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Desirable policies of a strategic petroleum reserve in coping with disruption risk: A Markov decision process approach

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ABSTRACT

A Markov decision process model is proposed to examine the desirable sizes and policies of a strategic petroleum reserve (SPR) for oil consumption countries. Oil consumers operate SPRs to cope with various market states. Market uncertainties include oil supply, oil price and disruption situations in which oil supply is highly stochastic. The decision criterion is to minimize total disruption losses and SPR costs. The output of the proposed model finds optimal SPR acquisition, drawdown and refill policies in response to different market states. In a representative numerical case, we examine desirable SPR size and how China should absorb into or release from its SPR in special scenarios. In a new scenario of long-duration disruption risk in particular, we find that high disruption duration risk may increase the optimal SPR size significantly, i.e., 9% greater in this case. Meanwhile, the result shows variation in the SPR drawdown policy when considering various disruption durations. Finally, a United States case has been studied with the developed model. We find interesting results by comparing the results of China and the U.S. Under the scenario of 20% disruption, although with different SPR capacities, both countries should release all SPRs to reduce GDP loss as much as possible.

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1. Introduction

Oil, the blood of industry, has been a critical fuel for many decades of rapid world economic growth. Due to the imbalance of reserves distribution, oil must be transported long distances. Concurrently, affected by a number of factors, e.g., geopolitics, logistics and weather, the world oil supply has shown huge uncertainty and risk of disruption. In the past half century, the world oil market has endured at least 11 significant oil supply shocks [15-17]. The most severe crises, in the 1970s, cost oil importers hundreds of billions of dollars in the form of lower GDP and higher payments for oil imports [30].

Such massive economic damage could be dampened through being well-prepared with an advance response measure, i.e., a strategic petroleum reserve (SPR). A SPR could be used in disruptions to make up for the shortfall caused by interrupted oil supply. Moderating a rise in oil prices, thereby, limits adverse macroeconomic effects from a supply disruption [9]. Most recently, the coordinated release of SPR in August 2011 during the Libya war successfully addressed the problem of supply interruption, demonstrating the ability of a SPR in responding to an oil supply shortfall effectively and decisively [14].

It costs billions of dollars to establish a huge quantity of reserves. The decision maker should consider minimizing disruption loss and total cost when implementing a SPR policy [16]. Several earlier studies have focused on SPR decision problems. Nordhaus [28] examined the optimal stockpile size and tariff rate of the United States by using a two-period optimization model. Tolley and Wilman [34] reformulated the model to allow for the presence of an embargo threat. Recently, Bai et al. [2] contribute to the issue by identifying the marginal benefit of a SPR. The dynamic programming method has been widely used in studying such SPR problems. Teisberg [33] formulated a dynamic programming model that was able to determine the optimal SPR size and fill-up and drawdown strategies contingent upon supply and demand conditions. Later studies further improved Teisberg's model, primarily from the perspective of disruption costs and market risks. For such studies, also see Bai et al. [1], Chao and Manne [8], Oren and Wan [29], Wei et al. [36] Wu et al. [37,38], and Zhang et al. [39].

Game theory can be used to analyze the stockpiling competitive and cooperative relationships among different market agents such as importers and exporters, governments and speculators. Base on the assumption of a potential embargo threat, Nichols and Zeckhauser

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[27] proposed a multi-period game model to investigate the stockpiling strategies of oil consumers and pricing strategies of a cartel. Balas [3] treated a disruption as part of a producer's strategy and employed a two-person gaming model to examine oil stock size for consumers. Murphy et al. [22–24] formulated Nash game models to investigate the competition and cooperation between consumers and public and private reserves. These studies examined equilibrium policies for existing market agents. Following Murphy et al. [25,26], Fan and Zhang [11] analyzed interactions between China and India's SPR policies. Murphy and Oliveira [26,27] discussed the possibility of using financial tools to manage a SPR better in a financial market in which both public and private benefits and their interactions were considered.

A Markov decision process (MDP) approach is very efficient in handling stochastic decision problems [19,20]. The SPR decision problem could also be considered a sequential decision problem. The market state, i.e., oil supply, evolves randomly with a non-aftereffect property. Therefore, the sequential nature of SPR management, together with the inherent uncertainty of the oil market state, explains the modeling of SPR management problems as Markov decision processes (MDPs).

In the study, a SPR-MDP model is proposed to survey SPR decision problems such as desirable SPR size, acquisition, and drawdown and refilling policies. The market states are assumed stochastic. In a normal state, SPR costs derive from facility construction, oil acquisition and maintenance. In disruptions, an SPR provides benefits by making up for supply shortages and reducing economic losses. The objective of our model is to minimize the sum of social losses and SPR costs over an infinite time horizon.

The study makes a threefold contribution to the literature. First, SPR cost and disruption loss have been reconsidered. We assume the reward function includes consumer welfare loss, excess wealth transfer, macroeconomic adjustment loss and SPR cost. However, differing from earlier studies, we assume that losses from excess wealth transfer and macroeconomic adjustment loss only exist in a disruption state. In a normal state, even when there is a price fluctuation, the economy is able to adjust to the change smoothly without any loss. To address this additional requirement, we improved the model by introducing a boundary constraint. Second, we take a first step in examining SPR policy in response to a new scenario of long-duration risk. We assume if a disruption occurs, there is higher probability that the disruption will last into a next stage. The numerical result shows that overlooking long-duration risk may result in a significant difference in optimal policy. Third, we relax the constraint on decision period into an infinite time horizon.

The remainder of this paper is organized as follows. Section 2 provides the formulation of a SPR-MDP model and the solution procedure. Section 3 specifies the variables and parameters, and Section 4 describes the main results of our case study. Section 5 concludes.

2. Model formulation

In this section, we first define all the necessary elements and then formulate the model for SPR issues. To make the model reasonable, we propose the following assumptions.

(i) The oil normally arrives in a uniform stream sufficient to meet the nation's requirements. The demand is assumed constant and only changes when China's stockpile changes. Seasonal demand is not considered in the model because the change is not appreciable and is usually predictable.
(ii) Decisions for SPR acquisition, drawdown or refill are made at the beginning of each stage.
(iii) We use monthly time steps, although this can be relaxed by appropriately scaling the time variable.

2.1. Notation

The model formulation follows conventions and notation from Bai et al. [2]. We provide the formulation by initially defining relevant parameters and variables, and then providing state-transition, reward function, constraints and the objective function.

t: time stage (month)
P_t: oil price in time t ($\$/bbl$)
s: oil supply (million barrels)
λ_s: disruption magnitude (%)
λ_d: disruption duration (month)
λ_p: disruption probability (%)
a_t: SPR acquisition (or drawdown) rate (million barrels per month)
$\overline{a}$: SPR acquisition limit for each stage (million barrels per month)
$\underline{a}$: SPR drawdown limit for each stage (million barrels per month)
u_t: SPR capacity in time t (million barrels)
$\overline{u}$: SPR capacity limits (million barrels)
p_t: oil price at stage t (dollars per barrel)
g: GDP value (million dollars)
e: oil-price elasticity of GDP
δ: ratio of SPR construction cost to purchase cost
γ: discount rate
η: SPR unit holding cost (dollar per month)
σ: demand elasticity on oil price
q: regular supply quantity (million barrels per month)
D: oil demand (million barrels per month)
c^w: consumer welfare loss (million dollars)
c^f: excess wealth transfer (million dollars)
c^a: macroeconomic adjustment loss (million dollars)
c^c: SPR facilities construction cost (million dollars)
c^p: SPR acquisition (release) cost (revenue) (million dollars)
c^h: SPR holding cost (million dollars)

Parameters λ_s and λ_d indicate disruption magnitude and duration, respectively. Concerning constraints on SPR facilities, we use $\overline{a}$ and $\underline{a}$ to indicate the maximum SPR acquisition and drawdown capacity of each stage. Oil-price elasticity of GDP (e) denotes percentage change in GDP in response to percentage change in oil price [18]. Similarly, Demand elasticity of oil price σ indicates percentage change in demand in response to percentage change in oil price.

2.2. State and decision variables

Decision variable a_t. SPR acquisition or drawdown quantity $a_t \in A$ in stage t.

State variable w_t. State information $w_t \in W$ arrives at the beginning of stage t, which includes SPR size $u_t \in U$ and oil supply $s_t \in S$. The state variable can be indicated as a Cartesian product of SPR size U and oil supply S where U and S are countable. We define supply state $i \in I$, which could be normal ($i=0$) or disruption ($i=1, 2, \dots, N$). Oil supply s_t depends on regular supply quantity q and supply state i_t.

2.3. State transition function

State variable w_t follows the basic rules of a Markov process. Transition probabilities from state i to j are given by matrix $Pro=$

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