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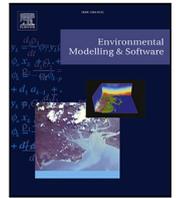
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# A review of tools and resources to support Decision-Making Under Deep Uncertainty

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## ABSTRACT

Decision-making under Deep Uncertainty (DMDU) offers approaches to support robust, adaptive strategies for complex decision-making. However, practical uptake of DMDU remains limited, partly due to fragmented access to resources and a lack of an inventory of available tools. This study introduces a comprehensive catalogue of tools and resources. Through a structured survey and expert elicitation, we identify 28 resources and 16 tools that support DMDU research and practice and classify them using an established DMDU taxonomy. Our analysis reveals a focus on introductory guidance regarding theory and methods of DMDU application, with some bias toward water-related applications. Technical, method-specific resources on how to implement existing frameworks remain limited. Our results identify tools supporting all core DMDU components, though they highlight persistent scalability challenges. The resulting online catalogue provides a foundation for expanding the use of DMDU in practice and is intended as a living, community-driven platform.

## 1. Introduction

Decision-making Under Deep Uncertainty (DMDU) is a promising field of research for addressing complex, high-stakes decisions where the future is unpredictable and difficult to model (Lempert, 2003; Marchau et al., 2019). In traditional decision-making approaches, assumptions about the future are often based on probabilistic predictions or historical data. DMDU shifts this paradigm by embracing uncertainty as a core feature, recognizing that the future is inherently uncertain, and emphasizing robust decisions. This shift includes moving beyond a “predict-then-act” approach, which bases decisions on forecasted outcomes, to more exploratory “what-if” methods that evaluate a wide range of plausible scenarios. For example, Groves et al. (2019) illustrates how DMDU can help water supply facility managers identify vulnerabilities and promising management strategies in light of plausible drought stress and increasing demand by stress testing candidate policies across a set of possible measures and identifying scenarios in which current policies will fail. Similarly, DMDU can facilitate the discussion of flexible short-term actions and possible long-term options to deal with uncertain sea level rise in coastal regions and deltas (Ryan et al., 2022; Bloemen et al., 2019; Ranger et al., 2013).

Despite the rich body of DMDU literature, decision-makers have been slow to integrate DMDU methods into real-world planning frameworks. One barrier to the adoption of DMDU methods is the absence of a definitive catalogue of the tools and resources available to help policy-makers apply DMDU methodologies in practice. Both resources and tools play a role in facilitating the implementation of DMDU. Tools provide direct computational support for applying DMDU methodologies, help users conceptualize complex decision problems, and visualize analytical results. Resources provide guidance on when and how to apply DMDU tools and methods in real-world applications. Building on the definition by Voinov et al. (2018), we define relevant tools in this study as a software package or an implementation of modeling technique(s) used to facilitate DMDU methodology to support a broader DMDU workflow. Thus, we understand tools such as simulation models, scenario generators, or algorithms for robust optimization to implement a methodology. Similarly, we define resources as a set of informational, educational, and procedural support, such as best-practice guidelines, case studies, and serious games that enable awareness raising and practical application of DMDU approaches.

DMDU resources and tools support a wide range of methods and frameworks. Robust Decision Making (RDM, Lempert, 2003) and its

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variants (see Bartholomew and Kwakkel, 2020) emphasize stress-testing strategies across diverse plausible futures, using tools such as exploratory modeling and multi-objective optimization to identify robust policies (e.g., Quinn et al., 2018; Gold et al., 2023). Alternatively, Dynamic Adaptive Policy Pathways (DAPP, Haasnoot et al., 2013) focuses on designing strategies that include initial actions, long-term options, and signals for adaptation to identify flexible and adaptive strategies that avoid lock-ins and account for path-dependence in decision-making (e.g., Craddock-Henry et al., 2018; Haasnoot et al., 2024; Kool et al., 2024; Schlumberger et al., 2024). Info-Gap decision theory (IG, Ben-Haim, 2006) provides a framework for managing decisions amidst significant knowledge gaps, prioritizing robustness and opportuneness to balance risk tolerance and seizing unforeseen opportunities (e.g., Viala et al., 2025; Eslahi et al., 2024). Engineering Options Analysis (EOA, de Neufville et al., 2019) extends traditional real options analysis by addressing deeper uncertainties and evaluating multiple options to identify the best flexible solution under uncertainty. Lastly, (DS, Brown et al., 2012) is a climate risk assessment methodology that integrates bottom-up vulnerability assessments with diverse sources of climate information to maximize their utility in decision-making. By modeling decisions, identifying thresholds, and linking stochastic analysis with climate projections, it identifies climate states associated with risks and estimates probabilities to inform robust adaptation strategies (e.g., Poff et al., 2016; Zhang et al., 2021).

Since the inauguration of the DMDU research community about a decade ago, the scientific community has engaged in reviewing and comparing these methods (e.g., Bartholomew and Kwakkel, 2020; Gersonius et al., 2015; Hall et al., 2012; Kwakkel et al., 2016; Kwakkel and Haasnoot, 2019; Matrosov et al., 2013; Moallemi et al., 2020a; Roach et al., 2015, 2016; Walker et al., 2013; Webber and Samaras, 2022), and even reflected on the applicability of these methods in practice (Stanton and Roelich, 2021). One notable contribution is by Kwakkel and Haasnoot (2019), who developed a taxonomy of elements used in each of the DMDU approaches, building on Herman et al. (2015). Combining elements from this taxonomy allows researchers and practitioners to develop tailored, context-specific applications of DMDU methods.

This study introduces the first effort to collect and categorize tools and resources developed within the DMDU community. Our objective is to create a concise overview of recent state-of-the-art resources and tools available for DMDU research and practice. We structure our categorization of DMDU resources and tools using the DMDU taxonomy presented by Kwakkel and Haasnoot. This structure is intended to help readers discover DMDU tools and resources that are relevant for individual DMDU methods and identify gaps in existing tools and resources. Our results are collected in an online catalogue of existing tools and resources, which can be found here: [https://juliusschlumberger.github.io/Repository\\_DMDU\\_Tools\\_Resources/](https://juliusschlumberger.github.io/Repository_DMDU_Tools_Resources/). This catalogue is intended to be a living document open to future contributions from the DMDU community. The catalogue is oriented to both researchers and DMDU practitioners, but is particularly designed to facilitate the adoption of DMDU methodology for policy makers interested in applying DMDU methods in real-world problems. We intend the catalogue to serve as a complement to the existing DMDU textbook (Marchau et al., 2019), which provides an overview of DMDU approaches and provides examples of DMDU methods. Our study also highlights areas of DMDU that are well covered by existing tools and resources and identifies gaps where further developments are necessary.

The remainder of this paper is organized as follows: Section 2 provides an overview of our methods, describing the survey we conducted to collect tools and resources from the DMDU community, and presenting our framework for classifying tools and resources. Section 3 presents the survey results summarizing currently available resources (Section 3.1) and tools (Section 3.2), mapping collected tools and resources to the DMDU taxonomy of Kwakkel and Haasnoot. Finally, Section 4 provides a discussion of the collected tools and

resources, identifies gaps in support for DMDU methods, and highlights opportunities for future development.

## 2. Methods

This paper originated from a session that the co-authors of this study organized at the Annual Meeting of the DMDU society in Delft in 2023, showcasing recently developed tools and resources for applying DMDU. In this study, we provide a structured overview of tools and resources that support DMDU approaches by conducting a structured survey of the DMDU community. The survey was shared within the DMDU community using the official mailing list of the Society for Decision Making Under Deep Uncertainty, which includes 1400+ researchers and practitioners from around the world and different disciplines. Between March and May 2024, tools and resources were collected. Through the survey, we asked the DMDU community to provide general information about the tools and resources anonymously, including a brief description, target audience, relevant thematic area, and details on public accessibility (see Appendix A for the full survey outline). In total, we received 33 entries. We filtered this list to include only tools and resources that could be accessed by our author team, showed evidence of continued maintenance, and contained complete documentation. We complemented the list of candidates using inputs provided by the co-authors ( $n = 16$ ).

Individual co-authors were responsible for the initial review and analysis of each entry, which included collecting additional information where needed. Additional information was mostly collected by examining the tool or resource directly and consulting associated documentation or reports. The initial review and analysis was then confirmed through an independent second review by another co-author. In cases where differences in analysis or conclusions arose, the two reviewers first discussed the discrepancy; if consensus could not be reached, the matter was brought to the entire group of co-authors for resolution. Similarly, for tools and resources where co-authors had contributed to their development, a second review and discussions within the group ensured that potential biases and conflicts of interest did not affect the analysis of the different tools and resources. We screened out resources and tools based on relevance and accessibility. As such, we excluded multiple resources unrelated to the core concepts of DMDU (see Fig. 1). We also excluded tools and resources that were not publicly accessible (total screened-out resources:  $n = 4$ ). The proposed exclusions were discussed collectively by all co-authors, ensuring rigour and transparency in the decision-making process.

To characterize tools and resources, we follow the taxonomy provided by Kwakkel and Haasnoot (2019), which describes the specific functionalities relevant for analysis in the context of DMDU while being agnostic about the specific method (Fig. 1). The first component of the DMDU taxonomy is policy architecture, which reflects how decision-makers frame adaptive policies. The DMDU taxonomy categorizes methods for generating scenarios and generating policy alternatives. Generation of scenarios refers to methods for combining a set of uncertain characteristics into a manageable number of alternative future states of the world that should be considered. For example, while there are infinite combinations of uncertain future sea level rise, population growth, and economic development, a set of scenarios can be generated that captures the relevant decision context. Scenarios could be pre-specified based on expert judgment (e.g., van Vuuren et al., 2012), explored within the plausible ranges specified (e.g., sea level rise between 0 and 1.5 m by 2100; Herman et al., 2016) or specifically searched for as critical points (e.g., best case, worst case; Kwakkel and Pruyt, 2013) in the uncertainty space. Generation of policy alternatives refers to processes for identifying potential actions, including searching for the policy properties that result in an intended outcome (e.g., Quinn et al., 2017), exploring uncertain characteristics of policy alternatives,

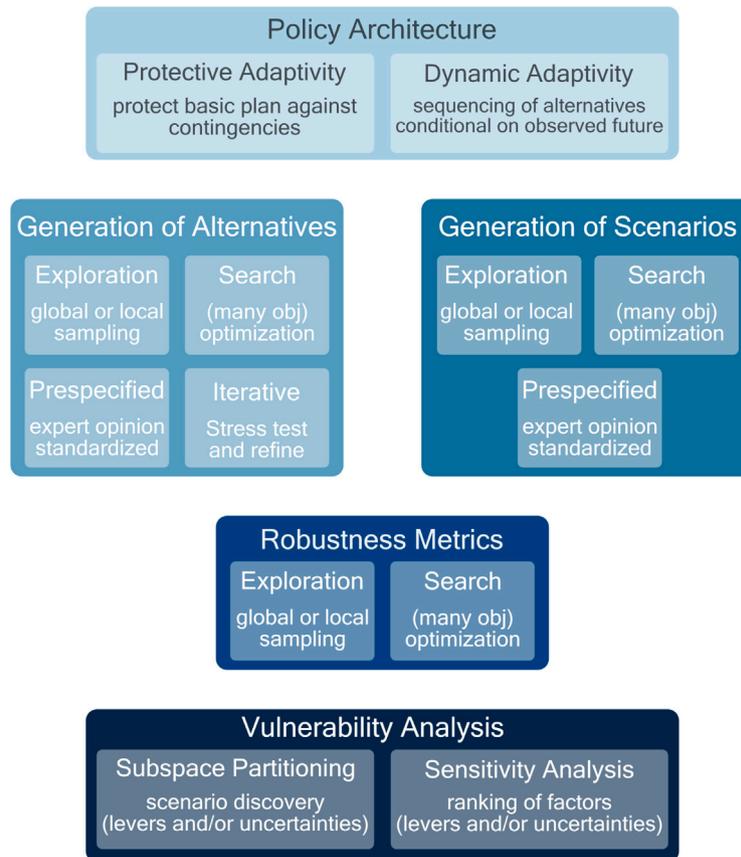


Fig. 1. A taxonomy of components that make up the DMDU approaches (redrawn based on Kwakkel and Haasnoot (2019) in line with CC BY 4.0).

and refining or predefining actions based on expert knowledge (e.g., Muccione et al., 2024).

Additionally, the DMDU taxonomy classifies methods for measuring robustness, which aggregate the performance of a policy action across multiple scenarios into one indicator. A policy action could thereby satisfy certain conditions (e.g., protect a city in 9 out of 10 cases), or a set of policies could be compared to determine regret (e.g., the reduced impacts outweigh the costs for policy A but not for policy B) (Lempert and Collins, 2007). Closely related are processes for the vulnerability analysis of the policy actions, to determine how the performance of a particular policy alternative is affected under different scenarios, e.g., using sensitivity analysis to determine the relative importance of different uncertainty sources (Herman et al., 2015) or the partitioning of the uncertainty space into sub-spaces with similar outcomes. The application of the DMDU taxonomy components is well-suited to an iterative and constructive approach to decision-making, where the findings are used to explore alternative policy architectures (Kasprzyk et al., 2013). Policy alternatives could serve as contingency actions to support an overarching strategy or flexible plans that require a change of strategies when certain external conditions are met (Haasnoot et al., 2013; Walker et al., 2001).

In this study, we utilize the DMDU taxonomy to structure our review of tools and resources identified by the community. For classification of the tools, we additionally consider the programming language and coding skill level required. Most DMDU tools identified in this study are not sector-specific, so we chose not to categorize tools by sector. For the characterization of DMDU resources, we explore the scope of

the resource by means of the taxonomy elements it covers. We further characterize the resources based on different categories: accessibility, purpose, level of analysis, and methods. Based on expert judgment, we characterize the accessibility of a resource to distinguish between resources with different intended users. Resources with accessibility A are intended for use by policy- and decision makers, but not by technical experts who are ultimately going to carry out the analysis. Such resources consist of introductions to DMDU as a whole or specific methods and provide just enough information for decision makers to follow the workflow of technical officers. Serious games are always intended to introduce an audience to a new (DMDU) topic, and are thus also classified as accessibility A. Resources with accessibility B are intended for use by technical experts who do not have expertise in DMDU methods specifically, but who are familiar with quantitative and model-based methodologies, while accessibility C is used for those resources which are intended for specialized DMDU technical experts and/or academics, and thus tend to take for granted knowledge of DMDU concepts and/or sectoral knowledge. For the purpose, we distinguish between (a) how-to guidance, which offers stepwise instructions to follow for the application of a DMDU analysis, (b) introductions, which provide a high-level introduction to the underlying concepts and relevant analysis steps, or (c) and serious games, which offer a low-barrier entrance to explore the effects/relevance of DMDU analysis through gamification, thus purely serving the purpose of raising awareness. The level of analysis is distinguished into qualitative, semi-quantitative, and fully quantitative analysis, inspired by Haasnoot et al.

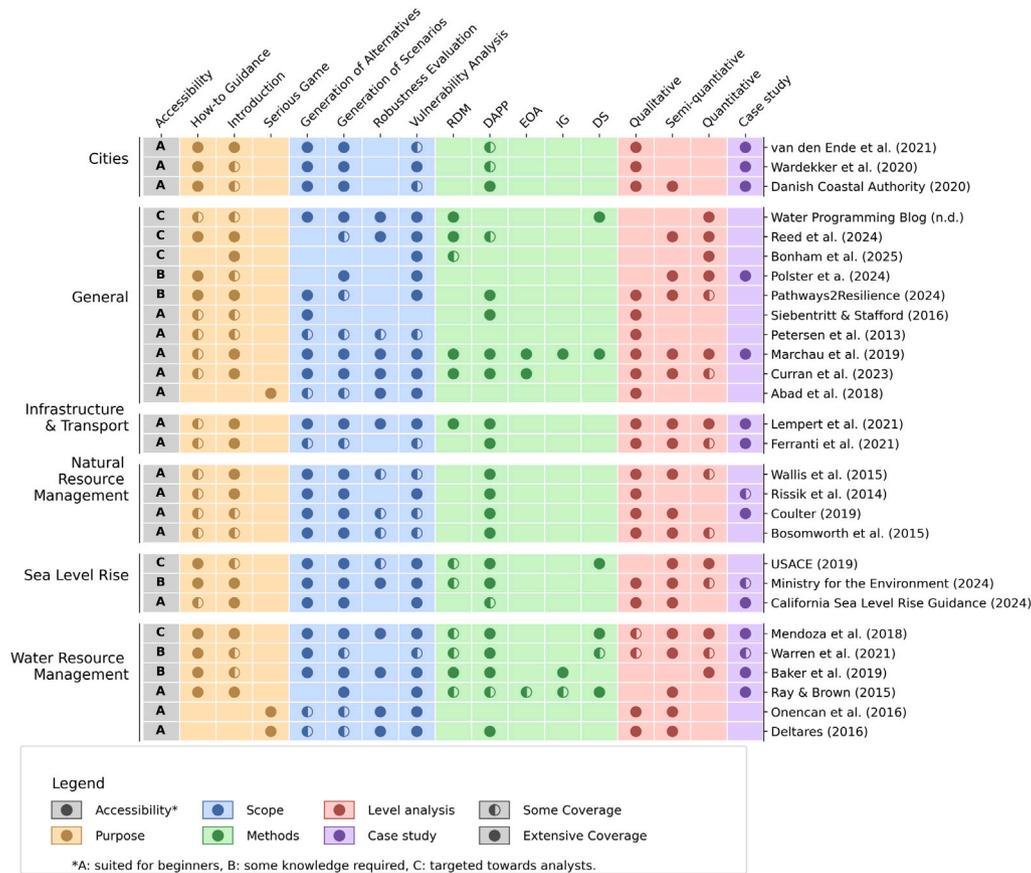


Fig. 2. Summary of the collected resources. We compare the purpose of analysis, DMDU elements addressed, DMDU methods mentioned, level of analysis, and availability of case studies across these resources.

(2024). We also investigate whether illustrative case studies are part of the resource.

### 3. Results

#### 3.1. Resources to enable DMDU in practice

We collected 28 resources (see Table B.2 for a summary). As shown in Fig. 2, they differ in terms of (1) their purpose, offering an introduction to the key concepts, guidance on how to apply these, or experiencing the effects on decision-making through gaming aspects; (2) which DMDU methods and elements are addressed (see Section 2); and (3) their inclusion of examples and experiences from case studies that offer additional insights or inspiration for the reader. In the following section, we will discuss patterns and key characteristics of these resources.

##### 3.1.1. Purpose of the resource

The identified resources vary widely in their purpose, from high-level awareness-raising documents to detailed step-by-step guides and serious games. High-level guidance documents, such as Ferranti et al. (2021), Rissik et al. (2014), Lempert et al. (2021), Marchau et al. (2019) and Curran et al. (2023) focus on introducing key concepts and frameworks, often targeting readers unfamiliar with certain DMDU

methods and the concept of DMDU in general. Other resources like Mendoza et al. (2018), Danish Coastal Authority (2020), Ministry for the Environment (2024), Ray and Brown (2015), and Reed et al. (2024) and the Pathways2Resilience (P2R; 2024) offer step-by-step guidance, delve into methodologies, and illustrate practical tools (with examples) and outputs for users to apply in their contexts.

The high-level documents provide limited or no specific instructions for implementation, instead serving as entry points to the topic by simplifying complex concepts and raising awareness of DMDU's importance. For example, in specific sectors like transportation or natural resource management. These resources offer limited implementation support, instead serving as conceptual overviews for practitioners and decision-makers. In contrast, the step-by-step guidance resources balance technical depth and accessibility, catering to practitioners with varying levels of expertise. Resources such as U.S. Army Corps of Engineers (2019) and Baker et al. (2016) lean towards a technical audience, with detailed methodologies and descriptions but introductory content that might require some prior knowledge. Several documents, such as CLIMAAX (2025) and van den Ende et al. (2022), emphasize participatory and context-specific approaches while providing targeted guidance. Both lack explicit links to the broader DMDU context, focusing instead on localized applications or specific methodologies like participatory foresight or climate risk assessment.

The resource provided by Bosomworth et al. (2015) deserves special attention as it consists of a comprehensive playbook offering a high-level introduction to the key concepts and steps required to implement

adaptation pathways for natural resource management. For each step, reference is made to a more comprehensive resource list provided by Wallis et al. (2015) and developed in the context of the same project.

Serious games (Abad et al., 2020; Deltares, 2014; Onencan et al., 2016) are a special group of resources, which focus on the experiential learning approach, allowing users to engage dynamically with concepts such as deep uncertainty, robustness, and flexibility in decision-making. These resources are unique in fostering social learning and stakeholder engagement, but do not serve as stand-alone guidance for implementing DMDU frameworks.

### 3.1.2. Scope of these resources

As shown in Fig. 2, all elements of the DMDU taxonomy in Fig. 1 are well represented in the collected resources. Most resources touch upon all elements to varying degrees. For example, U.S. Army Corps of Engineers (2019) provides in-depth technical guidance regarding how to account for sea level rise scenarios and deal with the exploratory aspect of future uncertainties in USACE infrastructure. At the same time, robustness analysis is mentioned multiple times, although with much less explicit guidance. This is a pattern that can be recognized across multiple resources (e.g., Bosomworth et al., 2015; Coulter, 2019; Warren et al., 2021). Three guidance documents offer significantly more details regarding robustness analysis, ranging from technical guidance (Mendoza et al., 2018) to in-depth elaboration on different methods (Baker et al., 2016; Reed et al., 2024) to high-level introduction (Lempert et al., 2021).

Similar patterns can also be observed regarding vulnerability analysis. Many resources acknowledge its importance as part of forming a system definition, analyzing needs for adaptation under future scenarios, or as part of a sensitivity analysis/stress-testing, but vary significantly in the depth and specificity of guidance. While some, like Mendoza et al. (2018), Reed et al. (2022) and CLIMAAX (2025), excel in offering tools and methodologies, others provide extended background information (e.g., Baker et al., 2016; Ministry for the Environment, 2024; Rissik et al., 2014; Wallis et al., 2015) or rely on general references without discussing aspects of practical application (e.g., Bosomworth et al., 2015; California Sea Level Rise Guidance, 2024; Coulter, 2019; Curran et al., 2023; Wardekker et al., 2020). Bonham et al. (2025) offers a taxonomy of general vulnerability analysis approaches based on a review of current practices.

Most resources guide the identification of policy options, although the depth of coverage varies. For instance, Ferranti et al. (2021), Wallis et al. (2015), Warren et al. (2021) and Mendoza et al. (2018) emphasize the generation of pathways and options. Still, guidance is often conceptual, offering guiding questions or groups of options (e.g., for sea level rise differentiating between measures to protect, accommodate, adapt or retreat; Ministry for the Environment, 2024). Participatory approaches are prominently highlighted in resources for the identification of policy options (e.g., Danish Coastal Authority, 2020; Ministry for the Environment, 2024; Siebentritt and Stafford Smith, 2016; Pathways2Resilience, 2024). This results in considering alternative scenarios and policy options in some resources. For example, Wardekker et al. (2020) and van den Ende et al. (2022), who offer guidance regarding a set of foresight techniques, connect the identification of alternatives to scenario development and visions of the future. By contrast, U.S. Army Corps of Engineers (2019) and Baker et al. (2016) focus more on structured decision-support tools, aligning alternative identification with rigorous, quantitative frameworks.

Scenario generation is a strength across most resources, although the approaches differ significantly in scope and technical depth. For example, resources like Mendoza et al. (2018), Ray and Brown (2015), Reed et al. (2024), and Ministry for the Environment (2024) provide extensive guidance on creating scenarios and understanding their implications, including tools and platforms for exploring climate change impacts. Conversely, resources like CLIMAAX (2025) and Wardekker

et al. (2020) delve into participatory scenario development, enabling regions to explore incremental changes and future visions.

Some of the resources put more effort into raising awareness on the relevance of DMDU by guiding self-reflective processes (e.g., Coulter, 2019; Ferranti et al., 2021; Petersen et al., 2013; Rissik et al., 2014). Beyond that, elements such as checklists to support the guidance can be found in multiple resources (e.g., Mendoza et al., 2018; Ministry for the Environment, 2024).

Two resources are especially noteworthy for their scope. Baker et al. (2016) guides water resource management and water supply facilities in their choice of investment appraisal and optimization methodologies. In doing so, the guidance does not purely focus on DMDU. Still, it offers a decision-making framework that helps decision-makers determine whether complex/advanced (DMDU) methods are needed or whether the current practice is sufficient. On the other hand, Water Programming: A Collaborative Research Blog (Reed Research Group, 2025), is a digital resource that covers many modeling-related topics for DMDU, with a strong focus on aspects of scenario generation and robustness analysis, along with fundamental skills relevant for modelers in DMDU. It consists of explanations and example codes to help technical experts new to DMDU.

Overall, the resources collectively cover all dimensions of DMDU but are widely different in terms of the depth of their treatment. The majority of resources ( $n = 10$ ) follow similar outlines or patterns of simplification to introduce the relevance and key steps to conduct (e.g., Ferranti et al., 2021; Bosomworth et al., 2015; Siebentritt and Stafford Smith, 2016; California Sea Level Rise Guidance, 2024). There are only a few resources that provide technical, in-depth guidance ( $n = 5$ ), and even less focus on offering guidance regarding one (or few) specific dimensions of the DMDU analysis (e.g., CLIMAAX, 2025; van den Ende et al., 2022).

### 3.1.3. Methods addressed with these resources and level of analysis

When observing the methods referenced in each resource, we found DAPP to be by far the most often represented ( $n = 19$ ), followed by Robust Decision Making ( $n = 9$ ) and Decision Scaling ( $n = 5$ ). When resources explicitly focus on one method in particular ( $n = 11$ ), they also tend to do so for DAPP. In other cases, DAPP is combined with RDM and IG or EOA. For example, Warren et al. (2021) suggest the use of RDM or DS methods to complete one of the analytical steps of DAPP. Reed Research Group (2025)'s blog instead covers RDM, DAPP, and DS through different blog posts, with a particular focus and coding examples on computational science aspects. Marchau et al. (2019) is a central resource, offering an in-depth introduction to each DMDU method and some practical applications.

Aside from in Marchau et al. (2019), EOA is only represented by one resource (Curran et al., 2023), where it is described as a 'computer-assisted reasoning approach' together with RDM. Baker et al. (2016) and Ray and Brown (2015). Interestingly, four resources (Bonham et al., 2025; CLIMAAX, 2025; Petersen et al., 2013; Abad et al., 2020) do not focus on any specific methodologies but instead generally cover aspects of scenario discovery, robustness, vulnerability analysis, and strategic foresight, respectively.

Each considered DMDU methodology can be approached through a qualitative, semi-quantitative, and/or fully quantitative level of analysis within a resource. Six resources approach either DMDU as a whole or DAPP specifically qualitatively. One example is Rissik et al. (2014), a first introduction to adaptive pathways planning for Natural Resources Managers in Australia, structured around self-reflective questions. Resources like Danish Coastal Authority (2020) and Onencan et al. (2016) go one step further and present both qualitative and semi-quantitative approaches to DAPP for Danish municipalities and computer-assisted strategic foresight. Four resources are entirely (and only) quantitative: Reed Research Group (2025)'s blog on DMDU modeling approaches, Baker et al. (2016)'s guidance to investment appraisal and optimization in water resource management and water supply

facilities, Reed et al. (2024) on methods for sensitivity analysis using statistical to machine learning approaches and Ray and Brown (2015) focusing on climate risk stress-testing, building on DS. The resources are intended for experienced technical users, namely modelers in the DMDU field, water resources, and water supply facility managers. Finally, eight resources cover all three levels of analysis, thus showcasing how users from different backgrounds, skills, and familiarity with DMDU methodologies can approach comparable methods differently. Key examples in this category include Pathways2Resilience (2024) on pathways for European regions at various maturity levels, Mendoza et al. (2018) for the Climate Risk Informed Decision Analysis (CRIDA) decision-making framework combining RDM, DS, and DAPP, and Lempert et al. (2021)'s DMDU Guidebook for applications in transportation planning.

### 3.1.4. Resources making use of case studies

Half of the resources ( $n = 14$ ) use case studies to further showcase either elements of the DMDU methodology, the usability of presented tools, and/or expected outputs. In two cases, resources reference external sources with detailed descriptions of case studies, or case studies are lightly described in annexes (Rissik et al., 2014; Ministry for the Environment, 2024). Case studies play a more important role in the rest of the resources, as visualized in Table 1.

Case studies are taken from real-life examples ( $n = 9$ ), or stylized cases are created ( $n = 3$ ), or a combination of the two ( $n = 2$ ). Real-life examples range from the Thames 2100 project (London, UK; Ferranti et al., 2021) to the Assens and Vejle municipalities in Denmark (Danish Coastal Authority, 2020), Latvia (CLIMAAX, 2025), a range of central and north European locations (Abad et al., 2020), the Nile basin (Onencan et al., 2016) and the Western Balkans (Lempert et al., 2021). Stylized cases are instead specifically developed for other resources, as although they may less strongly relate to practice, they remain useful when real-life applications (within, e.g., a specific field or sector) are still in their infancy. This is, for example, the case in Coulter (2019), where a stylized case in British Columbia (Canada) is presented to showcase how adaptation pathways may be applied to agriculture and food production.

## 3.2. Tools to implement DMDU

We identified 16 tools utilized by the DMDU community to facilitate exploratory modeling, analysis, and decision-making, summarized in Fig. 3. Most tools identified in this study apply to any domain ( $n = 13$ ), though three were developed for domain-specific analysis in transportation and water resources systems (column 1 of Fig. 3). Python is the most common interface across collected tools, followed by web applications. Users can interact with two tools using R; two additional tools work with custom Graphical User Interfaces (GUIs). While most tools are accessed via programming language interfaces (i.e., Python), no tool we identified requires advanced coding knowledge, and users familiar with basic syntax can utilize each effectively.

We categorize the tools identified in this study according to their ability to facilitate four components of the taxonomy of DMDU approaches by Kwakkel and Haasnoot, 2019 (Fig. 1) - *generation of alternatives*, *generation of scenarios*, *robustness evaluation*, and *vulnerability analysis*. The fifth component of the taxonomy, *policy architecture*, may be explored using any of the identified tools but is not an explicit focus of any tool. Of the 16 tools we identified, nine facilitate the generation of alternatives, nine contain components for generating scenarios, six can be used to quantify robustness, and eight facilitate vulnerability analysis. Three tools, the EMA Workbench (Kwakkel, 2017), Rhodium (Hadjimichael et al., 2020), and openMORDM (Hadka et al., 2015), can facilitate analysis of all components of the DMDU taxonomy. In the remainder of this section, we provide a detailed

overview of the capabilities of the tools identified for each element of the taxonomy and highlight commonalities and differences between the tools.

### 3.2.1. Tools for the generation of alternatives

In the DMDU taxonomy, the generation of alternatives refers to determining how policy options, or the components thereof, are configured given the specification of available policy levers (Kwakkel and Haasnoot, 2019). The taxonomy classifies strategies for generating alternatives into four broad categories: *prespecified*, *iterative*, *exploration*, and *search*. Tools that evaluate prespecified alternatives analyze combinations of policy levers predetermined by the user. All tools identified in this study with the capability of exploring policy can be used as prespecified by the user. For example, the Colorado River Basin Post-2026 Operations Exploration Tool – built and maintained by the United States Bureau of Reclamation to enable Colorado River Basin stakeholders and other interested parties to explore operational strategies as part of a multi-stakeholder policy development process – allows users to input the river basin management strategies into the tool. The Pathways Generator, a tool by Deltares, enables users to specify adaptation tipping points and resulting policy actions before generating a suite of policy pathways across uncertain and changing future conditions.

*Iterative* generation of alternatives refers to a cyclical process where analysts start with prespecified policy options, conduct experiments to stress test and evaluate these options, and then refine new policies based on the experimental results. Iterative search tools require capabilities for exploring performance across multiple future states of the world, evaluating performance, and synthesizing results to develop updated policies. While all tools we identified may technically be utilized for the iterative generation of alternatives, in Fig. 3, we highlight tools with specific capabilities to facilitate iterative generation, including easy-to-implement data structures, functions, and output. Of the policy generation tools we identified, four tools, EMA Workbench, Rhodium, openMORDM, and OpenMOLE, are well suited for the *iterative* generation of alternatives.

The third category of alternative generation, *exploration*-based strategies, relies on the careful design of experiments to enumerate feasible policy alternatives across a broad sampling of policy lever combinations. Sampling strategies used for *exploration* may include Monte Carlo sampling, Latin Hypercube sampling, or factorial sampling methods. The tools identified included capabilities for generating alternatives through *exploration*. The EMA Workbench and Rhodium are declarative Python libraries that include a suite of tools that facilitate the design of experiments using multiple sampling strategies. openMORDM, an R library, and OpenMOLE, a custom toolset developed to explore, diagnose, and optimize numerical models, also contain a suite of tools for sampling high-dimensional spaces, which can be adapted to alternative policy actions.

While *exploration*-based strategies may yield insights about the performance of a sampling of policy alternatives, many real-world decision problems have too many potential combinations of decision variables to explore practically, even with the most advanced high-performance computing facilities. For example, a problem where a user must specify the value of 12 decision variables, each with 10 possible values, has one trillion ( $10^{12}$ ) possible alternative combinations. *Search*-based strategies for generating alternatives utilize optimization algorithms to efficiently search for combinations of feasible decision variables and return a small set of high-performance options. Four tools identified in our survey contain functionality to facilitate the search-based generation of alternatives: EMA workbench, Rhodium, openMORDM, and OpenMole. Each tool uses Multi-objective optimization to discover sets of high-performance options. The EMA workbench and Rhodium utilize Multi-objective Evolutionary Algorithms (MOEAs) through the Project Platypus Python library, which contains a suite of MOEAs that users can select. openMORDM includes a similar set of MOEAs that are written

**Table 1**

Case studies explored in the analyzed resources. We compare the sectoral focus of the case study, its location, and projected change period, and what the case study was used to showcase within the respective resource. Note how the sectoral focus of individually presented case studies does not always match that of the resource. Focus is distinguished into sea level rise (SLR), water resource management (WRM), water management (WM), Community Engagement (CE), Infrastructure & Transport (IT), Energy (E), and Product Design (PD).

	Focus	Publication	Location	Uncertainty range
Develop pathways or options	E	Marchau et al. (2019)	Global	Up to 2200
	SLR	Ferranti et al. (2021)	London, UK	SLR +4 m
		Ferranti et al. (2021)	Somerset County, UK	Flooding +50%
	WRM	Ferranti et al. (2021)	London, UK	2020 to 2037
		Coulter (2019)	British Columbia State, Canada *	-
		Marchau et al. (2019)	New Zealand	2015 to 2100
Mendoza et al. (2018)		The Netherlands *	Flood plain +20%	
WM	Baker et al. (2016)	London, UK	2020 to 2060	
	Danish Coastal Authority (2020)	Veijle and Assens, DK	Discharge +24 m <sup>3</sup> /s, SLR +5 m	
Generation of scenarios	SLR	California Sea Level Rise Guidance (2024)	California State, USA	SLR +2 m
	WM	CLIMAAX (2025)	Latvia	2025 to 2100
CE	van den Ende et al. (2022)	Various	Various	
	Wardekker et al. (2020)	Various	2020 to 2200	
Robustness evaluation	E	Marchau et al. (2019)	Australia	Next 20 years
	IT	Marchau et al. (2019)	Colorado, USA	2020 to 2060
		Marchau et al. (2019)	Netherlands	2015 to 2100
	PD	Marchau et al. (2019)	-	-
	WRM	Mendoza et al. (2018)	Water Treatment Plant, The Zambia	Climate +7% drier
		Baker et al. (2016)	East Anglia, UK	-
Baker et al. (2016)		London, UK	-	
Vulnerability analysis	WRM	Baker et al. (2016)	South East England	-
		Baker et al. (2016)	South East England	2015 to 2030
		Baker et al. (2016)	London, UK	2010 to 2060
		Baker et al. (2016)	London, UK	-
		Baker et al. (2016)	Colorado Springs, US	-
	IT	Lempert et al. (2021)	Western Balkan	-
Lempert et al. (2021)	Africa	-		
Ray and Brown (2015)	Sub-Saharan Africa *	-		

in R. OpenMole incorporates a single MOEA, the Nondominated Sorting Genetic Algorithm II (NSGA-II), an algorithm also included in EMA workbench, Rhodium, and openMORDM.

### 3.2.2. Tools for the generation of scenarios

In the DMDU taxonomy, *Generation of scenarios* covers how context scenarios are identified given various uncertainties. Scenarios can either be prespecified by decision-makers, developed through *exploration*, or discovered through guided *search*. Prespecified scenarios are often designed to capture a maximally diverse representation of future conditions to present decision-makers with narratives of system performance (Bradfield et al., 2005). While there are many resources from outside DMDU literature on developing prespecified scenarios, no DMDU tools identified in this study have explicit capabilities for crafting prespecified scenarios. This is likely because *prespecified scenarios* require a strong understanding of how a system will behave under uncertainty and may be biased by status quo assumptions (Moallemi et al., 2020b). As an alternative, many DMDU tools facilitate scenario generation through *exploration*, which, like the generation of alternatives through *exploration*, uses carefully designed experiments that rely on sampling methods to generate plausible sets of future states of the world. The broad sampling conducted in exploratory experiments shifts the focus from traditional “predict-then-act” paradigms to “consequence-driven” analysis that allows decision-makers to examine an extensive range of “what-if” scenarios during the planning (Lempert and Collins, 2007; Groves and Lempert, 2007).

Many tools we identified in this study are explicitly designed to facilitate exploratory methods for scenario generation. Tools such as EMA

Workbench, Rhodium, OpenMole, TMIP EMAT, and SALib include a variety of sampling methods to generate plausible scenario ensembles as part of broader analysis workflows. Sampling strategies built into these tools include Sobol sequences, full-factorial, fractional-factorial, Latin Hypercube, and Monte Carlo sampling. EMA Workbench, Rhodium, OpenMole, and SALib also include parallel computing modules to facilitate the rapid exploration of scenario ensembles. Search-based scenario generation methods rely on multi-objective optimization to discover consequential future scenarios for evaluation (Kwakkkel and Haasnoot, 2019). To discover consequential scenarios, multi-objective optimization algorithms search through possible future states of the world to identify scenario ensembles that balance multiple criteria, including coverage, density, and interpretability (Kwakkkel and Haasnoot, 2019). Coverage measures how much of the uncertainty space is represented in an ensemble, density measures the decision relevance of ensemble scenarios, and Interpretability measures the complexity of discovered scenarios. Among the tools identified in this study, only the EMA Workbench includes search-based functionality for scenario generation.

### 3.2.3. Tools for the robustness evaluation

Robustness metrics transform the model output into measures that quantify the performance of policy alternatives across future states of the world (McPhail et al., 2018; Lempert, 2003; Herman et al., 2015). In DMDU literature, a wide variety of robustness metrics are utilized (McPhail et al., 2021), including expected value metrics (Wald, 1949), which quantify expected performance across modeled scenarios,

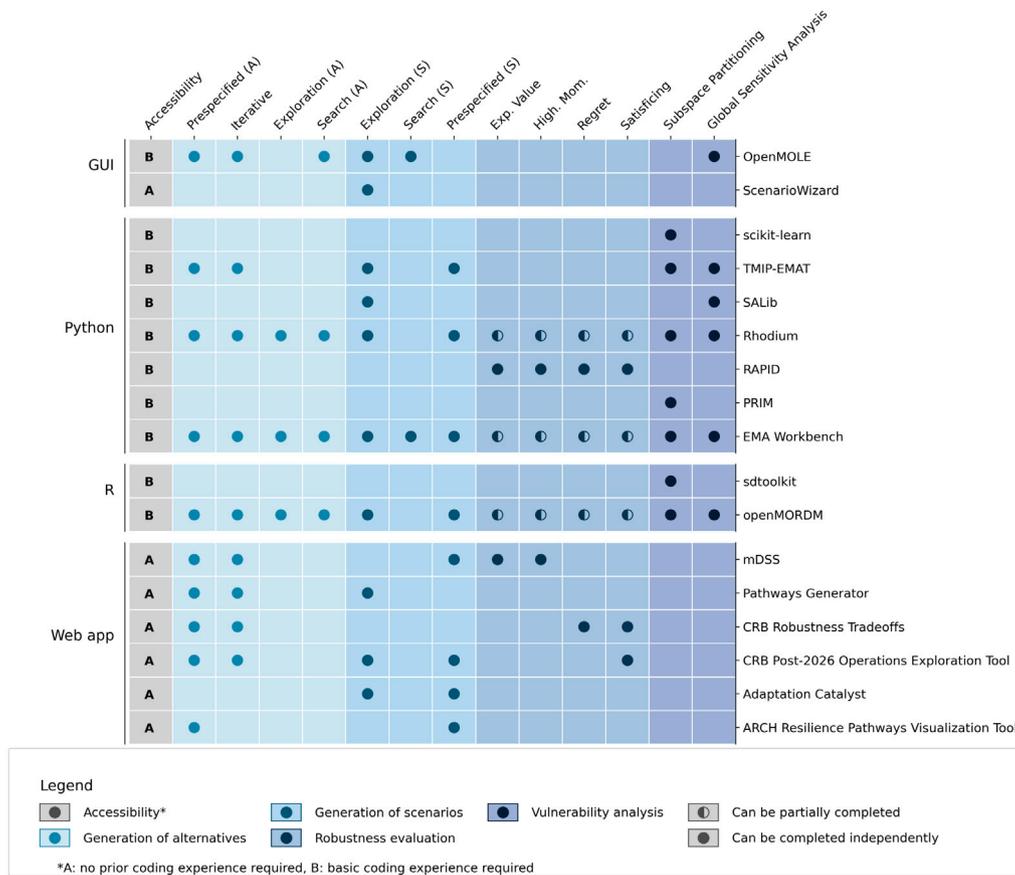


Fig. 3. Summary of the collected tools. A full circle represents a DMDU component that can be completed independently by a given tool. A half circle indicates functionality that can be partially completed by a given DMDU tool. Letters in the accessibility column represent two levels: A - no prior coding experience required, B - basic coding experience required.

higher order moments (McPhail et al., 2018), which measure the variation of system performance across scenarios, regret (Savage, 1951), which measures the deviation from a plausible condition or performance of the best option, and satisficing (Starr, 1963; Herman et al., 2015), which measures the fraction of scenarios where the policy maintains a predefined level of performance. Across the tools identified in this study, only the Robustness Analysis Producing Intelligent Decisions (RAPID) Python package contains explicit capabilities for calculating all four types of robustness metrics. RAPID is built to post-process output from DMDU tools, such as the EMA workbench, and allows users to develop custom robustness metrics for evaluating alternatives. The domain-specific tools designed to support Colorado River management also contain explicit tools to evaluate Regret and Satisficing-based robustness measures of river basin management policies. mDSS, another tool built for water resources decision support, contains capabilities for assessing robustness using expected value and higher-order moments. Results from Rhodium, EMA workbench, and OpenMORDM may be processed manually by users to explore robustness, as demonstrated in Gold (2019).

### 3.2.4. Tools for the vulnerability analysis

Vulnerability analysis refers to analytical techniques used to understand how robustness is influenced by policy levers and uncertainty (Kwakkel and Haasnoot, 2019). Global sensitivity analysis may be used for factor prioritization — identifying the relative influences

of uncertainties or policy levers on outcomes of interest (Reed et al., 2022). Factor prioritization can help decision-makers determine which factors are most important to outcomes of interest and reduce the dimensionality of subsequent model evaluations of the problem by identifying factors that can be fixed in future analyses. Global sensitivity analysis capabilities are a core feature of the SALib Python package, which includes a simple and easy-to-use syntax that can interface with other packages and modeling languages. EMA Workbench and Rhodium have built-in capabilities utilizing SALib global sensitivity analysis methods within their native workflows. OpenMOLE and TMIP-EMAT contain their own sets of independent tools to perform global sensitivity analysis. Another core element of vulnerability analysis in DMDU literature is scenario discovery, a general methodology for using classification and data mining tools to discover a small number of “key driving forces” that influence the outcome of a decision problem (Groves and Lempert, 2007). Subspace partitioning techniques such as the Patient Rule Induction Method (PRIM) delineate consequential regions of the uncertainty space by identifying thresholds across uncertainties. Python implementations of PRIM are contained within the EMA Workbench TMIP-EMAT and Rhodium. PRIM is available in R through the sdtoolkit, and openMORDM. Other subspace partitioning strategies, such as Classification and Regression Trees and their variants, are included in EMA Workbench, Rhodium, and standard Machine Learning packages, such as the scikit-learn Python package.

### 3.2.5. Reflection on tools addressing all relevant categories

Across the DMDU tools identified in this study, the EMA Workbench (Python), Rhodium (Python), and openMORDM (R) stand out for their abilities to facilitate all components of the DMDU taxonomy proposed by Kwakkel and Haasnoot (2019). Importantly, these three tools are open source and open access. The three tools are also model agnostic, which can be integrated with existing modeling frameworks across various programming platforms and languages. OpenMOLE, built for model calibration, and SALib, built for sensitivity analysis, are examples of tools built outside the DMDU community that are highly applicable to DMDU analysis. Specialized tools, such as RAPID, can interface with other DMDU tools to facilitate robustness evaluation and visual analysis, and workflows may easily combine multiple DMDU toolsets within a study. Rhodium and EMA Workbench both have built-in parallel computing capabilities. However, the reliance on Python, a high-level and comparatively slow programming language, limits the scalability of these tools when the runtime of simulation models is significant.

## 4. Discussion and conclusion

In this study, we develop a catalogue of 44 tools and resources utilized by the DMDU community, seeded through a community-wide survey. We analyze their coverage in terms of purpose, scope, and links to key concepts of DMDU, and derive patterns regarding their coverage and gaps. These patterns should not be interpreted as universally representative of all existing tools and resources, but rather as characteristics of the specific set analyzed here. We acknowledge that the study design, particularly its reliance on survey responses and co-author contributions, may introduce limitations and potential biases, for instance by reflecting areas, tools, or methods with which contributors are more familiar. To mitigate this, we sought to ensure balanced representation across categories during the collection period. This study introduces and applies a system to characterize the strengths and focus of existing resources in the context of DMDU, offering first insights into emerging patterns. This work also contains the first open repository ([https://juliuschlumberger.github.io/Repository\\_DMDU\\_Tools\\_Resources/](https://juliuschlumberger.github.io/Repository_DMDU_Tools_Resources/)) of DMDU tools and resources. We intend this repository to be a living document enabling members of the DMDU community to contribute additional tools and resources. We hope that this ongoing, community-driven effort will gradually build a more extensive and representative overview over time.

Through the survey, we identified many resources that provide introductory and high-level guidance, both in terms of general introductions (e.g., Curran et al., 2023; Marchau et al., 2019) and sector-specific information. Based on the collected results, we find that existing sector-specific guidance follows known sectoral biases of the DMDU community towards water (resource) management and water supply and flood protection infrastructure (e.g., Ministry for the Environment, 2024; Lempert et al., 2021; Warren et al., 2021). Future community efforts should seek to expand sector-specific guidance to cover emerging DMDU focus areas such as energy and healthcare. Researchers and practitioners in emerging areas of DMDU application can use DMDU tools and resources provided in our catalogue for templates on how to successfully structure sector-specific guidance and tools. For example, frameworks for structuring and guiding DMDU analysis in the water sector and transportation sectors, such as Fer-ranti et al. (2021), Deltares (2014), and Lempert et al. (2021), can inform the development of sector-specific resources for healthcare and energy applications. Similarly water sector tools, such as the CRB Robustness Tradeoffs dashboard and the CRB Post-2026 Operations Exploration Tool serve as strong examples for the operationalization of DMDU concepts in real-world planning problems. Based on the general

availability of methodological guidance, we believe there is little need for further resources focusing on non-sector-specific introductions or high-level/conceptual frameworks.

In contrast to the prevalence of high-level guidance resources, our survey results indicate a general lack of in-depth guidance for individual DMDU methods. Of the resources we identified, only Reed et al. (2024), Mendoza et al. (2018), and U.S. Army Corps of Engineers (2019) provide detailed technical guidance regarding specific components of DMDU analysis. Future efforts to advance DMDU in practice should build on these resources to expand available method-specific guidance. The DMDU community should also work to consolidate available guidance into easy-to-use “toolboxes” that walk users through various components of DMDU analysis, similarly to van den Ende et al. (2022). Reviews like Bonham et al. (2025) on vulnerability analysis approaches and overviews of sensitivity analysis methods by Reed et al. (2024) offer good examples of how such toolboxes could be created for the community. Additionally, the DMDU community should look to examples in other fields, such as Warren et al. (2023) – who collected qualitative methods supporting collaborative system analysis – to illustrate how DMDU resources can connect to adjacent research communities that explore similar research themes.

Regarding existing tools highlighted by the DMDU community, survey results indicate a prevalence of easily accessible software platforms supporting most areas of the DMDU taxonomy created by Kwakkel and Haasnoot (2019). While many tools require basic coding skills in Python or R, none of the collected tools require advanced coding skills. The increasing prevalence of AI-assisted coding tools (Gibney, 2025) should further improve the accessibility of these tools in the coming years. Furthermore, most tools are model agnostic, meaning they can easily connect to simulation models built in various software languages (e.g., C++, Fortran, Excel).

Despite the flexibility and accessibility of available tools, a core challenge for the DMDU community remains the development of tools that support scalable DMDU analysis on High-Performance Computing (HPC) systems. Exploratory modeling-centered methods like RDM, scenario discovery, and DS rely on computational experiments involving hundreds of thousands or millions of model simulations. Similarly, multi-objective evolutionary optimization often requires hundreds of thousands of function evaluations to converge to high-quality solution sets. While Python-based tools such as the EMA workbench and Rhodium have native functionality to facilitate parallel computing, their reliance on the Python programming language for implementations of processes such as multiobjective evolutionary optimization can limit the scalability of computational analysis. It may not be suitable for more large-scale ensemble-based workflows. A second challenge for scalable DMDU analysis is the large volume of data that can be produced from ensemble model runs. No identified DMDU tool includes native support or guidance regarding using efficient data structures (e.g., HDF5, NetCDF) to manage large volumes of data. Future development efforts should focus on building accessible frameworks that facilitate DMDU analysis on HPC systems and efficiently manage large volumes of data. These development efforts must be paired with new DMDU resources that guide users through performing analyses on HPC systems.

Finally, our results highlight an opportunity for the community to co-develop tools and resources utilizing emerging forms of interactive media. For example, CLIMAX (2025) and Reed et al. (2024) include embedded interactive coding tutorials that allow users to directly apply theoretical concepts for themselves. Similarly, Reed Research Group (2025) offers a significant breadth of how-to guidance on various topics with a great co-benefit for involved researchers to improve science communication skills. Future developments can help close the gap between DMDU research and practice by co-developing tools and

resources, providing guidance on DMDU concepts, and facilitating their implementation through accessible and scalable coding interfaces.

**CRedit authorship contribution statement**

**Julius Schlumberger:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **David Gold:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Valeria Di Fant:** Writing – review & editing, Writing – original draft, Formal analysis. **Gundula Winter:** Writing – review & editing, Methodology, Conceptualization. **Mehmet Ümit Taner:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Jan Kwakkel:** Writing – review & editing, Methodology, Conceptualization.

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**Appendix A. Survey**

*A.1. General information regarding the resource*

Name of the tool or resource	<i>(free-text)</i>
Short description	<i>Briefly describe what the resource does. Mention strengths and key areas of application.</i>
Keywords	<i>Up to three keywords.</i>
Primary use (Single choice)	<ul style="list-style-type: none"> <li>• Training/Learning/Awareness raising</li> <li>• Testing/Developing new methods</li> <li>• Analysis in the context of DMDU</li> </ul>

Type of resource (Single choice)	<ul style="list-style-type: none"> <li>• Qualitative DMDU analysis</li> <li>• Quantitative DMDU analysis</li> <li>• Case Study</li> <li>• Serious Game</li> <li>• Course/Lecture</li> <li>• Other: _____</li> </ul>
Primary users (Multiple choice)	<ul style="list-style-type: none"> <li>• Students</li> <li>• Practitioners</li> <li>• Researchers</li> <li>• Policy-Makers</li> <li>• Other: _____</li> </ul>
Public availability	<ul style="list-style-type: none"> <li>• Yes</li> <li>• No</li> </ul>
Links to documentation	<i>Add URLs or references where the resource is described.</i>
Thematic areas (Multiple choice)	<ul style="list-style-type: none"> <li>• Climate Change Adaptation</li> <li>• Health</li> <li>• (National) Security</li> <li>• Infrastructure</li> <li>• Energy Transition/Mitigation</li> <li>• Water</li> <li>• Other: _____</li> </ul>
Policy cycle application	<p><i>The policy cycle describes how policy is formulated and evaluated.</i></p> <ul style="list-style-type: none"> <li>• Agenda Setting: Foresight scanning, emerging issues</li> <li>• Formulation: Policy impact assessments</li> <li>• Adoption: Support &amp; Advice to regulatory bodies</li> <li>• Implementation: Verification methods, guidance</li> <li>• Evaluation: Assess efficiency &amp; effectiveness</li> <li>• Support: Crisis response, updates</li> </ul>
DMDU methods (Multiple choice)	<ul style="list-style-type: none"> <li>• Robust Decision Making</li> <li>• Dynamic Adaptive Policy Pathways</li> <li>• Info-Gap Theory</li> <li>• Decision-Scaling</li> <li>• Other: _____</li> </ul>
Spatial scale of application	<ul style="list-style-type: none"> <li>• Not limited</li> <li>• Local</li> <li>• Regional</li> <li>• National</li> <li>• Global</li> </ul>
Quantitative analysis types	<ul style="list-style-type: none"> <li>• Decision analysis</li> <li>• Policy generation</li> <li>• Scenario generation</li> <li>• Vulnerability analysis</li> <li>• Robustness analysis</li> <li>• Flexibility analysis</li> </ul>
Additional comments	<i>(free-text)</i>

**Appendix B. Collected resources and tools**

See [Tables B.2](#) and [B.3](#).

**Data availability**

Data will be made available on request.

**Table B.2**

Short description of all resources.

Authors	Short description
<a href="#">Abad et al. (2020)</a>	The serious game 'RAMSETE III' simulates crisis management decision-making under uncertainty. Players collaborate to handle evacuation timing during a storm, learning effective communication and strategic planning in critical situations.
<a href="#">Baker et al. (2016)</a>	Guidance for decision-making in water resource management, focusing on investment appraisal and optimization for long-term planning. The framework emphasizes sustainability and robustness in resource allocation.
<a href="#">Bonham et al. (2025)</a>	This scientific resource reviews existing vulnerability analysis approaches in the context of DMDU to offer a taxonomy and different purposes.
<a href="#">Bosomworth et al. (2015)</a>	A playbook guiding users through climate change adaptation pathways. It outlines five key activities ('plays') for planning and adaptation, with brief descriptions and references to additional resources for detailed guidance.
<a href="#">California Sea Level Rise Guidance (2024)</a>	This report integrates the best available science on sea level rise and coastal hazards. It provides practical guidance for planning under different scenarios, including adaptation pathways for California's coastal management.
<a href="#">CLIMAXX (2025)</a>	A handbook on quantifying climate risks for hazards like floods, droughts, and heatwaves. It includes tools for customizing and uploading CRAs (climate risk assessments), fostering iterative learning with future scenario exploration.
<a href="#">Coulter (2019)</a>	Two reports provide guidance for agricultural communities on shared adaptation goals and pathways. A technical guide complements this with a detailed application of adaptation in food production, including a hypothetical case study.
<a href="#">Curran et al. (2023)</a>	A guide for planning under uncertainty, offering methods for decision-making in sectors like land-use, infrastructure, and coastal adaptation. It distinguishes between creation and analysis approaches, with examples from various fields.
<a href="#">Danish Coastal Authority (2020)</a>	A concise guide to dynamic planning for climate adaptation and flood risk management. It aims to help municipalities in Denmark adopt adaptive, risk-based approaches to planning and mitigation.
<a href="#">Deltares (2014)</a>	Sustainable Delta' is a serious game for stakeholders to understand water systems and plan restoration measures. Teams develop a water management plan addressing challenges like flooding and drought in fictional river settings.
<a href="#">Ferranti et al. (2021)</a>	This briefing introduces adaptation pathways for infrastructure resilience under uncertain future climate conditions. It includes a framework with nine steps for developing pathways (e.g., defining scope, identifying hazards, generating options, and evaluating pathways). Case studies from the Thames Estuary, Dutch Delta Programme, and others illustrate the method, alongside stakeholder feedback and benefits. The approach combines <a href="#">Quinn et al.'s (2018)</a> Rail Adapt framework with practical applications for UK infrastructure planning.
<a href="#">Lempert et al. (2021)</a>	A guide for incorporating Decision Making Under Deep Uncertainty (DMDU) into transportation planning. It reviews methods like scenario planning and Adaptive Pathways, with steps for applying these techniques to IDB projects.
<a href="#">Marchau et al. (2019)</a>	This can be seen as the general introduction to DMDU. It offers insights into the underlying concepts and provides examples for all relevant cases
<a href="#">Mendoza et al. (2018)</a>	A decision-making framework for climate risk-informed analysis (CRIDA), targeting water resource managers and infrastructure planners. It supports robust planning under uncertainty for flood risk and water supply management.
<a href="#">Ministry for the Environment (2024)</a>	New Zealand's Ministry developed this guidance for adapting to coastal hazards under climate change. It follows a 10-step decision cycle, integrating short- and long-term planning for adaptive pathways and coastal risk management.
<a href="#">Onencan et al. (2016)</a>	WeShareIt' is a collaborative board game for policymakers to balance energy, food, and nature needs at basin and national levels. Players explore strategies to strengthen collaboration and prepare for future uncertainties.
<a href="#">Pathways2Resilience (2024)</a>	Pathways2Resilience project guidance outlines a step-by-step Regional Resilience Journey framework. It includes climate strategy, action, and finance plans, tailored for project managers and technical experts. Scenarios are addressed briefly.
<a href="#">Petersen et al. (2013)</a>	Guidance on managing and communicating uncertainty in assessments. It supports analysts in addressing critical uncertainties, framing problems, and involving stakeholders, leading to better decision-making under uncertainty.
<a href="#">Ray and Brown (2015)</a>	This guidance was developed to introduce a climate stress-testing methodology for water resource management infrastructure. It offers insights into the fundamental concepts, the how-to guidance, and a specific case for illustration. Furthermore, high-level information is provided regarding other DMDU methodologies.
<a href="#">Reed et al. (2024)</a>	This guidance text has been developed in support of the Integrated Multisector Multiscale Modeling (IM3) Science Focus Area's objective to formally integrate uncertainty into its research tasks. The guidance offers a deep-dive into methods to be used for sensitivity analysis and exploration of uncertainty. Along the introduction of the underlying concepts, the resource offers tutorials for the application.
<a href="#">Reed Research Group (2025)</a>	A blog by Pat Reed's team at Cornell focusing on computational approaches like Multiobjective Evolutionary Algorithms, simulation models, and visualization for solving complex planning problems.
<a href="#">Rissik et al. (2014)</a>	A technical guide for Australian natural resource managers on adaptation planning. It addresses challenges intensified by climate change and outlines a flexible planning framework to remain effective under changing conditions.
<a href="#">Siebentritt and Stafford Smith (2016)</a>	A non-technical guide to developing and applying adaptation pathways in organizations, emphasizing critical elements for participatory planning. The process is adaptable for quantitative inputs but focuses on user-friendly methods.
<a href="#">U.S. Army Corps of Engineers (2019)</a>	An engineering pamphlet offering procedural guidance for analyzing future sea level change (SLC) impacts on USACE projects. It focuses on assessing physical and ecological risks, but not as formal planning guidance.
<a href="#">van den Ende et al. (2022)</a>	A step-by-step guide on engaging citizens in foresight exercises to build climate-resilient futures. It includes methods like exploratory scenarios, pathways, and case studies from multiple European countries.
<a href="#">Wallis et al. (2015)</a>	Two complementary reports: a playbook on adaptation pathways detailing five activities and a technical report exploring these steps in depth. The latter includes links to resources and literature, enhancing understanding of climate change adaptation planning.
<a href="#">Wardekker et al. (2020)</a>	This approach integrates incremental, participatory scenario planning with local communities to develop desirable futures. It inventories 'hinge points' for critical challenges and uses real-world case studies to refine methods.

**Table B.3**  
Short description of all tools.

Tool name	Short description	Citation
Open MOLE	A platform to run, explore, optimize, and perform diagnostics on a numerical model.	Romain Reuillon, Mathieu Leclaire, and Sebastien Rey-Coyrehourcq, OpenMOLE, a workflow engine specifically tailored for the distributed exploration of simulation models, published in Future Generation Computer Systems, 2013.
ScenarioWizard	A software application for the creation of qualitative scenarios using Cross-Impact Balances.	Weimer-Jehle, W. (2024–25). ScenarioWizard: Constructing consistent scenarios using cross-impact balance analysis [Web application]. ZIRIUS, University of Stuttgart. Access at <a href="https://www.scenariowizard.org">https://www.scenariowizard.org</a> .
scikit-learn	A Python library supporting basic machine learning algorithms.	Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., ... & Duchesnay, É. (2011). Scikit-learn: Machine learning in Python. the Journal of machine Learning research, 12, 2825–2830.
TMIP-EMAT	A platform supporting exploratory modeling and analysis. Primarily focused on the transportation sector.	Lemp, J., Rossi, T., Newman, J., & Copperman, R. B. (2021). Uncertainty in Travel Forecasting: Exploratory Modeling and Analysis TMIP-EMAT: A Desk Reference (No. FHWA-HEP-21-032). United States. Federal Highway Administration. Office of Planning, Environment, and Realty.
SALib	A Python library for global and local sensitivity analysis.	Herman, J. and Usher, W. (2017) SALib: An open-source Python library for sensitivity analysis. Journal of Open Source Software, 2(9). doi:10.21105/joss.00097
Rhodium	A Python library for robust decision making, many objective robust decision making, and exploratory modeling	Hadjimichael, A., Gold, D., Hadka, D., & Reed, P. (2020). Rhodium: Python library for many-objective robust decision making and exploratory modeling. Journal of Open Research Software, 8.
RAPID	A software package for identifying robust decision alternatives	McPhail, C., Maier, H. R., Westra, S., van der Linden, L., & Kwakkel, J. H. (2021). Guidance framework and software for understanding and achieving system robustness. Environmental Modelling & Software, 142, 105059.
PRIM	An implementation of the Patient Rule Induction Method in Python	Hadka, D. and Plevin, R. (2024). Patient Rule Induction Method for Python. <a href="https://github.com/Project-Platypus/PRIM?tab=readme-ov-file">https://github.com/Project-Platypus/PRIM?tab=readme-ov-file</a>
EMA Workbench	A research platform for using exploratory modeling to analyze complex and uncertain systems.	Kwakkel, J. H. (2017). The Exploratory Modeling Workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making. Environmental Modelling & Software, 96, 239–250.
sdtoolkit	An R package to perform scenario discovery using PRIM	Bryant, B. (2009). <a href="https://uncertainfutures.github.io/tools/sdtoolkit/">https://uncertainfutures.github.io/tools/sdtoolkit/</a>
openMORDM	An R package for many-objective robust decision making	Hadka, D., Herman, J., Reed, P., & Keller, K. (2015). An open source framework for many-objective robust decision making. Environmental Modelling & Software, 74, 114–129.
mdSS	Decision support tool to facilitate participatory processes for integrated management of natural resources	Giupponi, C., 2007. Decision Support Systems for Implementing the European Water Framework Directive: the MULINO approach. Environmental Modelling and Software 22, 248–258.
Pathways Generator	A tool to explore policy pathways using an interactive visual dashboard	<a href="https://publicwiki.deltares.nl/spaces/AP/pages/119053001/Pathways+Generator">https://publicwiki.deltares.nl/spaces/AP/pages/119053001/Pathways+Generator</a>
CRB Robustness Tradeoffs	An interactive tool for exploring robustness of management policies in the Colorado River Basin	Bonham, N., Kasprzyk, J., Zagona, E., & Smith, R. (2024). Interactive and multimetric robustness tradeoffs in the Colorado River basin. Journal of Water Resources Planning and Management, 150(3), 05023025.
CRB Post-2026 Operations Exploration Tool	A web-based platform to explore different operational strategies for water management on the Colorado River Basin through a DMDU lens.	Smith, R., Martin, S., Zagona, E. A., Kasprzyk, J. R., Bonham, N., Daniels, N., & Jerla, C. (2024, June). The Colorado River Basin Post-2026 Operations Exploration Tool: Connecting Policymakers and Stakeholders Through a Web-Based Decision-Support Platform. In Water Science Conference (WaterSciCon24 (pp. 207–02).
Adaptation Catalyst	A software for visualizing climate pressures, adaptive capacity, and co-benefits and costs of climate adaptation strategies.	Mcevoy, S., Hoogvliet, M., van Deursen, W., (2019). Adaptation Catalyst eTool. Deltares. <a href="https://publicwiki.deltares.nl/spaces/AP/pages/142674737/Adaptation+Catalyst">https://publicwiki.deltares.nl/spaces/AP/pages/142674737/Adaptation+Catalyst</a>
ARCH Resilience Pathways Visualization Tool	A tool for assessing the current resilience level of a historical area using an online self-assessment questionnaire.	Luckerath, D., Milde, K., Wischott, V., & Klose, A. (2024). The ARCH Resilience Assessment Dashboard: An Online Scorecard Approach to Assess the Resilience of Historic Areas. in EGU General Assembly Conference Abstracts.

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