European Symposium on Computer Aided Process Engineering – 15
L. Puigjaner and A. Espuña (Editors)

Environmental Life Cycle Assessment as a tool for Process Optimisation in the Utility Sector

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Abstract

A methodology is presented to calculate the optimum operating conditions of a petrochemical plant utility sector, to minimize the overall Life Cycle Environmental Impact. The battery limits of the system studied are extended to include the relevant environmental impacts corresponding to the electricity imported generated in thermoelectric, hydroelectric and nuclear plants. The Overall Environmental Impact is calculated as a weighted sum of the following Potential Environmental Impact categories: Global Warming, Acidification, Eutrophication, Photochemical Oxidation, Ozone Depletion, Human Toxicity and Ecotoxicity. The contribution of each component emission to these environmental categories is evaluated multiplying its flow rate by the corresponding Heijungs factor. A Mixed Integer Non Linear Programming problem is formulated and solved in GAMS. Global Warming is the most relevant contribution. Significant reductions in the Overall Environmental Impact and particularly in Global Warming are achieved selecting the pressure and temperature of high, medium and low pressure headers and the optional drivers that can be electrical motors or steam turbines. Improvements are also reported in the operating cost, natural gas, water and electricity consumption.

Keywords: Environmental Life Cycle, Utility, Optimisation.

1. Introduction

The purpose of this paper is to show that environmental life cycle assessment (ELCA) can be used as a quantitative objective function for process optimisation when a detail modeling is available. ELCA is therefore associated to process optimisation rather than to a product as it has been extensively used in the literature. This is a new approach that leads to important improvements. The utility sector has been chosen as the case study due to its significant contribution to the energy consumption in the process plants and consequently to the operating cost in an scenario of increasing fuel costs. Further more in the particular sector analysed: the steam and power generation, when the battery limits are extended to include the environmental impact of the energy imported the optimal operating conditions calculated minimising the total operating cots and the environmental impact are similar leading to significant reductions in the consumption of

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fossil fuels and simultaneously reducing the combustion emissions in the boilers, mainly Carbon Dioxide helping to comply with Kyoto protocol. Thus, a new methodology and a useful computational tool are developed to promote a sustainable development. In the utility sector improvements in environmental impact and operating cost are achieved simultaneously, because both functions are directly related to the amount of fuel burned in the boilers. A detailed modeling of the utility sector is carried out using a property prediction of the enthalpies and entropies of steam and water.
The need to incorporate Environmental Impact objectives in process optimisation has been recognised in the last decade by authors like Stefanis et al. (1995), Dantus and High (1999), Cabezas et al. (1999) and Young et al (2000). Life Cycle Assessment (LCA) has been traditionally used to quantify and assess the environmental performance of a product. Azapagic and Clift (1999) have proposed the use of the environmental life cycle assessment in the selection of alternative technologies for a given product, by using linear models.
In this work, the potential environmental impact is modelled according to the methodology presented by Heijungs et al. (1992). Several potential environmental impacts categories associated to Global Warming, Acidification, Eutrophication, Photochemical Oxidation, Ozone Depletion, Human Toxicity and Ecotoxicity are added to obtain an Overall Environmental Impact as suggested by Cabezas et al. (1999).
There are continuous and binary optimisation variables. The operating conditions selected are the temperature and pressure of high, medium and low pressure steam headers, deaereator tank pressure, and letdowns flow rates. Binary variables are introduced to select the alternative drivers configurations, steam turbines or electrical motors and also to select if some drivers are on or off. The Mixed Integer Non linear Programming problem is solved in GAMS, Brooke et al (1998). Significant reductions in the order of 15 % are observed in the overall environmental impact and operating cost.

2. Steam and power generation plant

The utility plant provides steam, power and cooling water to the chemical plant. It consumes fossil fuels, a non-renewable resource, burnt in the boilers and a scarce resource as water. The pollution comes mainly from the combustion emissions and the purged water. A schematic flow sheet is presented in Fig. 1. Boilers produce superheated steam at high pressure (high pressure steam header). The main equipment involved in utility systems are: boilers, high, medium and low pressure steam headers, steam turbines, pumps, deaereator tank, vents, let-down streams, water treatment plant, heat exchangers, electrical motors, etc. A rigorous modeling of the main equipments involved and the property prediction to evaluate the steam and water enthalpy and entropy is used, they are posed as equality constraints in the optimisation problem. The plant has alternative drivers, electrical motors and steam turbines for the pumps. Binary variables are used for the drivers selection and other equipments that can be off or on such as the boilers and their auxiliary equipment. The operating conditions selected with the optimisation problem are the temperature and pressure of the high, medium and low pressure steam header, the deaereator tank pressure, letdown flow rates and the binary variables.

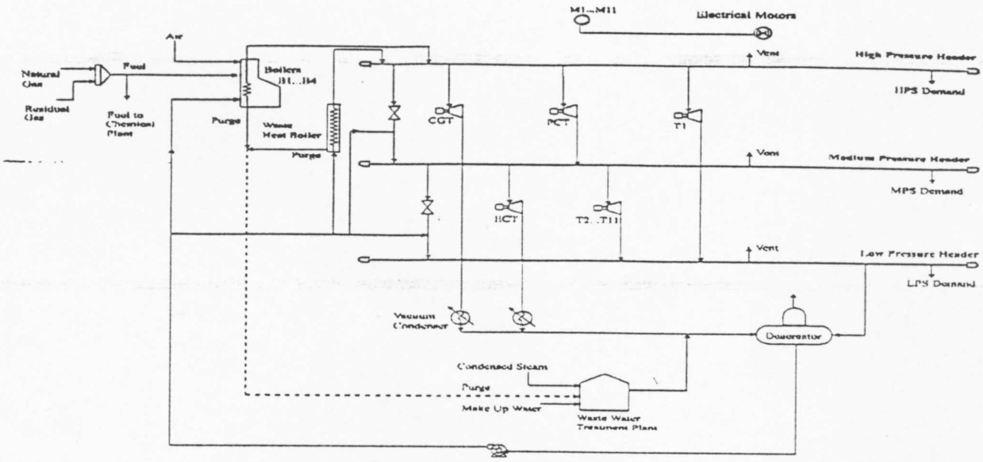

Fig. 1 – Steam and power generation plant

3. Environmental Life Cycle Assessment

The limits of the production plant are extended to contemplate raw material extraction, transport, production, use and waste disposal. The system boundary definition is extended compared with the conventional analysis in which the systems boundary is drawn around the process plant. LCA considers the whole material and energy supply chains. The material and energy flows that enter or leave the system include material and energy resources and emission to air, water and soil. These are referred to as environmental burdens and they arise from activities encompassing extraction and refining of raw material, transportation, production, use and waste disposal. Although Environmental Life Cycle Assessment (ELCA) has been firstly associated with a product, in this work ELCA will be applied to analyse and select optimally the process operation. It will be incorporated as a tool in process optimisation rather than in products or technology selection at a decision making level.

While process engineering is normally concerned with the operations within the plant boundaries (1) in Fig. 2, LCA considers the material and energy balances in the supply chains, so that the limits between the system and the environment need to be defined including the main processes whose environmental impacts should be considered from raw material extraction to final disposal. Then, the limits of the system are extended from (1) to (2) to include the production of the electricity imported, as shown in Fig. 2. The main environmental impacts of imported electricity generated by thermoelectric, hydroelectric and nuclear plants are evaluated. The Electrical Interconnected Network in Argentina has approximately the following distribution: 53% of thermo electrical, 35% of hydro electrical and 12% of nuclear generation. The distribution of thermoelectric energy is: 30% gas turbine, 59% steam turbine burning natural gas, and 11% steam turbine burning fuel oil or gas oil. The combustion process of oil, coal and natural gas releases pollutants, such as nitrogen oxide, carbon monoxide, particulate matter, sulphur dioxide, volatile organic compounds, organic hydrocarbons and trace metals into the air as reported in the emissions factors published by USEPA AP-42 (1998). The emissions associated with exploration, extraction, transport and refining were taken into account for oil, coal and natural gas consumed in the electric power generation

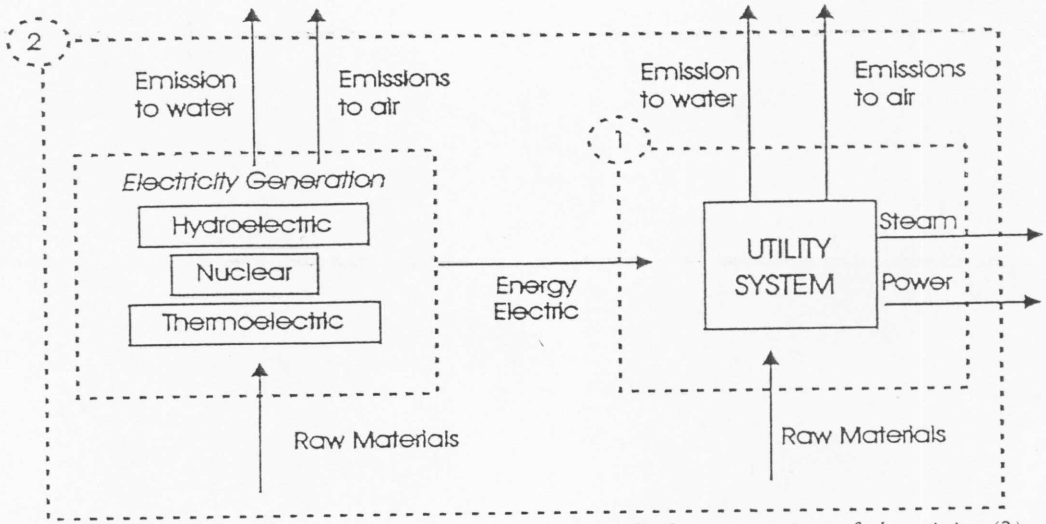

Fig. 2. Utility Sector (1) - Extended limits to include the generation of electricity (2)

Liquid effluents like cooling water purge, boiler blow down, demineralised water, etc. that are discharged from the utility systems and fossil fuel electric power generation release pollutants (chlorine, heavy metals, phosphorus, etc.) into surface waters as reported by Elliot (1989). Creation of a hydroelectric reservoir can contribute to greenhouses gases emissions when a large biomass is flooded during impounding as reported by AEA (1998). Gases generated by aerobic and anaerobic decomposition are mainly carbon dioxide, methane, and to a lesser extent nitrous oxide.

The environmental impacts of the electricity generated have been calculated and incorporated in the objective function for the selection of the operating conditions, following the methodology presented in the following section.

4. Environmental Impact evaluation

The following environmental impact (EI) categories are evaluated: global warming potential, acidification, photochemical oxidation, ozone depletion, human toxicity in air and water, ecotoxicity and eutrophication.

The contribution of the emission of component *k* to a given environmental impact category *j* is evaluated multiplying the flow rate q_k emitted into the environment by the factor h_{kj} published by Heijungs et al. (1992). The Heijungs factor h_{kj} represents the effect that chemical *k* has on the environmental impact category *j*.

$$\psi_{kj} = q_k\, h_{kj} \tag{1}$$

The environmental impact of each category ψ_j is calculated adding the contribution of all the components *k* as follows.

$$\psi_j = \alpha_j \sum_k \psi_{kj} \tag{2}$$

A normalizing factor α_j has been suggested by Cabezas et al. (1999) and can be calculated as the average value of the Heijungs factors of the components contributing to category j, where n_j is the number of chemical compounds k that contributes to the environmental impact category j.

$$\alpha_j = \frac{n_j}{\sum_k (h_{kj})} \tag{3}$$

The overall environmental impact is calculated as the sum of the contribution of each environmental impact (EI) category ψ_j, as shown in equation (4), with ω_j representing the relative weighting factor of EI category j.

$$\psi = \sum_j \omega_j \psi_j \tag{4}$$

Thus, the simulation of the processes should provide the emissions flowrates q_k to end up calculating the overall environmental impact ψ. Considerable uncertainty and lack of information can be found along the extended limits of the environmental life cycle assessment. So the environmental impact quantification relays on the data available outside the battery limits of the plant being analysed.

5. Numerical results of the optimisation problem

The main results, in Table 1, show the improvements achieved with the methodology proposed, where significant reductions in the overall environmental impact, operating costs, natural gas, water and electricity consumption are obtained simultaneously.
The objective function to be minimised is the overall environmental impact ψ as defined in equation (4), including the environmental impacts due to the generation of imported electricity. The modeling equations and water property prediction are posed as equality constraints in GAMS. The power and steam demands of the ethylene plant are posed as equality constraints. The main power demands correspond to the cracked gas, ethylene and propylene refrigeration compressors. Inequality constraints with 24 binary variables are also included in the optimisation problem. The number of equations included in GAMS is 10555. A Mixed Integer Non Linear Programming problem is formulated and solved in GAMS. The codes used to solve the NLP and MILP sub problems in GAMS were CONOPT ++ and OSL. The solution was found in 27.5 seconds and three major iterations in a Pentium III, 700Mhr workstation. In this work the weighting factors ω_j of equation (4) are equal to one. Global warming is the most important environmental impact category, representing 99.5 % of the overall potential environmental impact if the normalizing factors α_j are equal to one and represents 83.5 % if the normalizing factors are calculated with equation (3). In this last case the second contribution correspond to Acidification with 15.9 %. The solution point is not very sensitive to this parameter. In the initial point, 3 boilers out of four were on while in the solution point 2 boilers are on, thus the air fan and feed water pump corresponding to boiler 3 and 4 are off. The optimum operating values for temperature

and pressure of high pressure steam header are equal to the upper bounds on these variables.

Table 1- Main results minimising the Overall Environmental Impact

		Initial point	Optimal solution	% reduction
Environmental impact	PEI/h	638.91	544.91	14.71
Operating cost	$/h	1331.13	1093.00	17.9
Natural gas	ton/h	9.36	7.74	17.3
Make-up water	ton/h	31.33	21.86	30.23
Electrical power	HP	2832	1441	49.12

6. Conclusions

Environmental Life Cycle Assessment has been used successfully as the objective function in the selection of the operating conditions of a utility plant that provides the power and steam demands required by the chemical plant. Significant reductions in the order of 15 % or more in the Life Cycle Environmental Impact, operating cost, natural gas, water and electricity consumption can be achieved simultaneously increasing the efficiency of the plant. The methodology presented can be extended to the selection of the operating conditions of different processes and plants and to the synthesis and design stages. The simulation of the main processes in the life cycle boundaries are required to quantify emissions flow rates and their potential environmental impact.

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Acknowledgements

The authors greatly acknowledge the financial support given by CONICET, UNS and the ANPCyT grant.