Simultaneous process optimization on economic, energetic and environmental criteria

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ABSTRACT

The multi-objective optimization presented in this study allows to simultaneously optimize the technical, economic and environmental performances of a process during its design and operating phases. A technical model of the process is developed as a function of decision variables (size and operating conditions). The choice of given decision variables defines a specific process configuration, which is evaluated using cost models and environmental performance indicators. For given project requirements, the Multi-objective optimizer (MOO) systematically generates all realistic process configurations by investigating the whole space of decision variables. This allows to identify the optimal process configurations according to the performance objectives chosen and to analyze the trade-off between concurrent objectives such as economical costs and environmental protection. As such, the approach helps the process engineer to explore and assess the whole relevant technical possibilities at an early stage of development.

INTRODUCTION

Process development is guided by technical, economical and/or political criteria. In response to the growing environmental awareness, the industry now also seeks to integrate sustainability factors into the decision making process and this, at all stages of development, from the initial research project to the operating phase. The environmental impacts of every process may be mitigated by extensive downstream (or end-of-pipe) treatments such as wastewater treatment and waste disposal. However environmental impacts are usually more effectively reduced by minimizing directly the upstream impact sources through process optimization [1]. The performances of a process result from design choices which traditionally aim at minimizing the total annual cost while respecting technical constraints and project requirements but without explicitly accounting for environmental impact. The environmental performances of this process could be improved by reviewing these previously defined design choices. It is thus proposed to introduce environmental criteria directly in the early design phases in order to identify innovative environmental friendly process configurations. From a process engineering perspective, process performances can be improved by:

- enhancing the efficiency of the unitary equipments composing the process (pumps, energy recovery devices…),
- improving the process layout and adapting the operating conditions.

While the improvement of the equipments efficiency is the decisive task of equipment providers and plant operators, process engineers are mainly in charge of designing the process layout and defining operating conditions which meet given project specifications. This requires making choices over a vast number of options that rely on both continuous (e.g. flow rates, size of equipment) or discontinuous (choice of equipments, interconnections…) variables. At the moment, most of the industrial processes are still developed using standardized configurations based on engineer experience and commercial preferences, with no guarantee that the best performances have been achieved for the technologies available. With the aim of helping the process engineer during the process design, an advanced method has therefore been developed for the systematic investigation of the large number of process alternatives and the optimization of the process configuration.

PROCESS DESIGN FOR IMPROVED ENVIRONMENTAL AND ECONOMICAL PERFORMANCES

When developing new processes, the process design consists in identifying the best process configurations in a given context, so that they may later be assessed by detailed engineering. A process configuration corresponds to a list of equipments interconnected in a given process layout, for which specific sizes and operating conditions are defined. Referring to Figure 1, the process design is realized in several steps. The process synthesis consists in systematically generating process configurations. The process characterization represents the performances evaluation of the generated configuration while the process optimization aims at selecting the best configurations according to a given objective function (costs and/or environmental impacts).

Process design therefore requires three key components:

- The **technical modeling** of equipments and a systematic method for the process synthesis,
- Accurate **performances indicators** for process characterization,
- An **optimization method** for the process optimization problem.

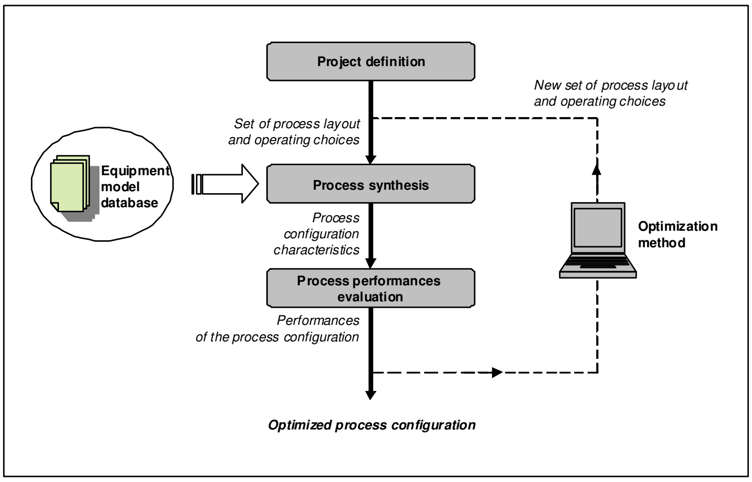

Figure 1: Process design methodology

In this project, the process optimization strategy has been applied to the reverse osmosis (RO) membrane desalination process, in order to minimize its costs and environmental impacts. Indeed, RO desalination is an alternative water treatment for potable water production, which may represent a major solution in facing the future potable water crisis [2]. Its development is still limited due to its high costs and potentially relevant environmental impacts. A computer-aided optimization methodology has thus been developed, which:

(i) includes a database of up-to-date RO equipment models,

(ii) performs the systematic generation of all feasible RO process configurations (process layout and operating conditions) with respect to project specifications and local context,

(iii) evaluates the technical, economical and environmental performances of these configurations,

(iv) optimizes the RO process configuration within a multi-objective framework.

Specific RO process technical modeling and performance evaluation are detailed in [3]. A focus is made in this article on the multi-objective optimization method. Its general principle may indeed be applied to all types of processes: stand alone technologies such as solid oxide fuel cells [4] or integrated system such as district heating [5].

MULTI-OBJECTIVE OPTIMIZATION METHOD

The optimization of a process consists in solving a mixed integer non linear programming (MINLP) problem [6, 7], which decision variables concern:

- The process layout (for RO: membrane type, number of modules per pressure vessel, number of stages, number of passes and piping network),
- The operating conditions (for RO: pressure vessel conversion rate, membrane average permeate flux…).

Within the technical limits of good practice of each decision variable, the optimization problem consists in identifying the sets of decision variables corresponding to process configurations with the best performances for the selected objectives. The optimal values of these decision variables are obtained by solving a **multi-objective optimization** (MOO) problem following the procedure presented in Figure 1. Each set of decision variables defines a specific process configuration which performances are evaluated for technical, environmental (total conversion rate, energy consumption) and economical criteria (investment and operating costs).

The assessment of the environmental impacts of RO desalination within an LCA framework points out that RO electricity consumption is responsible for more than 90% of RO plant life cycle impacts [3]. **Electricity consumption** is therefore considered as a representative measurement of the environmental performances of RO desalination plants. The costs are calculated using a "bottom-up" approach using capital cost estimation based on the equipments composing the RO process (pumps, membranes…). The resulting total costs are expressed by the **total water price (TWP)** in $\$/m^3$ of potable water, with accounts for operating costs and annualized capital costs.

These performance indicators are used as the objective functions of the MOO problem, which is solved using an evolutionary algorithm developed by Leyland et al. [8]. This MOO procedure allows to optimize the process simultaneously for diverse objectives without having to rank these objectives or to define an allocation between them [9, 10]. For two conflicting objectives such as the minimization of environmental impacts and the minimization of economical costs, the MOO results are not restrained to one unique solution but instead constitute a set of optimal solutions illustrating the trade-off between these objectives. These solutions define the so-called Pareto frontier (represented for example in Figure 2), which may be interpreted as a materialization of technical, economical or environmental constraints during process design. For a given electricity consumption the configuration on the Pareto curve represent the configuration with the cheapest cost of production that can be obtained. Similarly, for a given cost of production, the Pareto solution defines the one with the smallest electricity consumption. The following case study presents the information which may be generated by applying such methodology.

CASE STUDY ON BRACKISH WATER REVERSE OSMOSIS (BWRO) OPTIMIZATION

The analyzed potable water supply project has the following specifications:

- Potable water
  - Daily production capacity: 35000 m^3/d
  - Maximum permeate salinity: 0.3 g/L
- Water resource
  - Salinity: 3 g/L
  - Seawater temperature: 20°C
- Objectives
  - Minimize the total water price TWP in $/$m^3$ of potable water
  - Minimize the electrical consumption in kWh/m^3 of potable water

The goal is to define the best process configurations for this site specific project. The results of the optimization, e.g. the Pareto frontier of optimal RO process configurations, are displayed on Figure 2.

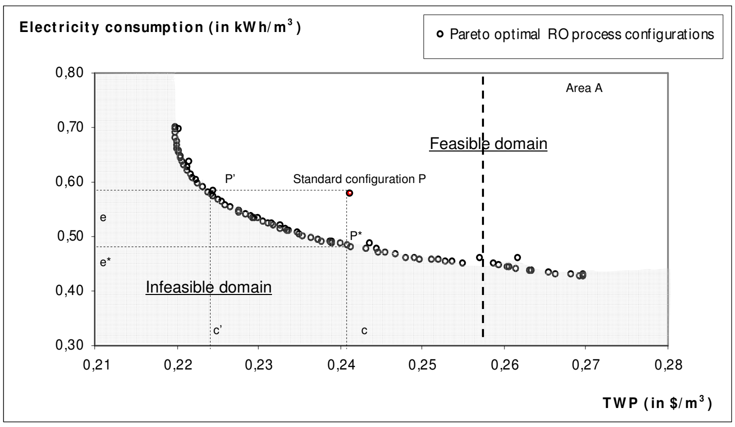

Figure 2: Optimized RO process configurations

For the sake of comparison, a standard RO process configuration has been located on Figure 2 (configuration P). This configuration P with performances (c, e) appears to be suboptimal because the configuration P' identified during optimization requires a lower cost c' for the same electricity consumption e while the configuration P* has an electricity consumption e* lower than e for the same cost c. Regarding the project specifications, the RO process configuration P' and P* are Pareto optimal because:

- for any cost c, it is technically infeasible to achieve lower electricity consumption than e*;
- for any electricity consumption e, it is technically infeasible to achieve lower cost than c'.

For the given project specifications, the optimal process configurations achieve a potable water production with a TWP between 0.22 and 0.27 $/m^3 and an electricity consumption between 0.4 and 0.7 kWh/m^3 (Figure 2). All the solutions used a two-staged process layout and an inter-stage booster pump (Figure 3). This generic two-stage layout is therefore proven to minimize simultaneously the electricity consumption and the TWP. The installation of inter-stage booster pumps also appears to be a "win-win" option from economic and environmental point of view.

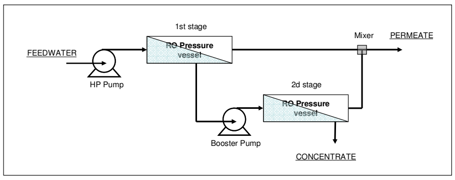

Figure 3: Optimal RO process flowsheet

The operating choice of the membrane permeate flux constitutes a trade-off between energy consumption and costs. Indeed, the TWP and the electricity consumption vary differently with the permeate flux. When membrane permeate flux increases, the required pressure on membranes and, in turn, the electricity consumption increase. Flux increase however decreases the required membrane area and therefore reduces the capital costs. For the project specifications, it appears to be cost efficient to operate the RO process with high permeate fluxes. On the contrary, low permeate flux allows to achieve lower environmental impacts, which are however counterbalanced by higher production costs.

Conclusions

An advanced process design method has been developed. It aims at identifying the best RO process configurations for given project specifications. The process configurations are systematically synthesized and evaluated by process performance modeling, capital cost estimation and environmental impact assessment methods. The performance indicators are used in a multi-objective framework that seeks to optimize the RO process configurations on economical and environmental objectives. A case study is presented for which the optimal layout and operating conditions are assessed as a function of the local context (e.g. feedwater salinity). The Pareto curve includes a list of optimal solutions ranging from environmental friendly solutions to the most economical one in which engineers and technology developers will select the final solution by applying multi-criteria analysis..

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