DECISION MAKING UNDER DEEP UNCERTAINTY

WHAT IS IT AND HOW MIGHT NOAA USE IT?

PRESENTED TO THE NOAA SCIENCE ADVISORY BOARD

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What is it and how might NOAA use it?

Report to the Science Advisory Board from the Ecosystem Science and Management Working Group

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Abstract

This report is an initial review of techniques to inform decision making under "deep uncertainty" (DMDU) and their potential use by NOAA. DMDU techniques are designed to be used in situations where uncertainty cannot be well characterized with existing data, models, or understanding. **To manage this type of uncertainty, multiple scenario development, engagement strategies and modeling techniques may be used to consider the implications of choices under likely and unlikely future conditions. These techniques couple systematic analysis with thoughtful deliberation, typically in coordination with stakeholders.** DMDU approaches differ from other methods in that they (a) seek to mitigate the risk of policy or program failures due to unanticipated or poorly understood future circumstances and (b) promote the consideration of solutions that are adaptable through time.

With assistance from external experts in DMDU techniques, the Ecosystem Sciences and Management Working Group (ESMWG) reviewed the potential application of these techniques to decision-making within NOAA, focusing on two broad areas under the agency's purview: coastal planning and fisheries management. **This review suggests that DMDU approaches have the potential to enhance existing NOAA decision processes in these and other settings.** The benefits of DMDU techniques include systematic and deliberative exploration of possible futures for management applications that could reduce the potential for unanticipated and unintended consequences. Because DMDU techniques seek to identify "low-regret" and/or robust solutions that are beneficial over a broad set of potential future situations, they have the potential to improve confidence that proposed policy and program actions are worthwhile. Some NOAA activities already rely upon approaches that share key characteristics with DMDU techniques, such as Management Strategy Evaluations (MSEs) within fisheries. Hence, DMDU techniques do not represent a radical departure from existing analytic strategies already used within some parts of the agency.

Comprehensive forms of DMDU techniques are resource-intensive to apply, suggesting that they are not suitable for all decision contexts. Therefore, screening methods would be useful for choosing conditions that justify the analytic and data collection resources required. The conditions under which DMDU techniques appear to be most appropriate are when decisions have high stakes. These include decisions with high benefits and costs, and that are potentially irreversible or difficult to adapt. Further, DMDU techniques can help to systematically sort through situations with multiple options and tradeoffs, and examine outcomes with probabilities that are poorly characterized and about which stakeholders disagree. In some cases, it may also be appropriate and cost-effective to use DMDU decision support elements in a piecemeal fashion, such as developing parsimonious sets of scenarios to use in models or to stress-test existing decisions.

If NOAA has interest in further using these techniques, we recommend exploring them further with managers, analysts, decision scientists and other experts to gather additional information about potential applications in specific situations. Some specific recommendations to consider are:

1. Include elements of DMDU where risk-based planning is already used
2. Explore potential applications of DMDU to inform coastal planning
3. Apply DMDU to design monitoring programs
4. Develop guidelines and data to enable systematic scenario development
5. Consider whether there are other promising areas of DMDU application within NOAA

NOAA could use seminars, workshops and test cases to thoroughly consider the barriers and opportunities for applying DMDU within programs.

1. Introduction

NOAA's mission encompasses a broad suite of responsibilities linked to climate, weather, oceans, and coasts, including the management and conservation of fisheries and coastal/marine ecosystems. All of these areas involve systems and outcomes characterized by different types and degrees of uncertainty, from understanding weather and climate changes over time to predicting fish stock trajectories as they respond to variations in fishing pressure, habitat, and other changes. Recent events—such as the emergence of marine heatwaves off the US Pacific coast (Di Lorenzo and Mantua, 2016)— highlight the management challenges that emerge due to unforeseen and difficult-to-predict events. An archetypal case is the increasing challenge of fishery management under a rapidly changing climate, which requires managers to address multiple uncertainties over different spatial and temporal scales.[1] Changing and less predictable systems strain the limits of traditional approaches to decision making under risk and uncertainty, which in their standard forms, require assigning (or assuming) a comprehensive set of outcomes and probabilities in the systems under study.

Mitigating risks created by climate and other changes requires an improved understanding of the implications of those changes, and methods to incorporate that understanding into planning and decision making. This report examines the potential for decision making under deep uncertainty (DMDU) techniques, a type of decision analysis, to offer increased capacity to characterize uncertainty, and to identify choices that generate benefits under a range of possible futures. Although DMDU approaches share methods with traditional risk assessment, a key distinction is that they rely less on a "best guess" projection of the future and more on making sound choices that reduce negative consequences, if the best guess is incorrect.

Input for this report was gathered from multiple sources, including a review of the DMDU literature, input from NOAA staff, and a multi-day workshop in July 2020. The workshop included presentations by experts on decision making under deep uncertainty, David Groves (RAND) and Julie Shortridge (Virginia

[1] For example, the Bering Sea (AK) has experienced rapid rates of ocean warming and winter sea ice loss, which is transforming the marine ecosystem and affecting commercial fisheries, subsistence harvests, and threatened or endangered species (https://www.beringclimate.noaa.gov/index.html).

Tech), and case study presentations where DMDU might be applied by, Sarah Gaichas (NOAA Fisheries) and Paul Kirshen (Boston U). See Appendix A for workshop agenda.

1.1 What is Decision Making Under Deep Uncertainty (DMDU)?

Deep uncertainty is characterized by: 1) an inability to make well-informed future projections of a system, based on available data and understanding and, 2) an inability to reduce this uncertainty by gathering additional information (Shortridge et al., 2017a; Marchau et al., 2019). Common examples include "situations where probabilities of different outcomes are unknown, previous data is deemed insufficient for estimating future consequences, [or] experts disagree on the consequences of different policies," (Shortridge et al., 2017a). DMDU approaches are best characterized as a suite of methods and decision-support tools that help identify robust and responsive solutions to unpredictable system dynamics. These approaches are also designed to accommodate adaptation over time, recognizing that systems can change in unforeseen ways (Marchau et al., 2019).

While DMDU techniques are not broadly applied by NOAA, similar approaches are used by the agency in several programs. Expanding these techniques could provide more transparent approaches to 'adjudicating uncertainty', or dealing consistently and objectively with informing natural resource management. Because DMDU techniques are not well-suited to all applications, the first steps for considering DMDU is to evaluate whether these techniques should be applied and if so, where they would be most informative.

1.2 How do methods differ from traditional approaches?

Over the past two decades, a suite of DMDU approaches have been developed (see, e.g., Lempert et al., 2003; Shortridge et al., 2017a; Marchau et al., 2019). The usefulness and opportunities for using different elements of these decision support tools and DMDU analyses fall along a continuum of decision characteristics (Figure 1).

DMDU methods are best suited to situations with five key characteristics: 1) decisions have high stakes (justifying the resources required for DMDU analysis), 2) decisions are complex with multiple tradeoffs, 3) decision options are numerous, 4) probabilities are poorly characterized, and 5) stakeholders disagree on the consequences of actions (Groves, 2020). DMDU methods have been most frequently applied to infrastructure decisions, although case studies exist for natural resource management.

In contrast to DMDU, traditional probabilistic risk assessment (PRA) characterizes system responses to potential management actions and assigns probabilities to reflect expected variability of future outcomes. However, under the five conditions just described, it is typically impossible to assign an exhaustive set of outcomes and probabilities to proposed policies or actions, at least not in a defensible and robust manner. The complexity of the systems being characterized and a lack of stakeholder agreement (e.g., on assigned probabilities or the benefits of specific actions) may further preclude applications of traditional forms of sensitivity analysis.

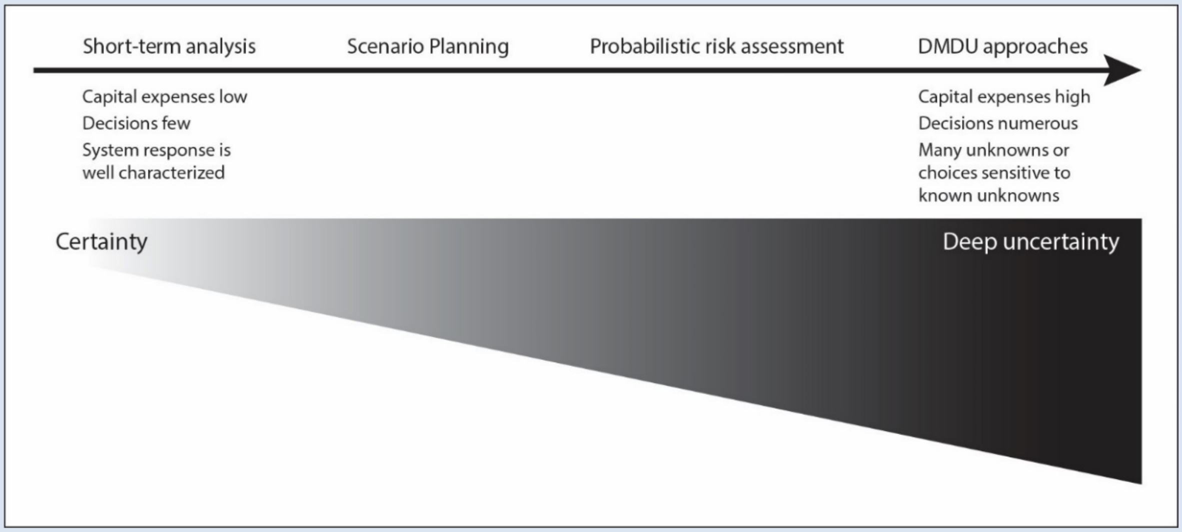


Figure 1. A continuum of decision support analyses and degrees of uncertainty
The many types of decision support analyses can be thought of as a continuum of increasingly thorough approaches to incorporating uncertainty in analysis. As uncertainty, decision complexity and the costs of making a "wrong decision" increases, improved characterization of uncertainty is desirable. Because DMDU approaches are often time consuming, this type of analysis is most appropriate when uncertainty is poorly characterized and the decision stakes are high.
DMDU frequently includes elements of Scenario Planning and Probabilistic Risk Assessment (PRA). The primary distinctions between DMDU and other approaches are 1) that DMDU takes a highly structured approach to scenario planning to ensure all major drivers of change and diverse perspectives are considered in scenarios, and 2) relevant uncertainty is included, even if it cannot be quantified. In contrast, traditional PRA requires that probability distributions are specified for uncertain variables (and as a result extremely uncertain variables may be omitted entirely). An extremely thorough sensitivity analysis in PRA can be similar to DMDU but may lack the decision focus on identifying the alternatives that consistently produce benefits across all potential futures.

Examples of DMDU techniques include Robust Decision Making (RDM; e.g., Lempert, 2019), Probability-Bounds Analysis, Info-Gap Theory, Resilience Analytics (e.g., Shortridge et al., 2017a) and Dynamic Adaptive Policy Pathways (DAPP; e.g., Haasnoot et al. 2019) or Dynamic Adaptive Planning (DAP; e.g., Walker et al. 2019). These methods share the characteristic that they do not attempt to provide one, best-guess "optimal" solution that ignores unlikely events (as would be typical in PRA). DMDU approaches seek to identify decisions that could succeed under a wide range of plausible, but not necessarily likely, outcomes, allowing for the possibility that success may be viewed differently by different stakeholder groups. DAPP or DAP examine strategic pathways of decisions based on tradeoffs and net benefits of alternative sequences of short and long-term actions. They frequently seek to identify the conditions that trigger the need for new risk mitigation investments, also called decision tipping points, and encourage identifying management transitions that can prevent future harm.

Common elements of DMDU methods include the use of analytic and deliberative processes to identify potential sources of uncertainty, while also engaging stakeholders in choosing scenarios, setting goals and exploring risk tolerances. RDM methods are some of the best described in the literature and these take an inclusive approach to identifying key dimensions of the problem including uncertainties, available options and strategies, relationships between system components (models), and performance metrics relevant to different groups (Groves, 2020). RDM seeks to identify "robust" solutions that meet stakeholder goals under a wide range of plausible outcomes (e.g., no- or low-regret strategies).

Although DMDU methods acknowledge that probabilities cannot be known with certainty, they vary in the degree to which various types of information, bounds, or priors on probability distributions are permitted to inform the analysis (Shortridge et al., 2017a). The full set of uncertainties affecting a system are typically unknown (Groves, 2020). To accommodate the complexity, lack of predictability, and path-dependence of the modeled systems, DMDU methods rely on heavy use of data- and computer-intensive exploratory modeling. That modeling often takes the form of simulation analysis of different scenarios and assumptions to characterize system behavior and identify situations or thresholds under which the system fails according to selected criteria (Marchau et al., 2019; Shortridge, 2020). Such modeling may involve thousands of repeated model runs to characterize the potential distribution of system responses to alternative futures in which weather, physical drivers, human behavior, strength of system feedbacks, and other characteristics are varied.

As a result of this heavy reliance on complex exploratory modeling, the decision to apply DMDU methods involves tradeoffs. These modeling methods have multiple advantages, including the ability to characterize systems that cannot be adequately evaluated using traditional forms of risk- or benefit-cost analysis, or to identify robust solutions in systems subject to intense stakeholder disagreement. They are also well-suited to systems in which adaptation is required over time, as the ability to adapt is a central feature of DMDU modeling. However, most of these methods are also costly and data-intensive, and results can be complex to interpret. Findings can sometimes exacerbate rather than ameliorate confusion (Shortridge, 2020), although engagement strategies can mitigate such problems. As such—like other complex decision-support tools such as Management Strategy Evaluation (MSE) in fisheries—DMDU methods can be effective and informative in some decision contexts but may not warrant the effort or be appropriate in others.

2. Types of decisions likely to benefit from DMDU application

Decisions on whether to apply DMDU techniques should balance the insight provided by these techniques against the analytic and management costs. Although data availability will limit the application of full-scale DMDU approaches in some cases, qualitative versions of DMDU are available for data-poor situations that make use of conceptual models and expert judgment to explore options and qualitatively assess costs and benefits (e.g., DAP or Assumption Based Planning; Walker et al. 2019). Even when data and models are early in development, DMDU can be beneficial, as revealed by an example study presented to the ESMWG of a potential water infrastructure project. The analysis clarified which aspects of uncertainty were most decision-relevant by demonstrating the higher sensitivity of optimal project choices to *model* uncertainty rather than *future scenario* uncertainty (Shortridge et al., 2017b). That insight allowed decision makers to target the investigations needed to develop more confidence in their project choices. In some cases, the insights from DMDU or partial DMDU techniques can be employed to inform decisions, even when full-scale DMDU is unwarranted or infeasible.

To consider applicability of DMDU techniques to NOAA decision support, the ESWMG considered which of the five key DMDU decision characteristics (listed in section 1.2) were present in illustrative case studies on (1) coastal planning and (2) fisheries management. These areas were chosen because they fall within the purview and expertise of the ESMWG. However, they are only a subset of many areas in which NOAA might apply DMDU approaches. For example, **any program where climate change has a significant role** in management decisions could also potentially benefit from DMDU processes, such as NOAA Arctic programs. Many other NOAA activities, such as coral reef conservation, are also subject to deep uncertainty (e.g., on combined effects of water temperature, ocean acidification, storm events, water pollution) and could potentially benefit from the insight afforded by DMDU methods.

Coastal Planning Projects: Coastal planning is a promising area for the application of DMDU decision tools, since many communities appear to be underinvesting in protection (Lorie et al., 2020), which may reflect the difficulties of making major investment decisions under deep uncertainty. Coastal planning encompasses a wide range of projects, policies, and plans designed to help communities resist and adapt to the effects of sea level rise and changes in storm frequency and/or intensity. Projects include elements constructed to mitigate storm hazards (e.g., sea walls, flood gates) and traditional infrastructure projects (e.g., water supply) to withstand changes over time.

A characteristic of coastal planning is that even when data availability is high, uncertainty (i.e., risks that cannot be quantified) makes the identification of optimal choices difficult. Infrastructure engineers often use PRA to inform project design, and the costlier the investment, the more effort that typically goes towards characterizing conditions and reducing uncertainty. Applying DMDU techniques can help build confidence in a decision among stakeholders and managers by exploring which options generate robust benefits (i.e., low regret), regardless of future outcomes. Further, some elements of DMDU can promote strategic thinking on sequencing of projects over time that can increase cost-effectiveness.

NOAA Fisheries programs: NOAA has multiple decision support processes used to establish fishing quotas, area and season closings, gear restrictions and other management decisions. Those decisions encompass economic and ecosystem goals and are typically supported with quantitative modeling, and are incorporated within fishery management plans, ecosystem-based fisheries management (EBFM), integrated ecosystem assessments (IEA), and Management Strategy Evaluation (MSE). Several of these management and planning efforts already use approaches that incorporate elements similar to DMDU methods (see below). Expanding these approaches to reflect a broader suite of management actions or types of uncertainty could reveal options to enhance benefits, better characterize how model structure may influence results, and minimize unintended consequences.

3. Case studies of DMDU methods

Two case studies were presented to the ESMWG to explore how current planning and decision support might benefit from DMDU techniques.

3.1. Coastal planning

Coastal project design decisions are complex because project performance is vulnerable to changing conditions (adaptation may be required), costs increase rapidly with increasing risk, and underperforming projects may lead to worse outcomes than if the project had not been built (e.g., Tonn et al., 2020). Policy and project outcomes are also contingent upon conditions that are deeply uncertain, including future trajectories of sea-level rise, frequency and intensity of coastal storms, and the amount of development in the coastal zone. Moreover, coastal adaptation is an area in which stakeholders may disagree over probabilities and the benefits of different outcomes.

At the same time, not all coastal planning projects are ideal candidates for DMDU approaches. In some decision contexts, goals are defined narrowly and models are available to characterize future uncertainties with sufficient precision to inform decisions and adaptation, without reliance on DMDU methods.

3.1.1. Illustrative Case Study - Boston Central Artery/Tunnel system, or "The Big Dig""

The ESMWG invited Paul Kirshen from the University of Massachusetts Boston School for the Environment to present an infrastructure risk analysis (using traditional PRA methods) that could be compared to DMDU. The "Big Dig" project is a vital link in the city's transportation network, yet is vulnerable to flooding because major components are below sea level. Sea level rise (SLR) was not considered in the project's original design, and this state-of-the-art risk analysis was conducted to examine options for protecting against SLR and storm surge (Douglas et al., 2016). The extent of flood vulnerability was not known prior to the project and the planning study had dual goals of evaluating the flood risk and the options to ameliorate such risk.

Using traditional PRA and extensive data collection and modeling, the project determined that the current flood vulnerability was low, but by the late 21st century, considerable flooding was likely at tunnel entrances and other structures that contribute to project function, such as ventilation. The modelers used the projected exceedance probability design flood values, and associated time periods when they may occur given SLR scenarios, to suggest when future risk mitigation actions should be made. The team further recommended a modular sea wall at flood entry points that could be lengthened or heightened as risk increased. Costs were modest for interim measures and escalated in time as flood risk increased. Thus, the proposed approach distributed installation and associated costs through time.

This study represents how research investment in projecting risks and identifying flexible risk mitigation solutions made traditional PRA (and benefit-cost analysis) work well in this case. When asked to comment on how this project planning would benefit from a DMDU approach, the expert panel suggested several elements of the project minimized the need for DMDU. The detailed data collection and sophisticated modeling provided bounded projections of risk, removing much uncertainty. The question of 'is this asset really going to flood?' was effectively answered. Also, the solutions were adaptable to higher or lower rates of SLR and adaptation was relatively inexpensive. As a result, it was relatively straightforward to design systems that were largely robust to the uncertainty of future flooding and sea-level rise.

Yet, despite the high quality of the analysis for the Boston tunnel case study, DMDU techniques could still add insight. First, the team did not model potential effects of cascading failures, such as the effect of damage to the regional electrical grid might have on the ability to deploy gates at portals. Second, not all elements of the decision were tested for robustness to uncertainty. For example, Dr. Shortridge commented that if certain types of storms make the temporary measures ineffective (e.g., if you can't get protective measures in place quickly enough), it could be helpful to have additional analyses to identify those conditions and alternative or complementary solutions.

There are coastal planning cases where DMDU techniques could offer more substantial advantages over traditional approaches. As an illustration, a common proposal to build a sea wall of fixed size and height at a flood entry point could be evaluated with a DMDU analysis of the conditions 1) under which the sea wall would fail, 2) whether those outcomes were acceptable to the community, and 3) the cost of engineering options to adapt the sea wall later to faster-than-expected SLR, compared to other flood risk mitigation options. DMDU techniques could also accommodate disagreement among stakeholders over outcomes, probabilities, or goals. Some relevant questions (offered by Dave Groves as examples) could be:

1. How would benefits change w/ different assumptions (SLR, hurricane intensity)?
2. How much more expensive are the adaptations based on the high SLR curve, versus mid or low SLR?
3. Would it save money in the long run to adapt to even higher SLR, if you knew for sure that the high SLR would happen?
4. If you ran the flooding model under many different assumptions, would the same areas be prioritized for protection?
5. Are there risk mitigation options that are more effective at protecting the entire community vs targeted assets?

Insights from this type of DMDU "stress-test" could lead decision makers to modify a choice that was identified as optimal under the "best guess" projections of future events. For example, decision makers might identify a preference for a modular sea wall over a fixed-size sea wall, because it would produce net benefits under all (or most) scenarios of plausible future conditions. In this way, the choice would be deemed more robust to uncertainty because would prevents catastrophic failure or overinvestment.

The adaptive planning aspects of DMDU may, in some cases, expand decision analysis to consider the optimal timing of project choices, not only which management options to take at the current time. Optimizing timing has the ability to increase cost effectiveness by avoiding inefficient investments, if the risk has been mischaracterized. The Boston tunnel example implemented a dynamic adaptive strategy, even without using DMDU. They staged the investments (flood doors, seawall expansions) to be installed as risk increased, rather than deploying the options before they were needed. Thus, DMDU does not necessarily bring completely novel thinking to project planning, but it may increase the likelihood that the most adaptive approaches are systematically considered across all project planning.

3.2 Fisheries Management

Fisheries management is another case in which deep uncertainty complicates management actions, such as setting quotas, area and season closings, and gear restrictions, while also achieving other environmental and ecosystem goals. These decisions are made based on estimates of current and future conditions that are subject to uncertainty and potential stakeholder disagreement (e.g., fish stock assessments and dynamics, climate change impacts, fish stock recovery paths). Data availability to support these decisions varies across fisheries and situations, and many fisheries are data-poor.

Because of these conditions, many NOAA-managed fisheries present situations that could benefit from the insight provided by DMDU techniques. In fact, NOAA currently applies decision support methods that share key attributes of DMDU, primarily Management Strategy Evaluation (MSE). NOAA ecosystem-based fisheries management (EBFM) and Integrated Ecosystem Assessments (IEA) also include aspects of MSE methods that parallel some DMDU approaches.

Fisheries management often takes the form of harvest control rules that are based on multiple goals, including economic, social and ecological objectives, managing sources of uncertainty, and balancing potential tradeoffs between diverse stakeholder groups. The MSE framework “involves assessing the consequences of a range of management strategies or options and presenting the results in a way which lays bare the tradeoffs in performance across a range of management objectives” (Smith, 1994). MSE models performance of alternative management actions virtually, before implementation in the field (Figure 2). Some situations facing NOAA fisheries management that are amenable to MSE include: 1) how directly harvesting forage fish affects other fisheries that rely on the forage fish, 2) how actions designed for protected species affect harvested species and can constrain management options, and 3) how climate change affects food webs that support multispecies fisheries with commercial and recreational user groups.

Given goals of MSE and similar management efforts, NOAA could investigate how DMDU may enhance existing MSE and related approaches rather than develop a set of entirely novel DMDU tools. The benefits of applying hybrid MSE-DMDU techniques will depend on factors such as the value of the fishery (whether it justifies the cost of DMDU methods), the availability of minimum data necessary to support DMDU techniques, and the degree and types of uncertainty that are relevant to management. An additional concern for both MSE and DMDU approaches is whether including multiple future scenarios could complicate communications with stakeholders.

3.2.1. Illustrative Case Study – MSE compared to DMDU

Dr. Sarah Gaichas of NOAA Fisheries presented an example MSE that designed a harvest control rule (HCR) for Atlantic herring in the Gulf of Maine, Georges Bank. The case study was developed in response to stakeholder concerns that management of this fishery did not balance commercial fishing benefits with benefits to other fisheries or the ecosystem. A major constraint on modeling was that results had to be produced within the management time frame of one year. This limitation drove development of models of intermediate complexity that used selected species (primarily common tern - *Sterna hirundo*, Bluefin tuna - *Thunnus thynnus*, and spiny dogfish - *Squalus acanthias*) to represent stakeholder concerns for a range of herring predators.

Six broad HCR categories (with 1000s of options) were analyzed, and of the more than 60 distinct model parameters, three were chosen for uncertainty analysis using input from stakeholders and prior analyses 1) herring productivity (a function of mortality and steepness), 2) herring growth rate, and 3) stock assessment bias. Values used in the uncertainty analyses were based on data used in recent stock assessments or estimates from stock assessment models. The management focus was on performance of harvest rules under current environmental conditions and did not use potential scenarios to examine future variability. Limits of this type are common within MSEs, as they must balance tractability with a capacity to provide relevant information to inform decisions.

An iterative process between modelers, managers, and stakeholders evaluated HCRs that achieved the Fishery Management Council-specified management goals and that were robust to the types of uncertainty being modeled. Goals were to maintain high fishery yield and herring biomass while avoiding fishery closures and negative impacts to predator (represented by tern) productivity. Multiple

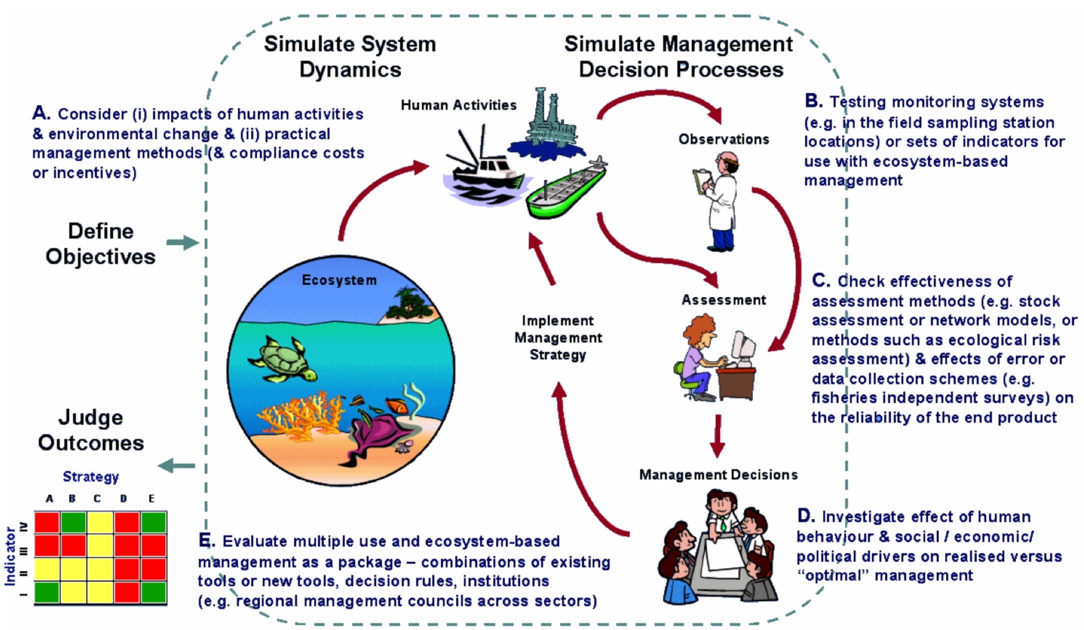
HCR options achieved these objectives and the major tradeoff was between the stability of herring fishery yields and median net revenues. Although all goals were met with the HCR chosen, the modelers suggested that the 15% restriction on interannual change in catch (present in 3 of 6 HCRs) may have limited the ability to "strike a more agreeable trade-off between stability and other metrics of interest" (Deroba et al. 2018).

When asked what DMDU might add to an analysis of this type, the invited experts noted that MSE shared many elements with DMDU in terms of stakeholder engagement in decision making, using models to test variable uncertainty, and examining tradeoffs among management objectives. They suggested that DMDU techniques could help with "adjudicating uncertainty," meaning that how uncertainty was incorporated in the analysis could be more thorough, transparent and participatory. One could also evaluate the robustness of the chosen HCR to additional sources of uncertainty that were not considered. Under the current MSE modeling approach, adding additional uncertain variables tends to move the HCRs to be more precautionary, but alternative methods of evaluating uncertainty could generate different results. The experts further suggested that continuous rather than sequential stakeholder engagement could alter how management options are developed, and reveal novel management alternatives by promoting compromise solutions.

The ESMWG discussion revealed other opportunities to potentially enhance fisheries management by expanding MSE with DMDU methods. Because there is substantial overlap between MSE and DMDU approaches, the differences are often nuanced. However, in general, the differences are:

1. MSE is oriented around the results of prescribed management actions, whereas DMDU promotes evaluation across a broader range of beneficial options, sometimes using optimization or other approaches to identify alternative solutions.
2. MSE emphasizes the management and ecological performance of alternative actions under the most likely outcomes, whereas DMDU emphasizes identifying possible pitfalls and conditions (even if rare) that would cause poor performance or failure of the actions.
3. MSE often tests uncertainty for a limited range of variables, whereas some DMDU techniques promote testing a broad range of variables and even alternative model structures to reflect different, and even unlikely, concepts about how the ecosystem operates.
4. MSE evaluates performance based on a limited subset of quantitative outcomes because the actions are designed primarily for informing harvest policy. DMDU permits many outcomes to be considered because there is a broad view of performance that may include many stakeholder interests.

Expanding MSE to encompass DMDU approaches more fully would not involve starting from zero, but nonetheless could involve substantial effort. Given the level of development of some MSE efforts, the basic tools and information needed for DMDU could be leveraged with moderate additional effort. However, the component models of MSE may require significant modifications to adequately incorporate some aspects of DMDU. For example, broadening the food web analysis to represent additional species or groups (to accommodate rare but impactful events), or expanding the models to include additional ecosystem services than fisheries, would require more complex models, which are available in some, but not all, NOAA regions. A caution is that expanding or modifying the scope of models could add substantial model uncertainty. Also, attempting to use an MSE for both MSE objectives and DMDU exploration has the potential to complicate the communication of the results to target audiences and stakeholders.



Source: CSIRO, Australia

Figure 2. Depiction of a typical MSE analysis showing the major steps.
Source: http://www.cmar.csiro.au/research/mse

4. Potential barriers to adoption in any NOAA activity

1. **Limited data or resources.** DMDU requires sufficient time and resources to develop a decision process that engages stakeholders and explores diverse (but not necessarily numerous) future scenarios. In some cases, an exploration of deep uncertainty would be useful, but data or models will be insufficient for many types of DMDU such as Robust Decision Making (Lempert, 2019), in which coupled quantitative models are used to explore management choices under different conditions. In this situation, qualitative DMDU approaches might be applied.
2. **NOAA must often make decisions within a constrained management time frame.** DMDU can be difficult to apply quickly, given the need to engage stakeholders, gather data and develop models that reflect a potentially broad array of goals and uncertainties. As described above in the MSE case study, management decisions must often be made within a constrained time frame, during which it may be difficult to develop a full DMDU analysis.
3. **Adapting decisions or models to new conditions or dimensions of the problem can be difficult**, **particularly from a management perspective.** DMDU generally promotes ongoing decision making and adaptation as more data or information becomes available. Such updating of the analysis and choices requires a process for re-evaluation that may be difficult when numerous stakeholders are involved.
4. **DMDU approaches will not be appropriate for all decisions characterized by deep uncertainty.** Analysts will need guidance about when to apply these techniques in order to avoid wasting

resources on lengthy analyses that will not fundamentally change decisions, or that are not well suited to the decision at hand. For example, in some cases a decision may be subject to deep uncertainty of various types, but in all foreseeable futures, the benefits of a decision outweigh the costs. In such cases, DMDU techniques may be unnecessary.

5. **DMDU methods and the community of practice across NOAA are not currently wide enough for a rapid roll-out of DMDU modeling.** The methods are complex and will need to be adapted to different types of decision processes. Adoption of DMDU is more involved than installing and distributing software. It is an approach and concept that will require training and development programs, seminars, work sessions, and broad discussion about DMDU across line offices and programs.

5. Conclusions

DMDU is not a single model or approach to inform decisions, but rather a set of tools and analytic techniques that share key characteristics. The suite of tools is broad and incorporates multiple decision science elements involving structured stakeholder engagement, probabilistic risk assessment, scenario analysis, optimization modeling, and benefit cost analysis. **What distinguishes DMDU from other approaches is that it places a priority on evaluating the ways that a decision may fail, in order to avoid unanticipated outcomes and inefficient investments.** While DMDU does not bring completely novel thinking to project planning, the development and use of systematic decision science approaches for complex decisions may increase the likelihood that management choices will be robust to uncertainty and that adaptive solutions are considered in a deliberative manner.

Among the primary benefits of DMDU is the provision of guidance on how to incorporate sources of uncertainty that may be ignored or oversimplified in typical probabilistic risk assessment because they cannot be adequately quantified. DMDU offers “systematic sharable reasoning” to reveal the implications of uncertainty for achieving project goals and can augment traditional analyses by providing a framework to consider the effects of “unknown unknowns.” However, the quality of the approach depends on the analytic team’s willingness to systematically explore numerous sources of uncertainty, including uncertainty of model structure and extreme outcomes for some system drivers. DMDU approaches are not “plug and play” and require careful development for each application.

The conditions under which DMDU approaches are likely to add value to existing decision processes depend on the decision context. The most thorough approaches of DMDU involve substantial investments in time and analytic resources that may be most useful when decisions have high impact, stakeholders have divergent goals, and the potential for decision regret is high. Some tools, such as robust decision making (RDM), may only be practical where substantial modeling and data resources exist. Other tools, such as dynamic adaptive planning, are amenable to data poor or resource-constrained situations because they can be conducted by using expert elicitation to coarsely estimate direction and magnitude of effects. Such analyses can be sufficient to inform some types of interim actions, including choosing what additional data to collect before selecting a long-term solution. In other cases, selected components of a DMDU technique might be applied—such as particular types of exploratory modeling or structured scenario planning—when full-scale DMDU techniques are unwarranted or infeasible. DMDU is not an “all or nothing” set of approaches, and can provide considerable insight even when comprehensive, full-scale approaches cannot be applied.

NOAA is already using techniques that include some characteristics of DMDU (e.g., fisheries MSE). However, expanding the application of systematic approaches to deep uncertainty analysis could provide benefits, even in these cases. Those benefits could include improved understanding of the potential range of future ecosystem change, reduced chances of being surprised by system behavior, and reduced potential for unintended consequences of management actions.

6. Recommendations

NOAA could potentially benefit from the targeted application of DMDU approaches to inform decisions in areas such as fisheries and coastal planning, where decisions are sensitive to deeply uncertain future conditions such as climate change impacts. However, the ultimate decision to pursue such approaches should come from those with a deep understanding of NOAA's missions, constraints and internal operations. DMDU has potential value to inform a subset of NOAA decisions, but is not applicable everywhere and does not remove all challenges of decision making under uncertainty. Should NOAA choose to pursue this approach for specific applications, additional study will be required to evaluate precisely where and how it could be most usefully applied.

We have identified opportunities for applying techniques to gain confidence in decisions but also constraints on application, including communication challenges, legal concerns, and potential delays in decision making. Potentially promising applications of DMDU insights and techniques include (but are not necessarily limited to) the following:

1. **Include elements of DMDU where risk-based planning is already used.** These applications might involve comprehensive, full-scale DMDU approaches or simply the incorporation of individual DMDU elements or insights. The goal would be to better represent the implications of uncertainty on decisions. For example:
    a. Decisions based on probabilistic risk assessment could be "stress-tested" for their potential to be (un)successful under alternative future scenarios. This approach differs from sensitivity analysis in that it captures events that cannot be characterized with probability distributions and uses scenarios to explore unlikely but still plausible outcomes.
    b. In the case of MSE - Systematically and transparently explore aspects of system dynamics and alternative policies that would not typically be conducted. MSE test cases could be explored, allowing analysts and managers to visualize the effort involved and viable strategies for adapting selected MSEs to explore DMDU approaches. Test cases would allow for an assessment of the potential "added value" provided by using more complete DMDU approaches.
    c. DMDU could also be incorporated into existing EBFM and IEA analytical approaches that are not MSE. However, the appropriateness and ease of using DMDU in these settings will depend on the specifics of the analyses and any decision constraints, such as short decision time frames, existing policies, and legal authorities.
2. **Explore potential applications of DMDU to inform coastal planning programs and activities**
    a. Outside of NOAA, DMDU has informed many coastal planning projects, suggesting the potential utility of these techniques within this setting. For example, DMDU could offer

value for developing robust coastal infrastructure solutions, particularly when proposed investments are costly and cannot be easily adapted once installed.

3. **Apply DMDU to design monitoring programs.** DMDU can be used to:
    a. Prioritize additional data collection by identifying decision-relevant uncertainty, which are the data gaps that are likely to change decisions.
    b. Prioritize monitoring of phenomena that are much more likely to change in unpredictable ways and seek to identify early warning signs of change.
    c. Consider how NOAA might make use of DMDU insights into the optimal sequencing of risk mitigation actions. Dynamic adaptive planning (DAP) is used to evaluate optimal interim decisions, including whether investments can be delayed, while awaiting new information that better constrains future conditions.
4. **Develop guidelines and data to enable systematic scenario development** to represent major sources of uncertainty across NOAA activities.
    a. Methods for developing a parsimonious set of scenarios by representing all major drivers of change (and their potential range) and avoiding including scenarios with distinct drivers but similar potential outcomes.
    b. Make use of the variability represented in climate change scenarios by making data more accessible.
5. **Consider whether there are other promising areas of DMDU application within NOAA that have not been explored thoroughly within this report.**
    a. This report has examined a few key areas in which DMDU techniques are likely to have high value and applicability. However, these techniques are likely to have value in applications beyond these examples. As two examples, policies on habitat restoration and aquaculture can be subject to deep uncertainty due to influences such as climate and ocean acidification.

7. Suggested next steps for NOAA

If NOAA has sufficient interest in DMDU, we suggest the following steps:

1. Initiate broader discussion of DMDU approaches within NOAA so that subject matter experts can consider its possible application to their programs to understand potential benefits and risks to using these techniques. Examples of potential activities might include:
    - OneNOAA Science Seminar series on DMDU.
    - Present to coastal resilience and environmental intelligence teams of the Interagency Arctic Research Policy Committee.
    - Brief new NOAA Climate and Fisheries Initiative team for possible use.
    - Brief relevant National Academy of Sciences boards regarding new research/potential use: Ocean Studies Board, Gulf Research Program, etc.
    - As relevant, initiate internal studies within the Line Offices to explore whether and how DMDU techniques might be applied.
2. Study the potential use of DMDU more thoroughly.
    - Identify what further research is needed to develop guidance on when and how to apply DMDU specifically for NOAA-relevant problems.

- Identify potential NOAA and NSF projects and funding opportunities that could further advance the DMDU knowledge base.
- Consider follow-up studies by the SAB to evaluate potential applications of DMDU within particular NOAA program areas in greater depth.

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Appendix A. Workshop Agenda

Spring 2020 Workshop Agenda

Decision Making under Deep Uncertainty (DMDU)
What is it? How might NOAA use it?

NOAA Ecosystem Sciences and Management Working Group

Day 1, July 15

Day 2, July 16

Pre-meeting prep – To minimize the meeting length, we ask all participants to watch two short pre-recorded talks on Deep Uncertainty prior to the meeting. They provide background on analytic approaches and use case studies to demonstrate the potential to support decisions. Familiarity with these presentations will enhance the progress that we can make in this relatively short workshop. The two (~20-minute) presentations and selected readings on the presentations are HERE.

Wednesday July 15, 2020 (All times are Eastern)	**Day 1 – Coastal Resilience Topic** *Agenda Items*	***Who***
1:50 Begin call-in	*All participants are asked to call in 10 minutes early to resolve any connection issues.*	
2:00 PM	**Call meeting to order** Consent to record meeting Introductions of participants Meeting format for the next 2 days	Mike Castellini and Rob Johnston
2:15 PM	**Goals of the Report on Decision Making under Deep Uncertainty** Meeting and report goals	Lisa Wainger
2:20 PM	**Q and A with the DMDU experts** Clarifying questions about the pre-recorded presentations	Julie Shortridge, Virginia Tech David Groves, Rand Corporation
2:35 PM	**Presentation** **Managing uncertainty in coastal infrastructure planning:** Case study of Boston Central Artery/Tunnel System	Paul Kirshen, University of Massachusetts Boston
3:00 PM	**Break**	
3:10 PM	**Discussant comments & discussion** • How might a "deep uncertainty approach" to the problem be different from (or similar to) the approach presented above? • What are the opportunities for NOAA to use decision making under deep uncertainty for resilience planning? • What are the barriers? • What are the primary differences between deep uncertainty approaches and what is being done now?	Julie Shortridge David Groves
3:30 PM	**Group Discussion** • What are the opportunities and barriers to using DMDU? • Which types of coastal resilience decisions can benefit from this level of support? • What are the existing and future model and information needs that support DMDU approaches?	Lisa Wainger facilitates

4:30 PM	**DMDU Subcommittee Discussion** How does today's discussion inform the report?	Lisa, Rob, Mike, Molly, Kenny, Jan, Robert + any other interested party
5:00 PM	**Adjourn for the Day**	

Thursday **July 16, 2020**	**Day 2 – Fisheries Topic** *Agenda Item*	***Who***
1:50 PM	Please log in early.	
2:00 PM	**Introduction of the Format for Day 2**	Lisa Wainger
2:15 PM	**Presentation** **Uncertainty in management strategy evaluation (MSE):** Case study of the Herring MSE for the New England Fishery Management Council	Sarah Gaichas, Ecosystem Dynamics and Assessment Branch, NOAA NMFS
2:40 PM	**Comments & discussion** • How might a "deep uncertainty approach" to the problem be different from (or similar to) the approach presented above? • What are the opportunities for NOAA to use decision making under deep uncertainty for fisheries? • What are the barriers? • What are the primary differences between deep uncertainty approaches and what is being done now?	David Groves Julie Shortridge
3:00 PM	**Break**	
3:10 PM	**Group Discussion** • What are the opportunities and barriers to using DMDU? • Which types of coastal resilience decisions can benefit from this level of support? • What are the existing and future model and information needs that support DMDU approaches?	Lisa Wainger facilitating
4:10 PM	**DMDU Subcommittee Discussion** How does today's discussion inform the report?	Lisa, Rob, Mike, Molly, Kenny, Jan, Robert + any other interested party
4:45 PM	**Review of Meeting and Next Steps**	Co-chairs and SAB Staff
5:00 PM	**Adjourn**	