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Biobjective optimization using Environmental and Economic Functions in Utility Plants

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Abstract

Environmental and economic objective functions are used simultaneously to select the operating conditions of a steam and power plant. Different methodologies to solve bi objective optimization problems were implemented successfully. The life cycle potential environmental impact and the operating cost of the utility plant are minimized simultaneously. A methodology is presented to estimate the potential environmental impacts considering the most important life cycle stages associated with imported electricity and natural gas in the utility plant. Mixed Integer Non Linear bi objective problems are formulated and different strategies are implemented and successfully solved in GAMS.

Keywords: bi objective optimization, life cycle environmental impact, utility plant.

1. Introduction

The formulation of multi objective optimization problems including environmental and economic metrics to support a decision making process can contribute to a sustainable development. Multi-objective optimization applied to environmental and economic objectives has been treated by authors like Ciric and Huchette [1] minimizing the amount of waste and the net profit of an ethylene glycol production plant. Dantus and High [2] proposed a method to convert a bi objective optimization problem into a single objective optimization problem; the method proposed is a variation of the utopia point distance minimization, including discrete variables to select the type of reactor to be used in the methyl chloride superstructure plant design.

In the present work the operating conditions of a steam and power plant are selected to minimize life cycle environmental impact and operating cost simultaneously solving a bi objective optimization problem. The environmental objective is the life cycle environmental impact associated with gaseous and liquid emissions, and solid wastes of an ethylene steam and power plant. In the life cycle context, the battery limits of the steam and power plant need to be extended in order to include emissions of imported natural gas and electricity generated by nuclear, hydroelectric and thermoelectric plants. The operating cost includes costs of imported electricity, natural gas, makeup water and water treatment. A Mixed integer non linear bi objective optimization problem is formulated and solved in GAMS [3].

2. Evaluation of environmental and economic objective functions

2.1. Potential Environmental Impact Evaluation

The Potential Environmental Impact (PEI) function considered is a multi objective function itself, since nine environmental impact categories are considered: global warming, acidification, ozone depletion, photo oxidant formation, eutrophication, fresh water ecotoxicity, human toxicity, source depletion and the impact due to ionizing radiation. The Potential Environmental Impact is calculated using the Guinée et al. [4] methodology. The contribution of the emission of a pollutant **k** to a given environmental impact category **j** is evaluated multiplying the pollutant **k** flow rate $\mathbf{F_k}$ emitted into the environment by a characterization factor $\boldsymbol{\gamma_{kj}}$ published by Guinée et al. [4]. This characterization factor represents the effect that chemical **k** has on the environmental impact category **j**. Hence, the Potential Environmental Impact, PEI, is calculated as follow:

$$\mathbf{PEI} = \sum_{\mathbf{j}}\sum_{\mathbf{k}} \boldsymbol{\alpha}_{\mathbf{j}} \times \mathbf{F_k} \times \boldsymbol{\gamma}_{\mathbf{k,j}} \qquad (1)$$

Where $\boldsymbol{\alpha_j}$ represent the weighting factors for each environmental impact category **j**. More information can be found in Eliceche et al. [5]. Eq.1 transforms the pollutants emissions flow rates into potential environmental impacts.

2.1.1. Evaluation of the Utility Plant Environmental Impact

The emissions of the steam and power plant are evaluated from the modelling of the main processes formulated in GAMS. The emissions come mainly from the combustion in the boilers of a mixture of natural gas, $\mathbf{F_{ng}}$ and residual gas, $\mathbf{F_{rg}}$. Liquid emissions of purge streams, $\mathbf{F_p}$, in the boilers and cooling system are also considered. The pollutants emissions from the utility plant (UP) are calculated as follow:

$$\mathbf{F_k^{UP}} = \mathbf{F_{gn}} \times \mathbf{e_{k,ng}} + \mathbf{F_{rg}} \times \mathbf{e_{k,rg}} + \mathbf{F_p} \times \mathbf{e_{k,p}} \qquad (2)$$

Where $\mathbf{e_{k,ng}}$ is the emission factor for pollutant **k** due to the combustion of natural gas, $\mathbf{e_{k,rg}}$ is the corresponding emission factor for residual gas combustion and $\mathbf{e_{k,p}}$ is the pollutant emission factor for liquid emissions. The emissions factors express the amount of pollutant **k** emitted by unit mass of natural gas, residual gas and liquid stream, respectively. A detailed analysis of each life cycle stage considered as well as the literature sources was presented in Martínez and Eliceche [6].

2.1.2. Life Cycle Environmental Impact Assessment of Imported Electricity and Natural Gas

Life cycle approach considers emissions during the entire life cycle of a product or service accounting by emissions from raw material extraction to waste disposal. In the utility plant, the life cycle emissions are considered for the natural gas feedstock and the imported electricity needed to move some electrical motors in the superstructure of the steam and power plant. Pollutant flow rate for natural gas (NG) life cycle $\mathbf{F_k^{NG}}$ is calculated in the following equation:

$$\mathbf{F_k^{NG}} = \mathbf{F_{ng}} \times \sum_{\mathbf{l}} \mathbf{e_k^l} \qquad \mathbf{l} = 1,\ldots,\mathbf{l_{ng}} \tag{3}$$

Where $\mathbf{e_k^l}$ is the emission factor for pollutant k in the life cycle stage **l**, $\mathbf{l_{ng}}$ is the total number of life cycle stages considered for the natural gas fuel cycle: exploration, extraction and transportation stages. As the residual gas is produced in the ethylene plant, no life cycle stage has been considered for it.

The imported electricity (IE) life cycle emissions have been assessed through the life cycle of different electricity generation plants. The electricity generation sector in Argentina has contributions from thermoelectric, hydroelectric and nuclear plants. Thermoelectric power generation consumes coal, oil and natural gas as fuels; nuclear power generation consumes natural uranium fuel. The estimation of pollutant emissions in the electric power generation includes the following life cycle stages: extraction and processing of raw materials, transport, refining (where it is applicable) and electricity generation itself:

$$\mathbf{F_k^{IE}} = \sum_{\mathbf{q}} \sum_{\mathbf{l_q}} \mathbf{W_q} \times \mathbf{e_{k,q}^{l_q}} \qquad \mathbf{l} = 1,\ldots,\mathbf{l_{ie}} \tag{4}$$

Where $\mathbf{W_q}$ is the electricity imported and generated with technology **q**, $\mathbf{l_q}$ superscript accounts life cycle stage **l** in electricity generated by option **q**, finally $\mathbf{e_{k,q}^{l_q}}$ is the corresponding emission factor of pollutant **k** in electricity generated with option **q**, for the life cycle stage $\mathbf{l_q}$. The life cycle stages considered are: (i) exploration, extraction, refining and transport of natural gas, oil, coal and uranium consumed in thermoelectric and nuclear plants; (ii) submerged biomass decay in hydroelectric plants (iii) waste treatment and disposal for nuclear plants and (iv) transport in the construction stage of hydroelectric and nuclear plants.

The utility plant potential environmental impact, PEI^{UP} is calculated as follows:

$$\mathbf{PEI^{UP}} = \sum_{\mathbf{j}} \sum_{\mathbf{k}} \alpha_{\mathbf{j}} \times \mathbf{F_k^{UP}} \times \gamma_{\mathbf{k,j}} \tag{5}$$

The component **k** life cycle emissions $\mathbf{F_k^{LC}}$ are estimated adding the component **k** emissions in the utility plant, life cycle of imported natural gas and electricity:

$$\mathbf{F_k^{LC}} = \mathbf{F_k^{UP}} + \mathbf{F_k^{NG}} + \mathbf{F_k^{IE}} \tag{6}$$

The life cycle potential environmental impact is evaluated as follows:

$$\mathbf{PEI^{LC}} = \sum_{\mathbf{j}} \sum_{\mathbf{k}} \alpha_{\mathbf{j}} \times \mathbf{F_k^{LC}} \times \gamma_{\mathbf{k,j}} \tag{7}$$

Global warming due to combustion emissions is the most relevant environmental category for steam and power plants and for fossil fuels electricity generation.

2.1.3. Evaluation of Economical Objective Function

The operating cost of the utility plant includes costs of imported electricity (IW), natural gas feed (NG), makeup water (MW) and water treatment (WT); where $\mathbf{c_{ng}}$, $\mathbf{c_q}$, $\mathbf{c_{MW}}$ and $\mathbf{c_{WT}}$ are the cost coefficients:

$$\mathbf{C} = \mathbf{F_{ng}} \times \mathbf{c_{ng}} + \left(\sum_{\mathbf{q}} \mathbf{W_q} \right) \times \mathbf{c_W} + \mathbf{F_{MW}} \times \mathbf{c_{MW}} + \mathbf{F_{WT}} \times \mathbf{c_{WT}} \qquad (8)$$

3. Formulation of Bi objective optimization problem

The multi objective (MO) optimization is a system analysis approach to problems with conflictive objectives. A key factor of MO optimization is that rarely exist a single solution that simultaneously optimizes all the objectives. In its place, there is a set of solutions where one objective cannot be improved except at expense of another objective. This set of compromise solutions are generally referred as non-inferior or Pareto optimal solutions. A variety of strategies to solve multi objective optimization problems exist, that can be found in Alves et al [7]. The general approach consists in converting the multiple objectives into a single objective. Some of these methods are: weighted sum, utopia point distance minimization, e-constraint method and global criteria method. The general formulation of a bi objective optimization problem considering continuous and discrete variables follows:

$$\begin{aligned}
&\underset{\mathbf{x,y}}{\mathbf{Min}}\ \mathbf{Z} = \mathbf{Z[PEI(x,y),C(x,y)]} \\
&\mathbf{s.t:}\ \ \mathbf{h(x)} = 0 \\
&\qquad \mathbf{g(x)} + \mathbf{A(y)} \le 0 \\
&\qquad \mathbf{x^{LB}} \le \mathbf{x} \le \mathbf{x^{UB}} \\
&\qquad \mathbf{x} \in \mathbf{R^n} \\
&\qquad \mathbf{y} \in \{0,1\}^{\mathbf{m}}
\end{aligned} \qquad P1$$

Where **x** and **y** are the continuous and binary optimization variables, respectively. Superscripts **U** and **L**, indicates upper and lower bounds on vector **x**, respectively. The equality constraints **h(x) = 0** are the system of non-linear algebraic equations that represent the steady state modelling of the process plant, including mass and energy balances; enthalpy and entropy prediction. The inequality constraints **g(x) + A(y) ≤ 0** represent logical constraints, minimum and maximum equipment capacities, operating and design constraints, etc. The A matrix includes linear relations between binary variables such as logical constraints. A detailed mathematical model of the utility plant is presented in Eliceche et al. [5].

Different strategies to solve bi objective optimization problems have been implemented successfully. The bi objective function Z in problem *P1* for the global method presented by Dantus and High [2] follows, with the nomenclature presented in section 2:

$$\mathbf{Z} = \omega_1 \times \left[\frac{\mathbf{PEI} - \mathbf{PEI}^*}{\mathbf{PEI}^{**} - \mathbf{PEI}^*} \right]^{\mathbf{p}} + \omega_2 \times \left[\frac{\mathbf{C} - \mathbf{C}^*}{\mathbf{C}^{**} - \mathbf{C}^*} \right]^{\mathbf{p}} \qquad (9)$$

Where $\boldsymbol{\omega_1}$ and $\boldsymbol{\omega_2}$ are weighting factors, these preference weights $\boldsymbol{\omega_i}$ are used to represent the relative importance of each objective. The decision-maker's preferences are also expressed in the compromise index **p** ($1 \le \mathbf{p} \le \infty$), which represents the decision-maker's concern with respect to the maximal deviation from the utopia point. As a result, the non-inferior solutions defined within the range $1 \le \mathbf{p} \le \infty$ correspond to the compromise set from which the decision maker still has to make the final choice to identify the best compromise solution [2]. The single asterisk indicates the minimum values of a given objective function solving a single objective optimization problem, while double asterisk indicates the alternative objective function value obtained. The objective functions used are life cycle potential environmental impact (PEI) given in Equation 6 and operating cost (C) given in Equation 8.

The convex weighted sum method presented by Westerberg [8] was also successfully implemented, using the nomenclature presented in section 2, as follows:

$$Z = \omega_1 \times PEI + (1 - \omega_1) \times C \tag{10}$$

Where ω_1 is the weighting factor, this factor is used to represent the relative importance of each objective. A similar method as those stated by Eq. (10) is the normalized weighted sum method [9], where each single objective function is normalized respect to the minimum value reached in single optimization of each function (e.g PEI* and C* in equation 9). The division by the minimum value avoids biases in the results generated by the different magnitude of each function.

4. Discussion of numerical results

A rigorous modelling of the utility plant is formulated in GAMS, including the power and steam demands of the ethylene plant [5]. The continuous operating variables selected are temperature and pressure of the high, medium and low pressure steam headers and the deareator pressure. Binary operating variables are introduced to represent discrete decisions such as the selection of: (i) alternative pump drivers such as electrical motors and steam turbines and (ii) boilers which are on or off, and their auxiliary equipment such as feed pumps and air fans. Thus a bi objective Mixed Integer Nonlinear Programming problem is formulated and solved in GAMS.

Different strategies were implemented to solve the bi objective problem. The solution point reported in Table 1 was obtained with the Dantus and High [2] method and the following parameters for Eq. (9): $\boldsymbol{\omega_1}=0.1$, $\boldsymbol{\omega_2}=0.9$, $\mathbf{p}=1$. The following GAMS options were used: DICOPT as the outer approximation algorithm; CONOPT3 to solve the Non Linear Programming sub problem and CPLEX to solve the Mixed Integer Linear Programming sub problem. The same results were achieved using the convex weighted sum and the normalized weighted sum methods (with $\omega_1=0.25$).

Significant reductions in the order of 12 % in life cycle environmental impact and 16 % in operating cost can be achieved selecting the operating conditions with the methodology proposed, as shown in Table 1.

Regarding the selection of pump's drivers, steam turbines are chosen rather than electrical motors, due to the fact that the environmental impact to power generated ratio is smaller in the steam and power plant than in the generation of the imported electricity.

Table 1. Multiobjective problem solution.

Objective Functions		Initial Point	Solution point	Reductions
PEI^{LC}	(PEI / h)	33627.33	29581.88	**12 %**
Cost	(U$ / h)	561.84	470.97	**16 %**

This is due to the fact that natural gas is burned with residual gas from the demethanizer column. The residual gas is a Hydrogen rich stream, having higher combustion heat and

lower combustion emissions than natural gas or any other fossil fuel. The operating cost is also cheaper with steam turbines than with electrical motors. The number of the boilers in operation is reduced from four to three, due to a proper selection of temperature and pressure of steam headers, mainly the high pressure steam header.
This is a process where improving process efficiency, environmental impact and cost are reduced simultaneously. They are not conflictive objectives in a life cycle approach. This is not the case if the environmental impact evaluation is reduced to the battery limits, where minimizing environmental impact and operating cost leads to different solutions mainly regarding the selection of alternative drivers.

5. Conclusions

A methodology has been presented to select the operating conditions minimizing simultaneously life cycle environmental impact and operating cost, solving a mixed integer nonlinear bi objective optimization problem. Different strategies to solve bi objective optimization problems were implemented successfully. Significant reductions in the in the order of 12 % in life cycle environmental impact and 16 % in operating cost can be achieved simultaneously, as shown in Table 1. The utility sector studied, has relevant contributions to combustion emissions, global warming, consumption of non renewable fossil fuels and water and also to operating cost. This is a plant where improving process efficiency, environmental impact and cost can be reduced simultaneously if a life cycle approach is followed. For these reasons it is very important to extend the battery limits to include life cycle analysis, when environmental objectives are used to support a decision making process.

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