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A diversified portfolio: joint management of non-renewable and renewable resources offshore

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Abstract

Most resource models and resource policies address non-renewable and renewable resources separately for optimal management. A stochastic control model is developed that includes ecological and economic uncertainty for jointly managing both types of natural resources. The model is applied to analyze options for offshore oil platforms with data from California. Model components include fisheries benefits, maintenance and extraction costs, decommissioning costs, and the market value of oil. Numerical sensitivity analysis helps determine how these components affect the options of removing and salvaging the platform, continuing diversified resource production or delaying extraction activity.

JEL classification: G11; Q20; Q30; L71

Keywords: Offshore oil extraction; Resource portfolio

1. Introduction

With energy independence becoming more critical, the U.S. has renewed focus on offshore oil drilling platforms (U.S. COP, in press). Offshore oil development has occurred in leased tracts in California and Gulf of Mexico waters (off of Texas, Louisiana,

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Mississippi, and Florida) from the mean high tide line to three miles offshore, and Federal waters (from 3 to 200 miles offshore). For California, seventy-nine leases lay offshore San Luis Obispo, Santa Barbara and Ventura Counties. Forty-three of these leases produce a total of 125,000 barrels of oil per day (Love et al., 2001). Thirty-six offshore leases of these three counties are undeveloped and are estimated to have 1 billion barrels of economically recoverable oil (PACFIN, 2000). Due to existing lateral and slant drilling technology, it is possible for many of the undeveloped leases to be accessed from existing platforms rather than constructing new platforms for each lease (California Coastal Commission, 1999).

There is evidence of the ability of the offshore oil platforms to support fisheries on the stable structure legs concurrent with oil production (Love et al., 2001). Offshore oil production in the U.S. offers an example of a non-renewable resource that can be included in a diversified portfolio of renewable and non-renewable resources. An offshore platform is flexible fixed capital for managing oil and fish simultaneously. The platform is privately owned so the platform owner can enjoy the benefits of fish as well as oil production.

Federal regulations require the platform operator to harvest attached sealife regularly to keep the thickness of the biomass to a minimum in order to avoid top heavy weight that could topple the platform (Federal Register 30 CFR250.900), resulting in possible damages and liability costs. This paper provides an empirical analysis of simultaneous non-renewable and renewable resource management decisions in the offshore oil and fisheries context. The analysis helps illuminate decommissioning choices of leaving the platform in place or completely removing it. These choices are of interest to the U.S. and other countries pondering the future of offshore platforms. The leave in place option offers the possibility to access several oil reserves from an existing platform through slant drilling and can support fisheries operations from its position.

The analysis includes stochastic behavior of oil prices that influences domestic offshore oil supply. The stochastic value for managed fisheries at the oil platform and the liability from possible accidents are also modeled. Important policies at the national and state level are evaluated. For example, the state of California has considered a legislative bill to leave the platforms in place for artificial reefs with ambiguous conditions on liability for the platform owners. Also, the federal government has pursued legal action to change the moratorium on the 36 undeveloped oil leases that would affect how much oil can be accessed and the costs for access by existing and new platforms.

The following section identifies existing literature related to financial portfolio analysis and oil resources. Section 3 provides a portfolio model to establish thresholds for optimal switching between alternatives for offshore oil and fisheries resources from oil platforms. A description of the data used to analyze platforms offshore from California is contained in Section 4. Section 5 presents results for the baseline and sensitivity analysis. Discussion of the results centers on the financial thresholds for switching that are derived for a comparison of the present value of each investment alternative. Conclusions about the findings and implications for offshore resources are offered in Section 6.

2. Literature review

No other papers exist that address joint decisions over offshore oil and fisheries management in the resource economics literature. One paper by Caswell (1991), qualitatively describes potential difficulties with both resources in the same location. However, no attention is directed towards the offshore platform's versatile use for accessing oil and fisheries resources. Irreversibility and uncertainty characterize both the development and disassembly of offshore oil drilling in terms of prices and costs. The finance literature with applications to minerals is relevant here since finance is the study of the allocation of economic resources both spatially and across time, in an uncertain environment (Merton, 1998). Paddock et al. (1988) shows that option value can be a significant proportion of the total value of offshore oil leases, especially when economic conditions change over time.

Dixit and Pindyck (1994) review the literature on decisions to switch between investing, abandoning, or mothballing projects in response to changing economic conditions. Each switch is an exercise of an option yielding an asset that combines a payoff flow with the option of switching again. Brennan and Schwartz (1985) model a decision to open or close a copper mine, relevant to other non-renewable resources. Their self-financing portfolio approach is an improvement on the practice of replacing the distribution of future prices by their expected values. This replacement has caused errors in the calculation both of the expected cash flow and the discount rates, creating a suboptimal investment. Instead, the portfolio approach has an interest rate that is non-stochastic and the yield on the commodity is a function of output price. The paper presented here for managing a joint offshore resource portfolio draws from Brennan and Schwartz (1985) as well as Dixit and Pindyck (1994). Specifically, the links to the previous papers include optimizing by comparing portfolio values of options for investment. Also, setting thresholds between the options helps determine the most efficient use of offshore oil platforms.

Mason (2001) revisits Brennan and Schwartz's analysis and adds the necessary temporal constraint on non-renewable resource stock to investigate how switching costs impact the decision to open or close a mine of a non-renewable resource. The analysis of oil and fisheries resources in the current paper must consider more than switching costs of Mason (2001), such as multiple stochastic benefits and stochastic liability for decisions on platform management and decommissioning.

Farzin (2001) models price changes and additions to proven reserves from discovered reserves and examines the effects of expected resource price, cumulative reserves development, and technology on oil importation. Managi et al. (2004) estimate oil prices with changes in technology in offshore oil drilling. However, their study does not include access to multiple reserves through one platform. Such access is relevant to the present analysis and the cost of oil drilling in general. Considine and Heo (2000) econometrically estimate a petroleum products inventory model with endogenous spot and forward price inventory, production, and net imports. Results show high inventory leads to depressed prices and production smoothing. Such studies are relevant for verifying the price trends used in the empirical part of the present analysis.

3. Model

The offshore platform is flexible fixed capital for access to both oil and fisheries resources. The model helps solve for the option values and optimal time to exercise the options associated with different uses of the offshore platforms involving oil and fisheries. The price of oil at any point in time is stochastic and is assumed to evolve according to geometric Brownian motion following from Paddock et al. (1988).

$$dP = \mu P\,dt + \sigma_P P\,dz_P \tag{1}$$

In Eq. (1), μ is the trend yield rate per period, σ_P is the variance term or standard deviation of the process and dz_P the normally distributed increment of the Weiner process.

The value of biomass at the platform is a stochastic process S

$$dS = \gamma S\,dt + \sigma_S S\,dz_S \tag{2}$$

where γ is the expected trend of value from commercial and recreational fishing from the platform and σ_S the variance on this evolution. Reed (1993) modeled the value of forest biomass in this manner. The assumption of the biomass value instead of biomass following geometric Brownian motion rests on two empirical facts. First, the stock of biomass on the platform is similar to an aquaculture site with predictable growth in a cubic plot within dimensions of the platform legs (Love et al., 1999). Second, biomass has commercial value as well as recreational value and existence value. Scuba diving amidst biomass at the platforms generates recreational value. It is useful to include a stochastic component for the value of the biomass to account for randomness in the measure of recreational and existence value. The empirical section will provide quantitative measures of the recreational value. Migration of the biomass off the platform is minimal because the shellfish (clams, scallops, mussels) are sedentary and remain attached to platform legs (Love et al., 1999).

Eq. (3) depicts the value of liability the platform owner bears for any accidents for three different cases: (1) extracting resources from the platform; (2) leaving the platform idle in place; and (3) removing the platform. Specific examples of platform liability costs include costs of harvesting the biomass to reduce the chance of an accident from the platform toppling. Paying a bond to cover accidents that do occur, such as the bond specified under the Oil Pollution Act of 1990 is another example of liability cost.

$$dL = \alpha L\,dt + \sigma_L L\,dz_L \tag{3}$$

The trend term α is the first moment of the claim size from a possible accident and has monetary value of damages to person or property. The variance or diffusion term σ_L is the second moment of the risk associated with having the platform resulting in an accident claim (Taksar and Zhou, 1998). All three stochastic processes evolve according to uncorrelated geometric Brownian motion.

The instantaneous change in the reserve is determined by the output rate. Given that the focus is on existing platforms where exploration reserves and development has already taken place, an assumption of deterministic, fixed, and finite reserves is plausible. Other reserves may be accessible from each platform through lateral and slant drilling in addition to horizontal drilling to a reserve directly below the platform. The empirical section will explore the accessibility to other reserves from one platform in more detail in the interest of showing how the size of reserve, R, might influence decommissioning decisions.

$$\dot{R} = -y_t \tag{4}$$

Similar to Mason (2001), the current level of reserves dictates the upper bound of extraction. Mason (2001) explains that the level of pressure in the well is positively related to the remaining level of reserves and the pressure that determines the ability to extract. This model will also adopt the Mason (2001) assumption of the existence of a maximal rate of extraction where $y_t \leq y_c R$ and $y_c R$ is a fixed percentage of remaining reserves to exhaustion of the resource (Mason, 2001).

The platform owner has three possible choices for the platform. One choice is to actively extract oil from the platform with fish simultaneously present. A second choice is to suspend oil extraction and leave the platform inactive. A third choice is to completely remove a platform that is deemed a terminal option. Complete removal is equivalent to ‘‘killing an option’’, in an irreversible way, thereby stopping the flow of resource values forever. This means foregoing the possibility of even higher biomass amenity value and oil value in the future as well as capital gains. Fig. 1 shows three alternatives for the platform owner with their respective value functions that are derived in subsequent paragraphs.

The platform owner retains all liability under all three alternatives. With an active or inactive platform the liability can keep evolving stochastically. However, under the terminal option, the liability is finalized as the expected present value of any accidents and damages to people, property and the environment during the effort to completely remove the platform. This difference in liability will become apparent in the boundary conditions for choosing between alternatives that are explained below.

The Function F represents the final irreversible or terminal option and is a function of liability associated with the platform and another costs K_1, a fixed cost of completely removing the platform. The following Bellman Eq. (5) is an intertemporal arbitrage condition with the random process of liability defined by Eq. (3), where ρ is the discount rate and $E_t\ \{\cdot\}$ is the expectation at time t. Eq. (5) indicates the total instantaneous liability value on the platform is the expected rate of capital appreciation (or depreciation).

$$\rho F_t(L) = \frac{1}{\mathrm{d}t} E_t\{\mathrm{d}F_t\} \tag{5}$$

Applying Ito’s lemma to the Bellman equation yields a stochastic differential equation that is the fundamental equation of optimality.

$$\rho F_t(L) = \alpha L_t \frac{\partial F}{\partial L} + \frac{\sigma_{\mathrm{L}}^2}{2} L_t^2 \frac{\partial^2 F}{\partial L^2} \tag{6}$$

The quadratic stochastic differential Eq. (6) is satisfied with Eq. (7), the familiar form of a value function that has been described in mathematical economics texts such as Miranda and Fackler (2002) and adapted in the literature such as in Mason (2001).

$$F_0 = A_0 L^{\beta_0} + A_1 L^{\beta_1} \tag{7}$$

In Eq. (7) A_0 and A_1 are unknown constants to be determined with $\rho > \alpha$ for a finite value. Exponents $\beta < 0$, $\beta_1 > 1$ are the roots of the following characteristic equation that solve the quadratic equation with the parameters of the stochastic process of L (Miranda and

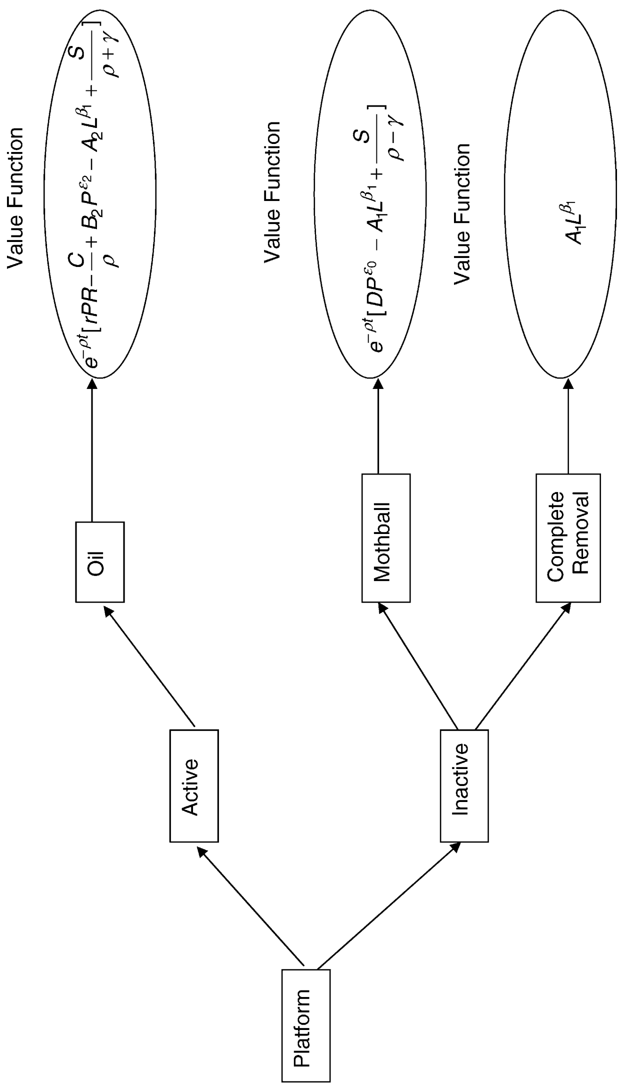

Fig. 1. Platform alternatives and value functions.

Fackler, 2002).

$$\beta = \left(\frac{1}{2} - \frac{\alpha}{\sigma_{\mathrm{L}}^2}\right) \pm \sqrt{\left(\frac{\alpha}{\sigma_{\mathrm{L}}^2} - \frac{1}{2}\right)^2 + \frac{2\rho}{\sigma_{\mathrm{L}}^2}}. \tag{8}$$

Due to non-exploding growth as $L \to \infty$, $A_0 = 0$ (Miranda and Fackler, 2002). For intuition, it seems logical that the value of the option to completely remove would be virtually worthless as liability gets small.

Therefore, Eq. (7) reduces to the following expression for the value function of complete removal.

$$F_0 = A_1 L^{\beta_1} \tag{9}$$

The following two boundary conditions help to determine a threshold level of liability, L^*, that would lead to complete removal.

$$A_1 L^{\beta_1} = \frac{L}{\rho - \alpha} - K_1 \tag{10}$$

$$\beta_1 A_1 L^{(\beta_1 - 1)} = \frac{1}{\rho - \alpha} \tag{11}$$

Eq. (10) is the value matching condition where the option to remove the platform equals the expected present value of the liability from complete removal less the fixed cost of removal. The smooth pasting condition is represented in Eq. (11) where the marginal change in the value functions with respect to liability is set equal (equal slopes). Solving the boundary conditions in Eqs. (10) and (11) yields the liability threshold L^* and the constant, A_1. Eq. (12) can indicate the value of liability to induce the decision to completely remove the platform.

$$L^* = \frac{\beta_1(\rho - \alpha)K_1}{\beta_1 - 1} \tag{12}$$

$$A_1 = \frac{[(\beta_1(\rho - \alpha)K_1)/(\beta_1 - 1)]^{1-\beta_1}}{\beta_1(\rho - \alpha)} \tag{13}$$

Now that this terminal option for complete removal has been defined, where the oil resource has been completely extracted, the decisions for a platform owner with an active platform can be explored. Eqs. (1)–(4) represent the state equations that will be used in characterizing the choices of the platform owner simultaneously. The owner chooses a strategy that maximizes the expected flow of returns from the platform's current activity and the expected return generated by switching to another activity. This objective for the owner is expressed in the optimality Eq. (14) where the rate of return on the platform asset, H, must equal the current income flow (dividend) to the activity H, plus the expected rate of appreciation (capital gain) on the asset using the best management strategy where Eq. (14) is the Bellman equation with oil, fish, and liability as random processes, defined by Eqs. (1)–(3).

$$H(R, L, S, P) = E\left[\int_0^\infty e^{-\rho t}[\delta_t(P_t y_t - C) + S_t - L_t]\right] \mathrm{d}t \tag{14}$$

subject to Eq. (4), where ρ is the discount rate and $\delta = 1$ for an active platform and $\delta = 0$ for an inactive or removed platform. For an active platform, profit is linear in y_t. Thus, the platform owner operates at maximum extraction or no extraction as long as price is not less than the marginal value of stock (Mason, 2001).

Through differentiation of Eq. (14) and substitution from Eqs. (1)–(3), a pair of Hamilton Jacobi Bellman (HJB) equations can be written according to the following two equations. Eq. (15) is the HJB equation for the active platform and Eq. (16) is the HJB equation for the inactive platform where the only difference between the two equations are that (15) has the first two components and (16) does not since oil extraction does not happen on an inactive platform.

$$\begin{aligned}\rho H_A(R,L,S,P) = P_t - C - \frac{\partial H}{\partial R}y_t + \mu P_t\frac{\partial H}{\partial P} + \frac{1}{2}\sigma_{\mathrm{P}}^2 P_t^2\frac{\partial^2 H}{\partial P^2} + \gamma S_t\frac{\partial H}{\partial S} \\ + \frac{1}{2}\sigma_{\mathrm{S}}^2 S_t^2\frac{\partial^2 H}{\partial S^2} + \alpha L_t\frac{\partial H}{\partial L} + \frac{1}{2}\sigma_{\mathrm{L}}^2 L^2\frac{\partial^2 H}{\partial L^2}\end{aligned} \tag{15}$$

$$\begin{aligned}\rho H_I(R,L,S,P) = \mu P_t\frac{\partial H}{\partial P} + \frac{1}{2}\sigma_{\mathrm{P}}^2 P_t^2\frac{\partial^2 H}{\partial P^2} + \gamma S_t\frac{\partial H}{\partial S} + \frac{1}{2}\sigma_{\mathrm{S}}^2 S_t^2\frac{\partial^2 H}{\partial S^2} + \alpha L_t\frac{\partial H}{\partial L} \\ + \frac{1}{2}\sigma_{\mathrm{L}}^2 L^2\frac{\partial^2 H}{\partial L^2}\end{aligned} \tag{16}$$

The autonomous problem has time entering with discounting. The derivation of the value functions is explained as follows.

The value functions that solve Eqs. (15) and (16), respectively are functions of all state variables. The functions are found by identifying the homogeneous components of these two non-homogeneous second order differential equations. The homogeneous components of the value functions are due to the state variables that take a general form of a quadratic where the in situ value of the oil reserve is PR (Mason, 2001). The homogeneous portion related to oil price for the active platform has the common form:

$$H_0 = e^{-\rho t}[B_1(PR)^{\varepsilon_1} + B_2(PR)^{\varepsilon_2}] \tag{17}$$

where $B_1$and B_2 are unknown constants to be determined, $\rho > \mu$ for a finite value, $\varepsilon_1 < 0$ and $\varepsilon_2 > 1$ are the roots of the following characteristic equation (Miranda and Fackler, 2002).

$$\varepsilon = \left(\frac{1}{2} - \frac{\mu}{\sigma_{\mathrm{P}}^2}\right) \pm \sqrt{\left(\frac{\mu}{\sigma_{\mathrm{P}}^2} - \frac{1}{2}\right)^2 + \frac{2\rho}{\sigma_{\mathrm{P}}^2}}. \tag{18}$$

Due to non-exploding growth as $P \to \infty$, $B_1 = 0$ (Miranda and Fackler, 2002). Therefore, Eq. (17) reduces to

$$H_0 = e^{-\rho t}B_2(PR)^{\varepsilon_2}. \tag{19}$$

For the homogeneous component related to variable L, the form is similar to the derivation in Eqs. (8) and (9) for the terminal option, but with a new unknown constant A_2 that can be solved for.

$$H_1 = e^{-\rho t} A_2 L^{\beta_1} \tag{20}$$

Eq. (21) is part of the optimal H for the active platform based on maximal extraction $y_t = y_c R$ solving Eq. (14) (Mason, 2001).

$$e^{-\rho t}\left[r(PR) - \frac{C}{\rho}\right] \tag{21}$$

The parameter r is defined by Mason (2001) as

$$r = \frac{y_c}{\rho + y_c - \mu}. \tag{22}$$

The complete solution to Eq. (15) is obtained by adding additively separable components: the solution of the homogeneous portions H_0 and H_1 from Eqs. (19) and (20) along with the solution in Eq. (21) as follows (Kamien and Schwartz, 1981). Eq. (23) is the value function H of the active platform.

$$H(R,S,P,L) = e^{-\rho t}\left[rPR - \frac{C}{\rho} + B_2(PR)^{\varepsilon_2} + A_2 L^{\beta_1} + \frac{S}{\rho - \gamma}\right] \tag{23}$$

The first two components of the value function are from the particular solution. The last component for biomass is the expected present value of biomass flow on the platform, given that the observable current level is $S = S_t$, that can be realized on both active and inactive platforms.

The value function for the inactive platform does not contain the first two components from the particular solution that the value function for the active platform contains. However, homogeneous components are similar to those in the active platform value function for the variables of interest. The component containing PR takes the form similar to that derived in Eqs. (17)–(19) according to mathematical principles from Miranda and Fackler (2002) as follows.

$$M_0 = e^{-\rho t} D(PR)^{\varepsilon_0} \tag{24}$$

The second component containing L takes the form similar to that derived in Eqs. (7)–(9) as follows:

$$M_1 = e^{-\rho t} A_1 L^{\beta_1} \tag{25}$$

The value function for the inactive platform in Eq. (26) has additively separable components M_0, M_1, and the realized biomass value similar to the active platform.

$$M(R,S,P,L) = e^{-\rho t}\left[DP^{\varepsilon_0} + A_1 L^{\beta_1} + \frac{S}{\rho - \gamma}\right] \tag{26}$$

It is necessary to determine unknowns B_2, A_2 and two stochastically evolving barriers P^* and L^* in all of these value functions. These unknowns will depend on the observable variables, S, P and L and are determined simultaneously from the following boundary conditions. The value matching condition in Eqs. (27) and (28) are relevant. Eq. (27) indicates the equality condition that makes the platform owner indifferent between continuing extraction and rendering the platform inactive. The condition equates the value of the option to leave the platform in place with the expected value of the inactive platform minus the cost of preparing the platform for inactivity. The final term, K_0, is the fixed cost of preparing to mothball the platform for inactivity by sealing oil wells and removing drilling equipment and whatever structure exists above 100 feet below sea level.

Eq. (28) is the value matching condition comparing continuing extraction with ceasing extraction and leaving the platform in place

$$rPR - \frac{C}{\rho} + \frac{S}{\rho - \gamma} + B_2(PR)^{\varepsilon_2} + A_2 L^{\beta_1} = \frac{S}{\rho - \gamma} + D(PR)^{\varepsilon_0} + A_1 L^{\beta_1} - K_0 \tag{27}$$

$$rPR - \frac{C}{\rho} + \frac{S}{\rho - \gamma} + B_2(PR)^{\varepsilon_2} + A_2 L^{\beta_1} = \frac{L}{\rho - \alpha} - K_1 \tag{28}$$

$$[r + \varepsilon_2 B_2 (PR)^{\varepsilon_2 - 1}]R = \varepsilon_0 D(PR)^{\varepsilon_0 - 1} \tag{29}$$

$$\beta_1 A_2 L^{\beta_1 - 1} = \frac{1}{\rho - \alpha} \tag{30}$$

Eq. (29) is the smooth pasting condition that holds at the optimal P^* where the slopes for marginal values from both active and inactive platform value functions are equated and the platform owner is indifferent between continuing and stopping activity on the platform, aligned with Eq. (27). Eq. (30) results from the smooth pasting condition that requires $\partial H/\partial L = 1/\rho - \alpha$ which must hold at L^*, where the platform owner is indifferent between mothballing the platform and complete removal.

Eq. (30) can be rearranged to express the constant A_2 as follows.

$$A_2 = \frac{L^{1-\beta_1}}{\beta_1(\rho - \alpha)} \tag{31}$$

Numerical simulations enable the system of equations to be solved for the thresholds P^* and L^* as well as A_2 and B_2 that determine which options are most viable for investment in oil drilling and fisheries from offshore platforms. Eqs. (12) and (13) solved from the boundary conditions of the terminal option are also included along with Eqs. (27)–(30). The system of equations is solved in Matlab.

4. Data and model calibration

The model is calibrated with data from several sources including a cost-benefit analysis of alternatives for decommissioning oil platforms (Fernandez and Hitz, 2001). The following paragraphs describe the data and calibration of parameters and variables that pertain to platforms off the California coast.

Table 1 lists the model parameters and numerical values for the application to California's offshore platforms. The baseline parameters are from Hermosa, a platform in federal waters subject to a federal policy change included in the sensitivity analysis. There are value ranges instead of point estimates for some parameters due to the fact that platforms vary across location. For example, the range of value for the cost of complete removal of a platform, K_1 (in real 1999 dollars), lies between \$8,500,000 and \$106,364,400 due to the fact that location, depth into the water, weight of the platform and salvage value

Table 1
Numerical values for California platform application

Parameter	Shallow	Baseline	Deep
K_1	\$8,500,000	\$101,270,000	\$106,364,400
K_0	\$2,085,900	\$16,792,000	\$18,560,200
C	\$600,000	\$3,186,400	\$4,732,800
R		1,000,000,000	
r		0.05	
μ		0.02	
σ_P		0.4	
γ		0.04	
σ_S		0.5	
α		0.03	
σ_L		0.3	
ρ		0.04	
Sensitivity analysis			
Increase R to 2,000,000,000			
Increase ρ by 0.02			
Increase γ by 0.01			
Increase σ_S by 0.01			
Increase σ_P by 0.01			
Increase C by 10%			

Table 2
Platform variation in depth and weight

Platform	Well and conductor specifications			Projected platform removal weights		
	Water depth (ft.)	Wells to plug	Conductors	Jacket weight (tons)	Deck weight (tons)	Total weight (tons)
Gina	95	12	12	434	815	1470
Hogan	154	40	40	1263	2259	4110
Edith	161	18	23	3454	4134	8298
Houchin	163	36	36	1486	2591	4637
Henry	173	23	24	1311	2500	4247
A	188	52	55	2516	2601	6350
B	190	57	57	2516	2601	6355
Hillhouse	192	47	52	2000	2500	5538
C	192	38	43	2516	2601	6270
Gilda	205	63	64	3220	3792	9342
Irene	242	24	24	3110	2500	7652
Ellen	265	61	64	3200	5350	11634
Habitat	290	20	20	3200	3514	8853
Grace	318	26	35	3090	3800	9390
Hidalgo	430	10	10	10950	8100	21421
Herraosa	603	13	16	17000	7830	28131
Harvest	675	19	21	16633	9024	30190
Eureka	700	50	60	18500	5200	29192
Gail	739	21	22	18300	7693	31320
Hondo	842	29	29	12200	8450	27250
Heritage	1075	27	49	32420	9826	60556
Harmony	1198	26	51	42900	9839	69920

Source: MMS, ‘‘Offshore Facility Decommissioning Costs, Pacific OCS Region," March 31, 1999.

will determine the cost and vary greatly across platforms. Table 2 indicates the variation in depth and weight of California platforms that would influence the range of values used in a general equation for K_1.

$$K_1 = XY(z) \tag{32}$$

In Eq. (32) X equals the net unit cost per ton of removal, Y equals the total tonnage per foot of platform, and z equals the total depth in feet of the platform down to the seafloor.

From Table 2 the depth ranges from 95 to 1200 ft below sea level and the total weight, $Y(z)$ varies from 1470 to 69920 tons (Minerals Management Service, 1999). The possible combination of the shallowest platform and least tonnage (95 ft deep and 1470 tons) would correspond to the low end of \$8,500,000 for K_1. Likewise, the deepest platform and heaviest corresponds to the high end of \$106,427,000 for K_1. The term X, the net cost in the equation for K_1 takes into account the removal costs per ton minus the scrap value of \$250 per ton for salvaged steel from the platform resold to the auto industry (Minerals Management Service, 1999).

The cost of mothballing a platform to render it inactive, K_0, can range from \$2,085,900 to \$18,560,200 (in real 1999 dollars). The range in cost exists because removing drilling equipment and plugging of wells also depend on depth and weight of the platform as well as configuration of the structure.

The variable R for the oil reserve can change value due to the fact that more oil wells can be accessed from existing platforms, as indicated in Table 3. For example, through lateral and slant drilling leases 319, 320, 322, 323A, 452 and 453 can be accessed from platform Hermosa to extract oil in addition to the wells below Hermosa. The existing federal congressional moratoria and presidential leasing deferrals do not restrict development of already federally leased areas. Thirty-six federal leases remain in a "non-producing" status since they are undeveloped. The amount of reserves for the baseline scenario prior to expanding the number to include the quantity of oil in the undeveloped leases for Hermosa is 1,000,000,000 tons. A subsequent sensitivity analysis increases R to 2,000,000,000 tons.

The parameter C for operating costs associated with the active platform is calibrated from average quarterly pumping fuel and labor costs in 1999. These costs are depth

Table 3
Federal leases developable from existing or new platforms

Lease number	Reaching from existing platform
210, 527	Platforms Gail and Grace
460, 462, 464	New platform required
319, 320, 322, 323A	Platform Hermosa
452, 453	Platforms Harvest, Hermosa and Hidalgo
443, 445, 446, 449, 499, 500	Platform Irene
420, 424, 425, 429, 430, 431, 433, 434	New platform required
426, 427, 432, 435	New platform required
415, 416, 421, 422	New platform required

Source: California Coastal Commission, 1999. California Offshore Oil and Gas Leasing and Development Status Report. San Francisco, CA. p. 23.

dependent. Therefore, the range listed in Table 1 corresponds with the low and high depths of platforms yielding C ranging from \$600,000 to \$4,732,800.

The parameter r parallels Mason (2001) as a fixed percentage of remaining reserves with a value of 0.05, similar to Dixit and Pindyck, (1994) and Slade (1998).

The mean drift and standard deviation of the series $\ln(P_{t+1}/P_t)$, $\ln(S_{t+1}/S_t)$, and $\ln(L_{t+1}/L_t)$, where t equals years 1997–2000, provide maximum likelihood estimates of parameters μ, σ_P, γ, σ_S, α, σ_L, respectively for the state equations. The $\ln(\cdot)$ is the natural log operator for the time series of each variable to derive the parameters corresponding with geometric Brownian motion (Reed and Clarke, 1990).

Quarterly average crude oil price data for 1997–2000 was used by Considine and Heo (2000) for estimating the parameters of the annualized drift $\mu = 0.02$ and variance $\sigma_P = 0.4$ for the geometric Brownian motion process of oil price, P, and is referenced for this offshore application (2000).

Quarterly visitation rates for recreationists to oil platforms for viewing biomass (diving, fishing) are accessed for 1997–2000 from boat operators specialized in transport to the platforms. The visitation rates from this specific group focused on the platforms are precisely correlated with the amenity value of the platform biomass. Conrad (1997) has used visitation rates for estimation of amenity value of forestry biological resources in this manner with the following logic. If V is the visitation rate and $V = \eta S$ with $\eta > 0$, recalling Eq. (2), $\mathrm{d}S = \gamma S\,\mathrm{d}t + \sigma_S S\,\mathrm{d}z_S$, then $\mathrm{d}V = \gamma V\,\mathrm{d}t + \sigma_S V\,\mathrm{d}z_S$. It is possible to obtain estimates of γ and σ_S with data on V. The quarterly visitation rate is multiplied by the trip fee charged by the boat operator to regress as a series $\ln(S_{t+1}/S_t)$following the procedure of Reed and Clarke (1990) for maximum likelihood estimation that results in parameters for the geometric Brownian motion trend and variance terms. The trip fee of \$60 per person (throughout time period 1997–2000) is referenced from Liberty dive boat in Channel Islands Harbor, the sole operator for diving at platform Grace. The drift term, γ equals 0.04 and the variance term, σ_S equals 0.5 for the biomass value stochastic process.

The oil producer faces strict liability for the platform and wells. The liability covers personal injury, property damage, and environmental damages. Liability for accidents during lease clearance and abandonment is a cost for the complete removal alternative. For both mothballing and continued drilling alternatives, liability for any recreational or fishing accident that might occur constitutes an additional cost. A potential hazard in terms of platform instability stems from substantial buildup of sea life attached to the underwater legs of the platforms during wave action exceeding fifteen feet and current drag in excess of seven knots from seasonal storms (Dougall, 1996). Removal of the biomass growth reduces the top heavy weight of a platform thereby reducing the risk of toppling the platform in the event of severe weather conditions.

Relevant information for estimating the parameters α, σ_L in Eq. (3) for liability includes costs of harvesting the biomass thereby reducing the chance of the platform toppling. The cost of a bond to cover accidents that do occur, specified by the Oil Pollution Act of 1990 is also relevant. Quarterly average data of fees for labor and equipment to remove biofouling (shellfish) from 1997–2000 are obtained for the regression following Reed and Clarke (1990) for maximum likelihood estimates. The bond value of \$7.5 million is added to the labor and equipment fees for 1997 corresponding to a bond assessed on a platform owner, Veneco Company.

One man's biofouling is another's gourmet dinner (Dougall, 1996) and the harvested shellfish are sold commercially. Therefore the parameters in the L equation are derived from net liability cost figures where the commercial value of the harvested shellfish is subtracted from the costs of Eq. (3), corresponding to the same time series used in $\ln(L_{t+1}/L_t)$. The commercial value for mussels, scallops, clams and oysters from the platform legs during the cleaning over the quarterly data is obtained from average annual prices for the wholesale market (PACFIN, 2000). An example of the quantity harvested for preventing accidents is 500–5000 bushels of oysters and 1000–10,000 pounds of scallops per year (PACFIN, 2000).

The bond that is included in the estimation for the liability parameters is described further here. Once the lease is developed, lessees are required to post a bond in an amount specified by the State of California that does not exceed 50% of the cost of fixed and floating structures to guarantee maintenance and the cost of their removal.[1] Originally, this requirement was applied to leases issued after 1956. However, this same clause was added to pre-1956 leases when production occurred. For example, in 1997, Veneco had to post a \$7.5 million bond to continue oil extraction from three leases. Chevron posted a \$10 million bond when drilling from Platform Heidi into Exxon's Lease in 1987 (Santa Barbara County Energy Division, 2000).

The discount rate ρ is set at 0.04 based on the real interest rate average during the years 1998–2000 (Federal Reserve System, 2000).

5. Results

The data described above provides parameter values for calculating the Eqs. (20)–(25). It is possible to display when the thresholds P^* and L^* representing critical values are reached. These thresholds help determine if a switch from an active platform to an inactive one or a switch to complete removal of a platform is the optimal choice. If the time period that P reaches the P^* barrier is sooner than when L reaches L^*, the platform is left in place. If instead, L reaches L^* sooner than P reaches P^*, then complete removal is most likely and the period of resource extraction on the platform is shown to differ under both scenarios. Two figures help to jointly determine if removing or leaving the platform in place is likely. The baseline case depicted is established from the midpoint of range values for the parameters. In Fig. 2, the active platform with both the oil and fisheries benefits along with stochastic liability costs stays active until P reaches P^* at $t = 33$. The fact that the log normal random variable of biomass value has a mean equal to $\exp[\mu + 1/2\sigma^2] = 0.165$

[1] If the bonding that is associated with lease arrangements for offshore oil drilling could account for liability after oil extraction, there could be a tangible way for platform owners to gauge what the strategy for decommissioning would be up front at the beginning of the lease. Details related to the lease bonds follow. Public Resources Code 6829 (d) requires lessees to furnish and maintain a bond to guarantee full compliance with the terms and conditions of the lease and applicable regulations. The actual amount of these bonds, specified in the early lease agreements range from \$25,000 to \$65,000 for lease issued prior to 1956 (Minerals Management Service, 1999). Lease agreements issued after 1956 onward set this amount at \$50,000 for individual leases. The amount of the bond is subject to review and modification every 3 years based on the change of the Bureau of Labor Statistics Code Number 0561 Crude Petroleum.

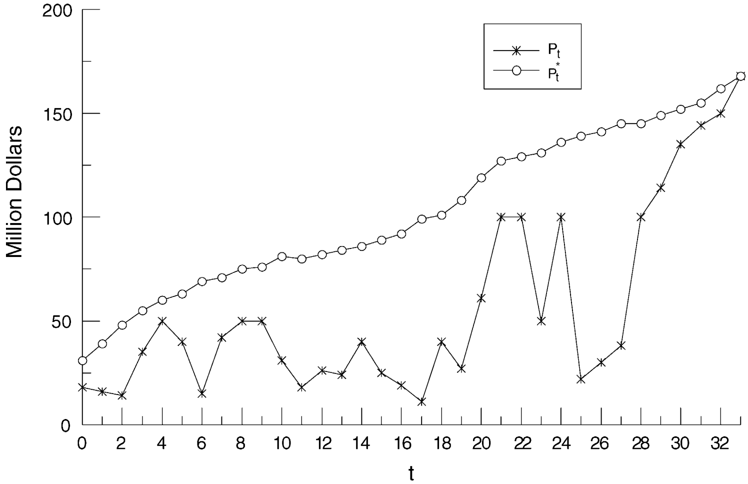

Fig. 2. Baseline scenario where P_t meets the barrier P_t^*.

which is larger than the discount rate of 0.04 helps to sustain the oil and fisheries activity through that time period. In Fig. 3, the inactive platform is likely to be completely removed given that the sunk costs of removal are less than both increasing, stochastic liability costs and costs of preparing to leave the platform in place. At the end of year three, the point of tangency of L and L^* shows the sunk cost of complete removal is quickly surpassed by liability. Rising liability from leaving the platform in place is due to the risk of possible accidents and toppling of the platform.

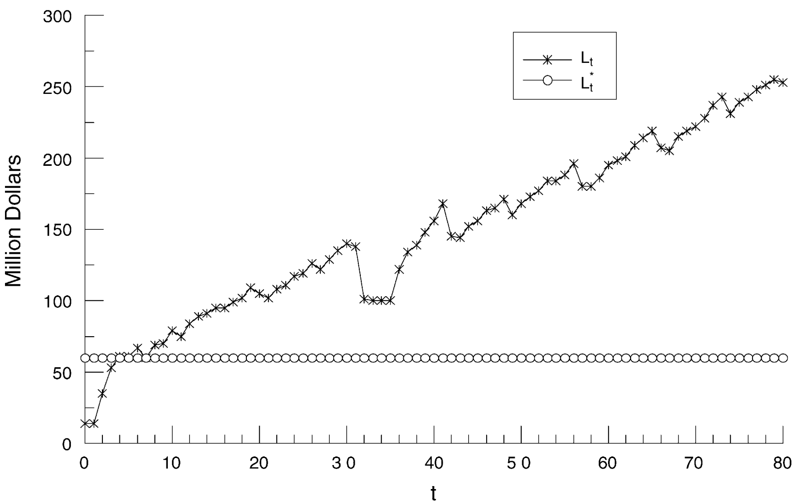

Fig. 3. Baseline scenario where L_t meets the L_t^* barrier.

A sensitivity analysis is conducted in order to examine realistic conditions that might change the baseline parameter and variable values indicated in Table 1 to influence platform decisions. The first modification to the baseline scenario is regarding oil reserves. Since the Bush Administration wants to eliminate the ban on undeveloped leases, the size of R could increase by twice as much of the baseline reserves. Through lateral and slant drilling from the existing platform, Hermosa, six undeveloped leases can be accessed as indicated in Table 3. The Ninth circuit federal appeals court in December 2002 has blocked the Bush Administration from removing the ban (U.S. 9th Circuit Courth, 2002). However, it is useful in this paper to explore numerically the consequences of removing the ban due to the persistence of the federal government pursuing further action on undeveloped leases. When reserves increase, the active platform's horizon changes with the final period of extraction extending to year 58.

An increase in the rate of discount, σ, by 0.02 speeds the intersection of P with the P^* threshold to $t = 21$ for the active platform, leading to faster extraction of the resources. The increase in the rate of discount also increases the L^* threshold. This means the point of tangency is reached in an earlier time period (year 1) for an inactive platform.

An increase of 0.01 in the variance term, σ_S, in the biomass stochastic process means the active platform yields a higher value to consider stopping extraction of both resources. An increase in σ_S can increase the P^* barrier and leads to intersection with the P process at $t = 35$. This means it is advantageous to jointly extract oil and fisheries resources longer than the baseline case. With the increase in σ_S, the L^* threshold increases and the point of intersection with L is at 0, thereby leading to immediate complete removal. An increase of 0.01 in σ_P, the variance of the oil price stochastic process increases the P and P^*, so the point of tangency is at $t = 38$. The oil in the ground is worth more due to the increase in variance. Therefore, the platform owner will delay extraction in order to generate even higher revenue when it is finally extracted.

As the annual operating costs for an active platform, C, increase by 10%, the net revenues are reduced and the threshold P^* increases by 3%. Therefore, P reaches the point of tangency at $t = 26$, when a switch is likely. As α, the trend term in the liability Eq. (3), increases by 0.01, L^* increases. Therefore, complete removal is more likely according to the point of tangency between L and L^* in year 2. In this case, higher liability costs associated with a platform left in place outweigh the benefits of fisheries revenues.

6. Conclusions

This paper has developed a portfolio model to examine option values and optimal choices for offshore platforms with oil and fisheries resources under changing economic conditions. Each choice is an exercise of a financial option and yields an asset that combines a payoff flow with the option of switching again. For the empirical application, it is never optimal to mothball and leave in place an inactive platform offshore California, given that the stochastically evolving liability costs far exceed the costs of complete removal within 3 years in the baseline case. The active platform provides benefits from oil and biomass resources whose values evolve stochastically. The oil platform owner's decision takes into account oil and biomass resources and their price dynamics as well as the producer's vested rights, current regulation, and historic experience. For example, besides its oil dividends, Veneco earns revenues from shellfish harvesting and recreational activity on Platform Grace (Minerals Management Service, 1999). Existing platforms may also provide the opportunity to engage in lateral and slant drilling to access oil deposits other than directly below the platform and help the reactivation option. With this type of drilling possibility, the sensitivity analysis indicates a higher level of reserves that changes the profile of platform extraction and longevity.

Determining the terminal period of an active platform depends on drift and variance terms in the stochastic oil and biomass values as well as costs of maintaining an active platform. Increasing the cost of preparing the platform to leave in place, or increasing the variance in the biomass or oil value stochastic process, raises the critical thresholds P^* and L^* for active and inactive platforms. Therefore, complete removal of the platform is the best option and is reached sooner than in the baseline case.

Stochastic liability costs and regulations to harvest biomass to avoid risk of top heavy platforms play roles in this analysis. Both influence the platform owner to maintain the active platform for deriving benefits from both fish and oil for the lifetime of the oil resources. Complete removal is the best option following dual resource activity from the active platform.

There has been speculation that platforms provide protection for other fish by precluding trawling and large scale commercial fishing in the immediate area (Love et al., 2001). This assertion has not been included in the analysis in any quantified way due to lack of validation of such speculation. Effort is needed to tag and track the distance travelled by fish from the platform to correlate with the current stock of fish that might be trawled, but are not, due to the inability of vessels to navigate around the platform (Fernandez and Hitz, 2001).

If new technology changes mean floating platforms become viable, the estimates of new investment costs would have to be adjusted. However, from the initial forecast of such technology, there is no indication that the substantive results of this analysis would change. A switch to new investment is not optimal when the existing platform's options provide attractive returns from the joint oil and fisheries resources.

The range of costs for complete removal of the platform includes estimates from data based on removing four platforms at one time (Fernandez and Hitz, 2001). Subsequent research might entail a comparative study of economies of scale to remove several platforms at once versus one platform at a time in order to explore other platform issues.

This study's model and empirical application provide guidance to evaluate more environmental and natural resource investment where multiple resources are involved. Efforts to gather empirical data to apply the model elsewhere can result in policy-relevant economic research.

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