DMDU

The Society for Decision Making under Deep Uncertainty

Annual Meeting 2026
Conference Program

With Support From:

LIEUTENANT GOVERNOR
BILLY NUNGESSER

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Attendee Information

Getting Around Use our interactive Google Map to navigate between accommodations, the venue, and other key locations throughout Baton Rouge. Click here to access the map.

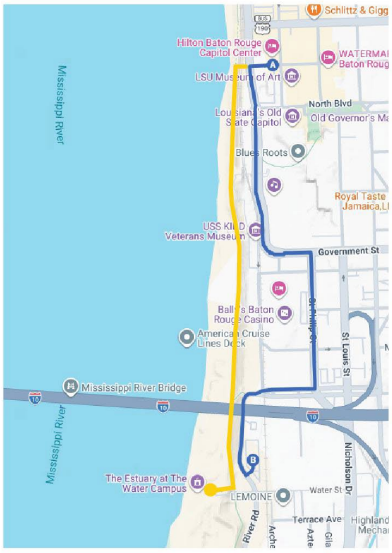
Driving Directions from the Hilton From the Hilton, head south on Lafayette Street toward Convention Street. Turn right onto Convention Street, then left onto River Road. Continue south following River Road beneath the Mississippi River Bridge toward The Water Campus. Continue south following River Road beneath the Mississippi River Bridge toward The Water Campus. As you approach The Estuary, the parking lot will be on your left, directly across River Road from the venue's ramp. Allow 10–15 minutes for driving and parking. Travel times may vary depending on downtown traffic.

Walking Directions from the Hilton Attendees staying at the Hilton Baton Rouge Capitol Center can reach The Estuary on foot. From the hotel, head south toward the riverfront and follow the riverfront route toward The Water Campus. Continue toward the Mississippi River Bridge and The Estuary at 1110 S. River Road. The venue is approximately 1.6 km (1 mile) from the hotel, along the Mississippi River. Allow approximately 20–25 minutes for the walk.

Parking Attendees arriving by car should use the parking lot along River Road, directly across from The Estuary. Follow the signs for The Water Campus and use caution when crossing River Road to reach the venue entrance. Parking is free.

Walking Directions
A short walk from the Hilton, attendees can follow the Mississippi River Levee Trail to the Estuary at The Water Campus.

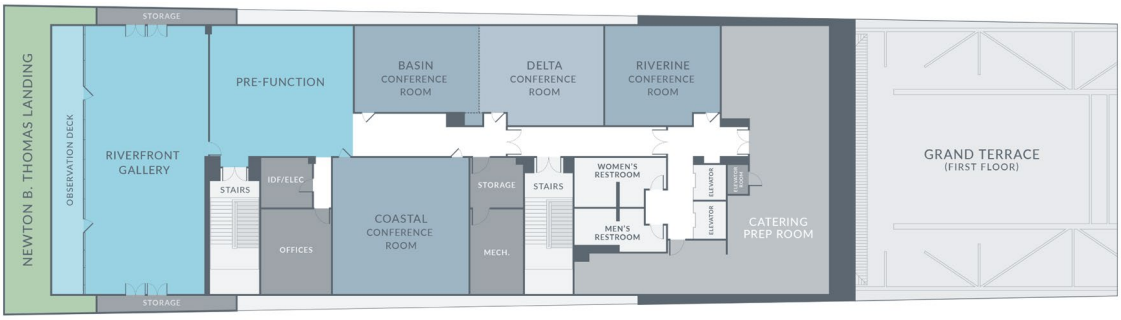
Driving Directions
A 10 to 15 minute drive from the Hilton, attendees can travel to the Estuary at The Water Campus and park in the River Road lot.



Free Parking is Available
Attendees arriving by car should use the parking lot along River Road, directly across from The Estuary. Follow the signs for The Water Campus and use caution when crossing River Road.



Venue Map & Room Layout
All conference programming will take place in the 3rd floor of The Estuary.



Monday, November 9 — Training Day

8:30 AM | Registration
Location: First Floor Lobby

9:00 AM | Coffee and Networking
Location: Coastal Conference Room

9:30 AM | Training Day Plenary — Steven Popper
Location: Riverfront Gallery

Details: Introduction by Edmundo Molina (Tecnológico de Monterrey), followed by a question-and-answer session.

10:45 AM | Short Break
Location: Coastal Conference Room

11:00 AM | DMDU Case Studies Panel
Location: Riverfront Gallery

Details: Chaired by Jordan Fischbach (The Water Institute). Panelists: Jan Kwakkel (TU Delft), Nathan Bonham (Bureau of Reclamation), Renee Collini (The Water Institute).

12:00 PM | Lunch and Social Hour
Location: Coastal Conference Room

1:00 PM | Building DMDU Thinking / DMDU Beyond Data Analysis
Location: Riverfront Gallery

Details: Moderator: Colleen McHugh (The Water Institute). Panelists: Nastaran Tebyanian (The Water Institute), Henry Graumlich (Calleguas Municipal Water District), Ali Rellinger (PLACE/Mississippi State University), Lynée Turek-Hankins (Dartmouth College).

2:10 PM | Technical Breakouts — Part 1

Basin Conference Room	Delta Conference Room	Riverine Conference Room
Methods Track — Part 1 **Robust Decision Making** Presenters: Rob Lempert (RAND)	**Thinking and Planning with DMDU — Part 1** **Decision Framing and Problem Framing** Presenters: Jessica Henkel (The Water Institute), Nastaran Tebyanian (The Water Institute)	**Tools Track — Part 1** **Colorado River Basin DMDU Explorer Tool** Presenters: Nathan Bonham (Bureau of Reclamation, Lower Colorado Region) **EMA Workbench** Jan Kwakkel (TU Delft)

3:10 PM | Break — Coastal Conference Room

3:30 PM | Technical Breakouts — Part 2

Basin Conference Room	Delta Conference Room	Riverine Conference Room
Methods Track — Part 2 **SiSePuede Model Overview** Presenters: James Syme (Tecnológico de Monterrey) **Vulnerability Analysis and Scenario Discovery** Presenters: Edmundo Molina (Tecnológico de Monterrey)	**Thinking and Planning with DMDU — Part 2** **Articulating and Communicating DMDU Value** Presenters: Colleen McHugh (The Water Institute), Patrick Kane (The Water Institute)	**Tools Track — Part 2** **Extreme-scale Model Exploration with Swift** Presenters: Jonathan Ozik (Argonne National Laboratory)

4:30 PM | Training Day Closing

Location: Riverfront Gallery

Details: Closing remarks by Edmundo Molina (Tecnológico de Monterrey).

Tuesday, November 10

8:30–9:00 AM | Continental Breakfast and Networking

Location: Coastal Conference Room

9:00–10:00 AM | Opening Keynote: The Honorable Mary Landrieu - Webinar Link

Location: Riverfront Gallery

10:00–11:30 AM | Concurrent Sessions 1–3

Basin Conference Room	**Session 1: Foundational Methods & Emulation Tools - Webinar Link** Chair: Lillian Lau (Cornell University) **Metamodeling for Optimization--a Comparative Analysis** Presenter: James Syme (Tecnológico de Monterrey) **Hacking Adaptation – Using Policy Hackathons in Adaptation Planning** Presenter: Sadie McEvoy (Deltares) **A Robust Decision Making-Multi-Dimensional Dynamic Adaptive Pathway Approach to Manage Geo-Economic Uncertainty in a Range of Possible Futures** Presenter: Mark Workman (Foresight Transitions Limited) **Neural Simulation-Based Inference for DMDU** Presenter: Pedro Nascimento de Lima
Delta Conference Room	**Session 2: How Can DMDU Help Reform the Regulatory State? - Webinar Link** Chair: Rob Lempert (RAND)

	Panelists: Rob Lempert (RAND), Christopher Nelson (California Polytechnic State University, SLO; RAND), Steve Neugeboren (US EPA (ret))
Riverine Conference Room	**Session 3: Practicing DMDU in Different Institutional Contexts - Webinar Link** Chair: Casey Helgeson (Penn State University) Panelists: Casey Helgeson (Penn State University) & Nastaran Tebyanian (The Water Institute)

11:30 AM–12:30 PM | Lunch

Location: Coastal Conference Room

12:30–2:00 PM | Concurrent Sessions 4–6

Basin Conference Room	**Session 4: DMDU & Democratic/Governance Processes - Webinar Link** Chair: Allison DeJong (The Water Institute) **DMDU and Citizen Assemblies: A post-fire case study from Pacific Palisades, California** Presenter: Rob Lempert (RAND) **Vulnerability Analysis for Redistricting: Characterizing Maps Using Uncertain Community Splits** Presenter: James Syme (Tecnológico de Monterrey) **Negotiating Management Alternatives under Uncertain Future Conditions using a Self-Organizing Map Framework** Presenter: Joseph Kasprzyk (University of Colorado Boulder) **Constraint, Conflict, and Change: 3Cs Determining Societal Development under Deep Uncertainty** Presenter: Richard Silberglitt (RAND - Retired)
Delta Conference Room	**Session 5: Coastal Adaptation and Retreat - Webinar Link** Chair: Renee Collini (The Water Institute) **The Barrier Island Restoration Tradeoff Analysis Toolkit: A Python Library for DMDU in Sediment Management** Presenters: Patrick Kane (The Water Institute), Nastaran Tebyanian (The Water Institute), Diana Di Leonardo (The Water Institute), Soupy Dalyander (The Water Institute), Travis Swanson (The Water Institute)
Riverine Conference Room	**Session 6: Institutional Practice & Policy Translation - Webinar Link** Chair: Colleen McHugh (The Water Institute) **Uniting siloed disciplines to advance decision support systems for climate risk management** Presenter: Lynée Turek-Hankins (Dartmouth College) **Lost (and Found!) in Translation: Overcoming Barriers to DMDU for Non-**

	Specialist Policymakers Presenter: Henry Graumlich (Calleguas Municipal Water District) **Participatory Engagement for Critical Mineral Community Decision-Making** Presenter: Selena Gerace (University of Wyoming) **The Challenges and Opportunities for DMDU Applications in the Mining Sector** Presenter: Christopher Dacey (Hydroture)

2:00–2:30 PM | Afternoon Break

Location: Coastal Conference Room

2:30–3:00 PM | Group Photo

Location: Dock Steps

3:00–4:30 PM | Concurrent Sessions 7–9

Basin Conference Room	**Session 7: Adaptive Pathways** - **Webinar Link** Chair: Nastaran Tebyanian (The Water Institute) **Institutionalizing Early-Warning Signals in Dutch Delta Governance** Presenter: Arthur Petersen (University College London) **Developing Dynamic Adaptation Pathways for Compound Flooding in Jackson County, Mississippi** Presenter: David Rounce (Carnegie Mellon University) **Evaluating the Explainability and Updateability of Climate Adaptation Roadmaps under Deep Uncertainty** Presenter: Takuya Nakashima (The University of Tokyo) **Extending Adaptation Pathways with Backcasting: Identifying Pivotal Decisions through a Dual Approach with DAPP-Δ** Presenter: Renske de Winter (Deltares)
Delta Conference Room	**Session 8: DMDU Methods Advances in the Health Decision Sciences** - **Webinar Link** Chair: Jonathan Ozik (Argonne National Laboratory) Panelists: Javier Rojas Aguilera (RAND School of Public Policy), Thomas Trikalinos (Brown University), Arindam Fadikar (Argonne National Laboratory), Jonathon Ozik (Argonne National Laboratory)
Riverine Conference Room	**Session 9: Water Resources & Reservoir Operations** - **Webinar Link** Chair: Jordan Fischbach (The Water Institute) **Applying DMDU in a Formal Public Decision-Making Process: the Colorado River Basin Long-Term Planning Experience** Presenter: Rebecca Smith (US Bureau of Reclamation) **Adapting DMDU Techniques to Analyze Many Diverse Resources in a Colorado**

	River Basin Long-Term Planning Process Presenter: Nathan Bonham (US Bureau of Reclamation) **Distributive, Procedural, and Corrective Justice in Affordable Water Supply Planning under Uncertainty** Presenter: Sarah Fletcher (Stanford University)

4:30–6:00 PM | On Your Own
Location: The Water Institute Offices (2nd Floor), The Dock, your hotel, or time outside

6:00–8:00 PM | Evening Reception
Location: LSU Center for River Studies

Wednesday, November 11

8:30–9:00 AM | Continental Breakfast and Networking
Location: Coastal Conference Room

9:00–10:00 AM | Morning Plenary: AI and DMDU - Webinar Link
Location: Riverfront Gallery

Details: Chaired by Nidhi Kalra (RAND) and David Groves (World Bank Group)

10:00–11:30 AM | Concurrent Sessions 10–12

Basin Conference Room	**Session 10: DMDU in Health & Social Policy - Webinar Link** Chair: Edmundo Molina (Tecnológico de Monterrey) **Dynamic Adaptive Decision Support in Healthcare: Bridging Science and Practice through Multi-Case Learning in Hospital Settings** Presenter: Anke Aarninkhof - Kamphuis (University of Twente) **Scenario Discovery in a Foresight Study on Sport and Physical Activity** Presenter: Guus Luijben (Dutch National Institute for Public Health and the Environment (RIVM))
Delta Conference Room	**Session 11: Enhancing DMDU with AI - Webinar Link** Chair: Dr. David Groves (World Bank Group) **AI-Augmented Policy Red Teaming for Decision-Making Under Deep Uncertainty** Presenter: Jaakko Kuosmanen (Finnish Academy of Science and Letters) **Surrogates and Chatbots: Natural Language Interaction and Surrogate Modeling as a Vehicle to Enable Engagement With DMDU Analyses** Presenter: James Syme (Tecnológico de Monterrey) **Can a Structured LLM Do Assumption-Based Planning? Validating an AI-Enabled DMDU Tool**

	Presenter: Nidhi Kalra (RAND)
Riverine Conference Room	**Session 12: Defense, Deterrence & Strategic Competition - Webinar Link** Chair: Diana Di Leonardo (The Water Institute) **A Geospatial Framework for Estimating SSBN Force Structure Across Deeply Uncertain Strategic Futures** Presenter: Kurt Klein (RAND) **Modelling Adaptive Drug Trafficking Networks** Presenter: Coen van den Elshout (Delft University of Technology) **An RDM-based Approach to Simulating Competition Under Deep Uncertainty** Presenter: David Kong (RAND School of Public Policy)

11:30 AM–12:30 PM | Lunch

Location: Coastal Conference Room

12:30–2:00 PM | Concurrent Sessions 13–15

Basin Conference Room	**Session 13: Foundational Methods & Emulation Tools (Part 1) - Webinar Link** Chair: Nastaran Tebyanian (The Water Institute) **Integrating SuPy into Exploratory Modelling for Urban Climate Adaptation: A Proof-of-Concept Application** Presenter: Simona Mannucci (Sapienza University of Rome) **Conditional Protection Matrices for Decision Making Under Partial Information** Presenter: Kurt Klein (RAND) **Sneaking Deep Uncertainty into Transportation Planning: The Boston MPO Growth Rate Explorer** Presenter: Martin Milkovits (Boston Region MPO) **Integrating Foresight Methods to Enable Robust Planning Under Deep Uncertainty** Presenter: Richard Silberglitt (RAND - Retired)
Delta Conference Room	**Session 14: Bridging Practice, Education & Capacity Building - Webinar Link** Chair: Steven Popper (Tecnológico de Monterrey) **DMDU with hundreds of decision makers: how DMDU principles and approaches can support climate adaptation in the farming and forestry industries** Presenter: Julie Shortridge (Virginia Tech) **Advancing DMDU Education: Moving to the Next Stage** Panelists: Steven Popper (Tecnológico de Monterrey), Rob Lempert (RAND), Edmundo Molina (Tecnológico de Monterrey)

Riverine Conference Room	**Session 15: Coastal Adaptation and Retreat** - **Webinar Link** Chair: Alyssa Dausman (The Water Institute) **Coastal Adaptation Under Uncertainty: A Participatory MCDM Analysis of Coastal Squeeze Solutions** Presenter: Anamaria Bukvic (Indiana University Bloomington) **Considering retreat can be crucial to identify robust adaptation strategies in nourishment-dependent coastal communities** Presenter: Prabhat Hegde (Princeton University) **Multi-Objective Optimization in the 2029 Louisiana Coastal Master Plan** Presenter: Patrick Kane (The Water Institute) **A Framework for Optimizing Green-Grey Infrastructure Selection** Presenter: Paul Lagarde (ERDC)

2:00–2:30 PM | Afternoon Break

Location: Coastal Conference Room

2:30–4:00 PM | Concurrent Sessions 16–18

Basin Conference Room	**Session 16: Water Resources & Reservoir Operations** - **Webinar Link** Chair: Joseph Kasprzyk (University of Colorado) **Bayesian-Belief Direct Policy Search for Adaptive Water Supply Planning with Endogenous Learning** Presenter: Mofan Zhang (Stanford University) **Leveraging evolutionary multi-objective reinforcement learning and sensitivity analysis to better navigate implementation uncertainty in cooperative water supply investment pathways** Presenter: Lillian Lau (Cornell University) **Continuous Adaptation of Reservoir Control Policies via Bayesian Updating Across a Climate Exposure Space** Presenter: Marta Zaniolo (Duke University) **Quantifying Explanation Uncertainty in XAI Emulators for Water Shortage Attribution in the Western U.S.** Presenter: Yifan Luo (Cornell University)
Delta Conference Room	**Session 17: Developing Priority Research Questions for DMDU in Insurance** - **Webinar Link** Panelists: Allison DeJong (The Water Institute), Rob Lempert (RAND), Adam Pollack (University of Iowa)
Riverine Conference Room	**Session 18: Grid & Electric Infrastructure Resilience** - **Webinar Link** Chair: James Syme (Tecnológico de Monterrey)

	When the Model Is Also Uncertain: DMDU for AI-Driven Grid Planning Presenter: Ruobing Wang (RAND School of Public Policy) **Robust Substation Upgrade Strategies for Electric Heavy-Duty Truck Charging Under Deep Adoption Uncertainty** Presenter: Fletcher Passow (Stanford University) **Protecting the Bulk Electric System From Geomagnetically Induced Currents: A Robust Decision Making Approach** Presenters: Kurt Klein (RAND)

4:00–5:30 PM | Poster Session, Networking Mixer and Awards Presentation

Location: Riverfront Gallery, Prefunction and Basin Conference Room

Thursday, November 12

8:30–9:00 AM | Continental Breakfast and Networking

Location: Coastal Conference Room

9:00–10:00 AM | Decision-Maker Plenary - Webinar Link

Location: Riverfront Gallery

Details: Chaired by Jordan Fischbach (The Water Institute). Panelists: Alyssa Dausman (The Water Institute), Katie Freer-Leonards (CPRA), Darin Lee (CPRA), Eric White (CPRA).

10:00–11:30 AM | Concurrent Sessions 19–21

Basin Conference Room	**Session 19: Polycrisis, Geopolitics & Compound Risk - Webinar Link** Chair: Edmundo Molina (Tecnológico de Monterrey) **Anticipatory Closure under Polycrisis? Reflections from a Disaggregative Delphi on Environmental-Geopolitical Uncertainty in the Gulf of Finland** Presenter: Aleksi Neuvonen (Demos Helsinki) **Stress-Testing National Climate Targets: A 136 Country Scenario Discovery Assessment of NDC Feasibility and Failure Regions** Presenter: Edmundo Molina (Tecnológico de Monterrey) **Robust Policy Design for Coupled Crises: A Multi-Objective Analysis of the Climate–Inequality–Radicalization Polycrisis** Presenter: Javier Rojas (RAND School of Public Policy) **From Theory to Practice: A Review of Robust Decision Making in Real-World Contexts** Presenter: Alexandra Bilder (RAND)
Delta Conference Room	**Session 20: What Is "Effective" Adaptation? - Webinar Link** Chair: Renee Collini (The Water Institute)

	What is "Effective" Adaptation? Sharing knowledge and practice on evaluating Climate Adaptation Under Deep Uncertainty Panelists: Sadie McEvoy (Deltares), Ali Rellinger (Mississippi State University), Qiyamah Williams (Mississippi State University), Jessica Henkel (The Water Institute)
Riverine Conference Room	**Session 21: Robust Climate Decisions Under Deep Uncertainty: Advancing IAMs for Decision Support - Webinar Link** Chair: Nidhi Kalra (RAND) **Local siting decisions under uncertainty shape the health benefits of deep decarbonization** Presenter: Jinyu Shiwang (Princeton University) **Aggregating Global Change Scenario Ensembles through Robustness Metrics** Presenter: Gi Joo Kim (Tulane University) **Normative Uncertainty Dominates Climate Mitigation Decisions and Disproportionately Affects Least Developed Regions** Presenters: Jan Kwakkel (Delft University of Technology) **Uncertainty decomposition in a coupled IAM–ABM: the interplay of social, economic, and climate dimensions of feasibility** Presenters: Giacomo Marangoni (Delft University of Technology)

11:30 AM–12:30 PM | Lunch

Location: Coastal Conference Room

12:30–2:00 PM | Concurrent Sessions 22–24

Basin Conference Room	**Session 22: AI Safety, Governance & Adversarial Uncertainty - Webinar Link** Chair: Jordan Fischbach (The Water Institute) **Adversarial Decision-Making Under Deep Uncertainty in Agentic AI-Based Cyber Attacks on Critical Infrastructures: An Integrated Resilience Framework** Presenter: Joseph Ponnoly (Cinfodens LLC) **A Robust Decision Architecture for Artificial Intelligence** Presenter: Rob Lempert (RAND) **Finding Climate Black Swans: AI-Assisted Horizon Scanning for Unseen Climate and Weather Extremes** Presenter: Tom Wood (King's College London)
Delta Conference Room	**Session 23: Flood Risk and Urban Stormwater - Webinar Link** Chair: Lillian Lau (Cornell University) **Unrefined national building inventories can mislead risk assessments and decisions** Presenter: Adam Pollack (University of Iowa)

	A simple adaptive strategy for drainage system retrofits to manage stormwater under deep uncertainty Presenter: Siqi Ke (Dartmouth College) **Climate Change Worsens Localized Flood Damages: a Case Study in Philadelphia, Pennsylvania** Presenter: Parin Bhaduri (University of Delaware)
Riverine Conference Room	**Session 24: Robust Energy Planning & Scenario Generation - Webinar Link** Chair: Patrick Kane (The Water Institute) **Scenario Space Exploration for Robust Energy Planning** Presenter: Amir Fattahi (TNO Energy and Material Transition; Utrecht University) **GSA-Informed Scenario Generation for Computationally Efficient Robust Decision Making in Energy System Planning** Presenter: Lorenzo Caravetta (Department of Energy - Politecnico di Milano) **Leveraging DMDU Techniques to Overcome Challenging Uncertainties in Probabilistic Risk Assessment of Nuclear Energy Systems** Presenter: Tatsuya Sakurahara (University of Pittsburgh)

2:00–2:30 PM | Closing Remarks

Location: Riverfront Gallery

Details: Remarks from Alyssa Dausman (The Water Institute) and Edmundo Molina (Tecnológico de Monterrey)

Abstracts

Session 1: Foundational Methods & Emulation Tools — Basin Conference Room

Metamodeling for Optimization--a Comparative Analysis

Authors: James Syme (Tecnológico de Monterrey), Edmundo Molina (Tecnológico de Monterrey), Alexa Martinez (Tecnológico de Monterrey), Fabian Fuentes (Tecnológico de Monterrey), Juan Antonio Robledo Lara (Tecnologico de Monterrey)

Despite advances in computational power and algorithmic performance, systemic optimization models remain challenging to scale and integrate into objective optimization. Building on a discussion presented at DMDU 2025, we present comparative results from computational experimentation on the performance of different models in single- and multi-objective optimization algorithms. We will demonstrate real-world results used to inform policy target setting in the context of a Nationally Determined Contribution (NDC) and discuss implications for use and next steps.

Hacking Adaptation – Using Policy Hackathons in Adaptation Planning

Authors: Sadie McEvoy (Deltares), Marjolijn Haasnoot (Deltares), Renske de Winter (Deltares)

With climate change, decision makers must now plan for impacts beyond what is known or has been experienced before. While traditional DMDU methods offer rigorous analytical approaches, there is a growing need to support decision makers who must act faster, evaluate adaptation across sectors, and balance current priorities with unclear long-term needs. New planning tools are needed to make rapid and integrated assessments, tackle emerging knowledge gaps and uncertainties, provide policy-relevant information, and facilitate meaningful co-design of solutions across sectors, knowledge domains and with multiple stakeholders. Policy hackathons are one approach we have used to understand vulnerability to climate change and explore adaptation options under uncertainty, in the Netherlands, Brazil and Egypt.

Six policy hackathons addressing topics of sea level rise, extreme rainfall events, urban flooding and integrated river management were analysed for their roles in adaptation planning processes. The hackathons reflect a range of policy questions, hackathon styles, and planning contexts. Analysing the hackathons identified common themes in their roles and impact on planning. In particular, they support DMDU by:

- providing insight to urgent, emergent, or sensitive topics that lack a clear path forward;
- delivering first-order, integrated or multidisciplinary assessments of complex questions;
- influencing planning processes and catalysing action when decision makers are ‘stuck’; and
- supporting social learning across disciplines and activating networks.

In this presentation we will share the results of our study, provide illustrations from the cases, and offer lessons for achieving impact with policy hackathons for adaptation.

A Robust Decision Making-Multi-Dimensional Dynamic Adaptive Pathway Approach to Manage Geo-Economic Uncertainty in a Range of Possible Futures

Authors: Mark Workman (Foresight Transitions Limited), Razan Alanazi (Imperial College London), Yousef Alshammari (Imperial College London), Diarmid Roberts (Foresight Transitions), Geoff Darch (Foresight Transitions), Quillan Shaw (Imperial College London), Edoardo Taricco (Foresight Transitions), Solomon Brown (Foresight Transitions)

The Kingdom of Saudi Arabia (KSA) is seeking to scale up both blue and green hydrogen production. The sector faces deep uncertainties around future demand, export opportunities, financing, technology costs, regulation, and certification standards. Traditional techno-economic optimisation approaches, which assume deterministic futures, struggle to capture these uncertainties and firm-level perspectives of investment viability.

This contribution applies a novel integrative framework combining two Decision-Making under Deep Uncertainty (DMDU) methodologies: Robust Decision Making (RDM) and Dynamic Adaptive Policy Pathways (DAPP). RDM-DAPP is used to examine the resilience of hydrogen business models in KSA. Drawing on a participatory scoping exercise with 10 expert interviews, a discounted cash flow (DCF) model is developed to stress-test firm investment viability across 5,000 possible futures. RDM was used to identify robust policy levers that improve firm investment viability, while DAPP translated these results into adaptive policy sequences aligned with national objectives.

Findings show that a portfolio of policies is required to enable hydrogen project success. Production Tax Credits (PTCs) consistently enhance robustness across a range of possible futures. Portfolios combining CAPEX subsidies, carbon pricing, and official agreements provided superior robustness compared to standalone measures. Blue hydrogen firms demonstrated greater robustness due to lower exposure to electricity cost volatility, whereas green hydrogen required stronger policy support. A DAPP approach, stress-tested these business models against geo-economic shocks analogues to the 2008 Global Financial Crisis, highlighting how policymakers adapt policy interventions to multi-dimensional geo-economic uncertainties in order to sustain investor confidence in hydrogen sector development in KSA.

Neural Simulation Based Inference for DMDU

Author: Pedro Nascimento de Lima (RAND)

DMDU methods call for modelers to stress-test strategies across an ensemble of plausible futures but there is less clarity on how exactly to identify a plausible and defensible set of states of the world. This talk explores whether and how a new wave of inference methods collectively known as neural simulation based-inference (SBI) could support DMDU analyses. Neural simulation-based inference (SBI) methods are being used in fields as diverse as cosmology and neuroscience to help overcome the limitations of statistical methods that require tractable likelihood functions. In neural SBI, modelers can use neural networks to learn the conditional density of model parameters given the data (i.e., the posterior). Some features of neural SBI are promising to DMDUers because they can plausibly work with larger models, require fewer model evaluations than previous approximate bayesian computation methods (i.e., tens of thousands rather than millions) and could allow "amortized" inference and inference across multiple model specifications. There is surprisingly little crosswalk between this new stream of inference methods and DMDU, and this talk begins to bridge this gap.

Session 2: How Can DMDU Help Reform the Regulatory State? — Delta Conference Room

How Can DMDU Help Reform the Regulatory State?

Authors: Rob Lempert (RAND), Christopher Nelson (California Polytechnic State University, SLO; RAND), Steve Neugeboren (US EPA (ret))

The use of scientific information in the American regulatory state is largely based on the Weberian facts-values division of labor in which experts determine the relevant facts and the political system specifies the societal values. This facts-value division fails, however, to appropriately incorporate both scientific uncertainty and societal values into regulatory decision making, in particular under conditions of deep uncertainty. The seminal National Research Council report Understanding Risk: Informing Decisions in a Democratic Society recommended distinguishing between getting the science right and getting the right science. The former asks experts to provide information that meets the highest standards of their field. The latter asks experts to engage with lay people to identify the scientific questions of most interest. One important benefit of DMDU is that it opens the aperture on the policy-relevant questions 'getting the science right' can address compared to traditional approaches to risk analysis. As one example, DMDU can help specify the scientific information needed to support the development of adaptive decision strategies. A growing body of practice and literature envisions a regulatory state better able to address deep uncertainty by incorporating this science right/right science distinction into its design. But there has been little consideration of how DMDU might enhance this regulatory reform project. This panel will thus bring together experts on the regulatory state and DMDU practice to explore what opportunities DMDU might bring to any project of regulatory reform under conditions of deep uncertainty.

Session 3: Practicing DMDU in Different Institutional Contexts — Riverine Conference Room

Presenters: Casey Helgeson (Penn State University), Nastaran Tebyanian (The Water Institute), Patrick Kane (The Water Institute), Allison DeJong (The Water Institute), Colleen McHugh (The Water Institute), Garvin Pittman (The Water Institute), Diana Di Leonardo (The Water Institute), Jordan Fischbach (The Water Institute)

In this session, we will share research and experience on how working within different institutional contexts shapes opportunities and challenges for practicing DMDU, drawing on examples from both a large-scale academic research project and an applied research institution. We address questions about how DMDU analyses and associated co-production are enabled or restricted by institutional characteristics, incentive structures, available resources, professional roles, and project structures. Across the presentations, we consider how these contexts shape the identification of decision problems, the ability to build buy-in for exploratory approaches, the integration of DMDU thinking into decision-support processes, and the management of teams, clients, and deliverables in applied DMDU work.

1. Embedding DMDU in Transdisciplinary Academic Research

Casey Helgeson

Key questions motivating this year's meeting include how DMDU methods and processes can best: (a) integrate into institutional decision making, (b) overcome science-policy barriers, and (c) inform challenging societal decisions. These questions mirror more general ones examined under headings such as engagement, co-production, transdisciplinary research, and actionable science. In this talk, I will present a case study of a large ($20M, 13-institution) transdisciplinary research project that proposed DMDU-inspired decision analyses as the key boundary object for both disciplinary integration and co-production of research. The project aimed to advance fundamental understanding while informing climate adaptation planning in the Northeast US. We examine the project in terms of successes and challenges in bridging across disciplines and between researchers, decision makers, and

stakeholders to inform decision making. Through this analysis, we investigate the large-scale academic research project as a medium for advancing goals (a)–(c) for DMDU. We report findings on: how project scale constrained identification of appropriate planning problems and co-production partners; how decision analysis performed as a center of integration gravity within the project; and how project personnel experienced trade-offs among research goals such as advancing their careers, contributing to fundamental knowledge, and having real-world impact.

2. Practicing DMDU at the science-policy interface: challenges and opportunities

Nastaran Tebyanian, Patrick Kane, Allison DeJong, Colleen McHugh

Practicing DMDU at a boundary organization that sits between research and real-world decision making provides unique opportunities and challenges for overcoming science-policy barriers. This presentation shares our experiences navigating this challenge across several decision-support and policy projects at the Water Institute. Examples include working without a single central decision maker; building buy-in for exploratory modeling in contexts where decisions are often expected to rely on a single definitive answer; introducing "DMDU thinking" before DMDU methods to research partners and decision makers as part of the process; designing analyses with communication and storytelling in mind; and tailoring the complexity of problem formulation and modeling to available research resources and time. The presentation also highlights the opportunity to build on past experiences through continued engagement with the same partners.

3. Project management for DMDU in practice

Nastaran Tebyanian, Garvin Pittman, Diana Di Leonardo, Jordan Fischbach

Working within an applied research institution often requires scientists, project managers, and principal investigators to collaborate within structured project workflows. This setup can differ from academic contexts, where the roles of project manager and PI may be less distinct, and from private companies or consultancies, where project management often follows more standardized delivery models.

In this presentation, we discuss how project management for DMDU projects is similar to and different from project management for other applied science projects, and we identify the main considerations that arise in practice. Drawing on examples from our work, we highlight these considerations across project scoping, proposal development, team and client collaboration, and the design of deliverables. We hope this presentation helps start a broader conversation within the DMDU community about what effective project management means when applying DMDU in practice.

Session 4: DMDU & Democratic/Governance Processes — Basin Conference Room

DMDU and Citizen Assemblies: A post-fire case study from Pacific Palisades, California

Authors: Rob Lempert (RAND), Maryam Zar (Palisades Recovery Coalition), Jay Balagna (RAND School of Public Policy), Eliana Bernstein (Palisades Recovery Coalition)

Last year's DMDU Society meeting ended with a panel discussion "Can DMDU Support the Re-Imagining of 21st Century Democracy?" This talk describes a recent engagement consistent with that theme. In the aftermath of the devastating fires of January 2025, Pacific Palisades, California (part of

the City of Los Angeles) faces difficult, values-laden, and highly technical policy challenges. In particular, extensive experience from disaster recovery across the United States makes clear that the Palisades would benefit from some type of special assessment district, a newly-chartered government body which can consolidate various types of tax and other revenue sources, issue debt from bond markets, and make coordinated investments in recovery. However, attempts by Los Angeles city and state of California officials to establish such a district have been stymied by political conflict and community distrust of government institutions. In response, the Palisades Recovery Coalition, a local NGO, convened a citizen assembly to make recommendations to elected officials and the community regarding what powers any disaster recovery district for the Palisades ought to be granted and how it ought to be made accountable to the public. The assembly was organized as a deliberation with analysis process and DMDU-inspired information products were among the analysis made available to the assembly. This talk will report on this Palisades citizen assembly, how it was organized, the analysis it used, its impacts on local policy debates, and its implications for the question "can DMDU support the re-imaging of 21st Century democracy?"

Vulnerability Analysis for Redistricting: Characterizing Maps Using Uncertain Community Splits

Author: James Syme (Tecnológico de Monterrey)

Communities of Interest (COIs) are foundational to representation in a number of global democracies that rely on territorial constituencies, including the United States. For example, 37 states require that redistricting plans preserve community boundaries--this is often taken to mean that communities should not be split across districts. However, these usually territorial communities are often un- or under-defined, creating deep uncertainty over where their true boundaries lie.

Using (1) socioeconomic data from the U.S. Census and (2) cellular device geolocation data, I combine a dual graph model of territorial COI partitions with exploratory modeling to explore the uncertainty space of these communities. Then, I use techniques from vulnerability analyses to characterize and compare redistricting plans in the context of how they split communities. I then explore the validity of this approach for comparing redistricting plans, limitations, and future applications.

Negotiating Management Alternatives under Uncertain Future Conditions using a Self-Organizing Map Framework

Authors: Joseph Kasprzyk (University of Colorado Boulder), Madeline Pernat (University of Colorado Boulder), Edith Zagona (University of Colorado Boulder)

Stakeholders with competing objectives often must choose among management alternatives under a wide array of plausible future States of the World (SOWs). In the presence of conflict among those objectives, the parties to the decisions may have difficulty understanding how and why they view the same alternatives differently. Existing methods for Decision Making Under Deep Uncertainty provide a limited view of performance, focusing on aggregate calculations of performance of alternatives such as robustness metrics, which summarize performance across the entire ensemble of SOWs.

This presentation introduces the MAPS (Mapping Alternative Performance across SOWs) framework. MAPS is a visual decision-support approach that fills the knowledge gap for conflicting stakeholders by using the Self-Organizing Map (SOM), simultaneously performing clustering and dimension reduction. The large ensemble of SOWs is clustered into interpretable groups arranged on a two-dimensional map, onto which multiple layers of data are superimposed. Condition layers visualize

uncertain drivers and allow stakeholders to focus on particular regions of the map. Performance layers show how alternatives perform in the same regions of interest. By overlaying these layers, stakeholders can jointly examine the full landscape of uncertainty and trace which future conditions cause one party's goals to be met while others are missed.

The framework is demonstrated with a Colorado River Basin case study, illustrating how MAPS can identify potential conflict zones between Upper and Lower Basin stakeholders and lead to identification of compromise alternatives. The co-authors participated in the creation of the Colorado River Basin Post-2026 Operations Exploration Tool with Reclamation and Virga Labs, and the current presentation extends the negotiation ability for the Basin beyond the initial exploration tool.

Constraint, Conflict, and Change: 3Cs Determining Societal Development under Deep Uncertainty

Author: Richard Silberglitt (RAND - Retired)

The current state of any society is metastable, with boundaries set by constraints on its activities and the environment in which it exists. Change requires relaxation or adjustment in the effects of these constraints. Attempts at change bring conflict between elements of society that prefer the status quo and those that seek change, and even between those that seek different types of change. The resolution of these conflicts determines the nature of the new state, and the new boundaries set by its constraints. Some constraints are external, such as disease and climate change, while others are internal, such as the development and use of remedial technologies such as vaccines and energy from non-fossil sources. Societies can cycle through phases of ignorance of constraints that have little or acceptable impact, recognition of the impact of constraints, efforts to address constraints, and change to a state in which conflicts are resolved and the impact of constraints is again acceptable. This cycle can be represented by a commonly used two-dimensional scenario chart on which the strength of constraints decreases along the x-axis and the effectiveness of actions and policies to mitigate the effect of constraints increases along the y-axis. The usefulness of this framing to support policy analysis for societal problems fraught with deep uncertainty will be demonstrated using two examples from prior foresight exercises: (1) transportation policy aimed at the reduction of traffic fatalities in the United States; and (2) energy policy for countries of the Association of Southeast Asian Nations (ASEAN). In the former case, it elucidates the importance of synergy between changes in infrastructure and safety culture, while in the latter case, it provides a framework for evaluating the effect of policies aimed at increasing energy security.

Session 5: Coastal Adaptation and Retreat — Delta Conference Room

The Barrier Island Restoration Tradeoff Analysis Toolkit: A Python Library for DMDU in Sediment Management

Authors: Patrick Kane (The Water Institute), Nastaran Tebyanian (The Water Institute), Diana Di Leonardo (The Water Institute), Soupy Dalyander (The Water Institute), Travis Swanson (The Water Institute)

Barrier island systems are vitally important natural sources of coastal risk mitigation as well as providers of habitat for a range of critical species along the Louisiana coastline. Multiple factors driving island change are also subject to deep uncertainty, including sea level rise, sediment fluxes that are difficult to measure, and storm frequency and intensity. These uncertainties compound over the decadal planning horizons necessary for planning restoration projects and effective management of

sediment sources. Yet in comparison to other deeply uncertain management decisions, barrier island management has received relatively little attention from the broader DMDU community. The Barrier Island Restoration Tradeoff Analysis (BIRTA) Toolkit is a Python library that includes code based on the Rhodium library, bringing DMDU methodology into decision support for barrier island management along the Louisiana coastline. This session covers the development of the BIRTA Toolkit from the perspective of integrating physical science data and modeling with DMDU methodology for decision support. Individual talks will cover the source data underlying the model and the deep uncertainties embedded in it, the development of a reduced complexity barrier island system model suitable for integration, the development of an interface for managing Multi-objective Robust Decision Making experimental design and optimization with the reduced complexity model, and decision maker perspectives on the development process and utility of the methods.

Session 6: Institutional Practice & Policy Translation — Riverine Conference Room

Uniting Siloed Disciplines to Advance Decision Support Systems for Climate Risk Management

Authors: Lynée Turek-Hankins (Dartmouth College), Adam Pollack (University of Iowa), Casey Helgeson (Penn State University), Klaus Keller (Dartmouth College)

Researchers have built countless products to help practitioners manage climate-related risks, but there is limited evidence that these products are consistently used or that they meaningfully improve outcomes. By contrast, there is a long history of effective decision support in other application areas. Why does decision support work well in some domains, but remains elusive for climate risk management? This session will examine this guiding question through a two-part format that combines the applied expertise of decision support practitioners with the collective experience of the DMDU community. In the first half, a panel of practitioners who design, implement, and evaluate decision support systems across three distinct domains will discuss how they (1) integrate decision support into existing workflows, (2) improve usability and accessibility, (3) measure success, (4) sustain use, and (5) adapt to shifting contexts and priorities. The second half of the session will feature an interactive studio, where we will explore applied decision support problems facing the audience using insights from the panel discussion and an emerging framework for multidisciplinary decision support. Audience members will have the opportunity to learn from each other in a structured format and help advance ongoing research on the topic. It is sure to be a highly dynamic and interactive session that provides insights for multiple application areas!

Lost (and Found!) in Translation: Overcoming Barriers to DMDU for Non-Specialist Policymakers

Author: Henry Graumlich (Calleguas Municipal Water District)

The practical application of DMDU concepts has benefited from recent syntheses of practice. Two notable examples include Robert Lempert's "Decision Making Under Deep Uncertainty and the Great Acceleration: The Role of Experts and Policy Analysis in a World in Transition," (1) and Tebyanian et al's "A Beginners Guide to Decision Making Under Deep Uncertainty for Water Utilities" (2). Both provide useful overviews of DMDU approaches to analyzing decisions characterized by deep uncertainty. In terms of practical application, both propose iterations of deliberation with analysis. Through exploratory iteration, goals and constraints, options and tradeoffs, are clarified with the goal of discovering robust paths to address core vulnerabilities into the future. From the analysts' perspective, this provides an idealized application of expertise to address complicated problems. In my experience, from the policymakers' perspective this often seems to be a baffling excursion into

unfamiliar concepts and unnecessary complications. Something is lost in the translation of useful DMDU approaches to how policymakers frame their decision making role. How can we better understand the policymakers' perspective to facilitate the utility of DMDU approaches?

Based on 35 years of experience working with policymakers in water resource issues, this presentation uses real world examples to explore common barriers to understanding DMDU concepts, how DMDU can be represented to policymakers in terms that they intuitively understand, and translation of the value of DMDU analysis into more approachable decision making processes.

1. Lempert, Robert J., Decision Making under Deep Uncertainty and the Great Acceleration: The Role of Experts and Policy Analysis in a World in Transition. Santa Monica, CA: RAND, 2025. https://www.rand.org/pubs/perspectives/PEA3789-1.html.
2. Tebyanian, N., Fischbach, J. R., Kane, P. B., DeJong, A., & Cameron, C. (2026). A Beginner's Guide To Decision Making Under Deep Uncertainty For Water Utilities. Water Utility Climate Alliance.

Participatory Engagement for Critical Mineral Community Decision-Making

Author: Selena Gerace (University of Wyoming)

Much of the DMDU literature focuses on decision-making and analysis related to water resource management, but these DMDU methodologies have not been widely applied to energy resources and mining. The resource planning and policymaking challenges related to critical mineral extraction and processing exemplify the conditions of deep uncertainty—including a lack of knowledge or shared understanding about the future demand for critical minerals, the quantity and location of critical mineral resources, and the potential environmental and social consequences of extracting, transporting, and processing critical minerals.

In the summer of 2026, as part of an Alfred P. Sloan Foundation funded research project exploring the legal, social, and environmental justice considerations associated with the buildout of a domestic U.S. supply chain for critical minerals, we will apply DMDU approaches to the stakeholder engagement component of our project to better understand how communities can navigate critical mineral recovery from mine waste and other byproducts of extraction. We're particularly interested in how these opportunities are perceived and governed in places with very different extractive histories and socioeconomic dependencies. As such, we are focusing on two distinct communities with different identities and relationships to extractive industries. One will be Gillette, Wyoming —a community that's economy and identity are deeply tied to coal, oil, and gas production. The other will be Bonita Peak Mining District, Colorado — a region with a legacy of hard rock mining and ongoing environmental remediation challenges, including a Superfund designation

We will use mixed methods participatory engagement approach including surveys, interviews, and stakeholder advisory groups to co-produce a common understanding of community goals, possible policy solutions and actions, challenges, unknowns, and tradeoffs when considering the potential for critical mineral recovery. We will use collected information to develop an XLRM framework for analyzing decision making pathways while exploring model-less RDM applications.

The Challenges and Opportunities for DMDU Applications in the Mining Sector

Author: Christopher Dacey (Hydroture)

Despite operating in conditions that closely match the defining characteristics of Deep Uncertainty, the mining industry has seen limited adoption of DMDU-related frameworks. Critical investment and development decisions spanning planning, operations, environmental compliance, closure, and post-closure stewardship are often made in the absence of agreed-upon system models, probability distributions, or valuation of long-term consequences, particularly where liabilities extend in perpetuity.

This gap spans domains including environmental impacts, long-term waste and water management, and socio-environmental system response, including social license to operate. These challenges have historically been evaluated using disparate assessment and modeling frameworks, including hydrogeologic, hydrologic, water balance, geochemical, ecological risk, and mine development models, without an integrating decision-analytic structure to systematically explore uncertainty, trade-offs, and robustness. The result is a reliance on legacy approaches that can obscure vulnerability, amplify tail risks, and contribute to undesired outcomes and well-documented failure modes.

This presentation advances a diagnosis and a pathway forward. First, it characterizes extractive industry decision contexts as archetypal DMDU problems, highlighting structural barriers to adoption, including regulatory framing, institutional incentives, and model fragmentation. Second, it outlines how DMDU methods, such as Robust Decision Making (RDM), Dynamic Adaptive Policy Pathways (DAPP), and multi-objective robustness analysis, can be adapted across disciplinary models, stress-test system performance, and support defensible, transparent decisions under deep uncertainty. Further, the concept of "decision quality assurance" for complex decisions is introduced as a value proposition.

The presentation argues that embedding DMDU within extractive industry development and practice is not merely a methodological aid, but a valuable evolution of integrated assessment and planning for managing long-lived risks, achieving development goals, building stakeholder trust, and redefining "best available technology" and "best management practices" in high-consequence contexts.

Session 7: Adaptive Pathways — Basin Conference Room

Institutionalizing Early-Warning Signals in Dutch Delta Governance

Authors: Arthur Petersen (University College London), Marjolijn Haasnoot (Deltares), Susan van 't Klooster (SAVIA Future-Proof Advisory)

Monitoring of early-warning signals in the Dutch Delta Programme has become increasingly institutionalized through the Signal Group, which translates changing physical, socio-economic, and societal developments into advice for adaptive decision-making under deep uncertainty. The Signal Group now occupies a formal place in the program cycle, with annual advice, interaction with program actors, an explicit role in informing the six-yearly review of delta decisions and preferred strategies, and an annual response from the Delta Commissioner (on behalf of the national program) to its advices. This development reflects a broader shift from retrospective evaluation toward anticipatory monitoring: not only asking whether actions were implemented, but whether emerging signals indicate that strategies, assumptions, or timelines need to change. The external evaluation of the Signal Group of 2022 showed, however, that institutionalization was initially incomplete. The group's mandate and scope were not always clear, its visibility in the Delta community was limited, and its monitoring arrangements were too closely tied to a fixed dashboard rather than to a flexible

assessment of salient signals. The main challenge remains how to act on uncertain signals. As the literature on adaptation pathways and planned adaptive regulation stresses, early warnings are rarely definitive; they may be weak, ambiguous, politically contested, or hard to translate into concrete action, especially when lead times, institutional fragmentation, and multiple decision levels are involved. Acting too early risks costly overreaction, while acting too late may close off adaptation options. Key outstanding issues include pro-active monitoring without over-reliance on indicators, smarter signal handling, and linking early-warning knowledge to administrative responses. The Signal Group's institutionalization partly addresses these by enabling flexible signal interpretation and decision-making, yet challenges persist in timely, effective action under deep uncertainty.

Developing Dynamic Adaptation Pathways for Compound Flooding in Jackson County, Mississippi

Authors: David Rounce (Carnegie Mellon University), Matthew Weathers (The Water Institute), Alison Rellinger (Mississippi State University), Qiyamah Williams (Mississippi State University, Mississippi Sound Estuary Program), Renee Collini (The Water Institute), Sadaf Mahmoudi (Carnegie Mellon University)

Compound flooding resulting from the combination of storm surge and extreme rainfall greatly impacts coastal communities across the Gulf and is projected to get considerably worse with sea-level rise. To help communities be resilient in the face of these changes, they need to be equipped with the models and data that will enable them to evaluate how effective different adaptation strategies will be for various sea-level rise scenarios. In the proposed work, we will share how compound flood modeling using SFINCS and applications using FloodAdapt (i.e., SFINCS paired with the damage model Delft-FIAT) can be used to support adaptation planning, with a specific emphasis on the utility of dynamic adaptation pathways. Specifically, we will discuss how large ensembles of synthetic events can be used to inform adaptation planning for communities in Jackson County, Mississippi. We will also discuss opportunities associated with leveraging tools like FloodAdapt as well as the challenges associated with building adaptation pathways in a robust way with these tools. These challenges include how to select the compound events to use for evaluating the various adaptation strategies and how nested models can be used to circumvent limitations resulting from the computational expense. Overall, we will close with a perspective on the utility of SFINCS and FloodAdapt for supporting adaptation pathways, opportunities for future directions, and how this knowledge can be transferred to other coastal communities across the Gulf.

Evaluating the Explainability and Updateability of Climate Adaptation Roadmaps under Deep Uncertainty

Authors: Takuya Nakashima (The University of Tokyo), Kenya Suzuki (The University of Tokyo), Ryota Wada (The University of Tokyo), Takahiro Oyama (nies)

Adaptive pathways are widely used to support climate adaptation decisions under deep uncertainty. While effective for exploring how actions can be sequenced across uncertain futures, pathways are often evaluated using fixed system relationships and performance measures. Previous studies have assessed pathways in terms of robustness, timing, flexibility, costs, lock-in, and monitoring triggers. However, less attention has been paid to the validity of the roadmap itself when cross-sectoral relationships and evaluative criteria change over time.

This study develops a framework for evaluating the explainability and updateability of climate adaptation roadmaps under changing relationships and measures. An explainable roadmap clarifies

which uncertainties are considered, which relationships are assumed, which measures and thresholds define success or failure, and when the roadmap should be revised. The framework evaluates roadmaps in terms of robustness, transition feasibility, future options, lock-in, cross-sectoral trade-offs, assumption transparency, and updateability.

The framework is illustrated using a cross-sectoral river-basin adaptation model linking flood risk, agriculture, water availability, ecosystem condition, land use, and adaptation cost. Monte Carlo simulation generates alternative futures under different assumptions about system dynamics, institutional coordination, and evaluation measures. The resulting pathways are used to compare conventional fixed-measure pathway evaluation with roadmap evaluation that considers changing relationships and measures.

The analysis assesses not only whether a pathway performs well under uncertain futures, but also whether the assumptions, metrics, thresholds, and revision conditions supporting the roadmap remain transparent, contestable, and updateable. The framework shows how actions with strong short-term performance may reduce long-term roadmap usefulness by narrowing future options or reinforcing cross-sectoral lock-in. It also highlights how monitoring, coordination, and flexible enabling actions can increase a roadmap's value as a shared and updateable basis for adaptation discussions.

Extending Adaptation Pathways with Backcasting: Identifying Pivotal Decisions through a Dual Approach with DAPP-Δ

Authors: Renske de Winter (Deltares), Noor ten Harmsen van der Beek (Deltares), Karianne de Bruin (Deltares), Esther van Baaren (Deltares), Sadie McEvoy (Deltares), Marjolijn Haasnoot (Deltares)

Deltas and coastal regions face increasing pressures from climate change and socio-economic developments, requiring adaptation to remain liveable. Present-day strategies often focus on incremental measures, while more transformative decisions, such as shifts in land use or planning objectives, may become necessary over time. We present DAPP-Δ (1), an extension of the Dynamic Adaptive Pathways Planning (DAPP) approach. The method combines forward-exploration of adaptation pathways with backcasting from future land and water use states.

At the DMDU conference, we introduce DAPP-Δ, including experiences from real-world applications and serious gaming sessions with practitioners (2). The dual approach enables the identification of synergies and conflicts between potential adaptation measures and envisioned future states under uncertain change, supporting decision-making under deep uncertainty by identifying pivotal decisions.

The method is illustrated through an application in the southwest of the Netherlands, developed in co-creation with regional stakeholders. The region faces multiple adaptation tipping points due to uncertain sea-level rise, economic developments, and upcoming large-scale investments in aging infrastructure. A wide range of transformative future states further increases uncertainty for near-term investments. We demonstrate that DAPP-Δ supports identification of pivotal decisions beyond incremental adaptation, helps uncover maladaptation risks, and emphasizes considering multiple societal goals and changes, as these jointly determine short- and long-term investments that shape the solution space over time under deep uncertainty.

1. Ten Harmsen van der Beek, N., Renske de Winter, Esther van Baaren, Ferdinand Diermanse, Arno Nolte, Marjolijn Haasnoot (2025) Identifying transformative decisions: A dual approach to

adaptation pathways design using forward-exploration and backcasting, Climate Risk Management, https://doi.org/10.1016/j.crm.2025.100716.
2. De Winter R., Ten Harmsen van der Beek, N., E. van Baaren., M. Brinkhuis, A. Vlaar, S. van Vuren (2025) Inzicht in de beste adaptatiebeslissingen door verbinden korte en lange termijn, H20-waternetwerk (in Dutch)

Session 8: DMDU Methods Advances in the Health Decision Sciences — Delta Conference Room

DMDU Methods Advances in the Health Decision Sciences

Authors: Pedro Nascimento de Lima (RAND), Javier Rojas Aguilera (RAND School of Public Policy), Thomas Trikalinos (Brown University), Jonathan Ozik (Argonne National Laboratory), Arindam Fadikar (Argonne National Laboratory)

Session Overview: Health Decision Science relies on models whose computational cost and uncertainties challenge conventional probabilistic decision analysis. This session brings together four contributions that develop and apply methods for decision making under deep uncertainty (DMDU) in the health decision sciences.

The talks span treatment sequencing for rare cancers, HIV prevention decision-making, Bayesian optimization for stochastic simulators, and the design of pandemic surveillance networks. Together, they illustrate how to separate well-characterized risks from deep uncertainties, use surrogate and calibration machinery to make expensive models tractable, and identify policies that perform robustly across uncertainty sets or scenario ensembles rather than optimally against a single assumed world.

1. Designing Layered Genomic Surveillance Networks via Robust Optimization

Javier Rojas Aguilera, RAND School of Public Policy

Untargeted metagenomic surveillance could enable earlier detection of novel pandemic threats, but decision makers lack quantitative guidance on where to sample, which traveler and community sampling modes to deploy, and how much sequencing capacity to maintain. We present a simulation model and a robust optimization approach for designing layeredsurveillance networks that can combine community wastewater with airport- and aircraft-based sampling (airport triturator wastewater, aircraft lavatory wastewater, and pooled traveler nasal swabs). We develop both a simulation model and a “twin” non-linear analytic model and solve it via robust optimization to support decision-making subject to budget and capacity constraints and deep uncertainty about pathogen characteristics. We illustrate this approach on a case study that compares alternative approaches for expanding the US Centers for Disease Control and Prevention (CDC) Traveler Genomic Surveillance program.

2. Robust Treatment Sequence for Small Bowel Neuroendocrine Cancers

Thomas A. Trikalinos, Brown University

I consider a decision analysis under deep uncertainty for patients with small bowel neuroendocrine cancers who progress on initial management. The available treatments are peptide receptor radionuclide therapy (PRRT), everolimus (E), and cabozantinib (C), administered sequentially until failure. The optimal sequence is uncertain. PRRT appears to be the most effective when used first, but confers a small risk of life-limiting radiation-induced blood cancers. Delaying PRRT may reduce that

risk but could also reduce its effectiveness; similarly, the effectiveness of everolimus or cabozantinib may decline with later use. These tradeoffs are not well characterized and are difficult to represent with conventional probabilistic uncertainty alone.

I describe a decision analysis that separates deep uncertainties from well-characterized risks. Uncertain quantities related to treatment effect attenuation and PRRT-associated malignancy are represented as uncertainty sets, while the remaining parameters are modeled probabilistically. Using a microsimulation model that predicts expected life length given parameters, I identify sequences that are not uniformly worse than alternatives, and those that optimize the worst case across all uncertainties.

3. DMDU with Computationally Expensive Models: HIV Prevention as a Case Study

Jonathan Ozik, Argonne National Laboratory

Detailed agent-based simulations are increasingly used to support policy decisions, but their computational cost and complex uncertainty structure make systematic scenario analysis challenging. We present a data-driven, uncertainty-aware decision support (DDUADS) workflow for using stochastic simulation models as decision-support tools under limited computational budgets. The approach combines several established techniques (sensitivity screening, Bayesian calibration using simulation-based inference, and multi-surrogate model integration for translational efficiency) into a coherent pipeline that enables uncertainty-aware policy analysis. Rather than producing a single baseline, the calibration stage yields a posterior distribution over plausible model parameterizations, allowing flexible, uncertainty-aware forward projections. We demonstrate the DDUADS workflow on the INFORM-HIV agent-based model of HIV transmission in Chicago to evaluate potential disruptions in antiretroviral therapy (ART) and pre-exposure prophylaxis (PrEP) use. While the specific application is HIV modeling, the challenges and techniques described here arise in other simulation studies and can be applied to decision support in other domains.

4. Off the Grid: Efficient Trajectory Discovery with Adaptive Batch Sampling

Arindam Fadikar, Argonne National Laboratory

Bayesian optimization (BO) aims to find parameters of expensive simulation models efficiently using surrogate models. A stochastic simulation model, however, also requires additional information on setting up its random stream, usually through the specification of a random seed. The usual practice in applying BO to stochastic simulations is to summarize over outputs across random seeds and to recover optimal parameter settings. However, in doing so, trajectory-level details are lost. We introduce a trajectory-oriented BO (TOO) method that uses a novel surrogate technique that models both parameters and random seeds with a Gaussian process, enabling prediction at the individual trajectory level. It is paired with an adaptive Thompson Sampling-based BO algorithm to find the optimal (parameter, seed) combinations given the data. Applied to stochastic epidemic models, including compartmental and agent-based models, it improves sampling efficiency and can accelerate identification of trajectories consistent with observed data compared to parameter-only approaches.

Session 9: Water Resources & Reservoir Operations — Riverine Conference Room

Applying DMDU in a Formal Public Decision-Making Process: the Colorado River Basin Long-Term Planning Experience

Authors: Rebecca Smith (US Bureau of Reclamation), Nathan Bonham (US Bureau of Reclamation), Alan Butler (US Bureau of Reclamation), Carly Jerla (US Bureau of Reclamation), James Prairie (US Bureau of Reclamation), Sarah Baker (US Bureau of Reclamation), Logan Callihan (US Bureau of Reclamation)

The U.S. Bureau of Reclamation applied DMDU in a formal, yearslong planning process to develop and adopt new operating guidelines for Lake Powell and Lake Mead, the largest reservoirs in the country. These reservoirs are central to the Colorado River Basin (CRB), which supplies water and power to growing metro areas, large irrigation districts, prized environmental and recreational assets, and important tribal and cultural resources in seven U.S. states and two Mexican states. The last 26 years in the CRB have been drier than any period in at least 1,200 years, forcing Reclamation and stakeholders to contend with critically low reservoirs while planning under deeply uncertain supply, demand and policy conditions. The planning process was subject to the National Environmental Policy Act and the Endangered Species Act, which include analysis, documentation, and public engagement requirements. These formal requirements and the complexity of the resources and institutions in the CRB presented novel opportunities and challenges for applying DMDU. This talk will describe lessons learned and raise questions for the DMDU community to consider as it continues to expand its reach.

Adapting DMDU Techniques to Analyze Many Diverse Resources in a Colorado River Basin Long-Term Planning Process

Authors: Nathan Bonham (US Bureau of Reclamation), Rebecca Smith (US Bureau of Reclamation), Alan Butler (US Bureau of Reclamation), Carly Jerla (US Bureau of Reclamation), James Prairie (US Bureau of Reclamation), HB Zeff (University of North Carolina Chapel Hill)

The public process to develop and adopt new operating guidelines for Lake Powell and Lake Mead required the U.S. Bureau of Reclamation to analyze the potential effects of different operational alternatives on dozens of resources throughout the Colorado River Basin. These resources ranged from reservoir elevations to invasive species in the Grand Canyon to salinity downstream of Lake Mead. The data for this wide range of resources was generated through different modeling chains at different timesteps, and the resource experts spanned multiple government agencies and consulting firms. One major product of this process is a formal Environmental Impact Statement (EIS), a static document required by the National Environmental Policy Act and designed to inform stakeholders and the public about potential impacts and support a policy decision by the federal government. This talk describes the outreach undertaken to bring different resources and experts into the DMDU framework and the technical adaptations developed to create a unified approach to employing DMDU analysis in the EIS.

Distributive, Procedural, and Corrective Justice in Affordable Water Supply Planning under Uncertainty

Authors: Sarah Fletcher (Stanford University), Greta Markey (Stanford University), Jennifer Skerker (Stanford University), Khalid Osman (Stanford University)

Climate change threatens water security in cities worldwide, necessitating expensive but deeply uncertain adaptation measures. Under-resourced communities face the greatest risk – from both water insecurity and the burden of costly adaptation measures. When utilities invest in new infrastructure, they increase household water bills, which can threaten affordable water access for low-income populations. Traditional model-based decision-support approaches for planning water supply infrastructure capture utility-scale outcomes and are driven by utility goals. Here we present an approach to assess the equity of water affordability outcomes of urban water planning decisions under deep climate uncertainty using three lenses. First, we address distributive justice by operationalizing household-level affordability metrics using an integrated water system-economic-financial model. Second, we address corrective justice by estimating the cost burden that different types of households impose on water systems compared to the costs they pay. Finally, we address procedural justice through community-engaged research methods that compare affordability metrics to qualitative, experiential measures of affordability. We use these lenses to inform the design of customer assistance programs and water rates in Santa Cruz, California. We find that robust, equitable solutions could require $10M in annual assistance, or 23% of Santa Cruz' current annual water revenue. These findings highlight the need for large-scale state and federal investment to achieve water supply that is both reliable and affordable for low-income populations. Our work underscores the importance of an environmental justice-informed approach to model design in identifying transformative solutions that fully address the needs of under-resourced communities.

Session 10: DMDU in Health & Social Policy — Basin Conference Room

Dynamic Adaptive Decision Support in Healthcare: Bridging Science and Practice through Multi-Case Learning in Hospital Settings

Authors: Anke Aarninkhof - Kamphuis (University of Twente), Hans Voordijk (University of Twente), Geert Dewulf (University of Twente)

Healthcare systems increasingly face persistent and evolving uncertainties related to demand, workforce capacity, and systemic pressures. Addressing these challenges requires decision-making approaches that move beyond optimization under known conditions toward adaptive strategies under deep uncertainty. This study contributes to advancing Decision Making under Deep Uncertainty (DMDU) at the science–policy interface by introducing and applying a Dynamic Adaptive Decision Support (DADS) model in hospital settings.

The main objective is to assess how this novel DADS approach enhances the structuring, interpretation, and navigation of uncertainty in strategic decision-making. We present a multiple-case study of hospitals in which DADS is applied to support board-level decision processes. Across these cases, the model enables the identification of critical uncertainties, the exploration of adaptive strategies over time, and the design of flexible, monitorable decision pathways.

Building on Aarninkhof-Kamphuis et al. (2026), this contribution advances both the conceptual and practical application of DMDU. It demonstrates how DADS can bridge analytical rigor and real-world decision contexts, translating abstract deep uncertainty into actionable insights for strategic decision making in hospital settings.

In line with the conference theme, this work emphasizes methodological innovation alongside practical relevance. It highlights how adaptive decision support can be embedded within existing

decision processes, while also addressing challenges related to implementation, stakeholder engagement, and organizational uptake.

The session will actively engage participants and invites hospitals worldwide to contribute cases or explore opportunities to test and further develop the DADS model. By fostering exchange between researchers and practitioners, this work aims to accelerate the adoption and refinement of DMDU approaches in healthcare systems.

Scenario Discovery in a Foresight Study on Sport and Physical Activity

Authors: Guus Luijben (Dutch National Institute for Public Health and the Environment (RIVM)), Willem Auping (Delft University of Technology), Patrick Steinmann (Delft University of Technology)

As part of a foresight study on sport and physical activity, we estimated future trends for several key indicators by conceptualizing sport and physical activity as a dynamic system. We developed a simulation model informed by insights and feedback loops identified during Group Model Building (GMB) workshops with domain experts. By systematically varying model parameters within plausible ranges, we simulated multiple scenarios projecting developments up to the year 2040. This approach enabled us to assess how different societal trends may impact outcomes related to sport and physical activity over time. To explore the range of possible futures, we employed scenario discovery techniques, focusing on the extremes of the outcome distributions. In this presentation, we will share the results of our simulations as well as practical lessons learned during the process.

Session 11: Enhancing DMDU with AI — Delta Conference Room

AI-Augmented Policy Red Teaming for Decision-Making Under Deep Uncertainty

Author: Jaakko Kuosmanen (Finnish Academy of Science and Letters)

Deep uncertainty often enters public institutions before it enters formal DMDU analysis. It is embedded in the framing of policy problems, the drafting of legislative texts, and the design of early impact assessments. Yet many DMDU methods remain difficult to integrate into ordinary policy routines. This paper introduces Science Sparring, a novel Finnish policy red-teaming method, and examines how artificial intelligence can support its use as a scalable front end for DMDU. The presentation argues that AI augmented science sparring can expand DMDU practice while preserving human judgement, institutional accountability, and democratic legitimacy.

In Science Sparring, brokers convene multidisciplinary researchers and civil servants around policy hypotheses (e.g., early policy drafts). Researchers act as a red team, critically examining assumptions, causal mechanisms, knowledge gaps, unintended consequences, and vulnerabilities embedded in the draft. Since 2019, Science Sparring has been co-developed with Finnish ministries and applied to over 30 policy issues including climate impact assessment, biodiversity legislation, R&D funding evaluation, demographic change, and emergency supply.

The presentation focuses on exploring through DMDU lens ongoing pilots in which AI is brought into sparring situations as an analytic co-facilitator. AI listens to and synthesises real-time discussion, identifies emerging assumptions and possible groupthink, and generates challenge prompts from pre-defined epistemic archetypes, such as a pessimistic systems thinker. It is suggested that in the sparring sessions AI effectively functions as a structured prompt for second-order reflection.

The contributions of the presentation are both methodological and critical. The presentation argues that AI-augmented Science Sparring is a novel method that can help scale DMDU principles by lowering the practical threshold for robustness thinking inside public institutions. At the same time, the pilots reveal governance challenges concerning confidentiality, facilitative authority, algorithmic steering, transparency, and trust.

Surrogates and Chatbots: Natural Language Interaction and Surrogate Modeling as a Vehicle to Enable Engagement With DMDU Analyses

Authors: James Syme (Tecnológico de Monterrey), Edmundo Molina (Tecnológico de Monterrey), Alexa Martinez (Tecnológico de Monterrey)

Institutionalizing Decision Making under Deep Uncertainty (DMDU) methods remains a persistent challenge, particularly due to the computational complexity of models, the technical expertise required for their use, and limited continuity in institutional capacity. These constraints often inhibit sustained engagement between modeling teams and decision makers, reducing the long-term impact of Robust Decision Making (RDM) analyses.

This paper presents a generalizable analytical framework to facilitate continuous interaction between RDM-based modeling systems and policy stakeholders. The approach integrates three core components: (1) the development of statistical surrogate models that approximate complex simulation models, enabling rapid exploration and interrogation of large ensembles of futures; (2) the deployment of AI-based conversational interfaces capable of dynamically querying these surrogate models to perform real-time exploratory analysis; and (3) the integration of retrieval mechanisms to incorporate study-specific context from policy documents, technical reports, and prior analytical outputs.

Together, these components enable an interactive decision-support environment in which stakeholders can engage more easily with uncertainties, evaluate policy trade-offs, and conduct scenario discovery without direct reliance on model developers. The framework is demonstrated through an applied use case in which stakeholders engage with an AI-enabled interface to interrogate model behavior, identify vulnerabilities, and assess the robustness of alternative strategies. We further discuss methodological considerations for training surrogate models, structuring model–interface interactions, and ensuring transparency and interpretability in AI-mediated analysis. Early results show promising potential to facilitate long-term adoption and interaction with DMDU analyses by stakeholders.

Can a Structured LLM Do Assumption-Based Planning? Validating an AI-Enabled DMDU Tool

Authors: Nidhi Kalra (RAND), Javier Rojas (RAND School of Public Policy), Tim McDonald (RAND)

Decision Making under Deep Uncertainty (DMDU) methods suit complex “wicked” policy problems, yet adoption is limited by required expertise, technical resources, perceived slow turnaround, and low visibility. Large language models (LLMs) could reduce these barriers, but off-the-shelf LLMs lack the rigor DMDU demands. We present a pilot AI-enabled ABP tool that pairs the ABP literature with structured AI protocols in a human-driven, AI-supported workflow. Two Claude-based agents work in sequence: the first extracts an explicit plan from source documents; the second performs the ABP analysis, identifying the plan’s load-bearing assumptions and resulting vulnerabilities. We evaluate each agent separately, testing plan accuracy and ABP quality against explicit criteria and expert review. Three use cases (mirror life risks, the future of NATO, and AI-enabled biological threats) are

reviewed by subject-matter experts, whose feedback drives iterative revision. We report where structured LLMs can support rigorous ABP, where human judgment remains essential, and what a minimum viable interface requires. We also outline a strategy of developing tools in parallel with deployment on live research projects, arguing the largest gains come from integrating tools into real deliberation and decision loops, making DMDU accessible to more practitioners.

Session 12: Defense, Deterrence & Strategic Competition — Riverine Conference Room

A Geospatial Framework for Estimating SSBN Force Structure Across Deeply Uncertain Strategic Futures

Author: Kurt Klein (RAND)

Maintaining a second-strike capability is a central requirement of nuclear deterrence, yet determining the force structure necessary to support that capability involves substantial uncertainty. Future strategic environments may differ in ways that affect survivability requirements, operational constraints, technological capabilities, targeting demands, and other factors relevant to force-structure planning. These uncertainties raise an important question: how should decision makers evaluate force-structure requirements when key aspects of the future operating environment remain unknown?

This presentation introduces a geospatial framework for estimating Columbia-class ballistic missile submarine (SSBN) force-structure requirements under deep uncertainty. The approach uses geospatial analysis to identify and evaluate underwater operating areas capable of supporting a secure second-strike capability under varying assumptions about future conditions. Rather than focusing on a single future environment, the framework is designed to explore how force-structure requirements change across alternative strategic futures.

The project combines geospatial analysis with exploratory assessment of uncertain future conditions that may influence force-structure requirements. These uncertainties may include technological developments, operational considerations, evolving target requirements, geopolitical conditions, and other changes that shape future strategic environments. By examining how different assumptions affect estimated force-structure requirements, the framework seeks to identify the factors most influential to planning outcomes and evaluate the robustness of alternative force-structure options.

Beyond the specific application to Columbia-class submarines, this research demonstrates how geospatial methods can be combined with decision making under deep uncertainty to support transparent, reproducible, and adaptable force-structure planning. The presentation will discuss the proposed framework, ongoing research, and opportunities for applying similar approaches to other long-term defense planning challenges.

Modelling Adaptive Drug Trafficking Networks

Authors: Coen van den Elshout (Delft University of Technology), Jan Kwakkel (Delft University of Technology), Willem Auping (Delft University of Technology), Patrick Steinmann (Delft University of Technology)

Despite increasing policy interventions, record quantities of illicit drugs continue to reach consumer markets worldwide. The illicit drug trade contributes to corruption, infiltration of legitimate institutions, and violence. Policymakers struggle to keep pace with criminal organizations, which rapidly adapt their trafficking routes and operational tactics in response to enforcement measures. This

adaptive behavior is often referred to as the waterbed effect, in which pressure on one trafficking route or modus operandi causes criminal activity to shift elsewhere. As a result, policymakers face a reactive cycle in which interventions displace rather than disrupt criminal activities.

Designing effective interventions requires anticipating criminal responses, yet this is complicated by the deep uncertainty surrounding illicit drug markets. Criminal networks are covert by nature, resulting in fragmented data, limited knowledge of network and trafficking structures, and an incomplete understanding of the mechanisms driving criminal adaptation.

To address these challenges, we are developing an expert-informed system dynamics model of global drug trafficking systems. The model integrates knowledge from security experts across multiple regions to represent trafficking routes, criminal decision-making, and responses to policy interventions. As an exploratory model, it enables the examination of criminal behavior under deep uncertainty and provides a foundation for evaluating alternative policy responses across a range of plausible futures. This presentation introduces the model structure, the expert-informed modelling approach, and preliminary results, and discusses how simulation modelling can support the design of more adaptive anti-trafficking policies.

An RDM-based Approach to Simulating Competition Under Deep Uncertainty

Author: David Kong (RAND School of Public Policy)

This study initially set out to design a novel analytical framework for simulating hybrid warfare the West Pacific in the context of U.S.-China competition, and ended up designing an approach to competition under deep uncertainty (CDU) where hybrid warfare is but one example.

CDU is defined as an interaction between two or more agents that features 1) competition with player-unique objectives, 2) shifting environment induced by agent actions, and 3) interactive complexity. Deep uncertainties stem from both the player type and interactive complexity. There exist tools to address each of these features, i.e., Game Theory, stochastic process (Markov Decision Process or MDP) and RDM. The proposed framework fills the gap, i.e., the lack of a one-stop approach to CDU, by integrating the three tools.

The design of the framework is RDM-based. It is essentially an RDM process with the simulation for competition functioning as the underlying decision mechanism. The simulation itself is not the traditional Markov Game (a combination of MDP and Game Theory) but a multi-objective optimization, with one unique objective for each agent and each objective being an MDP objective. Unique objectives are defined as those who share no linear relationship or metric, i.e., "comparing apples to oranges," which a Markov Game cannot handle and hence the gap.

Session 13: Foundational Methods & Emulation Tools (Part 1) — Basin Conference Room

Integrating SuPy into Exploratory Modelling for Urban Climate Adaptation: A Proof-of-Concept Application

Author: Simona Mannucci (Sapienza University of Rome)

DMDU is widely applied in domains such as water and coastal management, where exploratory modeling is used to evaluate strategies across large ensembles of plausible futures. In urban planning and design for climate change adaptation, and particularly in built-environment applications, DMDU

remains underexplored, despite being well-suited to situations in which the robustness of adaptation measures must be assessed jointly against multiple climate-related challenges affecting urban areas.

This contribution presents an ongoing integration of the EMA Workbench with SuPy, the Python implementation of the Surface Urban Energy and Water Balance Scheme (SUEWS), to support exploratory analysis of urban adaptation strategies affecting both thermal conditions and surface runoff. SuPy enables the simulation of coupled urban energy and water balance processes, making it possible to evaluate how changes in urban form and surface properties influence heat and runoff responses. The workflow combines alternative meteorological forcings associated with RCP 4.5 and RCP 8.5 with urban design decision levers, including vegetation fraction, the albedo of open spaces and roofs, and surface permeability.

A proof-of-concept application on a simplified urban grid is used to test the workflow and to explore the response of selected interventions across contrasting climate futures. Preliminary results demonstrate the feasibility of an EMA–SuPy workflow for urban climate adaptation and its potential to support robustness-oriented assessment of planning strategies across different futures for multiple climate challenges.

Conditional Protection Matrices for Decision Making Under Partial Information

Author: Kurt Klein (RAND)

Decision makers operating under deep uncertainty rarely remain completely ignorant about the future. Information accumulates over time through observations, intelligence, monitoring, and unfolding events. While these developments can reveal important information about future conditions, decision makers are often still left with the question of how strategies should change once some uncertainties become better understood while others remain unresolved.

This presentation introduces Conditional Protection Matrices, a decision-support artifact designed to support adaptive planning under partial information. A Conditional Protection Matrix shows which strategies hedge against remaining uncertainties given partial information revealed through signposts or observations. The matrices help decision makers identify opportunities to gain protection against unresolved uncertainties as knowledge about the future environment improves.

The presentation illustrates the concept through a Robust Decision Making study of protecting the U.S. bulk electric system from geomagnetically induced currents (GICs). In that application, planners could use information about hazard characteristics, infrastructure conditions, or other observable developments to determine which protection strategies remained robust against uncertainties that had not yet been resolved.

Conditional Protection Matrices extend the value of exploratory modeling by connecting signposts to actionable decisions. The matrices help decision makers understand where protection is most needed as information emerges, allowing resources to be directed toward addressing the most relevant risks while avoiding unnecessary actions. More broadly, they support staged implementation, focused monitoring, and adaptive decision making by helping planners translate partial information into practical choices under conditions of deep uncertainty.

Sneaking Deep Uncertainty into Transportation Planning: The Boston MPO Growth Rate Explorer

Author: Martin Milkovits (Boston Region MPO)

Historically, the core purpose of travel demand modeling at Metropolitan Planning Organizations in the US has been to fulfill the statutory requirement of providing transportation projections for the Long-Range Transportation Plan (LRTP). The travel demand model is necessary for analyzing major roadway and transit projects, and for environmental impact reviews of significant developments. A predictive approach is currently necessary for these applications. However, this limits the model's potential as an effective decision-support tool, particularly when faced with unresolvable uncertainties like climate change, the rise of remote work, and vehicle automation. Travel modeling risks becoming a mere compliance step, detracting from its potential as a source of insight. This shift has eroded confidence in its results and utility.

While Decision Making Under Deep Uncertainty (DMDU) methodologies offer robust analytical alternatives, integrating these approaches into transportation planning workflows remains challenging. A primary hurdle is accessibility and availability: complex scenario modeling data is often opaque to the planners and the transportation models are not able to rapidly respond to new questions and concerns.

To overcome this theory-practice gap, the Boston Region Metropolitan Planning Organization developed the Growth Rate Explorer (https://ctps.shinyapps.io/growth_rate_explorer/). This interactive, web-based application is designed to broaden conversations about travel forecasts into considerations of the factors that could threaten plans and change outcomes - paving the way to practice DMDU approaches with analytical support.

In this presentation, we will describe the model process and application structure and share practical lessons learned through stakeholder engagement. This will highlight the gap between advanced transportation modeling and planning practice, as well as the cultural - process shifts we anticipate needing to advance regional transportation planning under deep uncertainty.

Integrating Foresight Methods to Enable Robust Planning Under Deep Uncertainty

Authors: Richard Silberglitt (RAND - Retired), Steven Popper (Tecnológico de Monterrey)

Wicked problems of public policy are fraught for traditional analysis because of technical complexity, deep uncertainty, and contention over goals, perspectives, assumptions, future expectations, and even disagreement on problem definition. Model-based analytical approaches often are stymied by factors lying outside the model. To bring the power of these quantitative tools to bear, they must be placed within a broader context addressing the normative dimensions as well. VSCARP (Vision, Strategic Concepts, Assumptions, Robust Pathways) is a general-purpose participatory foresight method that allows participants to explore, frame, and share alternative visions. They then deliberate on scenario pathways that highlight the assumptions inherent in different courses of action and how future conditions, situations, and events may enable or prevent the success of strategies based on current beliefs. It supports adaptive and resilient planning by broadly diverse teams of stakeholders in the face of deeply uncertain and potentially rapidly changing policy environments. Based on four existing methods, its use of them in an integrated fashion produces results that no one method used alone could obtain. VSCARP has been applied to a diverse range of policy areas, including urban housing and transportation, workplace safety, economics, technology, urban planning, food security, technology

policy, and supply chains among others. Making use of both small- and large-group dynamics, VSCARP de-conflicts otherwise contentious discussions, creates a common language for deliberating dynamic change over time, sets a baseline for either follow-on or broadened collaboration, provides forensic analysis necessary for designing model-based support tools, such as RDM, that may then be incorporated in a deliberation-with-analysis process, and can lead to strong bases for further specific strategy development. This talk will lay out VSCARP principles, objectives, format, examples of use, and prospects for even wider application.

Session 14: Bridging Practice, Education & Capacity Building — Delta Conference Room

DMDU With Hundreds of Decision Makers: How DMDU Principles and Approaches Can Support Climate Adaptation In the Farming and Forestry Industries

Author: Julie Shortridge (Virginia Tech)

Natural resource industries, such as farming and forestry, form the backbone of many rural, state, and regional economies. These industries are highly climate vulnerable, while also holding tremendous potential for climate mitigation by reducing land-based GHG emissions and increasing carbon sequestration. Improved land management in farming and forestry could help address climate risks and harness mitigation potential; however, meaningful changes require widespread adoption of improved measures across a large and diverse body of private landowners and operators. This presentation will identify ways in which the principles and approaches within DMDU can help support climate adaptation in farming and forestry, drawing on recent projects in rural Finland and the Delmarva (Delaware-Maryland-Virginia) peninsula in the U.S. Both locations are experiencing rapid rates of regional climatic changes that are greatly impacting local farming and forestry industries and undermining broader sustainability goals. In both cases, key ideas from the DMDU field have proved useful in structuring project activities, integrating contributions across multiple fields, and targeting efforts into actionable recommendations. At the same time, the unique decision context within natural resource industries suggests several ways in which DMDU approaches could be adjusted or broadened for greater impact. This presentation will aim to advance discussion on how DMDU approaches can be most effectively applied to agriculture, forestry, and other contexts where action is driven by numerous independent actors.

Advancing DMDU Education: Moving To The Next Stage

Presenters: Steven Popper (Tecnológico de Monterrey), Rob Lempert (RAND), Edmundo Molina (Tecnológico de Monterrey)

As DMDU concepts and tools are increasingly accepted and even preferred for applications that elude more traditional methods, there is a need for DMDU education to keep pace. Classes incorporating DMDU techniques are spreading, but much of the training that occurs is still largely via the one-on-one quasi-apprenticeship model that characterized the discipline's earliest practice. How can the pace be accelerated, regularized, or made more effective? How can DMDU training go forward within settings ranging from structured classrooms to on-line offerings? What should constitute a DMDU curriculum tailored for different audiences and what would constitute its core? Should the DMDU Society offer guidelines for DMDU instruction?

This panel will address such questions from an initial perspective offered by the authors of a draft textbook on Robust Decision Making, a leading DMDU method, to be published by Springer Nature in the next year. One key question is, for example, is toward whom should such instruction be

directed? The book is intended to address an audience that varies widely. From its onset, the DMDU Society has viewed its efforts in education and training to serve two main groups. The first are those wishing to learn to apply DMDU methods. The second, however, are those audiences who receive and deliberate on DMDU findings for their own planning and implementation. The panelists will briefly present the concepts behind their book and outline its structure. The bulk of the session will be a group discussion reflecting the questions raised above. The intent is to seed that discussion by providing a specific example that could support the ensuing deliberation among session participants. The discussion can flow freely from that inception.

Session 15: Coastal Adaptation and Retreat — Riverine Conference Room

Coastal Adaptation Under Uncertainty: A Participatory MCDM Analysis of Coastal Squeeze Solutions

Authors: Anamaria Bukvic (Indiana University Bloomington), Thomas R. Allen (Old Dominion University), Patrick Biber (University of Southern Mississippi)

Coastal squeeze, or the loss of coastal habitats due to sea-level rise, erosion, and human development, represents a multi-objective decision problem under deep uncertainty, with often conflicting social, environmental, and economic goals. In rapidly changing coastal systems, policymakers and planners have to move forward with their decisions despite substantial uncertainties about future physical conditions and stakeholder preferences. This presentation reports on the workshop with 53 stakeholders vested in coastal adaptation in the Hampton Roads metropolitan area and the Eastern Shore of Virginia. The workshop's research activity used a participatory Multi-Criteria Decision-Making (MCDM) framework to evaluate adaptation options for coastal squeeze. Using the 1000Minds software and the PAPRIKA method, participants completed pairwise comparisons to derive criteria weights reflecting their organizational priorities and prioritize coastal squeeze solutions. The top-ranked strategies include creating upland migration corridors, offering incentives to guide development away from wetlands, marsh restoration, living shorelines, and property buyouts with land conversion for wetland accommodation. Our approach provides a highly participatory, structured, and transparent mechanism to facilitate decision-making and consensus-building under uncertainty. Such insights are critical for designing adaptive and flexible coastal management strategies under uncertain future conditions.

Considering Retreat can be Crucial to Identify Robust Adaptation Strategies in Nourishment-Dependent Coastal Communities

Authors: Prabhat Hegde (Princeton University), Adam Pollack (University of Iowa), Vikrant Vaze (Dartmouth College), Klaus Keller (Dartmouth College)

Many coastal communities rely on recurring beach nourishment to manage erosion risks driven by rising seas and intensifying storms. However, increasing hazards, escalating costs, and evolving environmental conditions threaten this strategy's long-term viability. As nourishment becomes harder to sustain, managed retreat is emerging as a credible adaptation lever. This raises the question: when to retreat, if at all?

Past studies provide important insights but are typically silent on the timing of retreat, the effect of uncertainties, and trade-offs between multiple objectives. Decisions neglecting these factors risk producing strategies that underperform across plausible futures or fail to reflect stakeholder priorities. Here, we address these gaps through a case study of Hutchinson Island in St. Lucie County, Florida,

where prior studies by the U.S. Army Corps of Engineers and academic researchers provide a well-documented basis for comparison.

We implement a multi-objective robust decision making framework that jointly evaluates the timing and sequencing of nourishment and retreat across many states of the world. We adopt a satisficing robustness perspective, defining robustness as meeting performance thresholds across uncertain states of the world. We analyze the effects of uncertainties, quantify trade-offs between key objectives, and identify the uncertainty drivers most strongly influencing performance. We show that accounting for uncertainty changes the expected performance of adaptation strategies and alters trade-offs between objectives, causing strategies acceptable under deterministic assumptions to fall short of decision-relevant performance thresholds.

In our case study, only retreat-triggering strategies meet a commonly used benefit–cost ratio threshold, highlighting the limitations of nourishment-only approaches under uncertainty. Meeting this threshold would require initiating retreat roughly two decades earlier than prior benchmarks; satisfying reliability pushes this to about five decades earlier. More broadly, our findings underscore the value of considering the interactions of retreat, uncertainty, and multiple objectives in coastal adaptation planning to improve decision analyses.

Multi-Objective Optimization in the 2029 Louisiana Coastal Master Plan

Authors: Nastaran Tebyanian (The Water Institute), Patrick Kane (The Water Institute)

The Louisiana Coastal Master Plan is a 50-year plan for the state's coastal restoration and risk reduction efforts. Since its inception it has always been an example of decision-making under deep uncertainty as the coastal landscape and associated flood risk over a 50-year period are necessarily deeply uncertain. Previous Master Plans have attempted to incorporate DMDU methods and insights like Robust Decision Making and Multi-Criterion Decision Analysis, but the extent to which these methods have been used has been limited by modeling capacity. Master Plan 2029 (MP29) represents a step forward for the incorporation of DMDU methods with model improvements allowing for more complex DMDU methods for multi-objective optimization to assess tradeoffs and robustness. The 2029 version of the Coastal Master Plan (MP29) analysis has broadened the number of primary objectives that can be considered for both restoration and risk reduction [KF1] projects to better assess tradeoffs between objectives. Specifically, the analysis design constructs many thousands of Pareto-optimal portfolios of projects through multi-objective optimization with genetic algorithms. However, rather than simply selecting a portfolio to proceed with, the analysis uses this ensemble of portfolios to develop prioritized lists of individual projects based on which most frequently appear across the portfolios. This analysis is coupled with the development of interactive visuals to better highlight the conditions under which individual projects might be desirable based on other considerations like performance across scenarios, cost or secondary metrics. This talk covers the development of methods suitable for the Master Plan's decision-making needs and data generation pipeline and in particular the novel use of these portfolio-based methods and visualization.

A Framework For Optimizing Green-Grey Infrastructure Selection

Authors: Paul Lagarde (ERDC), Thomas Clement (ERDC), Sally ("Catie") Dillon (ERDC), Amanda Tritinger (ERDC), Rusty Permenter (ERDC)

Selecting effective and cost-efficient infrastructure to reduce coastal flood hazard remains a labor-intensive process for public and private institutions. Doing so requires the consideration of several

criteria: economic development, engineering suitability, environmental acceptability, project costs, and other difficult-to-quantify, second-order benefits such as community resilience. Employing Natural Infrastructure (NI) is an attractive strategy in this multifaceted environment because of its ability to integrate hazard reduction with both engineering and social/ecological benefits. However, the effectiveness of NI is often site-dependent, and evaluating the effectiveness of NI at a given site can require complex modeling and lengthy monitoring periods. To help bridge this science-policy gap we introduce Green-iCOW, a mixed green-grey infrastructure optimization tool that extends iCOW (Ceres et al., 2019), a framework employing Robust Decision Making (RDM) to evaluate grey infrastructure combinations. Green-iCOW uses intentionally simplified physics to define rough cost and hazard reduction functions for mangrove forests and coastal wetlands. The inclusion of these categories allows planners to use Green-iCOW as a "filter" to quickly, transparently, and repeatably select near-optimal green-grey infrastructure combinations from a wide possibility space before employing a more detailed model for feasibility level design work. As an early-stage result we use Green-iCOW to show that inclusion of these green infrastructure options produces cost-optimal infrastructure configurations under a variety of physical and morphological assumptions, suggesting that green infrastructure inclusion increases the flexibility planners have while designing cost-optimal infrastructure even under deeply uncertain conditions. Ongoing development work will further refine the modeling of wetlands and mangroves, study specific locations in more detail, and integrate environmental suitability and community resilience benefit quantification.

Session 16: Water Resources & Reservoir Operations — Basin Conference Room

Bayesian-Belief Direct Policy Search for Adaptive Water Supply Planning with Endogenous Learning

Authors: Mofan Zhang (Stanford University), Megan Lickley (Georgetown University), Marta Zaniolo (Duke University), Arjun Nellikkattil (Georgetown University), Sarah Fletcher (Stanford University)

Climate change uncertainty challenges water supply planning, where long-lived infrastructure must ensure reliable supply under evolving conditions. Adaptive planning addresses this by incrementally expanding infrastructure only as needed, reducing unnecessary investments. Direct Policy Search (DPS), a reinforcement learning approach, has been widely used to identify adaptive rules that specify when and how much to expand infrastructure based on system conditions. However, standard DPS assumes static climate uncertainty, overlooking the potential to update uncertainty as new information emerges, potentially leading to over- or under-investment as the climate evolves. We introduce Bayesian-Belief DPS, a novel framework that integrates Bayesian learning into DPS to account for learning about climate uncertainty in adaptive planning. We do this by expanding the DPS state space to include a belief state, representing evolving climate uncertainty. The belief state is updated using Gaussian process regression as new observations become available. For instance, uncertainty about end-of-century climate is greatest early on but declines over time as data accumulates. We apply Bayesian-Belief DPS to contrasting infrastructure planning case studies in Mombasa, Kenya and the Maipo River Basin in Chile. In Kenya, we find that incorporating Bayesian-Belief indicators of precipitation change enhances robustness and cost-effectiveness, especially under nonlinear precipitation trajectories, where past trends do not linearly predict future change, and for long-lived investments. In Chile, we extend the approach to consider multiple Bayesian-Belief indicators including streamflow, precipitation, and glacier melt. We find that using Bayesian Belief indicators reduces the sensitivity of cost–reliability tradeoffs to the choice of indicator. By endogenously

modeling climate beliefs, Bayesian-Belief DPS advances DMDU methods by complementing flexibility with learning, enabling policies that respond to evolving uncertainty and improve robustness under deep uncertainty.

Leveraging Evolutionary Multi-Objective Reinforcement Learning and Sensitivity Analysis to Better Navigate Implementation Uncertainty in Cooperative Water Supply Investment Pathways

Authors: Lillian Lau (Cornell University), Patrick Reed (Cornell University)

Urban water utilities are increasingly turning to regional cooperation to cope with the combined pressures of hydroclimatic extremes, uncertain demands, and limited financial resources. The utilities can cooperate using dynamic and adaptive risk-based action triggers to coordinate short-term drought mitigation actions and long-term infrastructure co-investments. However, these actions are not likely to be perfectly implemented. This exposes participating utilities to implementation uncertainty, where unintentional deviations from a prescribed set of actions can degrade participating parties' individual and collective robustness.

To address this challenge, we contribute the Deeply Uncertain Pathways under Implementation Uncertainty (DU Pathways IU) framework that exploits evolutionary multi-objective reinforcement learning (eMORL) to discover pathway strategies that achieve high robustness to deeply uncertainty future conditions while maintaining performance gains under implementation uncertainty (IU). Our results show that the inclusion of IU during eMORL search yields a much larger and diverse set of robust pathway strategies, providing a richer context for informing the selection regional compromises. From this diverse set of strategies, we distinguish the effects of accounting for IU on three different compromise pathway strategies' actions. Here, we use Delta Moment-Independent Sensitivity Analysis to map how the independence or interdependence of the cooperating utilities actions impact their performance. We show that the strategies attained by optimizing under IU allow utilities better control over their individual performance under challenging conditions while enhancing the shared robustness of the whole region. Additionally, we demonstrate that failing to account for IU leaves individual utilities' performance vulnerable to degradation stemming from small changes in the implementation of their counterparts' risk-based actions. Overall, we show that directly accounting for IU allows utilities to achieve shared robustness while reducing the risks that may arise from imperfect coordination. These results are broadly applicable to utilities seeking robust and operable cooperative water supply management and investment pathways.

Continuous Adaptation of Reservoir Control Policies via Bayesian Updating Across a Climate Exposure Space

Author: Marta Zaniolo (Duke University)

Reservoir operating policies are rules that describe how much water to release from reservoirs in response to storage, inflows, and demand. In systems affected by climate change, routinely revisiting these rules is an important lever for adaptation without requiring further construction or investment. Recent studies have shown significant potential for improving reservoir operations by reoptimizing policies at fixed time intervals or when significant changes in flow or precipitation are detected. Both approaches, however, treat policy adaptation as an episodic event, whereas the climate and demand conditions that drive the need for adaptation change continuously.

We propose a framework that replaces discrete reoptimization triggers with a continuous policy

mapping defined over a climate exposure space. We systematically sample a multi-dimensional space of hydrological characteristics (e.g., mean flow, drought persistence, flood tail behavior) and train an optimal reservoir control policy for each combination using multiobjective evolutionary direct policy search. A Gaussian Process emulator then learns a "policy atlas", namely, a smooth mapping from climate characteristics to optimal policy parameters.

We apply this framework to Oroville Dam in California, simulating the system forward across an ensemble of climate scenarios. At each timestep, Bayesian state estimation uses the most recent streamflow observations to update a posterior over the current climate characteristics, which locates the system within the policy atlas. This allows policy parameters to update smoothly and continuously as new observations become available. Because uncertainty in the climate estimate propagates through the emulator, the framework also yields uncertainty in the recommended policy parameters at every timestep, providing a signal for when the current atlas region is poorly constrained and targeted reoptimization is warranted. We evaluate performance against fixed-frequency and trigger-based benchmarks across the full scenario ensemble.

Quantifying Explanation Uncertainty in XAI Emulators for Water Shortage Attribution in the Western U.S.

Authors: Yifan Luo (Cornell University), Danielle Grogan (University of New Hampshire), Shan Zuidema (University of New Hampshire), Richard Lammers (University of New Hampshire), Jiameng Zheng (Louisiana State University), Matthew Lisk (Pennsylvania State University), Karen Fisher-Vanden (Arizona State University), Sheila Olmstead (Cornell University), Vivek Srikrishnan (Cornell University)

Water scarcity in the Western U.S. arises from coupled interactions among hydroclimatic variability, human water use, infrastructure operations, and institutional constraints, making attribution of shortages to specific drivers challenging. Process-based hydrologic models can represent these dynamics, but their computational cost limits large-scale sensitivity analysis and their complexity complicates interpretation. This study presents an integrated framework that combines a deep learning emulator of the UNH Water Balance Model (WBM) with an ensemble of six eXplainable Artificial Intelligence (XAI) methods to characterize the dominant drivers of water shortages and the uncertainty in those explanations.

We emulate monthly unmet water demand ratios across Western U.S. Water Management Areas during 2010–2019 using a Convolutional Long Short-Term Memory (ConvLSTM) network trained on meteorological and human use inputs. The emulator reproduces WBM outputs with high test-set skill, enabling rapid regional attribution analyses that would be computationally expensive with the original process-based model. We then apply R^2-based leave-one-covariate-out (LOCO), permutation feature importance (PFI), SHapley Additive exPlanations (SHAP), connection weights, input gradients, and Local Interpretable Model-agnostic Explanations (LIME) to estimate dominant drivers of unmet demand.

We find that different XAI methods can produce substantially different attributions for the same emulator output, with the largest disagreement in mixed urban-agricultural basins. While precipitation is consistently identified as the dominant driver in the Pacific Northwest and Rockies, the relative importance of temperature and water use variables is highly method-sensitive. To address this, we introduce a consensus attribution framework that maps both the plurality dominant driver and cross-

method agreement strength, identifying regions of robust attribution and regions of high explanation uncertainty. This work demonstrates how quantifying explanation uncertainty transforms black-box emulators into transparent, reliable tools for scientific attribution in complex human-natural systems.

Session 17: Developing Priority Research Questions for DMDU in Insurance — Delta Conference Room

Developing Priority Research Questions for DMDU in Insurance

Author: Allison DeJong (The Water Institute)

The crisis of insurance availability and affordability in the US has spread beyond California and the Gulf Coast states, reaching states that have marketed themselves as climate havens. Homeowners face steep increases in the price of a homeowners policy, and are now navigating an uncertain flood insurance market with shifting changes in the NFIP. State regulators are caught between wanting to protect consumers from drastic rate increases and facing a market where no insurer may want to write policies. Existing frameworks like Crichton's risk triangle (hazard, vulnerability, exposure) and the success of IBHS research-based vulnerability reduction programs such as FORTIFIED indicate that solutions targeting structure vulnerability may be successful in mitigating price increases. However, the number of systems, actors, uncertainties, perils, and objectives across the insurance space points to the need for DMDU approaches.

This talk invites the DMDU research community as well as actuaries, hydrologists, modelers, finance professionals, and insurance practitioners to develop priority research questions in insurance using DMDU methods. This talk will identify some potential topic areas, drawing on research and practice from the Water Institute's work across flood risk, insurance, and planning, and will engage with attendees to synthesize key questions where DMDU could be helpful in framing decisions (such as portfolio optimization) or methods (such as investigating discrepancies across time and geographic scale) for actors in the insurance space. New approaches, such as parametric insurance, catastrophe bonds, all-hazard policies, and other risk transfer products will also be discussed, building on the Water Institute's work to develop and place Community-Based Catastrophe Insurance (CBCI) policies in Louisiana.

Session 18: Grid & Electric Infrastructure Resilience — Riverine Conference Room

When the Model Is Also Uncertain: DMDU for AI-Driven Grid Planning

Author: Ruobing Wang (RAND School of Public Policy)

Rapid growth in AI-related data centers is creating a new class of challenges for electric-grid planning and regulation. Large dynamic digital loads can add substantial demand on timelines far shorter than transmission expansion, generation development, and regulatory adaptation. Decisionmakers must therefore evaluate policies such as interconnection rules, co-location requirements, curtailment thresholds, and cost-allocation frameworks under deep uncertainty about future load growth, spatial clustering, behind-the-meter resource adoption, renewable variability, and extreme weather.

This presentation develops a Decision Making under Deep Uncertainty (DMDU) framework for stress-testing policy responses to AI-driven electricity demand growth. Using an XLRM structure, the analysis identifies key exogenous uncertainties, candidate policy levers, relevant modeling relationships, and performance metrics for evaluating grid reliability and resilience. A central challenge is that available engineering models differ in the risks they can represent: phasor-based and

electromagnetic-transient approaches capture different aspects of instability, creating model-form uncertainty in addition to uncertainty about future conditions.

The talk argues that simulation architecture should be treated as part of the decision problem rather than as a fixed analytic input. Doing so can help support more robust infrastructure decisions in settings where technological change is outpacing both regulation and established modeling benchmarks. Motivated by emerging U.S. debates over large-load interconnection, co-location, and behind-the-meter infrastructure, the presentation offers a prototype framework for extending DMDU to rapidly evolving socio-technical systems.

Robust Substation Upgrade Strategies for Electric Heavy-Duty Truck Charging Under Deep Adoption Uncertainty

Authors: Fletcher Passow (Stanford University), Sarah Fletcher (Stanford University), Ram Rajagopal (Stanford University)

Heavy-duty freight trucks make up only 1.8% of U.S. vehicles but produce 15% of transportation greenhouse gas emissions. Adopting electric heavy-duty trucks (e-HDTs) would reduce emissions and local air pollution, but the high-power charging required would also strain electric distribution grids near truck stops, warehouses, and factories. Upgrades to electrical substations — the critical interface between distribution and transmission grids — can take years and cost millions, while operators can acquire e-HDTs in under a year.

Grid operators are mandated to serve all customers, including anticipated e-HDT loads, yet they must also avoid building infrastructure that isn't "used and useful." Even recently proposed aggressive timelines from the California Public Utilities Commission put substation completion at 3–9 years — far beyond e-HDT procurement timelines. Proactive planning is therefore essential, but the wide range of plausible futures for e-HDT technology, economics, and policy makes this deeply challenging.

Existing models of e-HDT grid impacts report load estimates for single scenarios or small scenario sets, and none propose investment strategies evaluated for robustness across plausible adoption trajectories. This leaves grid operators without a principled basis for deciding how much to invest, where, and when.

To address this gap, we develop an adaptive planning framework for designing substation upgrade strategies that are robust to deep uncertainty in e-HDT adoption. Strategies vary along three dimensions: which substations to prioritize, what infrastructure to build, and when to act. We evaluate each strategy across a wide range of adoption scenarios using LAUREL, our existing grid impact model. Based on previous work, we hypothesize that prioritization based on business activity patterns and timing conditioned on observable adoption signals instead of calendar-year triggers will yield the most robust outcomes. We will also explore the trade-offs between strategies which emphasize traditional substation upgrades and those which focus on grid-scale batteries.

Protecting the Bulk Electric System From Geomagnetically Induced Currents: A Robust Decision Making Approach

Author: Kurt Klein (RAND)

Geomagnetically induced currents (GICs) generated by high-altitude electromagnetic pulse (HEMP) events pose a potential threat to the bulk electric system. Planning protective investments for these

hazards is complicated by the deep uncertainty surrounding event behavior, system characteristics, and future operating conditions. At the same time, stakeholders often define vulnerability differently. Electric utilities may prioritize limiting operational disruption, equipment damage, and compliance with reliability standards, while national security planners may focus on preventing large-scale cascading failures or preserving continuity of critical infrastructure functions.

This presentation summarizes the findings of a dissertation that applies Robust Decision Making (RDM) to evaluate methods for deploying neutral blocking devices (NBDs) to protect the U.S. bulk electric system from GIC-related risks. Using large ensembles of power-system simulations across uncertain hazard and infrastructure conditions, the research evaluates how different protection strategies perform under multiple definitions of vulnerability and varying levels of protective deployment.

The analysis shows that the most robust protection strategy depends both on how vulnerability is defined and on the level of protection deployed. Strategies that perform well for one stakeholder community are not always preferred by another, creating potential tensions in investment priorities. At the same time, the results identify opportunities for coordination by revealing where stakeholder objectives align and where incremental protection measures can reduce risk across multiple vulnerability definitions. The research further demonstrates how staged deployment approaches can reduce severe risks while preserving flexibility as additional information becomes available.

This work represents a novel application of RDM to GIC protection and power-engineering decision problems, areas where such approaches have seen limited use. The dissertation also develops new decision-support artifacts that help decision makers identify robust protection strategies, understand tradeoffs, support adaptive implementation, and coordinate planning under deep uncertainty.

Session 19: Polycrisis, Geopolitics & Compound Risk — Basin Conference Room

Anticipatory Closure under Polycrisis? Reflections from a Disaggregative Delphi on Environmental-Geopolitical Uncertainty in the Gulf of Finland

Author: Aleksi Neuvonen (Demos Helsinki)

This paper examines the epistemic dynamics of anticipations amidst geopolitical and environmental crises, utilizing a disaggregative Policy Delphi study (1). The Russian war in Ukraine has transformed the Gulf of Finland from a cooperative region into a zone facing data gaps and emerging hazards, including accidental and intentional chemical pollutant discharges. The ongoing Coastal Waters under Pressure (CoWup) project investigates these dynamics.

The CoWup Delphi panel, conducted between November 2025 and May 2026, involved 63 experts from environmental sciences, security studies, governance, maritime infrastructure, and regional policy. The Delphi explored futures related to hybrid threats, environmental degradation, institutional breakdown, climate change, and monitoring capacity in the Baltic Sea region under deteriorating geopolitical relations with Russia.

While the design of the CoWup Delphi panel aimed explicitly to elicit divergent perspectives and explore uncertainty spaces, the results revealed an unexpected tendency toward convergence and horizon narrowing. Participants showed strong reluctance to speculate on extreme or transformative

futures.

The paper interprets these findings through the lenses of polycrisis, creeping crisis, and perspectivist epistemology. It argues that prolonged crisis conditions may produce forms of "anticipatory closure," where experts stabilize around socially legitimate and emotionally manageable futures instead of exploring the full range of plausible uncertainty. This phenomenon resembles a camp-fire consensus effect (2), in which epistemic communities seek cognitive shelter through consensus and proximity to prevailing institutional narratives.

1. Tapio. P. 2003. Disaggregative policy Delphi: Using cluster analysis as a tool for systematic scenario formation. Technological Forecasting and Social Change, 70(1), 83–101.
2. Bolger, F. & Wright, G. 2011. Improving the Delphi process: Lessons from social psychological research. Technological Forecasting and Social Change 78(9), 1500-1513.

Stress-Testing National Climate Targets: A 136 Country Scenario Discovery Assessment of NDC Feasibility and Failure Regions

Authors: Juan Antonio Robledo Lara (Tecnologico de Monterrey), Edmundo Molina (Tecnológico de Monterrey), Javier Rojas (RAND School of Public Policy), James Syme (Tecnológico de Monterrey), Fabian Fuentes (Tecnológico de Monterrey), Alexa Martinez (Tecnológico de Monterrey)

This paper addresses a central policy question under the Paris Agreement: given current structural and policy trajectories, which countries are likely to miss their 2030 Nationally Determined Contributions (NDCs), and which underlying drivers define their implementation failure. We develop a country-resolved empirical model in which national greenhouse gas emissions are represented as a function of three families of drivers grounded in the mitigation feasibility literature: Capabilities (economic and institutional capacity), Constraints (physical and energy-system conditions), and Incentives (policy instruments and price signals). The model is estimated using a harmonized panel of 136 countries over 2002–2022 with 68 explanatory variables. We combine this with stochastic, country-specific projections of each driver to generate 1,000 internally consistent emissions futures per country through 2030.

The resulting ensemble enables three policy-relevant outputs. First, we estimate the probability that each country meets its unconditional 2030 NDC target. Second, we identify country-specific failure regions, defined as combinations of Capabilities, Constraints, and Incentives associated with target non-attainment. Third, we examine how these driver combinations cluster across regions and income groups.

We find that approximately 31% of countries have at least a 50% probability of meeting their 2030 targets. Failure is predominantly associated with Constraint variables. Total primary energy consumption appears in the failure region of nearly all countries, and a consistent three-variable combination—fossil share of electricity, renewable share of electricity, and primary energy demand—characterizes failure across all income groups. In contrast, Incentive variables (e.g., climate policy adoption, carbon pricing coverage) and many Capability indicators appear less frequently in failure regions.

The paper extends probabilistic NDC assessment to 136 countries, introduces a consistent driver-based decomposition of implementation risk, and provides a fully open and reproducible dataset, model, and ensemble framework for policy analysis.

Robust Policy Design for Coupled Crises: A Multi-Objective Analysis of the Climate–Inequality–Radicalization Polycrisis

Authors: Javier Rojas (RAND School of Public Policy), Rob Lempert (RAND), Steven Popper (Tecnológico de Monterrey), Dan Hoyer (University of Toronto), Zora Kovacic (Universitat Oberta de Catalunya), Jonathan Lamb (RAND School of Public Policy)

When crises couple, single-sector policy advice breaks down. Climate stress, wealth concentration, declining institutional trust, and political radicalization increasingly interact as systemic risk, producing cascading and mutually reinforcing dynamics across coupled human and natural systems. Decision makers already navigate these interactions individually, but DMDU has rarely addressed them as one integrated system.

At DMDU 2025, we introduced the Climate-Inequality-Radicalization (CIR) model, linking climate damages, Piketty-style capital concentration, structural-demographic elite dynamics, SIR-style social tipping, and a Political Stress Index. The model showed that the most concerning coupled futures, including trust collapse, radicalization tipping, and fiscal distress, are not remote edge cases. They are plausible outcomes generated by feedbacks already visible in contemporary societies. The policy analysis, however, was limited to a small set of fixed portfolios.

For DMDU 2026, we move from diagnosing these futures to designing policy for them. The goal is not methodological refinement. It is to give decision-makers a robust policy design tool for the coupled risks their institutions must now manage: climate transitions colliding with cost-of-living politics, fiscal stress feeding populist instability, and social trust weakening under simultaneous shocks. Using the CIR model, we test policy portfolios across futures in which these systemic risks compound, including carbon taxation, wealth taxation, social investment, and their combinations. We identify which combinations remain robust in the futures that matter most, and which hold only under narrower assumptions.

The result is a decision map. For each policy bundle, it shows which coupled futures it can withstand, whose outcomes it protects, and which trade-offs it cannot avoid. The international systemic-risk community, spanning climate, disaster risk, fiscal, and security practitioners, increasingly demands responses that are themselves systemic, yet rarely receives analysis that crosses these silos. Our contribution is to make their interaction analyzable in a form that real institutions can use.

From Theory to Practice: A Review of Robust Decision Making in Real-World Contexts

Authors: Alexandra Bilder (RAND), Grant Ellison (RAND), Rob Lempert (RAND)

Among Decision Making Under Deep Uncertainty (DMDU) methods, Robust Decision Making (RDM) is one of the most established and widely applied. RDM has been adopted by major multilateral development banks, integrated into routine planning cycles by agencies, and extended beyond climate policy domains. Despite more than two decades of growth and diversification, there is limited survey of RDM's applications and an understanding of how it is used in practice. This review introduces the first comprehensive effort to address that gap.

Drawing on a systematic search of published and grey literature, we screened 2,944 database records ad 604 website results using an AI-assisted human in-the-loop review protocol to identify 118 sources and 80 unique applications of RDM. We ask: 1) Who uses RDM in practice? 2) Where? 3) How? and 4) To what end?

We find that RDM has moved from theory to practice, with substantive evidence for its usability across diverse domains, geographies and populations, scales, and resource environments. Even as applications adapt the framework to widely varying contexts, they demonstrate high-fidelity to its core structure. Where deviations occur, they often reflect innovative use of RDM principles in resource-constrained settings. Participatory engagement is extensive, with distinct profiles emerging based on the degree of co-design and co-interpretation involved.

Challenges of RDM in practice center around resource and capacity constraints that can limit full implementation. Moreover, continued reliance on outside analytical teams may serve as a bottleneck for the integration of RDM into decisionmakers' formal planning processes. Another limitation is the near absence of documented formal evaluation processes to assess RDM's usefulness and acceptability to its intended users. We conclude with recommendations for analysts, practitioners, and funders on resource accessibility, pathways to institutional integration, and evaluation standards, alongside an open research agenda inviting the broader DMDU community to build on these findings.

Session 20: What Is "Effective" Adaptation? — Delta Conference Room

What is "Effective" Adaptation? Sharing knowledge and practice on evaluating Climate Adaptation Under Deep Uncertainty

Authors: Sadie McEvoy (Deltares), Alison Rellinger (Mississippi State University), Qiyamah Williams (Mississippi State University, Mississippi Sound Estuary Program), Jessica Henkel (The Water Institute)

As planners and decision makers increasingly implement climate adaptation, conceptions of what constitutes effective adaptation have broadened. Rather than focusing narrowly on cost-efficient, single-hazard risk reduction, effective adaptation is now understood in terms of its contributions to wider societal goals, like sustainability, equity, and development, across multiple hazards and time horizons. Evaluating adaptation effectiveness in these broader terms poses significant challenges rooted in deep uncertainty.

First, assessing performance across multiple and sometimes competing objectives is constrained by complexity and limits in knowledge, data, and analytical tools. Nature-based adaptation, for example, evolves over time and exhibits emergent properties that are difficult to predict and measure. Second, adaptation interacts dynamically with other policy domains. Conflicts, trade-offs, synergies, and co-benefits will shift over time, and with different levels of warming. This requires long-term perspectives, as well as multi-disciplinary evaluations. Third, effectiveness is inherently stakeholder-dependent: adaptation measures can distribute benefits and burdens unevenly, adding social and governance dimensions to evaluation.

This panel brings together researchers and practitioners to share experiences with evaluating adaptation effectiveness in real-world contexts. Panelists will address four guiding questions: (1) how effectiveness was defined and operationalized in their context; (2) which methods or combinations of methods were used to evaluate effectiveness; (3) key lessons or practical tips for evaluating effectiveness in practice; and (4) the most pressing challenges or methodological developments needed to advance evaluating adaptation effectiveness.

The panel aims to foster cross-case learning and interactive dialogue on how evaluation approaches can better support robust and adaptive decision making under deep uncertainty.

Session 21: Robust Climate Decisions Under Deep Uncertainty: Advancing IAMs for Decision Support — Riverine Conference Room

Local Siting Decisions Under Uncertainty Shape the Health Benefits of Deep Decarbonization

Authors: Jinyu Shiwang (Princeton University), Wei Peng (Princeton University), Gokul Iyer (University of Maryland), Vivek Srikrishnan (Cornell University), Klaus Keller (Dartmouth College)

Deep decarbonization can improve air quality and public health. The magnitude and distribution of health benefits depend not only on how much emissions decline nationally, but also on where reductions occur and which populations remain exposed. Most analyses emphasize national technology pathways, while local infrastructure siting and population vulnerability are often simplified, limiting understanding of which decisions most strongly shape future health outcomes. Here, we use an integrated framework that links energy, air quality, and health models to assess how national and local decisions jointly shape future fine particulate matter (PM2.5) attributable mortality and disparities in the U.S. We use an Integrated Assessment Model (Global Change Analysis Model, GCAM-USA) to simulate national decarbonization pathways, and apply alternative downscaling methods to translate state-level emissions into county-level that represent alternative siting choices. We then use a reduced-form air quality model (Intervention Model for Air Pollution, InMAP) to simulate ambient PM2.5 concentrations and assess health impacts under alternative socio-demographic assumptions. Sampling all these dimensions yields ~3,000 scenarios for systematic comparison of key drivers of health outcomes.

Across our modeled scenarios, local siting decisions often have greater effects than national pathways. More stringent air-pollution controls substantially reduce total mortality and narrow the range of effects but do not eliminate the effects of siting decisions. Across states, siting decisions dominate mortality changes in most cases, although national technology-driven sectoral emission shifts remain influential in selected states where emission changes are less strongly aligned with population exposure. Reducing aggregate mortality does not necessarily reduce disparities across population groups. For instance, race-specific vulnerability assumptions substantially increase racial disparities in PM2.5-attributable mortality, while alternative siting strategies do not consistently narrow disparities across race groups. These results suggest that assessments of health benefits should account for local siting and vulnerability, rather than just relying on national pathway analysis.

Aggregating Global Change Scenario Ensembles through Robustness Metrics

Authors: Gi Joo Kim (Tulane University), Jacob Wessel (Princeton University), Jonathan Lamontagne (Tufts University), Abigail Snyder (Pacific Northwest National Laboratory), Thomas Wild (Pacific Northwest National Laboratory), John Sabo (Tulane University)

Large ensembles of global change scenarios are widely used to explore uncertainties arising from complex human–Earth system interactions. In many applications, key insights are derived by aggregating outcomes across scenarios, yet the implications of different aggregation choices are often overlooked in the global change scenario literature. In contrast, the decision-making under deep uncertainty (DMDU) community has extensively examined how aggregation choices affect assessments of system robustness, often quantified using robustness metrics. Here, we bridge these two strands using a large scenario ensemble generated with a global, multi-sector model, the Global

Change Analysis Model (GCAM). Using the ensemble outcomes, we assess how the choice of different aggregation methods affects the robust interpretation of multisector outcomes. While the rankings of aggregation measures are often broadly consistent, we find meaningful differences that can substantially alter interpretations of scenario outcomes. Our work ultimately supports more explicit and robust use of ensemble aggregation methods in global change scenario analysis.

Normative Uncertainty Dominates Climate Mitigation Decisions and Disproportionately Affects Least Developed Regions

Author: Jan Kwakkel (Delft University of Technology)

Climate policy-making is shaped by deep and normative uncertainties that standard cost-benefit IAMs often reduce to a single welfare objective and reference scenario. We introduce JUSTICE, an IAM framework that combines decision-making under deep and normative uncertainty with welfare economics through a general social welfare function across regions, time, and climate states. This enables multi-objective optimization under multiple distributive justice framings. Results show that justice framing strongly shapes both mitigation ambition and its regional distribution. Prioritarianism recommends deeper emission reductions and assigns greater responsibility to developed regions, while utilitarianism distributes mitigation more uniformly. Normative uncertainty explains over half of the variance in near-term mitigation ambition, exceeding socioeconomic and climate-response uncertainties. Overall, explicitly representing justice framings and conflicting objectives broadens the decision space, clarifies trade-offs, and supports fairer, more legitimate climate policy design

Uncertainty Decomposition in a Coupled IAM–ABM: The Interplay Of Social, Economic, and Climate Dimensions of Feasibility

Author: Giacomo Marangoni (Delft University of Technology)

Social and political dynamics are difficult to incorporate into integrated assessment models, yet they may fundamentally reshape feasibility assessments beyond technological and climate constraints. Using JUSTICE-ABM, a 57-region IAM with bottom-up mitigation pathways derived from an agent-based model of household voting, we decompose variance across 6,144 runs. We find that social attitudes explain most of the variance in cumulative emissions, while temperature outcomes remain primarily driven by climate sensitivity, though still meaningfully influenced by social dynamics. Overall, feasibility uncertainty is outcome-dependent, asymmetric, and dominated by social dimensions for several policy-relevant outcomes

Session 22: AI Safety, Governance & Adversarial Uncertainty — Basin Conference Room

Adversarial Decision-Making Under Deep Uncertainty in Agentic AI-Based Cyber Attacks on Critical Infrastructures: An Integrated Resilience Framework

Author: Joseph Ponnoly (Cinfodens LLC)

Critical infrastructures such as electric power systems, water networks, transportation systems, and industrial control environments are increasingly exposed to cyber attacks that are adaptive, coordinated, and capable of triggering cascading physical, economic, and societal disruption. Advances in agentic artificial intelligence are making it plausible that offensive cyber agents could automate reconnaissance, exploit-path selection, deception, lateral movement, and adaptive action with limited human intervention. This creates a decision environment marked by deep uncertainty, partial observability, information asymmetry, adversarial manipulation, and need for split-second decisions in complex adaptive systems.

This paper proposes an integrated resilience framework for analyzing adversarial decision-making under deep uncertainty in agentic AI-based attacks on critical infrastructures. The framework combines agent-based modeling, Markov decision processes and partially observable Markov decision processes, the OODA decision cycle, sensemaking, and game-theoretic analysis within a cyber-resilience perspective. In this formulation, sensemaking explains how ambiguous or deceptive signals are interpreted into plausible situational understanding; OODA captures the recurring adversarial decision loop; MDP/POMDP models represent sequential decision-making by individual intelligent agents; game theory captures strategic interaction, asymmetric information, and adaptive conflict between attackers and defenders; and agent-based modeling represents how multiple heterogeneous agents interact to produce emergent system-level effects.

The paper is motivated by documented attacks on critical infrastructures and by emerging AI-assisted operational concepts in domains such as power-grid control. Its central contribution is a theoretically grounded framework for evaluating supervisory architectures, resilient response strategies, and fail-safe mechanisms for agentic AI-enabled cyber conflict. The framework is intended to support more robust analysis of autonomous attack-defense dynamics, cascading infrastructure risk, and governance choices in targeted cyber infrastructures including cyber physical environments.

A Robust Decision Architecture for Artificial Intelligence

Authors: Benjamin Boudreaux (RAND), Rob Lempert (RAND)

Many approaches to AI safety try to shape what an AI system wants by aligning the model's internal objectives with human values. As capabilities improve, this strategy faces the structural difficulty that a sufficiently capable system may satisfy any behavioral test we design while pursuing misaligned objectives we cannot detect. We propose a complementary approach grounded in decision-making under deep uncertainty. An intermediary mediates interactions between humans and a powerful AI, treating the AI as a capable but potentially unreliable oracle and applying Robust Decision Making (RDM) and Assumption-Based Planning (ABP) to translate its outputs into recommendations that are robust against the possibility that the oracle is wrong or deceptive. Human survival and human agency operate as minimum constraints across a scenario ensemble that includes adversarial cases, and task performance is optimized only among strategies that satisfy them. Each recommendation carries a vulnerability report identifying conditions under which it would fail. We describe a three layer architecture for this RDM wrapper, the principal open methodological challenges, and some proposed paths ahead.

Finding Climate Black Swans: AI-Assisted Horizon Scanning for Unseen Climate and Weather Extremes

Authors: Tom Wood (King's College London), Tom Matthews (King's College London)

The past 11 years have been the warmest in the instrumental record. With the climate moving into unprecedented territory, many types of extreme events are becoming more frequent, more severe, or both, raising the risk of very extreme societal impacts across interconnected physical, social, and economic systems. However, due to the complexity of the climate characterised by deep uncertainty, and our limited capacity to imagine and anticipate events with no historical precedent, we have a poor understanding of extreme ‘unseen’ event risks, including what is physically possible even where likelihoods are poorly constrained by historical data. Given the unquantified catastrophic risk potential, it is critical that we improve our understanding of unprecedented climate and weather events

with unknown or poorly constrained likelihoods, to enable society to anticipate, respond to, and mitigate potential impacts.

This study presents a novel framework for utilising artificial intelligence (AI) tools to explore the bounds of physically possible and decision-relevant extreme climate and weather risks. By integrating cutting-edge AI tools, including diffusion-based weather forecast models, statistical machine learning, and large language models (LLMs), in a modular workflow, the framework is designed to identify, test, and physically constrain storylines of unprecedented extreme events. The approach considers how AI can support generating new insights and testable hypotheses beyond what can be achieved using traditional modelling and analysis methods. The framework aims to discover possible physical pathways and anticipate direct, indirect, and cascading societal impacts. It also considers how these outputs can be translated into information useful for stress-testing policies, emergency plans, infrastructure assumptions, and adaptation strategies. Rather than treating AI as a replacement for traditional modelling or expert assessment, the framework positions it as a tool for exploring the bounds of possibility, and seeks to reduce societal vulnerability to surprise extreme weather events in a rapidly changing climate.

Session 23: Flood Risk and Urban Stormwater — Delta Conference Room

Unrefined National Building Inventories Can Mislead Risk Assessments and Decisions

Authors: Adam Pollack (University of Iowa), James Benedict (Los Alamos National Laboratory), Mithun Deb (Pacific Northwest National Laboratory), James Doss-Gollin (Rice University), David Judi (Pacific Northwest National Laboratory), William Lehman (United States Army Corps of Engineers), Nicholas Lutz (United States Army Corps of Engineers), Cade Reesman (Pacific Northwest National Laboratory), Elaine Sarazen (Dartmouth College), Youngjun Son (Pacific Northwest National Laboratory), Vivek Srikrishnan (Cornell University), Ning Sun (Pacific Northwest National Laboratory), Klaus Keller (Dartmouth College)

Flood-risk assessments increasingly rely on large-scale building inventories that offer fine spatial detail but limited and uneven quality assurance. As a result, exposure is often treated as a static, “ready-to-use” input, even though small errors in where assets are located or how they are characterized can propagate into loss estimates. Despite the centrality of exposure for understanding changing risk under climate and socio-economic change, the implications of adopting exposure data without refinement remain poorly quantified. Here, we test how exposure data quality influences flood-loss estimates and decision-relevant metrics by comparing damages derived from a widely used national building inventory to estimates produced with high-quality, feature-rich local building data across an ensemble of flood scenarios. We find that adopting an unrefined building inventory can systematically distort decision-relevant damage metrics. For example, roughly one-fifth of areas are misclassified with respect to a funding priority status metric used in the U.S. Simple, transferable exposure refinements—particularly corrections to building locations—substantially reduce these errors, yielding near-complete agreement with rankings based on high-quality local data. Our findings demonstrate that credible assessments of flood risk require explicit attention to the spatio-temporal reliability of exposure inputs, not only improved hazard characterization or vulnerability functions. We provide actionable guidance for diagnosing exposure errors and implementing practical corrections.

A Simple Adaptive Strategy for Drainage System Retrofits to Manage Stormwater Under Deep Uncertainty

Authors: Siqi Ke (Dartmouth College), Rose Kachelski (Dartmouth College), Vikrant Vaze (Dartmouth College), Klaus Keller (Dartmouth College)

Many stormwater drainage systems around the U.S. have been overwhelmed under extreme precipitation events, leading to urban flooding. They require upgrades to accommodate projected increases in demand driven by intensifying precipitation, the displacement of permeable land, and the ongoing deterioration of infrastructure. Identifying a sound retrofitting strategy can be challenging, given the deep and dynamic uncertainties over time surrounding changing conditions. Prior studies have broken important new ground by introducing adaptive decision strategies. However, they remain silent on how to define an easy-to-implement strategy that (1) handles multiple uncertainties like climate, urbanization, and infrastructure degradation, (2) balances various objectives, and (3) scales well with a large number of retrofit candidates. To address the questions, we propose an adaptive strategy with a capacity estimation policy that (1) incorporates signposts for explicit climate-change and land-use changes, as well as implicit infrastructure degradation, (2) balances the trade-off between expected implementation cost and flood damage, and (3) uses a simple structure that can scale well to large network design. We demonstrate the performance of this approach using a real-world test case under deep uncertainty and benchmark it against an adaptive pathway method in terms of Pareto improvements.

Climate Change Worsens Localized Flood Damages: A Case Study in Philadelphia, Pennsylvania

Authors: Parin Bhaduri (University of Delaware), Vivek Srikrishnan (Cornell University)

Extreme storm events, such as hurricanes, cause major damages to coastal areas, and these storms are expected to intensify as global temperatures rise. Local officials seek to identify areas that are most vulnerable to future flooding to better inform present-day adaptation decisions in the face of climate change. However, projecting local flood damages under climate change at fine spatial scales is subject to many uncertainties, some of which are commonly overlooked. For example, property-level exposure to future hurricanes are sensitive to the exact storm track trajectory, and damage estimates are influenced by property-level structural characteristics and the choice in depth-damage functions. In this study, we construct flood hazard inundation maps based on past hurricane events impacting Philadelphia, Pennsylvania under different assumptions of historical and future climate forcings. We then overlay these inundation maps with a high-quality inventory of residential property assets within our study area to compare asset-level flood damages across our set of flood hazard scenarios. We find that hurricane events under projected climate change scenarios produce a 15-30% increase in local flood damages compared to historical climate conditions, even when controlling for damage-related uncertainties and storm track variability. Furthermore, the spatial distribution of projected flood damages within our study area is sensitive to the representation of future climate forcings, with each scenario highlighting different neighborhoods that are vulnerable to future climate change. Overall, our findings contextualize projections of local flood damages under climate change, even when considering additional uncertainties in flood exposure and vulnerability. We provide guidance for interpreting climate change scenarios to improve local flood risk estimation and decision-making.

Session 24: Robust Energy Planning & Scenario Generation — Riverine Conference Room

Scenario Space Exploration for Robust Energy Planning

Authors: Amir Fattahi (TNO Energy and Material Transition; Utrecht University), Rebeka Beres (TNO Energy and Material Transition), Mobi van der Linden (TNO Energy and Material Transition), Felipe Blanco Rocha (TNO Energy and Material Transition), André Faaij (TNO Energy and Material Transition)

Long-term energy planning must meet climate targets while preserving affordability and security of supply under deep uncertainty in technology costs, markets, weather variability, and demand. Yet conventional scenario studies typically compare only a few narrative futures, obscuring interactions, feasibility boundaries, and regime shifts that are central to robust policy design. Building on robust decision making under deep uncertainty literature, we present a scenario space exploration workflow for large-scale whole-energy-system optimisation models, for which stochastic or robust optimisation is often computationally impractical.

We apply the workflow to a whole-energy-system model of the Netherlands in 2050, combining large ensembles, global sensitivity analysis, and scenario discovery. Rather than selecting a single preferred pathway, the approach stress-tests plausible uncertainty ranges and identifies the conditions under which desirable outcomes remain robust. The model is treated as a black box, requiring no reformulation and making the workflow readily transferable across modelling frameworks and decision contexts. Moment-independent sensitivity analysis reveals interaction-driven effects, thresholds, and regime shifts that screening methods, e.g., Morris, can miss, particularly for cross-border electricity exchange, adequacy under prolonged renewable scarcity, and financing conditions. Coupled with scenario discovery, the workflow identifies concise success conditions and avoidance rules for outcomes of interest, translating large ensembles into decision-relevant guidance.

The main contribution is to shift energy modelling from static scenario comparison towards interactive robust policy design. By making critical uncertainties, boundary conditions, and decision rules explicit, the workflow supports stakeholder dialogue on which combinations of conditions threaten policy goals and which strategies remain credible across a wide scenario space.

GSA-Informed Scenario Generation for Computationally Efficient Robust Decision Making in Energy System Planning

Authors: Lorenzo Caravetta (Department of Energy - Politecnico di Milano), Alessandro Amaranto (Sustainable Development and Energy Sources Department, RSE Ricerca sul Sistema Energetico), Marco Tangi (Sustainable Development and Energy Sources Department, RSE Ricerca sul Sistema Energetico), Emanuela Colombo (Department of Energy - Politecnico di Milano)

Applying Robust Decision Making (RDM) to energy system planning requires evaluating long-term investment strategies across large ensembles of deeply uncertain futures. In practice, this creates a tension between the richness of the uncertainty space and the computational cost of the models used to assess strategy performance. When the underlying model is an Energy System Optimization Model (ESOM), this tension becomes acute: running thousands of scenarios is often infeasible, yet a coarse or arbitrary sampling of the uncertainty space risks missing the conditions under which a strategy fails.

This paper proposes a framework to address this tension through the structured use of Global

Sensitivity Analysis (GSA) to inform scenario generation. Rather than sampling the uncertainty space uniformly or relying on expert judgment alone, GSA is used to identify which uncertain parameters most influence key performance metrics — including costs, unmet demand, curtailment, and emissions. This ranking is then used to design a targeted scenario ensemble that concentrates sampling where it matters most for robustness assessment, reducing the number of model evaluations required without sacrificing coverage of the scenarios that drive plan vulnerability.

The resulting workflow integrates GSA, scenario generation, and robustness assessment into a coherent pipeline applicable to multi-energy systems planning problems. Robustness is evaluated across multiple criteria — spanning worst-case, satisficing, and regret-based metrics — without imposing a priori assumptions on the decision maker's risk attitude.

We present the framework and discuss its methodological implications for the practical application of RDM to energy planning, including the trade-offs between uncertainty coverage, computational tractability, and the interpretability of robustness results for decision support.

Leveraging DMDU Techniques to Overcome Challenging Uncertainties in Probabilistic Risk Assessment of Nuclear Energy Systems

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Uncertainty is a central element in probabilistic risk assessment (PRA) for nuclear energy systems. The standard taxonomy in nuclear PRA distinguishes aleatory uncertainty, representing inherent randomness in underlying processes, from epistemic uncertainty, which stems from the lack of knowledge. Current practice addresses both types of uncertainties primarily through probabilistic methods: assigning probability distributions to uncertain parameters and propagating them through the risk model to quantify uncertainty in risk outputs. This approach, however, struggles with a specific class of uncertainties. Some sources of epistemic uncertainty resist probabilistic characterization, particularly when data are too sparse and expert knowledge is limited. In practice, these sources of uncertainty are addressed through sensitivity analyses on a small number of conservative, expert-judged cases. Selecting a defensible set of such sensitivity cases is itself a difficult judgment call.

This research proposes leveraging Decision Making under Deep Uncertainty (DMDU) techniques to address this gap. This paper first maps the uncertainty taxonomy used in nuclear risk analysis onto the concepts and framework of DMDU to delineate where probabilistic methods remain appropriate and where DMDU methods can offer a more suitable treatment. This paper then compares representative DMDU techniques, such as Robust Decision Making (RDM) and Info-Gap (IFG) theory, against current uncertainty analysis practice in nuclear PRA and identifies specific gaps that DMDU methods are positioned to address. An illustrative proof-of-concept case study is presented by applying DMDU techniques to the risk analysis of an advanced nuclear reactor design. This work represents the first proposed integration of DMDU techniques with nuclear PRA. The integration is framed as an enhancement to existing PRA practice, not a replacement, by preserving the regulatory and methodological infrastructure of current PRA practice while extending its capacity to handle sources of uncertainty that currently fall outside its reach.