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# Systematic retrofit design with Response Surface Method and process integration techniques: A case study for the retrofit of a hydrocarbon fractionation plant

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## ABSTRACT

This paper demonstrates the Retrofit Design Approach (RDA) and Response Surface Methodology (RSM) for the retrofit of industrial plants in which assessment of design options for improving existing processes in a site-wide and integrated manner is not straightforward, due to complex design interactions in the process. The design methodology applied in this study is based on the systematic use of a process simulator which is used to identify promising variables through sensitivity analysis. Hence, the most important factors are determined and a reduced model is constructed based on RSM. An optimization framework is then built using the reduced model based on key selected variables, which is optimized to find optimal conditions and performance of the process. This design methodology provides strategic guidelines for determining the most cost-effective design options. The retrofit of a hydrocarbon fractionation plant is presented as an industrial case study. This includes a large number of design options with different process configurations and operating conditions due to the interconnection of distillation columns in sequence and the integrated heat recovery within the plant. The case study results demonstrate the applicability of the proposed approach which is able to effectively deal with a large retrofit problems. This is possible with the aid of process simulation and RSM producing a reduced model which requires considerably less computational effort to solve.

*Keywords:* Process simulation; Heat exchanger networks; Distillation column design; Process integration; Response Surface Methodology

## 1. Introduction

In process industries, increasing profits is not the only consideration and maintaining a safe working environment and improving sustainability are also very important. Modern plants are designed and operated in a highly integrated manner and consequently techno-economic analysis of existing plants for debottlenecking or retrofitting is too complicated to be dealt with using a simple model. In order to identify cost-effective process changes and evaluate their impacts on the site, it is necessary to build a modelling and design framework which allows full and thorough investigation of the plants overall performance. For small industrial plants, conventional modelling techniques and optimization tools are readily applicable for simulation and optimization of appropriate plant flowsheets for identifying the optimal design and operating conditions.

However, when facing a large design problem, the level of computational difficulty in the modelling and optimization, and the resources required to build models and obtain

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**Nomenclature**

| | |
|---|---|
| ACC | annualized capital costs |
| $ACC_{NewUnits}$ | annualized capital cost for new units |
| AF | Annualization Factor ($y^{-1}$) |
| ANOVA | analysis of variance |
| BC | base case |
| CC | composite curve |
| CCC | cold composite curve |
| CCD | Central Composite Design |
| $CC_{NewUnit}$ | capital cost of the new unit () |
| $CI(X_i)$ | capital investment of *i* |
| $CO_2T$ | annualized benefit from reduction in $CO_2$ emissions' tax () |
| Cp | heat capacity (kJ/(°C kg)) |
| CP | heat capacity flowrate (kJ/s) |
| DCS | distributed control system |
| DoE | Design of Experiments |
| EI | energy improvements |
| EPA42 | factor EPA-42 emissions factor (MMTon $CO_2$/MMBtu) |
| ER | energy recovery (kW) |
| ET | energy targeting (kW) |
| FD | factorial designs |
| $F_i$ | factor in EPA 42 for compound *i* [(Tonnes *i* s)/(Mt HC kJ)] |
| GA | genetic algorithms |
| GCC | grand composite curve |
| GRG2 | generalized reduced gradient |
| HC | hydrocarbon |
| HCC | hot composite curve |
| HCF | hydrocarbon fractionation process |
| HEs | heat exchangers |
| HEN | heat exchange network |
| Hi | enthalpy intervals (kJ/kg) |
| HPS | high-pressure steam |
| HUR | Hot Utility Reduction (MMBtu/y) |
| IPS | intermediate pressure steam |
| LP | linear programming |
| MaPr | marginal profit |
| MaPr* | marginal profit normalized |
| MARR | minimum acceptable rate of return (%) |
| MER | maximum energy recovery (kW) |
| MF | mass flowrate (kg/s) |
| MINLP | mixed integer nonlinear programming |
| MPCA | marginal profit capital affected |
| MPCA* | marginal profit capital affected normalized |
| MPS | medium-pressure steam |
| N/A | not available |
| NLLS | nonlinear least squares |
| NLP | nonlinear programming |
| NPr | net profit |
| NPW | net present worth |
| LLS | linear least squares estimation |
| LPG | gas liquefied from petroleum |
| LPS | low-pressure steam |
| OC | optimum case |
| PA | plant assets |
| PEMEX | Petroleos Mexicanos |
| PI | process integration |
| PLP | Project Life Period (10 y) |
| PP | payback period (y) |
| RMSE | Root Mean Square Error |
| RSM | Response Surface Methodology |
| SA | simulated annealing algorithms |
| SCC | Estimated Social Cost of Carbon |
| $SCCO_2$ | Estimated Social Cost of $CO_2$ (\$USD/t $CO_2$) |
| $S_{CO}$ | profit from the sales of co-product |
| SMS | sequential modular simulation |
| $S_P$ | profit from the sales of product |
| SRGHP | sales of RGHP |
| $T_{COND}$ | temperature for the condenser (°C) |
| $T_{EC}$ | total energy consumption (GJ/Y) |
| $T_{EVAP}$ | temperatures for the evaporator (°C) |
| $T_i$ | temperature intervals (°C) |
| $T_S$ | supply temperature (°C) |
| TT | target temperature (°C) |
| VCE | variable cost of energy |
| VCRM | variable cost of raw material |
| VF | vapour fraction |
| QC | minimum cold utilitiy energy needed (kW) |
| QH | minimum hot utilitiy energy needed (kW) |
| $\Delta T_{min}$ | minimum temperature difference (°C) |
| $C_{2+}$ | cryogenic liquids from internal supplier |
| $C_{3+}$ | cryogenic liquids from external supplier |
| $C_{5+}$ | Light Naphtas |
| $C_{6+}$ | Heavy Napthas |

engineering solutions increase considerably. For such large industrial plants, a common practice is to decompose the design problem into several smaller subsystems to solve independently or sequentially. This division simplifies the overall problem and decreases the computational time required to find solutions. However, there is no guarantee that resulting solutions will be globally optimal, and they will be locally optimal with respect to certain objective functions and design constraints. For a non-integrated and simplified design model such as this, the complex design interactions related to plant retrofit and process changes will not be systematically investigated.

When a very detailed rigorous modelling and design framework of the plant is implemented, simulation and optimization of such models will typically require significant computational resources. Although various deterministic and stochastic optimization techniques have been successfully applied to a wide range of industrial applications (Smith, 2013; Grossmann, 2013), it is often difficult to obtain optimal solutions with the available computational time and resources. Also, in-depth evaluation of economic trade-offs existing in the plant may not be envisaged when various design issues are interconnected and/or when different performance criteria are evaluated simultaneously. In particular, when the design problem is to retrofit the existing plant, it is more difficult to provide engineering solutions in practice due to inflexibilities associated with existing equipment size and process flowsheet configuration.

Heuristic rules or trial-and-error methods to screen retrofit alternatives or design options are often used in industries. Although such heuristic-based design procedures allow considerable engineers' flexibilities in building process models or carrying out economic trade-offs, these methods heavily relied on engineers' experience and/or insights for retrofit problems and, consequently, are limited for considering only manageable number of variables for the retrofit as well as

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