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Decision support for ranking Pareto optimal process designs under uncertain market conditions

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ABSTRACT

Considering the uncertainty of economic conditions, multi-objective optimisation can be favoured to single-objective optimisation for process design. However, from the Pareto sets generated by multi-objective optimisation it is not obvious to identify the best one, given that each solution is optimal with regard to the selected objectives. A method taking into account the economic parameters uncertainty to support decision making based on the Pareto-optimal solutions is proposed. It uses a Monte-Carlo simulation to define the probability of each of the Pareto optimal configuration to be in the list of the best configurations from the economical point of view. For a given economic context defined the most probable best configurations are identified. The proposed method is applied to two cases: the CO_2 capture in power plants and synthetic natural gas production from biomass resources. The results allow to identify the most attractive system designs and give recommendations for the process engineers.

1. Introduction

To meet the CO_2 reduction targets and to ensure a reliable energy supply, the development and wide scale deployment of cost-competitive innovative low-carbon energy technologies is necessary. Carbon capture and storage (CCS) in power plants and the use of renewable resources for the poly-generation of biofuels, heat and power are considered as promising measures. The thermodynamic performance of different process designs depends on the process configuration (i.e. technological options and operating conditions) while the market competitiveness depends in addition on the economic conditions, especially on the resource price. Therefore, it is important to evaluate and optimise the process designs with regard to multiple competing objectives such as efficiency, investment cost and environmental impacts. Since there is a trade-off between the objectives and that the economic performance is highly influenced by the market conditions, it is difficult to identify the best process design from multi-objective optimisation results by taking into account the economic parameters uncertainty.

The influence of the economic conditions is frequently investigated in literature based on extreme scenarios, as in (ZEP, 2011) for the European market and in (Finkenrath, 2011) for the global market, or on sensitivity analysis. A method to support decision making based on multi-criteria decision analysis taking into account uncertainties is developed by Basson and Petrie (2007). In (Bortz et al., 2014) a method for decision support in chemical process design based on the navigation on Pareto sets is proposed. The innovative slider concept (Burger et al., 2014) used to navigate on the Pareto frontiers supports decision making by choosing the best compromise between conflicting objectives. This method does not account for parameters uncertainties. Multiple decision making methods have been developed for management activities. However, the applications for process system designs are limited. To assist the multi-objective decision analysis an incentive model for primary energy savings and carbon dioxide emission reduction is presented in (Hu and Cho, 2014) to evaluate the Pareto operation decisions derived from a stochastic model including uncertainties. In (Gaspar Cunha et al., 2014) decision making and robustness strategies are combined with multi-objective optimization to optimize polymer extrusion processes.

So far systematic approaches taking into account the economic conditions fluctuation for the decision making based on the optimisation results are rarely applied and process integration aspects and life cycle assessment are not systematically assessed. Based on the systematic optimisation approach previously presented Gerber et al. (2011), Tock and Maréchal (2012), a method, taking into account the economic parameter sensitivity, to support decision making based on the Pareto-optimal solutions is proposed here.

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Nomenclature

Abbreviations

ATR	autothermal reforming
BM	biomass
CC	carbon capture
CCS	carbon capture and storage
CFB	circulating fluidised bed
CFBO2	circulating fluidised bed directly heated with O_2
CGCL	cold gas cleaning
CPI	current policy initiatives
DH	district heating
ETS	emission trading system
FICFB	fast internally circulating fluidised bed
pFICFB	pressurised fast internally circulating fluidised bed
GWP	global warming potential
HGCL	hot gas cleaning
IPCC	international panel on climate change
LCA	life cycle assessment
MEA	monoethanolamine
NG	natural gas
NGCC	natural gas combined cycle
PSA	pressure swing adsorption
SNG	synthetic natural gas
WGS	water gas shift

Greek letters

Δh^0	lower heating value, kJ/kg
ϵ	energy efficiency, %

Roman letters

COE	electricity production cost, $\$/GJ_e$
$\dot{E}$	mechanical/electrical power, kW_e
$\dot{m}$	mass flowrate, kg/s
$\dot{n}$	molar flowrate, kmol/s
$\dot{Q}$	heat flow, kW

The influence of the economic scenario on the decision-making is studied by taking into account the sensitivity of the economic performance to the carbon tax, the resource prices, the operating time, the investment and the interest rate.

1.1. Uncertain market conditions

The analysis of the fossil fuel market over the last years, reveals diverse patterns over time and with regard to the geographic location (i.e. Europe, the United States and Japan). This is revealed by the energy statistics (IEA, 2012) and the oil and gas market data reported by the IEA (IEA, 2011), as well as the publications of the European Comission reporting trends (European Commission, 2009), raw data (Eurostat, 2014) and future scenarios (EU, 2011). The large fluctuations result from multiple factors affecting the trading. In the past, the natural gas price evolution went in pair with the oil price. However, with the exploitation of shale gas this pattern changes. The coal price which is less affected by the oil price and is predicted to stabilise around $5\$/GJ_{coal}$ in 2030 (EU, 2011). Consequently, the gas to coal price ratio is projected to increase steadily and will together with the carbon price influence investment decisions in the power sector. European gas prices are about twice as high as US gas prices and are projected to be $10\$/GJ_{NG}$ in 2020, $12\$/GJ_{NG}$ in 2030 and $16\$/GJ_{NG}$ in 2050 for the EU 'Reference' energy scenario (EU, 2011). In a similar way, the carbon tax price is influenced by multiple factors. The emission trading system (ETS) directive has been established in the European Union to promote greenhouse gas emissions reductions in a cost effective and economically efficient manner (European Commission, 2012). The carbon price drop from around $25€/t_{CO_2}$ in 2008 to below $10€/t_{CO_2}$ in the second half of 2011 because of the surplus of allowances and international credits and the financial crisis. According to the predictions from the Energy Roadmap 2050 (EU, 2011), carbon tax prices will rise moderately until 2030 and then significantly to provide support to low carbon technologies and energy efficiency. For the current policy initiatives (CPI) scenario, taking into account the latest policies on energy efficiency, taxation and infrastructure, the carbon tax is predicted to increase to $15€/t_{CO_2}$ in 2020, to $32€/t_{CO_2}$ in 2030 and to $51€/t_{CO_2}$ in 2050. Comparing the costs projections for different energy and policy scenarios a large variation of the predictions is found. This highlights the large uncertainty of costs projections and the need to account for different economic scenarios when evaluating the competitiveness of processes to support investment decisions.

2. Methodology

The applied thermo-environomic modelling and optimisation approach illustrated in Fig. 1 combines flowsheeting and energy integration techniques with economic evaluation and life cycle assessment (LCA) (Gerber et al., 2011) in a multi-objective optimisation framework previously presented in Gassner and Maréchal (2009), Tock and Maréchal (2012). The main steps are summarized as following:

1 Establishment of the process superstructure and development of the process models.
2 Computation of the energy integration.
3 Assessment of the performance indicators.
4 Multi-objective optimisation.
5 Decision making.

After the assessment of candidate process technologies in a superstructure, energy-flow models are established with conventional flowsheeting software computing the chemical and physical transformations and the associated heat transfer requirements of each process option. The heat recovery and the combined heat and power production is optimised in the energy integration model by using the heat cascade constraints and a linear programming model minimising the operating cost (Maréchal and Kalitventzeff, 1998). The process needs are satisfied by different utilities including waste and process gas combustion, Rankine cycle, gas turbine and cogeneration. To evaluate the economic performance, the equipments are first sized and the costs are then evaluated by applying the approach and correlations reported in Turton (2009), Ulrich and Vasudevan (2003). A multi-objective optimisation based on an evolutionary algorithm (Molyneaux et al., 2010) is finally performed to assess the trade-offs between competing objectives and identify optimal process designs and operating conditions. Evolutionary algorithms working with populations instead of a single data point, generate multiple promising solutions in the form of a Pareto-optimal frontier. The Pareto-optimal solutions correspond to the configurations for which it is not possible to improve one objective without simultaneously downgrading one of the other objectives. It is a priori not obvious which configuration has to be chosen from the Pareto results.

Therefore, the aim is here to propose an approach which allows to identify the optimal process design from the Pareto-optimal solutions taking into account the economic conditions sensitivity.