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Systematic approach for the design of sustainable supply chains under quality uncertainty

Sergio Medina-González [a], Moisès Graells [a], Gonzalo Guillén-Gosálbez [b], Antonio Espuña [a], Luis Puigjaner [a,*]

[a] Chemical Engineering Department, Universitat Politècnica de Catalunya, EEBE. Av. Eduard Maristany, 10-14, Edifici I, Planta 6, 08019 Barcelona, Spain
[b] Centre for Process Systems Engineering (CPSE), Imperial College London, SW7 2AZ, United Kingdom

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ABSTRACT

Sustainable processes have recently awaked an increasing interest in the process systems engineering literature. In industry, this kind of problems inevitably required a multi-objective analysis to evaluate the environmental impact in addition to the economic performance. Bio-based processes have the potential to enhance the sustainability level of the energy sector. Nevertheless, such processes very often show variable conditions and present an uncertain behavior. The approaches presented for solving multi-objective problems under uncertainty have neglected the potential effects of different quality streams on the overall system. Here, it is presented an alternative approach, based on a State Task Network formulation, capable of optimizing under uncertain conditions, considering multiple selection criteria and accounting for the material quality effect. The resulting set of Pareto solutions are then assessed using the Elimination and Choice Expressing Reality-IV method, which identify the ones showing better overall performance considering the uncertain parameters space.

1. Introduction

During the last decade, industrial globalization has been continuously changing the business behavior, thus making it difficult to remain competitive in the global market for current processes/industries [1]. Additionally, the increasing government pressure on designing green processes has led to the need for developing more sophisticated strategies to design and manage industrial processes. The above together with the recent improvements in environmental analysis techniques has stimulated the emergence of sustainability strategies in process systems engineering (PSE) literature [2]. Here, one major challenge concerns how to combine multi-objective (MO) [3] approaches (maximize economic performance while minimizing environmental impacts) with uncertainty strategies for a reliable/quick response to unpredictable situations (including demands, prices, availability and quality uncertainties) [4].

Along these lines, industrial symbiosis (IS) appears as a promising strategy to bring together companies from different sectors in order to share resources (such as energy, materials and water) and provide stability to the markets [5]. The concept of IS covers multiple important gaps in the current PSE literature [6], since it attempts to enhance the process sustainability as well as the financial and social benefits for all the participants [7]. Nevertheless, in practice the application of IS strategies is a hard task to carry out, mainly due to the limited flow of information within industries, the lack of integration strategies, the complexity of synergy identification and the dynamic behavior associated to IS networks. In fact, several authors agree that in order to meet the highest sustainability standards, the synthesis and operation of robust industrial symbiosis systems should be improved in parallel with solution strategies for highly complex design and planning optimization problems [8]. Therefore, robust and flexible mathematical formulation should be developed to address IS problems using a PSE approach.

In the PSE literature, bio-based processes can be mentioned as one of the most representative example of IS, especially because of their structural and conceptual similarities. Actually, in the field of bio-based processes, multiple works can be found focusing on operating conditions, equipment units' efficiency, and raw material properties, among others. For example, Mikulandrić et al. [9] use an Artificial Neural Networks (ANN) method to predict the variability of the operational conditions (i.e., output temperatures) and model the dynamic behavior of a biomass gasification unit for its use in on-line applications. The above study uses a surrogate model which requires experimental training data. In parallel, Sepe et al. [10] combine traditional gasification techniques with a

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* Corresponding author.
E-mail address: luis.puigjaner@upc.edu (L. Puigjaner).

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Nomenclature

Abbreviations

MO	Multi-objective
SC	Supply chain
MOO	Multi-objective optimization
MILP	Mixed integer linear programming
PSE	Process systems engineering
SAA	Sample average approximation
STN	State task network
LCA	Life cycle assessment
LCI	Life cycle Inventory
IS	Industrial symbiosis
G-ICE	Gasifier Internal Combustion Engine
LV	Low voltage
MV	Medium voltage
LHV	Lower heating value
MC	Moisture content
O&M	Operation and maintenance
VI	Value of information
MFP	Micronized food products
ANN	Artificial neuronal network

Indices

s	Material state
j	Technology (treatment/pre-treatment equipment's)
i	Task
f	Origin sites
f'	Destination sites
t	Time period
c	Scenarios
k	Interval for piecewise approximation (economies of scale)
e	Supplier site
m	Market site
a	Midpoint environmental category
g	Endpoint damage category

Sets

T_s	Task that produce material s
$\overline{T}_s$	Task that consume material s
C	Set of scenarios
E_{rm}	Suppliers e that provide raw materials
$\hat{E}_{prod}$	Suppliers e that provide production services
$\overline{E}_{tr}$	Suppliers e that provide transportation services
FP	Materials s that are final products
$\bar{I}$	Task i with variable input
I_j	Tasks i that can be performed in technology j
$\bar{J}_e$	Technology j that is available at supplier e
$\bar{J}_f$	Technology that can be installed at location f
J_i	Technology that can perform task i
J_{Stor}	Technologies to perform storage activities
Mkt	Market locations
Ntr	Not transport tasks
RM	Materials s that are raw materials
Sup	Supplier locations
Tr	Distribution tasks
RS	Raw set of solutions
$\bar{x}^*$	Optimal set of solutions for scenario c
ϕ	Space of uncertain parameters
KO_1	Ascending pre-ordered set of solutions
KO_2	Descending pre-ordered set of solutions

Parameters

A_{sftc}	Maximum availability of raw material s in period t in location f and for scenario c
Dem_{sft}	Demand of product s at market f in period t
$Distance_{ff'}$	Distance from location f to location f'
$FCFJ_{jft}$	Fixed cost per unit of technology j capacity at location f in period t
FE^{limit}_{jfk}	Increment of capacity equal to the upper limit in interval k for technology j in facility f
$rate$	Discount rate
$Invest^{MV}$	Investment required for medium voltage
M	Big positive number
$NormF_g$	Normalizing factor of damage category g
$Price_{sft}$	Price of product s at market f in period t
$Price^{limit}_{jfk}$	Investment required for an increment of capacity equal to the upper limit of interval k for technology j in facility f
$Tortuosity$	Tortuosity factor
$Water_{sc}$	Moisture for material s and scenario c
$Water^{max}_{ij}$	Maximum moisture for task i performed in equipment j
α_{sij}	Mass fraction of task i for production of material s in equipment j
$\overline{\alpha}_{sij}$	Mass fraction of task i for consumption of material s in equipment j
β_{jf}	Minimum utilization rate of technology j capacity that is allowed at location j
ζ_{ag}	g endpoint damage characterization factor for environmental intervention a
$\theta_{ijff'}$	Capacity utilization rate of technology j by task i whose origin is location f and destination location f'
$\rho^{tr}_{eff't}$	Unitary transportation costs from location f to location f' during period t
τ^{ut1}_{sfet}	Unitary cost associated with task i performed in equipment j from location f and payable to external supplier e during period t
τ^{ut2}_{sfet}	Unitary cost associated with handling the inventory of material s in location f and payable to external supplier e during period t
χ_{est}	Unitary cost of raw material s offered by external supplier e in period t
$\psi_{ijff'a}$	Environmental category impact CF for task i performed using technology j receiving materials from node f and delivering it at node f'
ψ^T_{ija}	Environmental category impact CF for the transportation of a mass unit of material over a length unit
λ_c	Uncertain parameters vale
q	Indifference threshold
p	Preference thresholds
v	Veto thresholds
$Prob_c$	Probability of occurrence of scenario c

Variables

$DamC_{gftc}$	Normalized endpoint damage g for location f in period t and scenario c
$DamC^{SC}_{gc}$	Normalized endpoint damage g along the whole SC for scenario c
$EPurch_{etc}$	Economic value of sales executed in period t during scenario c
$ESales_{tc}$	Economic value of sales executed in period t and scenario c
$FAsset_{tc}$	Investment on fixed assets in period t and scenario c
$FCost_{ftc}$	Fixed cost in facility f for period t and scenario c
F_{jftc}	Total capacity technology j during period t at location f and scenario c
FE_{jftc}	Capacity increment of technology j at location f during period t and scenario c
HV_{sc}	Lower heating value for material s during scenario c

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