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Multi-objective self-adaptive algorithm for highly constrained problems: Novel method and applications

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ABSTRACT

As a substantive input to resolve the industrial systems and challenging optimization problems, which are multi-objective in nature, the authors introduce an emerging systematic multi-objective optimization methodology for large-scale and highly-constrained industrial production systems. The methodology uses a simulation-based optimization framework built on a novel multi-objective evolutionary algorithm that exhibits several specific innovative features to maintain genetic diversity within the population of solutions and to drive the search towards the Pareto-optimal set/front. This novel algorithm was validated using standard test functions and the results demonstrate undoubtedly that the proposed algorithm computes accurately the Pareto-optimal set for optimization problems of at least two-objective functions. Next, the algorithm was applied on a base case cogeneration optimization problem with three-objective functions named the modified CGAM problem. The modified problem includes concentrations and tax rates of pollutant emissions (i.e. CO_2 and NO_x). The multi-objective optimization of such a problem consists of simultaneously maximizing the exergetic efficiency of the cogeneration plant, minimizing the total cost rate (including pollutant tax rate), and minimizing the specific rate of pollutant emissions. A fuel-to-air equivalence ratio ranging from 0.5 to 1.0, and pollutant tax rates of 0.15 \$/kg CO_2, and 7.50 \$/kg NO_x were used to compute the surfaces of the Pareto fronts. The results found for the modified CGAM problem clearly demonstrate the applicability of the proposed algorithm for optimization problems of more than two-objective functions with multiple constraints. The results strengthen the fact that there is no single optimal solution but rather a set of optimal solutions that present the best trade-off alternatives from which a decision-maker can select the appropriate final decision. Also, the study emphasizes the key role of both economic and environmental issues in the optimization problem of energy systems.

1. Introduction

Multi-criterion optimization of energy systems in the context of fast and competitive decision-making includes both economic and operating considerations, i.e. increased product throughput, increased yield of higher value products, decreased energy consumption, decreased negative environmental impacts, extended equipment life, improved controllability, and reduced operating constraints. Efficient energy generation systems involving innovative technologies with high thermodynamic efficiencies and relatively low total investment cost are therefore needed. In this context, there is a need for a rigorous, robust, and efficient optimization tool that could provide optimal solutions regarding several conflicting objectives and highly constrained problems. An innovative optimization methodology is proposed using a simulation-based optimization framework built on a novel evolutionary algorithm, namely multi-objective self-adaptive algorithm for highly constrained problems (i.e. MOSAHiC), with the following features:

- An enhanced search technique on the objective function space, namely *boundary exploring search technique* (BEST) used for evaluating and selecting the trade-off solutions to create the mating pool.
- An innovative progression metric used to improve the exploration of the search space and the exploitation of the mating pool individuals.
- An innovative constraint handling (CH) technique.

This methodology is considered as a significant advance for industrial applications of multi-objective evolutionary algorithms (MOEAs). The proposed algorithm was validated using standard test functions and then assessed on a modified version of the CGAM problem integrating concentrations and tax rates of pollutant emissions (i.e. CO_2 and NO_x) and related objective functions.

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Nomenclature

$\dot{C}$	cost rate, $/s
e	specific exergy, J/kg
F_A	fraction of air to primary zone, %
f	objective function
$\dot{m}$	mass flowrate, kg/s
n_s	score value of constraint violation
$[NO_x]$	concentration of NO_x emissions, g/kg of fuel
P	pressure, Pa
PM	logarithm of the normalized Euclidian distance
R	universal gas constant, J/(mol K)
R_A	specific universal gas constant, J/(kg K) $\left[R_A = \frac{R}{M_A}\right]$
S	fitness value
t	residence time in the combustion zone, s
T	absolute temperature, K
T_m	mean temperature = $(T_{st} - T_3)/2$, K
V	volume, m^3
x	vectorial-variable
$\dot{W}$	work, J/s
$\dot{Z}$	levelized capital investment cost, $/year

Subscripts

a	actual
A	air
AC	air compressor
cz	combustion zone
f	fuel
GT	gas turbine
i	index, imposed
max	maximum
min	minimum
p	pinch
ph	preheater
pz	primary zone
sb	subdivision
st	stoichiometric flame
z	number of units index

Superscript

p	population

Greek letters

$\wp$	number of intervals in subdivided objective space
ε	constraint violation
ε_a	actual constraint value
ε_i	imposed constraint value
ξ	exergetic efficiency, %
ϕ	air-to-fuel equivalence ratio

Acronyms

AC	air compressor
APH	air preheater
BEST	best exploring search technique
CC	combustion chamber
CH	constraint handling
CGAM	Christos Georges Antonio Michael. The CGAM problem is a predefined and simple problem of optimization named after the first initials of the investigators C. Frangopoulos, G. Tsatsaronis, A. Valero, and M. von Spakovsky
EA	evolutionary algorithm
GT	gas turbine
HRSG	heat recovery steam generator
MOEA	multi-objective evolutionary algorithm
MOP	multi-objective optimization problem
MOSAHiC	multi-objective self-adaptive highly constraint
PM	progression metric
SDM	subdivision method

The CGAM problem is an economic optimization of a simple cogeneration system which involves physical, thermodynamic, and economic models. This problem was used by various scientists [1–5] to compare their thermodynamic optimization methodologies. The modified CGAM optimization problem consists of simultaneously maximizing the exergetic efficiency of the cogeneration plant, minimizing the total cost rate (including pollutant tax rate), and minimizing the mass flow rate of pollutant emissions, namely NO_x. The fuel-to-air equivalence ratio is ranging from 0.5 to 1.0. The pollutant tax rates are considered as 0.15 $/kg CO_2, and 7.50 $/kg NO_x. This modified CGAM problem is used as a base case energy system to test the validation of the MOSAHiC performance.

2. Multi-objective optimization algorithms

Multi-objective optimization algorithms are based either on exact or heuristics methods. Exact methods give systematically a global or local optimal solution. These methods are only efficient in the case of simple problems exhibiting mostly not more than two-objective functions. Heuristic methods are approximate methods which use some knowledge to obtain an acceptable solution in a short timeframe. Heuristics methods can be classified into two classes: specific heuristics methods and meta-heuristics methods. Specific heuristics methods are based on algorithms tailored to a certain domain. They use specific knowledge from that domain with the goal to obtain a good solution. Meta-heuristics methods are based on more general algorithms that can be used in a large variety of problems. The emphasis is put only on meta-heuristics methods, since the interest is on generic methods to be applied to various types of industrial problems. Meta-heuristics methods have two main advantages: they often find better solutions, i.e. corresponding to the best trade-offs between the objective functions in a reasonable time, and they include some mechanisms to depart from local optima. The major meta-heuristics methods used in the literature are: simulated annealing [6–8], tabu search [7,9], ant colony algorithm [10], and EAs [11,12]. In these methods each objective function is treated separately. There are two major methods to solve multi-objective optimization problems (MOPs): *a priori* and *a posteriori* [11]. In the *a priori* method, the decision-maker defines the objective importance before the search occurs and the MOP is transformed into a single objective problem. Afterwards, a classical single objective optimization algorithm is used to find the optimum. The *a priori* method includes lexicographic ordering, linear fitness combination technique, and non-linear fitness combination technique. The key drawback of the *a priori* method is the arbitrarily imposed limitation of the search space, which cannot allow finding all solutions in the true-Pareto-optimal set. Conversely, the *a posteriori* method is based on a simultaneous optimization of all objective functions. At the end of the search process, the decision-maker selects the desired trade-offs among all proposed solutions in the Pareto-optimal set. The *a posteriori* method includes: independent sampling technique, criterion selection technique, aggregation selection technique, Pareto-sampling technique, and hybrid selection technique. These techniques lead to the