm oil
i	index for biomass
j, j'	Index for technologies in biomass trigeneration system (BTS)
g, g'	Index for technologies in palm-based biorefinery (PBB)
p	Index for primary products in BTS
p'	Index for final products in BTS
h	Index for primary products in PBB
h'	Index for final products in PBB
q	Index for component balance of biomass i
q'	Index for component balance of primary product p in BTS
q''	Index for component balance of primary product h in PBB
e	Index for energy

Variables

C_i	marginal contributions for each company/plant i
n	total number of companies or plants
x_i	payoffs of companies/plants i
$v(S)$	characteristics function value
λ	independent continuous variable
$BETH_c^{SBB\_Generated}$	bioethanol produced in coalition c (t/d)
$CS_c^{SBB\_Reduced}$	potential carbon savings in coalition c ($kgCO_2$/d)
CS^{POM}	total cost savings of POM in USD per year
CS^{BTS}	total cost savings of BTS in USD per year
CS^{PBB}	total cost savings of PBB in USD per year
$E_e^{Con\text{-}POM}$	total energy consumed by POM in kW h
$E_e^{BTS\text{-}POM}$	total energy imported from BTS by POM in kW h
$E_e^{Imp\text{-}POM}$	total energy imported from external facility by POM in kW h
$E_e^{Gen\text{-}BTS}$	total energy generated by BTS in kW h
$E_e^{Con\text{-}BTS}$	total energy consumed by BTS in kW h
$E_e^{BTS\text{-}POM}$	total external energy exported to POM by BTS in kW h
$E_e^{BTS\text{-}PBB}$	total external energy exported to POM by PBB in kW h
$E_e^{Exp\text{-}BTS}$	total excess energy exported to grid by BTS in kW h
$E_e^{Con\text{-}PBB}$	total energy consumed by PBB in kW h
$E_e^{BTS\text{-}PBB}$	total energy imported from BTS by PBB in kW h
$E_e^{Imp\text{-}PBB}$	total energy imported from external facility by PBB in kW h
$ELEC_c^{SBB\_Generated}$	electricity generated in coalition c (kW h)
F_i^{OIL}	flow rate of palm oil o in kg/h
F_i^{BIO}	flow rate of biomass i in kg/h
F_{ij}^{I}	flow rate of biomass i to technology j in kg/h
F_{qj}^{I}	flow rate of component q in biomass to technology j in kg/h
F_{jp}^{I}	production rate of primary product p in kg/h at technology j
F_p	total production rate of primary product p in kg/h at technology j
$F_{pj'}^{II}$	flow rate of primary product p to technology j' in kg/h
$F_{q'j'}^{II}$	flow rate of component q' in product p to technology j' in kg/h
$F_{j'p'}^{II}$	production rate of final product p' in kg/h at technology j'
$F_{p'}$	total production rate of final product p' in kg/h at technology j'
$F_{p'}^{POM}$	total production rate of final product p' sent to POM in kg/h
$F_{p'}^{PBB}$	total production rate of final product p' sent to PBB in kg/h
F_{ig}^{I}	flow rate of biomass i to technology g in kg/h
F_{qg}^{I}	flow rate of component q in biomass to technology g in kg/h
F_{gh}^{I}	production rate of primary product h in kg/h at technology g
F_h	total production rate of primary product h in kg/h at technology g
$F_{hg'}^{II}$	flow rate of primary product h to technology g' in kg/h
$F_{q''g'}^{II}$	flow rate of component q'' in product p to technology g' in kg/h
$F_{g'h'}^{II}$	production rate of final product h' in kg/h at technology g'
$F_{h'}$	total production rate of final product h' in kg/h at technology g'
GP^{POM}	total gross profit of POM in USD per year
GP^{BTS}	total gross profit of BTS in USD per year
GP^{PBB}	total gross profit of PBB in USD per year
m_{steam}	mass flow rate of steam generation (kg/s)

Parameters

AOT	annual operating time in h/y
C_{ij}^{I}	cost of biomass i for technology j in USD/kg
C_{ig}^{I}	cost of biomass i for technology g in USD/kg
$C_{p'}^{POM}$	cost of final product p' from BTS to POM in USD/kg
$C_{p'}^{PBB}$	cost of final product p' from BTS to PBB in USD/kg
$C_{h'}$	cost of final product h' in USD/kg
C_o^{OIL}	revenue from palm oil o in USD/kg
C^{FFB}	cost of fresh fruit bunches in USD/kg
$C_e^{Imp-POM}$	cost of importing energy from external facility to POM in USD/kW h
C_{ij}^{Disp}	cost of disposing biomass i in USD/kg
C_{ij}^{Ext}	cost of purchasing biomass i from external facility for BTS in USD/kg
C_{ig}^{Disp}	cost of disposing biomass i in USD/kg
C_{ig}^{Ext}	cost of purchasing biomass i from external facility for PBB in USD/kg
$C_e^{BTS-POM}$	cost of energy from BTS to POM in USD/kW h
$C_e^{BTS-PBB}$	cost of energy from BTS to PBB in USD/kW h