A Multi-attribute Decision Analysis for Decommissioning Offshore Oil and Gas Platforms

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ABSTRACT
The 27 oil and gas platforms off the coast of southern California are reaching the end of their economic lives. Because their decommissioning involves large costs and a number of potential environmental impacts, this has become an issue of public controversy. As part of a larger policy analysis conducted for the State of California, we implemented a decision analysis as a software tool (PLATFORM) to clarify and evaluate decision strategies against a comprehensive set of objectives. Key options selected for in-depth analysis are complete platform removal, with high costs, and partial removal to 85 feet below the water line, with the remaining structure converted in place to an artificial reef to preserve the rich ecosystems supported by the platform’s support structure. PLATFORM was instrumental in structuring and performing key analyses of the impacts of each option (e.g., on costs, fishery productivity, air emissions) and dramatically improved the team’s productivity. Sensitivity analysis found that disagreement about preferences, especially about the relative importance of strict compliance with lease agreements, has much greater effects on the preferred option than does uncertainty about specific outcomes, such as decommissioning costs. It found a near-consensus of stakeholders in support of partial removal and "rigs to reefs" program. The project’s results played a role in the decision to pass legislation enabling an expanded California "rigs to reefs" program that includes a mechanism for sharing cost savings between operators and the state.

Keywords: Decision analysis, decommissioning, oil and gas platforms, multi-attribute utility, sensitivity analysis, rigs-to-reefs, artificial reefs

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INTRODUCTION

There are currently 27 operating oil and gas platforms in State Tidelands and on the federal Outer Continental Shelf (OCS) of southern California that will be decommissioned as they reach the end of their useful oil and gas production lifetimes, estimated to occur between 2015 and 2030 (Proserv Offshore 2010). Existing leases require lessees in both state and federal waters to completely remove the production facility and to restore the seafloor to its pre-platform condition when production ends. However, technological advances in the time since most of these leases were signed have created feasible alternatives to full removal. Alternative uses range from aquaculture to alternative energy production to artificial reefs intended to preserve the biological communities supported by the platforms and enhance biological production and/or fishing opportunities.

Decommissioning these platforms involves complex tradeoffs that have become a matter of public controversy, reflecting stakeholders' differing values and perspectives. For example, platform owners and operators are concerned about the large expense of complete removal, which may exceed a billion dollars for the 27 platforms (Proserv Offshore 2010); air quality regulators are concerned about the air emissions from decommissioning activities (Cantle and Bernstein 2015); some resource managers seek to preserve the rich ecosystems and biological production associated with platforms (Pondella et al. 2015); and some environmental advocates prefer a strict compliance approach that would hold operators to the terms of their original leases, which require complete platform removal (Bernstein et al. 2010). The strength of feeling associated with these perspectives exists against the backdrop of the disastrous 1969 Santa Barbara oil spill caused by a blow-out during drilling operations from Platform A.

To better understand the range of decommissioning options and assess the full array of potential impacts, the California Natural Resources Agency requested the California Ocean Science Trust (Cal OST) to commission a comprehensive policy analysis (Pietri et al. 2011). We were members of the team contracted by OST to conduct the analysis (Bernstein et al. 2010, Bernstein 2015). In this article, we describe the use of a mathematical decision model (PLATFORM) for the analysis, and some key results and insights it provided. We adopted methods from decision analysis, including:

- Decision trees to identify policy strategies
- Influence diagrams to structure the analysis
- A multi-attribute utility model to represent the stakeholders' objectives and preference structure
- Probability distributions to express uncertainties
- Sensitivity analysis to explore the effect of varying assumptions, particularly the importance stakeholders ascribed to objectives

We applied these methods and conducted the analysis in a computer model, PLATFORM, implemented in Analytica. Companion papers in this series provide details of key scientific and economic inputs to the decision analysis, including decommissioning costs (Bressler and Bernstein 2015), impacts on fish production (Pondella et al. 2015), air emissions (Cantle and Bernstein 2015), and socioeconomic impacts (Kruse et al. 2015).

We begin by outlining the wide range of possible decisions associated with alternative decommissioning approaches and outcomes and describe how we pruned the initial large
decision tree down to two major options (complete and partial platform removal) and a small number of variants for more careful evaluation. We then describe the key criteria or attributes used to evaluate these options. Three attributes (monetary costs, fish production, and changes to ocean access) were assessed using quantitative models, while other attributes (impacts on air and water quality, marine mammals and birds, benthic (sea floor) ecosystems, and compliance with lease agreements) were assessed on qualitative scales. We describe how the model treats uncertainty and perform an illustrative sensitivity analysis on costs. We present a multi-attribute decision framework to provide a comprehensive comparison of the decommissioning options against both quantitative and qualitative attributes. We then analyze the sensitivity of the preferred decision for each platform to stakeholder values to see how the relative importance assigned to each attribute affects the resulting recommendation, with a special focus on the controversial issue of compliance with lease requirements. We conclude with a summary of the key findings and a discussion of how this study informed the policy process. A key outcome of this process was California bill AB 2503, legislation that enables conversion of platforms to artificial reefs, transfer of ownership to the State of California, and sharing of the savings between operators and a public fund. Of particular interest is how this approach helped transform an issue that originally aroused considerable controversy into a policy for which there is now widespread support.

**DECISION OPTIONS**

Knowing the basic structure of offshore platforms is useful in understanding the decommissioning options. Each platform consists of five major sections, as shown in Figure 1:

1. **the deck structures** above water, commonly called the topsides, which also include,
2. **oil and gas processing equipment and piping**, which must be treated separately because of potential contamination issues,
3. **well conductors**, which are pipes from the top deck to the well (on the seafloor) for conducting drills and drilling muds down and oil and gas up for production,
4. **the jacket**, a steel lattice structure that supports the deck and anchors it to the seafloor, and
5. **shell mounds and drill cuttings**, which are debris on the seafloor around the platform, including the fallen remains of shellfish and other marine organisms that grew on the jacket, mixed with rock fragments and mud residue from drilling operations.
Potential Options

Over the past decades, a number of alternatives have been proposed to the complete removal of decommissioned offshore oil and gas platforms, including their use for:

- Artificial reefs, either left in place or transferred to a designated reefing location (rigs-to-reefs)
- Offshore wind energy projects, either as sites for wind turbines or as an offshore maintenance and logistics base
- Offshore wave energy projects, either as a site for anchoring wave energy generating equipment or as an offshore maintenance and logistics base
Potential Options

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- Artificial reefs, either left in place or transferred to a designated reefing location (rigs-to-reefs)
- Offshore wind energy projects, either as sites for wind turbines or as an offshore maintenance and logistics base
- Offshore wave energy projects, either as a site for anchoring wave energy generating equipment or as an offshore maintenance and logistics base
- Liquefied natural gas (LNG) terminals
- Platforms for solar panel arrays
- Aquaculture projects, either as a site for anchoring aquaculture facilities or as an offshore maintenance and logistics base
- Ocean instrumentation or tourism

Only the rigs-to-reefs option eliminates the ultimate need for platform removal. The others merely postpone the decision because the platform, even if converted to an alternate use (e.g., wind energy, aquaculture), will eventually reach the end of its structural life.

There are several options to dispose of the removed sections, for complete or partial removal:

- Onshore dismantling and recycling, or put into landfill for platform components at shipyards in the Los Angeles/Long Beach area or elsewhere.
- Placement of the clean upper jacket and lower deck structure on the ocean bottom at the base of the platform as part of an artificial reef
- Deep water disposal for jacket and lower deck structures that are not contaminated by hydrocarbons or other pollutants

These decision options are illustrated on the right of Figure 2.

There are three subsidiary options: Complete removal requires a decision on whether to use explosives (instead of non-explosive cutting methods) to sever the platform jacket and conductors, and whether to remove shell mounds or leave them in place. Partial removal may enhance the reef with quarry rock around the base of the platform. As explained more fully in Bernstein et al. (2010) each of these decisions involves a number of tradeoffs. For example, explosives can be a cheaper method of cutting platform structures underwater, but may increase risks to marine mammals. Removing shell mounds may reduce the long-term risk of the spread of contaminants from older (and more toxic) drilling muds buried at lower levels of the shell mounds, but at the risk of near-term dispersal due to dredging operations. Many of the platforms offshore southern California are in water much deeper than any previously dredged, so that shell mound removal may not always be feasible.
Options Selected for Analysis

Not all reuse or disposal options are viable technologically, economically, or politically. The analysis team screened options for detailed analysis using the following criteria:

- Viability within a ten-year timeframe
- Existing legal framework for implementation
- Technical feasibility
- Economic viability
- Degree of acceptance by state and federal managers from agencies with decision-making authority
- Degree of interest from proponents
- Relevance to the majority of southern California platforms

We applied these criteria qualitatively and found that options sorted clearly into the two categories in the Prioritization column of Table 1: Evaluated in Detail; Examined Briefly and Eliminated. Two use options (complete removal and partial removal as part of conversion to an artificial reef) and one disposal option (onshore dismantling) warranted detailed analysis. The analysis of the partial removal option included a suboption, placement of the clean upper jacket and lower deck structure on the ocean bottom as reef enhancement. These decisions dramatically reduced the number of branches in the decision tree, thus improving both the realism and the tractability of the analysis.

The 27 platforms differ considerably in their age, size, water depth, and location: This affects the costs and environmental effects of complete or partial removal, as well as their suitability for artificial reefing. Different decisions may therefore be appropriate for each platform. A key requirement for decommissioning is a heavy lift vessel (HLV) — a large ship with a crane of capacity up to 4000 tons to lift platform sections from the ocean onto barges for transport to shore. The cost to bring an HLV to California from either the North Sea or the Far East is a significant portion of the overall decommissioning cost. The economics dictate that multiple platforms should be decommissioned in a combined operation to share HLV transport and rental costs. The decision analysis must therefore consider entire decision strategies for some or all platforms together rather than treat each platforms separately.
## Table 1. Summary of alternative use and disposal options considered. The complete removal and partial removal/artificial reefing options, along with the onshore dismantling and disposal option, were considered in detail.

<table>
<thead>
<tr>
<th>Option</th>
<th>Prioritization</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
</table>
| Complete removal                     | Evaluated in detail | ● Required in leases  
● Highly valued by key stakeholders  
● Technically feasible for all platforms  
● Costed out in detail by MMS (now BOEM/BSEE) |                                                                      |
| Partial removal / artificial reefing | Evaluated in detail | ● Highly valued by key stakeholders  
● Abundant precedent in Gulf of Mexico  
● Fiscal incentive for both operators and state  
● Technically feasible for all but 3 state platforms  
● Detailed costs based on estimates for complete removal | ● Applicable only to one platform (Holly) in state waters because of shallow water depths |
| Artificial reefing using entire platform | Examined briefly and eliminated | ● Highly valued by key stakeholders  
● Preserves additional ecological habitat and recreational opportunities  
● Fiscal incentive for both operators and state | ● Increased liability due to retention of surface structure makes this of much less interest to state |
| Leave for reuse                      |                 |                                                                      |                                                                      |
| Alternative energy                   | Examined briefly and eliminated | ● Some interest in California and in Gulf of Mexico | ● No projects implemented on platforms  
● Current technology does not require platforms  
● Not technically feasible at large majority of platforms  
● No current interest by project proponents  
● Economic viability not demonstrated |
| Aquaculture                          | Examined briefly and eliminated | ● Some interest in California and in Gulf of Mexico | ● No projects implemented on decommissioned platforms  
● Current technology does not require platforms  
● Economic viability not fully demonstrated |
| Others (e.g., instrumentation, hotels) | Examined briefly and eliminated |                                                                      | ● Little interest  
● Economic viability not demonstrated  
● Current ocean instrumentation technology does not require platform |
## Decision Analysis Tool for Decommissioning Offshore Oil Platforms

<table>
<thead>
<tr>
<th>Option</th>
<th>Prioritization</th>
<th>Pros</th>
<th>Cons</th>
</tr>
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<tbody>
<tr>
<td><strong>Disposal</strong></td>
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</table>
| Onshore dismantling         | Evaluated in detail | • Required for deck structures containing hydrocarbons and other pollutants  
|                             |                 | • Required for complete removal option (assuming no deep water disposal) |                                           |
|                             |                 | • Technically feasible                                               |                                           |
|                             |                 | • Costed out in detail by MMS (now BOEM/BSEE)                         |                                           |
| Place upper portion on bottom | Evaluated in detail | • Useful as reef enhancement under the partial removal option       |                                           |
|                             |                 | • Valued by key stakeholders                                         |                                           |
|                             |                 | • No objection from state or federal managers                         |                                           |
| Deep water disposal         | Examined briefly and eliminated | • Potential fiscal incentive for operators                        | • Little interest among state and federal managers |
Figure 2. Decision tree showing decommissioning options considered. Options with green boxes were analyzed in greater detail, while options in gray boxes were omitted from quantitative analysis (see Bernstein 2015 for more detail.)
PLATFOR: A DECISION ANALYSIS TOOL

We developed PLATFORM as a computer model to evaluate alternative decommissioning decision strategies and the conflicting criteria (attributes) involved, with probabilistic treatment of the attendant uncertainties. Key objectives in the design for PLATFORM were to:

1. Provide a transparent structure for review and evaluation of the conceptual structure, assumptions, and formulas in the analysis
2. Improve the analysis team’s productivity and ability to share insights across separate portions of the overall analysis
3. Support sensitivity analysis to identify how inputs or assumptions affect conclusions
4. Provide stakeholders a tool for interactive exploration of decision strategies from varying perspectives, especially the relative importance placed on specific attributes

Model Development

PLATFORM was developed in Analytica, a general purpose visual environment for building quantitative decision models (Lumina 2012). Figure shows the top-level user interface for PLATFORM, as implemented in Analytica.

Figure 3: The main user interface for PLATFORM, with separate components to define decision options or scenarios, perform a quantitative cost analysis of the scenarios, and conduct multi-attribute analyses including all attributes.

The model incorporates user interfaces, a hierarchy of influence diagrams to build and organize the model, range sensitivity analysis to identify key sources of uncertainty or
Decision Analysis Tool for Decommissioning Offshore Oil Platforms

disagreement, and Monte Carlo simulation to represent uncertainties. Model dimension, including platforms, decision options, scenarios, attributes, and so on, make use of Intelligent Arrays™.

The preferred decommissioning method may vary among platforms according to depth and a number of specific conditions such as distance from shore, type of biological communities present, and the need to share HLV costs among multiple platforms. Accordingly, PLATFORM lets users define and compare scenarios, each of which selects decommissioning options separately for one, some, or all of the 27 platforms (Figure 4). Decision options include complete removal with or without explosive severing and removal of shell mounds, or partial removal with the option of adding quarry rock enhancement for the reefing option.

![Figure 4. Defining a scenario by selecting an option for each platform.](image)

![Figure 5: An Analytica influence diagram showing selected variables and influences involved in calculating the programmatic costs for decommissioning. (see Bernstein and Bressler (2015) for additional detail)](image)

Model details are organized as a hierarchy of modules, structured as influence diagrams (e.g., Figures 5 and 6). The project team's domain experts developed separate modules to estimate decommissioning costs, fish production, socioeconomic effects, and air quality impacts (Bernstein 2015) in collaboration with the project’s decision modelers. Each diagram identifies key variables, including data sources, uncertainties (oval nodes), decisions (rectangular nodes),
and result variables, with the influences drawn as arrows between them. For each component, the team first developed an influence diagram identifying the top level conceptual structure, and progressively added detail as necessary to complete the analysis. Thus, influence diagrams were initially purely qualitative, with detail added to structure the analysis as data gathering and evaluation progressed. Domain experts added numerical inputs and formulas to quantify the relationships expressed in each influence diagram. Companion articles in this series describe the details of each of these separate analyses.

Figure 6: An influence diagram for the module that estimates direct decommissioning costs. The oval nodes depict key uncertain quantities that affect total cost. (see Bernstein and Bressler (2015) for additional detail)

Sensitivity analysis lets users explore which uncertainties have the most effect on results and whether plausible changes in component estimates might change the preferred choice among options. Using decommissioning costs as an example, Figure 7 shows a "tornado chart" generated by PLATFORM using Analytica's built-in sensitivity analysis tools. It illustrates the effect on the total decommissioning cost for Platform Gilda of changing each cost component from a low value (-25%) to a high value (+25%), holding all other components at their base value. The input variables are sorted from most sensitive (widest bar) at the top to least sensitive at the bottom, giving the characteristic "tornado" look. The most sensitive variable is the cost of platform and structural removal, which is not surprising given that it is the largest cost element in the entire decommissioning process (Bressler and Bernstein 2015).
Continuing with the cost example, it is useful to treat uncertainties about decommissioning costs using probability distributions. Studies of 40 decommissioning projects involving 120 structures from 1994 to 2005 found that actual costs averaged about 12% higher than estimated costs, with a geometric standard deviation of 23% (Byrd et al, 2014). Assuming that similar bias and variation would apply to the California platforms, we applied an uncertainty factor to costs using a lognormal distribution with median of 1.12 and geometric standard deviation of 1.23. Figure shows the resulting uncertainty about costs for complete removal and partial removal for Platform Henry.
Figure 8. Uncertainty about decommissioning costs for complete removal and partial removal for Platform Henry shown as cumulative probability distributions.

STRUCTURING MULTIPLE OBJECTIVES OR ATTRIBUTES

Like many public policy decisions, platform decommissioning is complicated by multiple conflicting objectives (attributes) and stakeholders’ differing views about their relative importance. To ensure we captured key stakeholders’ major objectives, we reviewed the extensive literature and history of this topic (Bernstein et al. 2010) to create an initial list of concerns. We then refined and confirmed these attributes with the project’s Expert Advisory Committee (Pietri et al. 2011). This group included state and federal agencies with direct management or regulatory responsibility over one or more aspects of decommissioning, decommissioning experts from industry, policy experts from academia and consulting, and environmental impact specialists from academia. We supplemented the committee’s input with our own outreach to parties to past decommissioning projects in government, consulting, academia, and conservation organizations. Based on this input, we organized the objectives as the eight attributes shown in the influence diagram in Figure 9 (each node is a module in PLATFORM containing additional detail, as in Figures 5 and 6) and described in
Some attributes, such as cost, can readily be quantified. Others, such as impacts on marine mammals, are difficult to quantify due to inadequate data and/or incomplete understanding of causal processes. Some types of qualitative attributes, such as strict compliance with lease agreements, are naturally categorical. All too often, analyses focus on those attributes that can be quantified easily, even though other harder-to-quantify attributes may be of equal or greater importance. In this study, we used a multi-attribute framework to treat all identified attributes, whether quantitative or qualitative, as potentially important to any stakeholder. Table 2 summarizes these attributes, and how they were treated.
Table 2. Summary findings and characteristics of the eight attributes included in the multi-attribute analysis. Note that the analysis focused on identifying the difference between the complete and partial removal options across all eight attributes.

<table>
<thead>
<tr>
<th>Attribute description</th>
<th>Characteristics</th>
<th>Reference</th>
</tr>
</thead>
</table>
| Costs: The direct costs of decommissioning, including acquiring required permits, obtaining equipment such as heavy lift vessels (HLVs), cutting up the platform, removing some or all parts, transporting them to a disposal or recycling site, and processing removed equipment. Programmatic costs included for reefing option. | • Quantified in US dollars (2009)  
• Actions identical in both options (e.g., deck removal) did not affect choice of option | Bressler & Bernstein 2015 |
| Air quality: Much of the equipment used to dismantle, lift, and transport the elements of the platform runs on fossil fuel, usually diesel, emitting carbon dioxide and criteria pollutants. Only on-site emissions are considered, excluding emissions from transit of heavy lift vessels (HLVs) from the North Sea or east Asia | • Quantified for worst case, the largest platform (Harmony)  
• Qualitative for other platforms based on size comparison with Harmony | Cantle & Bernstein 2015 |
| Water quality: Removal of platforms, oil and gas processing equipment, and dredging of shell mounds and debris below the platform may have some impact on water quality due to dispersal of contaminants. | • Qualitative based on relative risk of spills, dispersal, past experience | Bernstein et al. 2010 |
| Marine mammals: Seals, sea lions, and other marine mammals often visit platforms due to the local concentration of fish. Complete removal will remove this food source. Removal of platforms, especially if explosives are used to sever steel supports, may disturb or injure marine mammals in the vicinity. | • Qualitative based on use of explosives, relative amount of vessel traffic, behavior and migration patterns, past experience | Bernstein et al. 2010 |
| Marine birds: Marine birds use platforms for roosting, enabling them to feed with shorter flights than from onshore roosting. At the same time there are some fatalities from flight collisions with platforms. Both options will remove surface structures, having the same impact on birds. | • Qualitative based on past studies  
• No difference between options, therefore did not affect choice | Bernstein et al. 2010 |
| Benthic impacts: The benthic zone is the ecological region on the seafloor, including surface and subsurface sediments. Complete removal of platforms will have some impact from anchoring the HLV, extracting the jacket piles, piping, and cabling, and, dredging or covering the shell-mounds. Partial removal will have much smaller impacts on the benthos. | • Qualitative based on relative amount of size of platform and shell mound, relative degree of disturbance, past studies | Bernstein et al. 2010 |
| Fish productivity: Biological productivity around the platforms provides sustenance for fish, including rock fish of value to commercial fishermen, and is an attraction for recreational divers. Complete removal will remove all such habitat and reduce productivity. | • Quantified as Kg/ year by platform  
• Model included amount of habitat per platform, data from monitoring surveys, population dynamics (i.e., reproduction, settlement, growth, survival/mortality rates) | Pondella et al. 2015 |
### Ocean access:
Partial removal option increases ocean area accessible for shipping and some fishing vessels, but reduces or leaves unchanged access to other user groups. Value of each option depends on the specific user group.

- Quantified changes to access in square nautical miles
- Qualitative for other aspects
- User group preferences classified as pro, con, or neutral for each option
- Most socioeconomic impacts not considered because of data gaps, large uncertainties, and small size relative to local economy

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### Strict compliance:
The original oil and gas leases required lessees to remove the platforms entirely at the end of their productive life and restore the seafloor to its original condition.

- Categorical based on requirement for strict compliance or willingness to consider other options
- Some environmental groups view this objective as paramount

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*Kruse et al. 2015*

*Bernstein et al. 2010*
Multi-attribute Decision Analysis

Multi-attribute utility theory (MAUT) provides a principled approach to evaluate decisions under uncertainty on multiple objectives or attributes based on von Neuman and Morgenstern decision and utility theory (Keeney 1968, Fishburn 1970, Keeney and Raiffa 1976). It provides ways to represent a person's preferences over alternatives characterized by n uncertain attributes, \( (x_1, x_2, ..., x_n) \) as a scalar utility function \( U(x_1, x_2, ..., x_n) \). Additive independence means that a person's preferences show no interactions among attributes — preferences over values of one attribute are not affected by the level of other attributes. For example, preferences over levels of impact on marine mammals should be independent of decommissioning costs. Additive independence is often a reasonable approximation to people's preference structures with limited uncertainty. Informal discussion with selected stakeholders suggested that it is a reasonable assumption in this case. Additive independence allows decomposition of the aggregate utility function into a simple weighted sum of attribute-specific utilities (Keeney & Raiffa 1976):

\[
U(x_1, x_2, ..., x_n) = \sum_{i=1}^{n} w_i u_i(x_i)
\]

The multi-attribute utility \( U() \) and single-attribute utility functions \( u_i(x_i) \) are constrained to be in the range 0 to 1, and the weights normalized to sum to 1:

\[
0 \leq U(x_1, x_2, ..., x_n) \leq 1, \quad 0 \leq u_i(x_i) \leq 1, \quad \sum_{i=1}^{n} w_i = 1
\]

This assumption lets us assess the utility function for each attribute separately from each other and from the weights used to combine them into a multi-attribute utility function. Applying this approach involves these steps:

1. Identify and organize attributes (as described above)
2. Define a clear scale for each attribute, either cardinal, meaning quantified, as in US dollars for direct costs, or ordinal, meaning a list of outcomes in order of preference
3. Define a single-attribute utility function to score the possible levels of each attribute into a utility from 0 (worst outcome) to 100% (best outcome)
4. Select swing weights (or equivalent costs) to model stakeholder preferences about relative value or cost for each attribute from which to obtain weights \( w_i \) using the SMARTS method (see the next section for details)
5. Combine the swing weights and attribute scores into an overall multi-attribute utility for each decision option.

For the qualitative attributes, we developed a five-point scale, ordered from the worst to best outcome plausibly possible for any platform. Intermediate points are labeled poor, medium, and good. Table 3 shows an example for rating potential impacts on marine mammals. It describes levels, from the worst — "Disturbance, disorientation and possible mortality" — to the best _ "No impact". It also identifies the corresponding decision option that might produce each outcome — from "Complete removal with explosive severing" for the Worst level, to "No action" for the Best level. The last column in Table 3 specifies the score for each level as a utility between 0 and 100%. By definition, the worst and best outcomes are scored at 0 and 100%, and so are not modifiable. Users of PLATFORM may select scores between 0 and 100% for each intermediate level (as illustrated in Table 3). Users may think about assessing the score for an intermediate level \( x' \) as the probability \( p \) that would make them indifferent between level \( x' \) and a lottery with probability \( p \) of the best outcome and probability \( (1 - p) \) of the worst outcome.
Table 3. Definition of levels for impact on marine mammals, a qualitative attribute, including a description, and the conditions or options that would give rise to that level. Scores of 70% and 50% are example scores to illustrate user input.

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
<th>Decisions</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best</td>
<td>Status quo, no effect</td>
<td>No action</td>
<td>100</td>
</tr>
<tr>
<td>Good</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>Slight effect on movement or migration of marine mammals</td>
<td>Partial removal</td>
<td>70%</td>
</tr>
<tr>
<td>Poor</td>
<td>Some disturbance or disorientation</td>
<td>Complete removal without explosive severing</td>
<td>50%</td>
</tr>
<tr>
<td>Worst</td>
<td>Disturbance, disorientation, and possible mortality</td>
<td>Complete removal with explosive severing</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4 defines the scale and provide scores for the strict compliance attribute. In this example, the user specified a score of 0% for the Medium level — the same as the Worst level — viewing it as just as non-compliant with the lease agreement, since it leaves part of the platform and the shell mounds in place.

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
<th>Decision options</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best</td>
<td>Platform is completely removed and sea bed restored, compliant with lease</td>
<td>Complete removal including shell mounds</td>
<td>100</td>
</tr>
<tr>
<td>Medium</td>
<td>Jacket up to 85 feet below MWL and shell mounds left in place, non-compliant with lease.</td>
<td>Partial removal of platform</td>
<td>0%</td>
</tr>
<tr>
<td>Worst</td>
<td>Entire platform left in place, non-compliant with lease.</td>
<td>Reuse of platform in place</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4. For the Strict compliance attribute, the levels, description, decision options and score, from the PLATFORM model.

The three attributes based on quantitative models are decommissioning cost, fish production, and changes in ocean access. From a public policy perspective, the maximum range of effects on these attributes are only a tiny percentage of, respectively, annual spending by the state of California or oil and gas companies, fish production in California waters, or the area of accessible ocean. It is therefore reasonable to assume a linear utility function for each of these attributes over the range of interest for these decisions, the default method in PLATFORM.
Figure 10 shows normalized score by attribute for platform Harmony for the complete and partial removal options. It is noteworthy that partial removal scores higher than complete removal on cost and all environmental impacts, except on birds for which they score the same, because both options remove the above-water platform structure. Complete removal performs slightly better on changes to ocean access because it removes the underwater parts of the jacket that must be avoided by many commercial fishing gear types. Strict compliance is the key exception to this pattern: partial removal scores zero and complete removal scores 100. Thus, the choice between complete and partial removal depends almost entirely on the judged importance of strict compliance relative to the costs and environmental impacts.

![Normalized score by attribute for platform Harmony for complete and partial removal. Higher scores reflect better outcomes, e.g., lower costs, better water quality.](image)

**Combining Attributes and Swing Weights**

PLATFORM offers two methods for assessing weights for aggregating over attribute scores, SMARTS (Simple Multi-Attribute Rating Tool with Swing weights) and an equivalent cost method that lets users express preferences for each attribute scores in terms of cost. The original SMART method proposed by Edwards (1977), like many simple methods for multi-criteria decision making, treats the weights \( w_i \) as representing the relative importance of each attribute in the abstract. Edwards & Barron (1994) extended SMART to SMARTs by adding swing weights. Swing weights recognize that the importance of each attribute should depend on the range of each attribute: Asking whether dollar cost is more important than impact on marine mammals in the abstract is an ill-defined question. It is more meaningful to ask whether the range of cost from zero to $100 million is more important to a stakeholder than the range of outcomes on marine mammals from none to the death of 20 sea lions.

Table 5 shows the user-interface screen that assists stakeholders in specifying swing weights for each attribute. A user first selects an attribute whose range they view as most important. For example, cost would be most important if one considers that shifting cost over its
full range from its worst level ($250 million, the cost of completely removing the largest platform, Harmony) to its best cost level (zero) to be worth more than changing any other attribute from its worst to its best level. Users set the most important attribute to the highest swing weight of 100. They then order the other weights from the second most important down to the least important, again based on each attribute’s full range. Finally, users specify a swing weight between 0 and 100 for each attribute relative to the most important. For example, if one thinks that the value of changing impact on marine mammals from its worst to its best level is worth about 20% of the value of changing cost from $250 million to zero, they would specify the swing weight for marine mammals as 20. Attributes considered to have about the same value can be assigned the same swing weight.

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Type</th>
<th>Best outcome</th>
<th>Worst outcome</th>
<th>Swing weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs</td>
<td>Quantitative</td>
<td>Status quo: $0</td>
<td>Complete removal: $250 million</td>
<td>100</td>
</tr>
<tr>
<td>Air quality</td>
<td>Qualitative</td>
<td>Status quo: Zero emissions</td>
<td>Complete removal: Emissions from 4400 ton HLV onsite for 113 service days for complete removal.</td>
<td>40</td>
</tr>
<tr>
<td>Water quality</td>
<td>Qualitative</td>
<td>Status quo: No impact</td>
<td>Complete removal: Accidental discharge of contaminated material at surface, or shell mound removal with toxic sediment contaminates water column.</td>
<td>15</td>
</tr>
<tr>
<td>Marine mammals</td>
<td>Qualitative</td>
<td>Status quo: No impact</td>
<td>Complete removal: Explosive severing for complete removal causes disturbance, disorientation, and some mortality to marine mammals.</td>
<td>20</td>
</tr>
<tr>
<td>Birds</td>
<td>Qualitative</td>
<td>Deck removal: Reduced mortality from flight collisions. Loss of offshore roosting replaced by new</td>
<td>Deck removal: Loss of offshore roosting reduces fitness and survival, which outweighs reduced flight collisions.</td>
<td>10</td>
</tr>
<tr>
<td>Benthic impacts</td>
<td>Qualitative</td>
<td>Status quo: No impact</td>
<td>Complete removal: Anchoring or shell mound removal leads to widespread impact and spreading contaminants.</td>
<td>10</td>
</tr>
<tr>
<td>Fish production</td>
<td>Quantitative</td>
<td>Status quo: 10,000 Kg/y</td>
<td>Complete removal: Zero fish production</td>
<td>25</td>
</tr>
<tr>
<td>Ocean access</td>
<td>Quantitative</td>
<td>Removal: Adds 2 Sq N Mi</td>
<td>Status quo: Limits access</td>
<td>20</td>
</tr>
<tr>
<td>Strict compliance</td>
<td>Qualitative</td>
<td>Complete removal complies with lease</td>
<td>Partial or no removal violates lease.</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 5: User interface screen to assist users in assessing swing weights for each attribute to estimate the value to a stakeholder of changing each attribute from its Worst to its Best outcome, relative to most important attribute. In this example costs are identified as the most important attribute and assigned a swing weight of 100.
Sensitivity to Preference Weights

Naturally, stakeholders differ about the relative importance of the attributes. Some see the large cost of complete removal as most salient. Others are most concerned about the potential environmental impacts. A few expressed the view that strict compliance with existing lease agreements is paramount. PLATFORM offers several tools (based on Analytica) to explore the sensitivity of its conclusions to such differences in values.

First, we examine the effect of varying each swing weight (see examples in Table 5) around its base values. For example, Figure 11 shows a range sensitivity analysis (tornado chart) for platform Harmony. The horizontal axis is the difference in utility between partial removal (Scenario 2) and complete removal (Scenario 1), which is 14.8% (the value of the central vertical line) with base swing weights shown in Table 5. With these values, partial removal is preferred to complete removal. The chart shows a horizontal bar for each swing weight, showing the effect on the utility difference of varying the weight from its lowest value (0) to its highest value (100), while keeping all others at their base value.

![Tornado Chart](image)

Figure 11: Range sensitivity analysis (or tornado chart) of the difference in value between complete removal (scenario 1) and partial removal (scenario 2) for platform Harmony, changing the swing weight for each attribute from 0 (low) to 100 (high) and Cost uncertainty from 10th to 90th percentile while keeping the other variables at their base values.

As usual with tornado charts, the variables are ordered from largest sensitivity (absolute difference between lower and upper value) at the top to smallest at the bottom. The largest sensitivity is for Compliance weight, followed by Air quality and Cost weight. The "Cost uncertainty" represents uncertainty about the total decommissioning cost (not the cost weight) ranging from the 10th to 90th percentile of the probability distribution over the difference in decommissioning costs between partial and complete removal (see Figure 8. Uncertainty about decommissioning costs for complete removal and partial removal for Platform Henry shown as cumulative probability distributions.), with its base value at the median (50th percentile). It is interesting that the Cost Uncertainty has the lowest but one sensitivity. In other words,
uncertainty about the factual question (the direct costs of decommissioning) has considerably less effect on results than stakeholder disagreements about relative preferences for the top seven attributes, as reflected in their swing weights.

It is interesting that the sensitivity bar for only one attribute, Compliance weight, reaches below zero. In other words, Compliance weight is only variable for which an extreme change could change the preferred decision — from partial to complete removal.

Compliance is one of just two attributes that favor complete removal (i.e., where a lower weight favors partial removal) as indicated by the blue bar in Figure 11 reaching to the left. It should not be surprising that a higher weight on Strict compliance favors complete removal. The other attribute is Ocean access, which favors complete removal because partial removal leaves the jacket at 85 feet below MWL, an underwater obstacle for commercial fishing that must be avoided. The remaining seven variables, including Cost weight, cost uncertainty, and all the environmental impacts, favor partial over complete removal, where so a higher weight or value decreases the utility difference between partial and complete removal.

Partial removal scores better on cost and all the environmental attributes except ocean access which has relatively minor effect. This implies that the key question in determining the recommended decision is the swing weight for Strict Compliance. In Figure 12 we show the recommended decision, Partial removal (light blue) or Complete removal (dark blue), for each of the 27 platforms as a function of the swing weight assigned to Strict Compliance. For swing weight of 0, the model recommends Partial removal for all platforms. For swing weight of 100 (the same as for direct cost), the model recommends Complete removal for all platforms.

The number of platforms recommended for Complete removal (shown in the bottom row) increases monotonically from zero to all 27 platforms as the swing weight for Strict Compliance increases from 0 to 100. Error! Reference source not found. orders the platforms by depth from shallowest to deepest. At intermediate swing weights, the decision analysis tends to recommend complete removal for the shallower platforms over the deeper platforms, because the decommissioning costs and environmental impacts are higher for the deeper platforms.
Figure 12: The preferred decision, Partial Removal (light blue) or Complete removal (dark blue) for each platform according to the swing weight set for Strict Compliance. The bottom row shows the number of platforms recommended for Complete removal. The platforms are ordered by depth.
CONCLUSIONS AND EFFECTS ON THE POLICY PROCESS

This decision analysis refined a large set of potential decommissioning options and their combinations down to a smaller decision tree with a more limited number of options deserving more detailed analysis: These primary options are complete removal of each platform and partial removal to 85 feet below water level, leaving the remaining platform components in place as an artificial reef to retain fish production and ecosystem value as part of “rigs to reefs” program. Removing the upper portion of the platform retains the majority of the ecological value while removing potential interference with shipping.

This study contributed new insights to our understanding of specific attributes, based on the detailed quantitative models in PLATFORM. It was the first to quantify fish production on these platforms in terms of biomass per year by depth zone and to estimate how this would be affected by the partial removal option (Pondella et al. 2015). Recent studies showing that the nursery zone for the commercially important rockfish species begin at about 30 meters depth, with adults ranging to deeper layers, implies that the partial removal option should not interfere substantially with rockfish lifecycles and production. The analysis of air emissions from the complete removal of the largest and deepest platform, Harmony, found the emissions to be considerable, even ignoring off-site emissions during transport of the HLV and shipping of removed platform components to disposal sites: 29,400 tons of carbon dioxide, 600 tons of NOx, and 21 tons of fine particulates (PM10). These levels suggest that permitting for such a project by air quality regulatory agencies would be problematic.

As with most analyses of controversial public policy decisions, the preferred recommendations depend on the stakeholder's point of view. With the aid of a multi-attribute decision analysis model, PLATFORM, we clarified how preferences among the objectives affect the recommended decision. We identified eight major objectives or attributes of importance to stakeholders. Two of these, impacts on marine birds and recreational diving (one aspect of socioeconomics), are identical for complete and partial removal, and so may safely be ignored when comparing these options. The decommissioning costs and the four remaining environmental impacts (impacts on air quality, water quality, marine mammals, and benthic habitats) are all greater (less desirable) for complete removal. Changes to ocean access, while slightly favoring complete removal because of the interference of the remaining artificial reef with commercial fishing, were considered of minor importance by stakeholders. This a single attribute, strict compliance with original leases, remains as a compelling reason for some stakeholders to favor complete removal.

The range sensitivity analysis for the deepest platform, Harmony (Figure 12), illustrates how the swing weight for strict compliance may be the only one that can change the decision from partial to complete removal when pushed to an extreme. Extending the sensitivity analysis to all 27 platforms, as illustrated in Error! Reference source not found., demonstrates that reducing the swing weight for strict compliance to zero results in recommending partial removal for all platforms. As this weight is increased, the model recommends complete removal, beginning with the shallower platforms. At a weight of 100, equal to the weight of costs, complete removal becomes the preferred option for all platforms.

Discussions with most stakeholders suggested they view strict compliance as less important than environmental impacts and decommissioning costs, especially if some of the savings from partial removal are applied to ocean conservation. Since partial removal with an
artificial reeding program preserves more of the marine ecosystems, costs less, and has lower environmental impacts than complete removal, there was, therefore, a near consensus for that option. The only active dissenters were local environmental organizations that argued that releasing operators from the requirement that "they clean up after themselves" and pay the costs of full removal would encourage oil and gas companies to propose more offshore drilling elsewhere.

The quantitative results presented here were calculated using PLATFORM, the Analytica-based tool developed for this study. All numerical data and assumptions underlying the cost estimates and other calculations are available for review within the model and may be updated as new information becomes available. Users may also modify the parameters of the multi-attribute utility model to explore the implications of alternative preferences. PLATFORM was used interactively by the project team and to present interim results to OST’s Expert Advisory Council. It is available, along with the final project report on the OST website (http://calost.org/science-initiatives/?page=past-projects) for use with the free Analytica Player. At least one major stakeholder in the oil and gas industry used the model independently to review the assumptions and explore the implications of alternative cost estimates. PLATFORM is also designed for future use by platform operators and other stakeholders to compare actual decommissioning strategies that are proposed for particular platforms or groups of platforms.

A rigs-to-reefs program, implied by the partial removal options, will require transfer of ownership from the original leaseholders to the state or another organization to manage the resulting artificial reefs and assume any liabilities involved. In a companion article based on the project report, Bernstein et al. (2015) examine the legal and institutional implications of an expanded artificial reef program in California, describe potential pathways for ownership transfer, and assess the state’s options for addressing liability concerns. This new synthesis of information contributed practical information to the development of legislation enabling an expanded reefing program in California. For example, while potential liability associated with platform reefs has been a consistent concern of state managers, Bernstein et al. (2010 and 2015) concluded, based on a review of a number of analogous programs and legal precedents, that the potential liability of an artificial reef program is not large and can be readily managed through a variety of mechanisms.

The original findings from this study, including the decision analysis and the PLATFORM decision model, were released in a report (Bernstein et al. 2010) and presented in public meetings to the California Ocean Protection Council and other groups. These results contributed to ongoing policy discussions in California on this issue, including the development of new state legislation that provides for the savings from partial removal to be split between the operators and a public fund for ocean conservation administered by the California Department of Natural Resources. The new legislation includes an incentive for early decommissioning, as operators keep 45% of the cost savings until 2017 after which their share falls to 35%. The resulting bill, AB 2503, was adopted by the California legislature, and signed into law by Governor Schwarzenegger in September 2010.

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