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An optimization model to improve gas emission mitigation in oil refineries

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ABSTRACT

Gas emissions are a major source of the air pollution that causes global warming, climate changes and ozone layer depletion. A large portion of these pollutants come from crude oil refining in the form of nitrogen oxides (NOx), sulfur oxides (SOx) and volatile organic compounds (VOC). Gas emissions can be mitigated during crude oil refining using different methods associated with different investment costs. The aim of this paper is to develop an optimization model that identifies the best mitigation technology with minimum cost. A case study is presented for a refinery in Saudi Arabia that has three mitigation alternatives for gas emissions reduction, namely, balancing, fuel switching and specialized technologies. The effect on the plant's profitability is studied with different reduction targets (20%–90% cut in emissions). The profit margin of the refinery for each scenario is formulated as a mixed integer nonlinear programming model. The model enables the plant's management to correlate emission reduction to its effect on the refinery's profitability. The results of the model urge the revision of legislation to offer incentive packages for plants that achieve higher pollutant reduction. Also, a universal curve is obtained for the fractional loss of profitability as a function of percent reduction of specific pollutant emissions. This is achieved by relating the loss in profitability to that of an equivalent "zero-emissions" refinery.

1. Introduction

Crude oil refining is considered a major source of air pollution as a result of the associated gas emissions. These gas emissions come mainly from incineration processes in the refinery. In fact, world-leading refinery capacities have moved toward developing countries known as the new seven sisters (Saudi Aramco – Saudi Arabia, JSC Gazprom – Russia, CNPC – China, NIOC – Iran, PDVSA – Venezuela, Petrobras – Brazil and Petronas – Malaysia) (Jovanovic et al., 2010). The newly adopted environmental regulations mandate reducing gas emissions. Indeed, the abatement of these emissions is of essential concern in most petrochemical industries, as investing in emission reduction techniques may adversely affect the profitability. Hence, refineries may hesitate to invest in pollutant mitigation technologies, as these investments are seen as a threat to their profitability without any direct financial returns other than the environmental context.

In general, refineries produce revenue by selling refined petroleum products. Profitability is usually affected by technical inefficiencies, market saturation, higher crude cost and technical limitations. The mathematical formulation techniques are common tools used to determine plants' profitability, e.g., nonlinear programming or mixed integer linear programming models (Sahinidis, 2004). Mathematical formulation techniques indeed help decision makers to arrive at better decisions related to technology implementation, revamping and retrofitting options, mitigation technologies etc. Hence, optimization models to formulate the effect of gas emission reduction on plants' profitability are highly needed (Ekins et al., 2007). Usually, they are done at the plant level and can be extended to complement analytical tools used for environmental systems analysis (Höjer et al., 2008). In addition, many studies exploring the economics of clean technologies and sustainability have appeared. For example, da Silva and Amaral (2009) analyzed environmental impact and related process costs

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simultaneously, which allowed management to identify the production process stages that have critical environmental impacts.

The objective of this paper is to develop a model that helps management to reduce gas emissions in oil refineries. The main contribution of this paper is the inclusion of the economic effect of gas emission abatement strategies on plants' profitability. In addition, the model enable the refinery to determine how much investment needed to reach zero-emissions. The needed investments are estimated based on the relation between profitability reductions and emissions (universal curve). The universal curve features the relationship between the fractional losses in profitability with percent reduction of emissions for a specific type of pollutant. The model can be used as an aid for managerial decisions on various future strategies.

2. Background

Gas emissions are groups of highly reactive gasses as defined by the national ambient air quality standard (NAAQS) (US Environmental Protection Agency, 2015a). The refining industry is responsible for a large portion of harmful gas emissions, which include oxides of nitrogen (NOx), sulfur (SOx) and volatile organic compounds (VOC). Currently, nitrogen oxides and five other major pollutants are listed as criteria pollutants. The others are ozone, lead, carbon monoxide, sulfur oxides (SOx) and particulate matter. NO_2 is linked with a number of adverse effects on the respiratory systems of humans. Current scientific evidence links short-term NO_2 exposures, ranging from 30 min to 24 h, with adverse chronic respiratory effects including airway inflammation in healthy people and increased respiratory symptoms in people with asthma.

Volatile organic compounds (VOC) are organic materials that have a high vapor pressure, or low boiling point, at normal ambient conditions, allowing molecules to vaporize in the air. Table 1 shows some VOC examples (Canadian Centre for Occupational Health and Safety, 2015). VOC emissions into the atmosphere are regulated by law, as some VOC are seriously hazardous to human health and/or the environment. VOC usually cause chronic rather than acute symptoms to human beings. To control VOC, plants may install a complete system for vapor recovery for nearly all tanks on the refinery. A refinery in Sweden applied the recovery system in 1995, and the estimated reduction of the volatile organic compound emissions was around half (Holmgren and Sternhufvud, 2008). Appendix A shows a brief description of gas emission reduction strategies.

3. Literature review

Refinery production is being widely addressed by mathematical models. This section provides an overview of previous studies carried out on refinery optimization and refinery monitoring to decrease gas emissions.

3.1. Mathematical models in refinery

Pinto et al. (2000) developed a mathematical model to analyze different market scenarios. Mathematical programming techniques can also be used to decompose large-scale refinery into smaller problems, as shown in Zhang and Zhu (2000): a site level (master model) and a process model (submodels). Similarly, Castillo and Mahalec (2014) provided a two-level optimization model to detail operating conditions (top level) and production plan (lower level). Alhajri et al. (2008) developed simplified empirical nonlinear process models to predict the operating variables, analyze crude characteristics and determine the yield of products and qualities used. A model was suggested to reduce SO_2 emissions by source production reduction, fuel gas treatment or fuel gas desulfurization treatment in the work of Dikshit et al. (2005). Zhao et al. (2014) provided a model to integrate the refinery production system and the utility system to minimize losses and increase profitability. Recently, mathematical models have been used in the integration of oil supply chains. The downstream part of the chain usually covers refinery operations. Guajardo et al. (2013) addressed the tactical problems that involve decisions in production, distribution to customers and inventory. Fernandes et al. (2014) studied the collaborative design to maximize profit on multi-echelon chain levels. In addition, mathematical modeling was also used in the upstream chain. The modeling helped to absorb the uncertainty in risk assessment, as shown in Gupta and Grossmann (2015). Shakhsi-Niaei et al. (2014) provided a long-term planning model to select possible oil projects.

3.2. Refinery emissions monitoring and measurement

Industrial gas emissions are also studied in the literature. De Kluizenaar et al. (2001) created a model for high-resolution emission (NOx and SO_2) maps for the republic of Ireland using a geographical information system and emission totals. Pierru (2007) developed a model to minimize refinery variable costs and determine the refinery's CO_2 emissions. Cai et al. (2013) developed a study in China for the chemical facility emissions caused by uncertainties such as equipment failure, false operation and natural disasters. A study of China's SO_2 emissions from 1995 to 2010 showed the significance of pollution abatement, production reduction and cleaner production (Liu and Wang, 2013). Wei et al. (2014) provided a VOC measurement for a petroleum refinery in Beijing (China's capital).

In Saudi Arabia, Ahmed (1990) discussed emissions in relation to major fuel-consuming facilities. Akimoto and Narita (1994) provided another study in Asia to define the spatial distribution of SO_2, NOx and CO_2 emissions for different sectors. González et al. (2011)

Table 1
Examples of VOC (Canadian Centre for Occupational Health and Safety, 2015).

VOC	Molecular weight	Saturated Vapor pressure (kPa)	Temperature (°C)
Acetone	58	23.998	20
Benzene	78	9.999	20.8
n-Butane	58	101.32	25
Carbon disulfide	76	39.596	20
Ethanol	46	0.001	20
Methylene chloride	85	58.661	25
Methyl-tert-butyl ether (MTBE)	88	33.330	25
Propylene − Oxide	58	59.328	20
Toluene	92	2.799	20