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Two-stage stochastic programming with fixed recourse via scenario planning with economic and operational risk management for petroleum refinery planning under uncertainty

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Abstract

This work proposes a hybrid of stochastic programming (SP) approaches for an optimal midterm refinery planning that addresses three sources of uncertainties: prices of crude oil and saleable products, demands, and yields. An SP technique that utilizes compensating slack variables is employed to explicitly account for constraints' violations to increase model tractability. Four approaches are considered to ensure solution and model robustness: (1) the Markowitz's mean-variance (MV) model to handle randomness in the objective function coefficients by minimizing the variance (economic risk) of the expected value of the random coefficients; (2): the two-stage SP with fixed recourse approach to deal with randomness in the RHS and LHS coefficients of the constraints by minimizing the expected recourse costs due to constraints' violations; (3) incorporation of the MV model within the framework developed in (2) to formulate a mean–risk model that minimizes both the expectation and the operational risk measure of variance of the recourse costs; and (4) reformulation of the model in (3) by adopting mean-absolute deviation (MAD) as the measure of operational risk imposed by the recourse costs for a novel refinery planning application. A representative numerical example is illustrated.

Keywords: Two-stage stochastic programming; Refinery planning; Optimization under uncertainty; Scenario analysis; Mean-variance; Mean-absolute deviation (MAD)

1. Introduction

It is a well-recognized problem that chemical process systems are subject to uncertainties presented by random events such as raw material variations, demand fluctuations, and equipment failures. The present work is intended to contribute towards mitigating this challenge by utilizing stochastic programming (SP) methods and analyses that are typically employed in computational finance applications, which have been demonstrated to be useful for screening alternatives on the basis of the expected value of economic criteria as well as the economic and operational risks involved [1,2]. Several approaches have been reported in the literature addressing the problem of production planning under uncertainty. Extensive reviews surveying various issues in this area are available, for example, by [3–6].

In general, planning models can be broadly categorized into three temporal classifications based on the addressed time horizons [7,8], namely (1) strategic (long-term, e.g. [9,10]); (2) tactical (medium- or midterm, e.g. [11,12]), and (3) operational (short-term, e.g. [13,14]). A discussion of their features and characteristics from a practical perspective is provided by [15]. The focus of this work is on the midterm tactical planning of petroleum refineries.

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Problems of design and planning of chemical processes and plants under uncertainty have been effectively treated in the process systems engineering (PSE) literature using the well-known approach of two-stage stochastic programming (SP) with recourse model. Under this framework, the problem is posed as one of optimizing an objective function that conventionally consists of two terms (or stages). The first corresponds to the "here-and-now" decisions of the global or planning variables, whose fixed values are selected ahead of, and thus independent of, the realization of the uncertain events. The second term represents and quantifies the expected value of the "wait-and-see" decisions due to the production variables, whose flexible values will be adjusted to achieve feasibility during operation, in response to revelation of the specific values of the uncertain parameters [16,17]. Further, variabilities due to production shortfalls and surpluses are accounted for by appending an additional second-stage term to the objective function, giving rise to the notion of operational risk [18] that results in a mean-risk structure of the model [19,20]. The presence of uncertainty is translated into the stochastic nature of the recourse costs associated with the second-stage decisions. Hence, the goal in the two-stage modelling approach to planning decision under uncertainty is to commit initially to the planning variables in such a way that the sum of the first-stage costs and the expected value plus deviations of the typically more expensive random second-stage recourse costs is minimized [21]. Approaches differ primarily in the way the expected value and its deviation terms are evaluated.

2. Problem statement

The midterm refinery production planning problem addressed in this paper can be stated as follows. It is assumed that the physical resources of the plant are fixed and that the associated prices, costs, and demands are externally imposed [22]. The objective is to determine the optimal planning by computing the amount of materials that are processed at each time in each unit, in the face of three major uncertainties that are considered simultaneously, namely (1) market demand for products; (2) prices of crude oil and the saleable products; and (3) product (or production) yields of crude oil from chemical reactions in the primary crude distillation unit. A hybrid of stochastic programming techniques is applied within the framework of the classical two-stage stochastic program with fixed recourse to reformulate a deterministic planning problem. This approach is accomplished by adopting the mean-variance (E–V or MV) portfolio optimization model of Markowitz [23,24] in handling risk arising from variations in both profit and the recourse penalty costs due to violations of the stochastic constraints. A numerical study based on the deterministic refinery planning model of [25,26] is utilized to demonstrate the implementation of the proposed approaches without loss of generality. The single-objective linear programming (LP) model is first solved deterministically and is then reformulated with the addition of stochastic dimension according to principles and approaches outlined under the general model development.

3. General formulation of the deterministic midterm refinery planning model

The basic framework for the deterministic planning model is mainly based on models formulated by [11,27], apart from those specific to refinery planning as proposed by [28–30]. Consider the production planning problem of a typical refinery operation with a network of M continuous processes and N materials as shown in Fig. 1. Let $j \in J$ index the set of continuous processes whereas $i \in I$ index the set of materials. These products are produced during n time periods indexed by $t \in T$ to meet a prespecified level of demand during each period. Given also are the prices and availabilities of materials as well as investment and operating cost data over a time period. A typical aggregated mixed-integer linear planning model consists of the following sets of constraints and objective function.

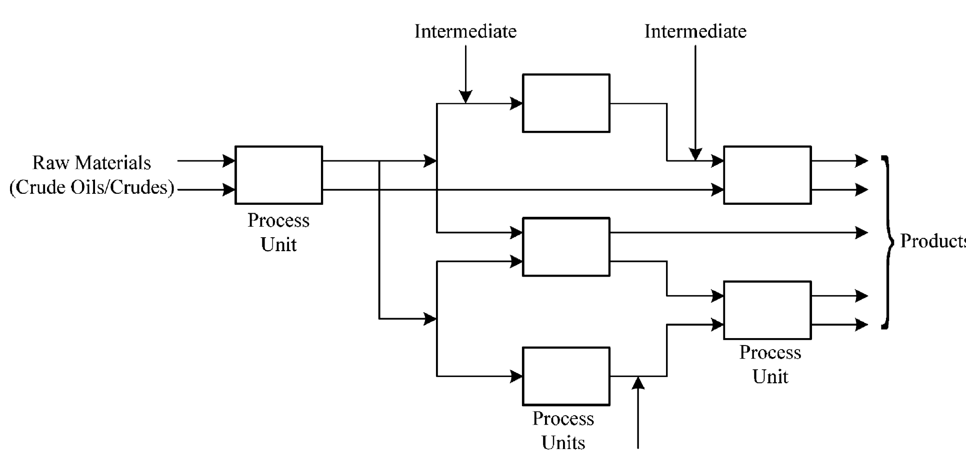

Fig. 1. A network of processes and materials of a typical oil refinery operation (based on [28]).